Adaptive Cycling: Enhancing Safety, Comfort, and Learning on a Bicycle for a Child with Achondroplasia

MQP

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Abstract

Children with Achondroplasia, the most prevalent form of dwarfism, face limited options for bicycles due to growth patterns and unique body proportions (short limbs and long torso). This project aims to design, prototype, and test a method to adapt a children's bicycle to comfortably fit a child with Achondroplasia and facilitate learning. We collaborated with the family and a 6-year-old child to identify unique product needs and user interfaces as well as conducted biomechanical analyses. The initial prototype incorporated "off-the-shelf" materials and hardware that proved the feasibility of modifying a 12" balance bicycle. The prototype was further improved via customization of crank length and back wheel brackets. Through testing and a user fit assessment, we successfully developed a bicycle that addresses the unique needs of a child with Achondroplasia while also holding paramount safety, comfort, and enhancement of the learning experience.

1. Introduction

Achondroplasia, the most common form of dwarfism, affects more than 250,000 people globally (Pfeiffer et al., 2021). Achondroplasia is a bone growth disorder that results in dwarfism due to a genetic mutation. Children with Achondroplasia have growth delays with shorter limbs and a longer torso making their proportions different than their average peers. Due to their unique small size and stature, bicycles tailored for children with Achondroplasia are not commonly found on the market. Our 6-year-old client with Achondroplasia dreams of learning to ride on a bicycle that will fit her body mechanics and size.

The goal of this project is to design, develop, and test a method to adapt a children's bicycle to comfortably fit a child with achondroplasia and facilitate learning. This goal was approached via 3 main objectives:

1. Develop a bicycle with adjustable features to maximize comfort and accommodate the physical characteristics of a child with Achondroplasia
2. Facilitate learning to ride by adapting the bicycle with features specifically tailored to support the learning process for children
3. Prioritize safety and conduct rigorous testing to ensure the bicycle meets safety standards.

After comparing different methods to adapt a bicycle to fit a child with Achondroplasia the team decided to modify a balance bicycle with added components. This method was translated to the design process, with the bicycle frame first lowered to accommodate a rider with an 11-inch inseam, followed by the incorporation of a gear mechanism while maintaining frame integrity, and lastly, addressing comfort and ergonomics to best support the rider.

Our primary deliverable was a custom fit bicycle that works for the client's unique geometry while enhancing safety, comfort, and the learning experience for our client as a first-time rider.

2. Literature Review

The following literature review describes the physical characteristics of Achondroplasia, existing bicycles designed for people with dwarfism, and a review of how children's bicycles should fit their body.

2.1 Achondroplasia

The most common form of dwarfism, Achondroplasia, affects more than 250,000 people globally (Pfeiffer et al., 2021). Achondroplasia is a result of a mutation in the FGFR3 gene that affects bone and cartilage growth (Pfeiffer et al., 2021). This makes the clinical features of a person with Achondroplasia include small stature, disproportional shortening of the legs and arms, macrocephaly with frontal bossing, midface hypoplasia, small chest size, abnormal curvature of the spine (kyphosis, lordosis), short fingers and trident-shaped hands, joint hypermobility in hips and knees, and tibial bowing (Pfeiffer et al., 2021). The center of gravity in a person with Achondroplasia is shifted cranially, meaning their center of gravity is higher up on their body compared to their average peer.

Growth and development of people with Achondroplasia is delayed due to effects of bone and cartilage growth. Height, arm length, and leg length develop far below the average population (Neumeyer et al., 2021). Head size shows accelerated growth in early infancy. This is because brain tissue volume and ventricular and extra-cerebral liquor spaces increase in children with Achondroplasia (Neumeyer et al., 2021). Children with Achondroplasia have reduced muscle strength in almost all muscle groups (Takken et al., 2007). Lower muscle strength may be caused by a decrease in muscle mass for their age due to the reduced neuromuscular coordination, or by altered biomechanics (Takken et al., 2007). Additionally, people with Achondroplasia do not have average muscle tone due to having short bones in combination with average length of muscles in their extremities. This causes relative muscle hypotonia and decreased muscle strength (Takken et al., 2007). However, shoulder abductor muscle strength was average, compared to their peers as these muscles are less affected by the short posture (Takken et al., 2007).

Joint kinematics and kinetics may be different in children with Achondroplasia, making their walking pattern different compared to their peers. The shorter legs in a person with Achondroplasia affect the time and distance parameters of walking, this reduces stride length and lowers walking speed (Broström et al., 2022). Other factors that could affect walking function include reduced lower limb muscle strength, relatively longer foot-to-leg ratio, large head size, limited elbow extension, and a broad pelvis (Broström et al., 2022). Children with achondroplasia have displayed kinetic deviations at the hip, knee, and ankle, consistent with a flexion pattern, along with reduced peak hip abduction movement (Broström et al., 2022).

Achondroplasia comes with many complications in childhood and adult life including back, leg, and joint pain, respiratory issues, tingling/numbness in extremities, hydrocephalus, and foramen magnum compression (Pfeiffer et al., 2021). Infants may also experience delays in developmental milestones including gross motor, fine motor, communication, and feeding skills (Pfeiffer et al., 2021). 75% of children and adolescents with this condition struggle with walking for extended periods of time, tire easily, and experience low stamina (Broström et al., 2022). Children may have reduced exercise capacity as the result of hypoactivity caused by restricted exercise-related functions due to specific pathophysiological factors (Takken et al., 2007). People with Achondroplasia tend to have a higher breathing frequency and need to ventilate more, giving them an elevated heart rate (Takken et al., 2007). This implies that people with this condition have a reduced cardiac stroke volume during exercise as a result of their smaller thoracic volume (Takken et al., 2007).

2.2 Existing Adaptive Bicycles for Achondroplasia

Research regarding adaptive bicycles returns limited options and success stories pertaining to a bicycle made for people, and more specifically, children with disproportionate dwarfism or Achondroplasia. The UK bicycle manufacturer, Islabikes, is at the forefront of making biking accessible for people with dwarfism. The company has become the first bicycle manufacturer in the world to mass-produce models specifically designed for the requirements of people with disproportionate dwarfism. Tim Goodall, managing director of Islabikes, said that inspiration for the line came after having a number of customers with dwarfism come into their bicycle shops and ask for children's bicycles that they could adapt to work for them (Walker, 2022). This pattern of requests ultimately led the company to design the JONI bicycle line specifically for their customers with dwarfism. The bicycle was developed in association with the Dwarf Sports Association (DSA), an organization that strives to make sports and activities more accessible for individuals with Dwarfism. The bicycle consists of an ultra-low step-through frame, shorter cranks, handlebars that curve back slightly, brakes designed for use with smaller fingers, and either 20-inch or 24-inch tires. The JONI is made for adults with disproportionate dwarfism. Although Islabikes does not have a custom model for children with disproportionate dwarfism, the company still offers amended versions of existing children's bicycles (Walker, 2022). The bicycle design came with some challenges, as it was difficult to produce steel tubes strong enough to support the ultra-low step-through design of the frame (Walker, 2022). Despite challenges, Islabikes has successfully made biking more accessible for adults with dwarfism, breaking down the barrier of finding a bicycle that fits as well as a bicycle that adults with dwarfism can afford compared to a custom-built model.

Although Islabikes has found success in the adult market of bicycles for dwarfism, there is a gap in children's models. The smallest children's pedal bicycles (12-inch wheels) typically require riders to have an inseam length of 14 inches to 18 inches, which does not accommodate the average inseam length of a female 5–6-year-old child with Achondroplasia (10 inches - 13 inches)(del Pino et al., 2018). A group of undergraduate students from Wichita State were faced with a similar problem. They had to create a bicycle for Jed, an 8-year-old boy with achondroplasia, who is pictured in Figure 1. Their criteria included proper wheel size, ergonomically correct posture while riding, ease of getting on and off the bicycle, and adjustable as Jed grows. The team went through a number of steps to get to their final product including: meeting Jed, concept design, prepping the bicycle for modifications, removing the top member of the frame. Painting the bicycle, and final assembly. The team determined a list of design features and modifications that would need to be made including raising the handlebar, removing the top bar from the frame, repainting the bicycle, and general cleaning and maintenance. The team chose to work with an existing 14-inch bicycle frame and install new pedals, tires, bell, and training wheels (WSUAssistiveTech, n.d.).

Figure 1: Jed on his Bicycle made by a Group of Undergraduate Students from Wichita State

2.3 Learning to Ride a Bicycle

Our team met with Finn Sinsigalli, a bicycle mechanic at Riverside Cycle in Manchester, MA, to learn more about various bicycle styles, what makes children's bicycles unique, and how to fit a child for a bicycle. Children are often introduced to bicycling with balance bicycles. Balance bicycles are bicycles without pedals as seen in Figure 2. They are powered by the child pushing off the ground with their legs,

and stopped by the child putting their feet on the ground. While the bicycle is moving, the child can hold their feet up or rest them on pegs and practice balancing in a similar way to riding a typical bicycle. Sinsigalli strongly recommended using balance bicycles to teach a child to ride a bicycle.

Figure 2: Example of a Balance Bike (No Pedals)

The other common way children are introduced to bicycling is through training wheels. Training wheels are attached on either side of the back wheel of a typical bicycle. These bicycles are powered by pedaling and stopped by using the typical brakes built into the bicycle. They do not require the child to balance on their own.

There are also different options for how children learn how to brake when learning to ride a bicycle. Both coaster brakes, where the child pedals backwards to stop, and handle brakes, where the child squeezes a lever on the handle, were discussed. Examples of coaster and handle brakes can be seen in Figure 3 below. Sinsigalli recommended coaster brakes for small or weak hands but informed us that both methods could be used on the same bicycle.

Figure 3: Hand Brake vs. Coaster Brakes Diagram

When children are learning how to ride bicycles, there are several recommendations to improve comfort and balance. The first is that a child should have both feet flat on the floor when they are sitting on the saddle (Ulrich et al., 2011). This means the saddle height should be equal to their inseam. They should be able to rest their arms comfortably on the handlebars with a slight bend in the elbow (*Kids Bike Fit Guide | Liv Cycling US*, n.d.). Lastly, their knee should be directly above the pedal when the crank is in a 3 o'clock position (K. Wolfson, personal communication, October 5, 2023). The correct riding position of a child on a bicycle can be seen in Figure 4. These are all factors we must keep in mind when modifying a bicycle to fit the client's body mechanics.

Figure 4: Correct Riding Position of Child on a Bicycle

Another factor to consider is the center of gravity. A low center of gravity is preferred for children learning to ride a bicycle, as it facilitates their balance and makes it easier to ride at low speeds (PT, 2021). As mentioned earlier, people with achondroplasia have a higher center of gravity. With this, weight may need to be added to a bicycle for the client to compensate for her very high center of gravity and facilitate her balance while riding. However, it is recommended that a bicycle does not exceed more than 40% of the child’s weight (PT, 2021).

2.4 Accessibility in Learning How to Ride a Bicycle

Learning how to ride a bicycle is a challenge for children, regardless of their physical abilities. Children with disabilities experience a more challenging learning curve while learning how to ride a bicycle, and sometimes give up entirely. Ulrich et al. uncovered some of these hurdles that are present when children with disabilities learn how to ride a bicycle in a study conducted. The study investigated physical activity and health related outcomes of teaching children with Down Syndrome to ride a 2-wheel bicycle. Sadly, there is a common trend of people with disabilities being less likely to be active than the general population. This can result in strain on families and healthcare systems (Ulrich et al., 2011). The challenge comes with finding ways to get people with disabilities active and exercising. Bicycle riding is one activity that allows children to engage in a physical activity that also has a substantial social aspect to it. Bicycle riding is something that children can do with their families, friends, and members of their community. Unfortunately, children with Down Syndrome often never learn how to ride a 2-wheel bicycle due to some of their developmental delays (Ulrich et al., 2011). Therefore, by teaching children with Down Syndrome how to ride a bicycle, they can become more active and reduce sedentary behavior.

In addition to focusing on the health benefits of teaching children with Down Syndrome how to ride a bicycle, the paper also introduces the "Lose the Training Wheels" bicycle training intervention program. The Lose the Training Wheels program is a 5-day training program with individual instruction for 75 minutes a day. The program is offered in a summer camp style with instructors and professionally trained staff for the clients. Adapted bicycles are used instead of a standard bicycle. The adaptations to the bicycle include roller wheels that replace the back wheel, as well as a handle attached to the rear for use by the trainer (Ulrich et al., 2011). See Figure 5 below for a visual of the specially engineered adapted bicycle provided by Lose the Training Wheels organization.

Figure 5: Specially Engineered Adapted Bicycle Provided by Lose the Training Wheels Organization

The training bicycle has a series of 8 roller wheels that are specifically designed to simulate an actual tire, while providing more stability and allowing riders to gain confidence. The wheels taper progressively from roller 1 to roller 8. The starting roller wheels (1 and 2) allow riders to pedal continuously without the fear of falling and to learn to stop and place their feet firmly on the floor. The most tapered rollers, 7 and 8, are used on participants' bicycles who have demonstrated good control (Ulrich et al., 2011). Decisions as to the progression of the roller wheels on the bicycle are decided by professional staff based on speed of pedaling, rider lean into curves, use of the handlebars to turn and control the bicycle, and overall relaxed posture of the rider (Ulrich et al., 2011). The study concluded that the training intervention program "Lose the Training Wheels" was successful in teaching children with Down Syndrome how to ride a 2-wheel bicycle, thus increasing their activity level and overall health. By introducing similar training programs for children with disabilities, the challenges and hurdles often associated with learning how to ride a bicycle can be eliminated, allowing bicycle riding to be a more accessible activity for all children.

2.5 Preliminary Interviews with Bicycle Shop Experts

Interviews were conducted with Finn Sinsigalli, Bicycle Mechanic at Riverside Cycles in Manchester by the Sea, MA; Kevin Wolfson, Custom Frame Designer at Firefly Cycles in Melrose, MA; and Toby Stanton, Custom Frame Builder at Hot Tubes in Shirley, MA. Finn Sinsigalli was a personal/ family contact, and Kevin and Toby were an internet contact focused on custom frame building. The interview at Riverside Cycles was a preliminary interview that introduced various components of bicycles and general design information about adult bicycles and children’s bicycles on the market. Entry level children’s bicycles are single speed bicycles consisting of a single gear system. This allows children to learn how to ride a bicycle without adding the complexity of shifting gears. Also, training wheels can only be added to single speed bicycles. Lastly, Sinsigalli noted that almost all children’s bicycles come with a chain guard for safety and to prevent loose clothing from getting caught in the gear (Sinsigalli, personal communication, Sept 15, 2023). On the topic of bicycle fit, Sinsigalli explained that saddle height should be equal to inseam height in children’s bicycles to ensure that the child’s feet can sit comfortably on the floor (Sinsigalli, personal communication, Sept 15, 2023). Additionally, weight distribution is important on a bicycle, and it is crucial to find the center of gravity of the rider to certify that the rider can easily balance and steer. Sinsigalli gave the tip of adding more weight to the bicycle below the rider’s center of gravity to make it easier to ride (Sinsigalli, personal communication, Sept 15, 2023).

When asked about different types of frames available on the market, Sinsigalli highlighted two different types of frame shapes: the step-through frame and the step-over frame. Figure 6 below shows a step through bicycle (left) and a step over bicycle (right) displayed at Riverside Cycles.

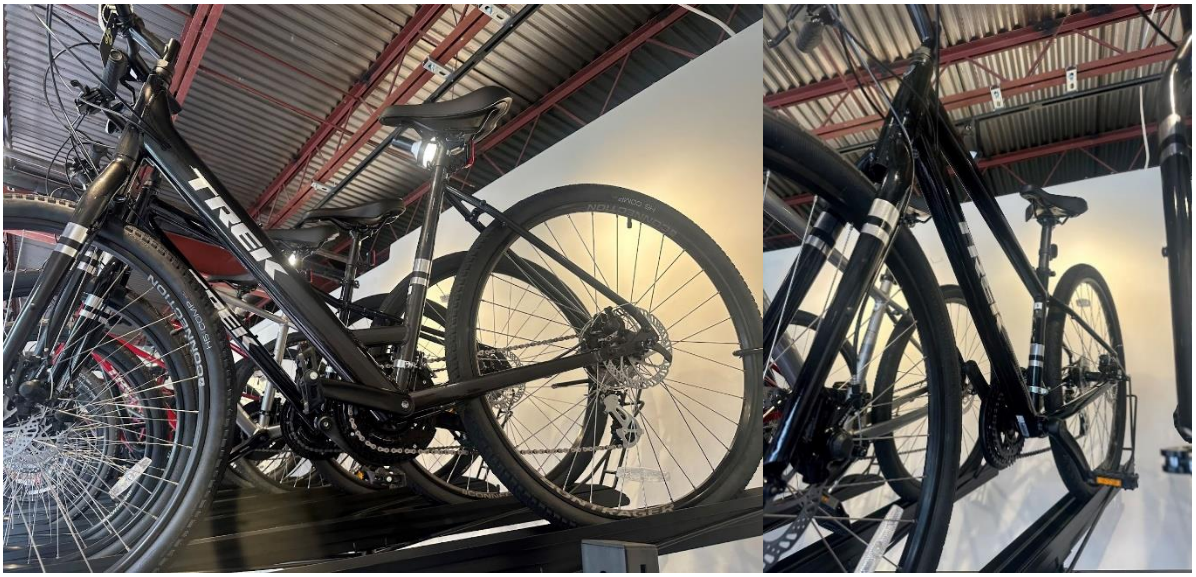


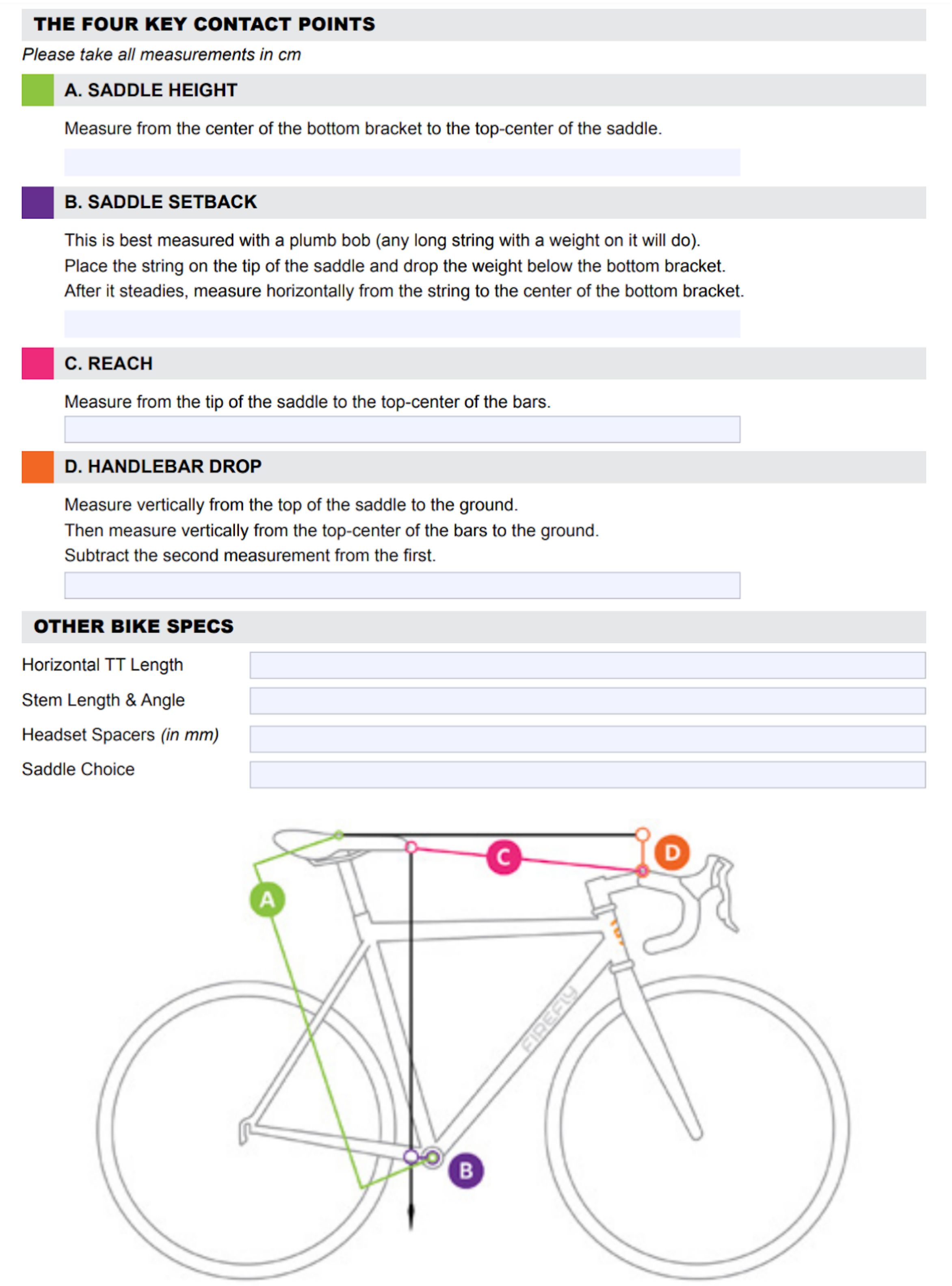
Figure 6: Step Through Bicycle (left) vs a Step Over Bicycle (right)

Continuing the conversation about frames, Sinsigalli commented that most bicycle frames are made from hollow aluminum or steel tubes. The shape and placement of each tube is very important to the structural integrity and dynamics of the bicycle. If a frame is welded incorrectly, bubbles can form and alter the structural integrity. When asked about the integrity of the frame when removing a tube, Sinsigalli said that removing the top tube would be detrimental to the frame and its safety. He recommended that we do not modify an existing frame for safety purposes. Regarding frame dimensions, Sinsigalli stated that bicycles are easier to ride at high speed when the wheelbase (distance between the wheels) is longer, and easier to ride at low speed when the wheelbase is shorter.

Sinsigalli concluded the interview with information about handlebars, brakes, and crank length. Sinsigalli suggested a U-shape could be more comfortable for the client given her limited reach. There are also numerous ways to make handlebars adjustable by height and angle (pivots). In regard to brakes, all children's bicycles at minimum had coaster brakes, and a few had coaster and handle brakes. Coaster brakes work because of friction and because children are a lot lighter than adults, less friction needs to be generated, making coaster brakes sufficient. In addition, Sinsigalli stated that a longer crank length makes a bicycle easier to pedal but would be harder for someone with short legs.

Informal informational interviews were conducted with custom frame builders to learn about the possibility of creating a custom frame for the client. Both interviews revealed that the 4 basic body dimensions needed to start construction of a bicycle are total body length (from the base of neck), inseam, arm length, shoulder width, and reach to handlebars. The saddle height, saddle set back, saddle bar reach, and saddle bar drop tells where contact points of the bicycle are. Wolfston shared the form Firefly Cycles uses to determine customer bicycle fit, see Figure 7 for the four key contact points and Figure 8 for the body info of the customer. Both Wolfston and Stanton said that their businesses use BikeCAD, a computer software that allows builders to enter the dimensions of the rider and customize frame dimensions with those measurements.

When asked about where the center of mass should be on a children's bicycle, Wolfston answered that the center of gravity of the person and the bicycle together should be relatively even between the front and back wheel. This allows better overall balance and control over the bicycle. The person should be balanced between the two wheels, the rear center and front center. Both Wolfston and Stanton also discussed the importance of testing comfortability and fit directly on the customer. They recommended having the client pedal the bicycle without moving to ensure that the client can ride comfortably without any discomfort.



THE FOUR KEY CONTACT POINTS

Please take all measurements in cm

🟩 **A. SADDLE HEIGHT**

Measure from the center of the bottom bracket to the top-center of the saddle.

🟪 **B. SADDLE SETBACK**

This is best measured with a plumb bob (any long string with a weight on it will do).
Place the string on the tip of the saddle and drop the weight below the bottom bracket.
After it steadies, measure horizontally from the string to the center of the bottom bracket.

🟥 **C. REACH**

Measure from the tip of the saddle to the top-center of the bars.

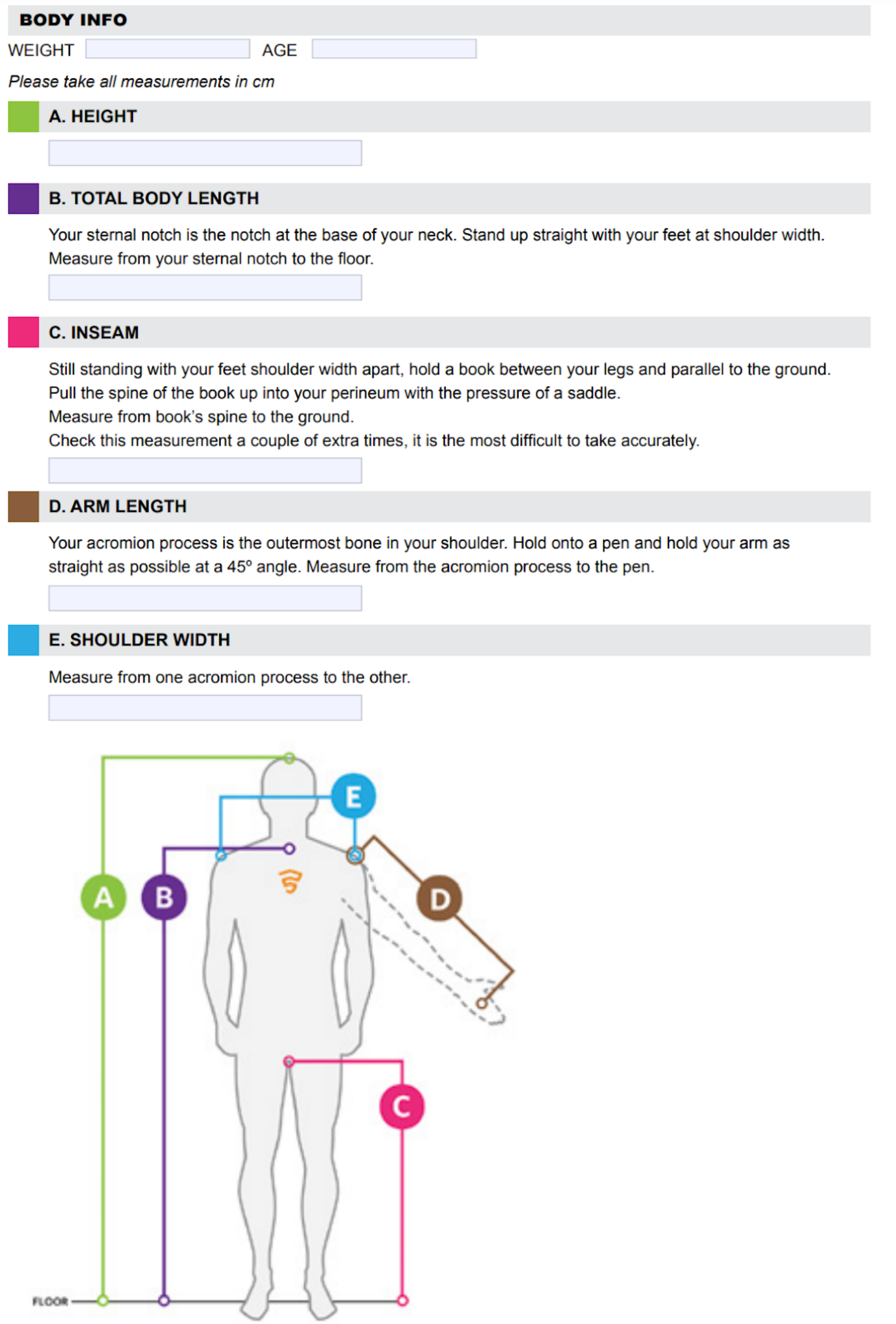
🟧 **D. HANDLEBAR DROP**

Measure vertically from the top of the saddle to the ground.
Then measure vertically from the top-center of the bars to the ground.
Subtract the second measurement from the first.

OTHER BIKE SPECS

Horizontal TT Length	
Stem Length & Angle	
Headset Spacers *(in mm)*	
Saddle Choice	

Figure 7: 4 Key Contact Points



BODY INFO

WEIGHT AGE

Please take all measurements in cm

A. HEIGHT

B. TOTAL BODY LENGTH

Your sternal notch is the notch at the base of your neck. Stand up straight with your feet at shoulder width.
Measure from your sternal notch to the floor.

C. INSEAM

Still standing with your feet shoulder width apart, hold a book between your legs and parallel to the ground.
Pull the spine of the book up into your perineum with the pressure of a saddle.
Measure from book's spine to the ground.
Check this measurement a couple of extra times, it is the most difficult to take accurately.

D. ARM LENGTH

Your acromion process is the outermost bone in your shoulder. Hold onto a pen and hold your arm as straight as possible at a 45° angle. Measure from the acromion process to the pen.

E. SHOULDER WIDTH

Measure from one acromion process to the other.

Figure 8: Body Information

3. Project Strategy

The main goal of our project is to design, develop, and test a method to adapt a children’s bicycle to comfortably fit a child with achondroplasia and facilitate learning, as this will be her first bicycle. Our priorities in the design process (in order of importance) are:

1. Safety.
2. The client’s comfort given her body mechanics, weight distribution, and experience.
3. And developing the bicycle with features tailored to support the learning process for children.

3.1 Customer Needs

In a preliminary interview with the client's family, our team learned that she is very active and is involved in sports such as dance. She currently has a Strider balance bicycle and Fisher Price tricycle, but the family currently cannot find any suitable pedal bicycle that fits her proportions and is similar to her brothers (who do not have Achondroplasia). When discussing the client’s proportions and body mechanics, the client’s parents shared that her physical therapist said that she favors one side over the other in exercises and riding her tricycle. People with Achondroplasia typically have bowing in their legs and the client has more bowing in their left leg, so she favors her right leg. The family stated that she is also top heavy compared to her peers and cannot take sharp turns on her tricycle. The family also noted that she has shorter legs and a longer torso but has high mobility in her hips and pelvis, like many other people with Achondroplasia as stated in the above section. Her arms are naturally slightly bent even when “fully extended.” She also has hypertonia, which is a condition where there is too much muscle tone so that there is muscle weakness, so her arms or legs are stiff and difficult to move.

When discussing the client’s “wants” for a bicycle with her parents, they mentioned that she would prefer a typical bicycle with removable training wheels to help facilitate learning. The family is looking for a single speed children's bicycle, similar to her peers. The client would mostly be riding this bicycle on pavement in their local neighborhood for short periods of time, not too much farther than a mile. In addition, this bicycle could potentially be passed on to other children in the Little People community after the client eventually grows out of it. The family voiced that their biggest frustration with finding a bicycle for the client involves her not being able to comfortably reach the handlebars and pedals at the same time.

During our initial observations with the client, we observed that the client struggled to complete a full pedal cycle when she was on a 12” pedal bicycle. We observed that this impedance was due to the crank length of the pedals being too large for her proportions and concluded that the client would benefit from a smaller crank length. We watched the client ride a strider balance bicycle that her family owns and noticed that she was struggling to trust herself and balance on the bicycle without her feet on the ground.

3.2 Product Specifications

Based on the goals and customer needs above, our team evaluated how we could alter different parts of the bicycles to best fit the client’s needs. Due to safety and durability, our team knew we needed to adapt an existing frame instead of trying to make our own. We decided that we will make the pedals and training wheels removable in order to help the client learn how to ride a bicycle. The bicycle will be a single speed bicycle to allow for the attachment of training wheels and most children learn on a single speed bicycle. We will also attach a chain guard for safety purposes. In addition, there will be no suspension in this bicycle because most children’s bicycles do not need suspension due to the rider’s lower weight. For functionality of the bicycle, our team wants it to be able to withstand mild weather (rain, moderate winds), ride on pavement or gravel, be able to sustain moderate length rides and hills, as well as it be easy for her to get on and off as well as easy to start and stop pedaling the bicycle. Our team identified that we would need to address handlebars, crank length, braking systems, and seat height for comfortability and reach as well as address the center of gravity of the bicycle to make it easier for the client to ride. These product specifications align with our main goal and priorities of safety, comfortability, and learning.

4. Design Process

When designing a bicycle that is not only accessible, but also comfortable for the client, we had to consider several features including brakes, saddle height, crank length, handlebars, and center of gravity and approach each in a way that addresses our priorities as stated in the previous section.

4.1 Brakes

With safety as our top priority, brakes were an important aspect to discuss. Based on our conversation with Finn Sinsigalli, we knew that coaster brakes would be ideal for the client not only as a beginner, but also based on her small hand size, which is 3.5 inches from wrist to fingertip. However, there was potential for designs that did not have an existing coaster brake system, so we researched three alternative options.

1. First, we discussed using hand brakes with a modified lever that the client can comfortably reach. However, reducing the distance between the lever and the handlebars could create a pinch point on the bicycle, where the client may get her fingers stuck or hurt, which is a major safety concern.
2. Our second thought was to develop a hand brake that operates by rotating an attachment to the handlebar or pushing a lever with the thumb instead of the fingers. When researching this further, safety became a big concern for us, so we were hesitant to modify brakes ourselves given our time, experience, and resources.
3. Our third option was to ensure that a wheel with existing coaster brakes is included in our design. This would require the use of an existing 12-inch wheel (at least for the back wheel) but would be the safest as we would not be modifying the braking system in any way. In addition to safety, coaster brakes are easy to learn on, since backpedaling to stop is intuitive for learners. Lastly, this is preferred given the client’s hand size and strength.

After researching and discussing these options, our team chose the third option for the reasons listed above. This limited our overall design as discussed in the following section.

4.2 Overall Design

The saddle height posed the biggest challenge in our design. It must be low enough for the client to put both feet flat on the floor to help facilitate learning. This means that the saddle height should be equal to the client's inseam as seen in Figure 9 below.

Figure 9: Client's Inseam Equal to the Saddle Height

The bicycles we collected for early prototyping had minimum saddle heights ranging from 16.5 to 18 inches for pedal bicycles, and 14 to 14.5 inches for balance bicycles (however balance bicycles could be ordered in saddle heights as low as 11 inches), all of which are designed for children of average height. We considered five main approaches to developing a bicycle with the appropriate saddle height.

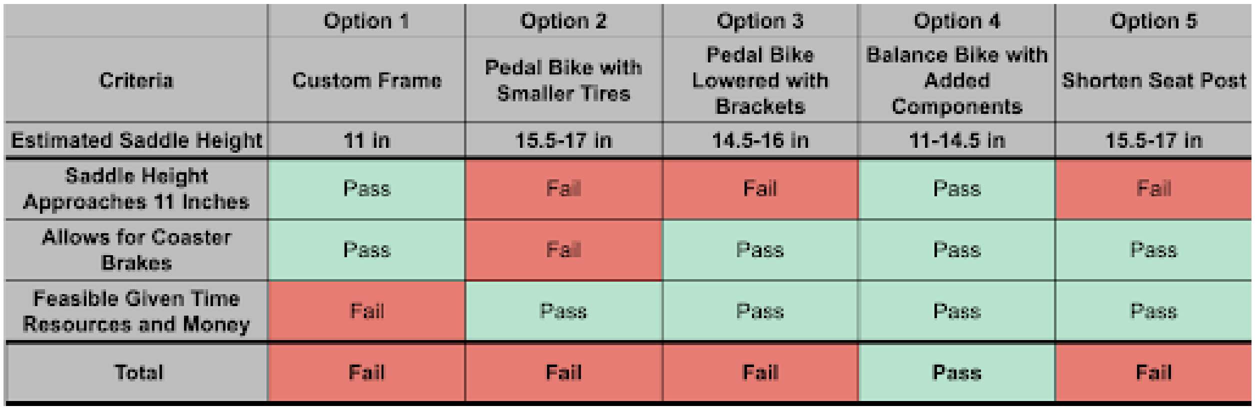
1. Our first approach was to design and develop a custom frame. This would allow us to make an ideal bicycle for the client's body mechanics, minimize the saddle height and incorporate all the necessary components for a learning bicycle. However, given the time, resources, and funding for our project this idea is not feasible.
2. The second was to put 10-inch wheels on a 12-inch pedal bicycle. This would lower the bicycle by one inch, creating a saddle height of about 15.5-17 inches. However, this would require a new braking system as the coaster brake is inside the 12-inch wheel's

hub. This conflicted with our previous decision to ensure a coaster brake is included in our design.

3. The third option was to lower a 12-inch pedal bicycle using brackets to extend the frame and allow the axles to connect to the frame in a higher location. This would lower the bicycle by two inches, creating a saddle height of about 14.5-16 inches. Additionally, the wheelbase would increase, making the bicycle more difficult to ride at a slower speed and could allow for sharp edges that would need to be addressed.
4. The fourth option was to find a balance bicycle that fits the client's inseam, add pedals, and replace the existing back tire with a coaster brake tire. This was a more complex option, as additional components would need to be secured to a frame they were not originally intended for. However, as stated earlier, balance bicycles can come in saddle heights ranging from 11-14.5 inches.
5. In combination with these methods, we discussed a fifth option of cutting the seat post shorter so the seat can be fully lowered into the frame, as some bicycles had the seat post exposed when the saddle was in its lowest position. However, this could result in interference between the saddle and the tire depending on the frame if it is not done correctly. This could possibly lower the bicycle by up to one inch, creating a saddle height of about 15.5-17 inches on a pedal bicycle, and 10-13.5 inches on a balance bicycle.

To weigh these five options, we asked the client’s family to measure her inseam, which was 10.5 inches. Our goal was to develop our frame to have an 11-inch saddle height, as the client would be wearing shoes while riding. Given this specification, we identified mandatory criteria for our design. If the option failed any criteria, it did not move forward. We used the Matrix below to display how our options measure up against our criteria and make an informed decision.

Table 1: Pass/Fail Matrix



	Option 1	Option 2	Option 3	Option 4	Option 5
Criteria	Custom Frame	Pedal Bike with Smaller Tires	Pedal Bike Lowered with Brackets	Balance Bike with Added Components	Shorten Seat Post
Estimated Saddle Height	11 in	15.5-17 in	14.5-16 in	11-14.5 in	15.5-17 in
Saddle Height Approaches 11 Inches	Pass	Fail	Fail	Pass	Fail
Allows for Coaster Brakes	Pass	Fail	Pass	Pass	Pass
Feasible Given Time Resources and Money	Fail	Pass	Pass	Pass	Pass
Total	**Fail**	**Fail**	**Fail**	**Pass**	**Fail**

Option 1 (developing a custom frame) was not feasible given time, resources, and money, so this failed and did not move forward. Option 2 (modifying a pedal bicycle to have smaller tires) did not approach 11 inches or allow for coaster brakes, so this failed as well. Option 3 (lowering a pedal bicycle using brackets) and option 5 (shortening seat post) were not viable on their own as the saddle height did not approach 11 inches. Option 4 (modifying a balance bicycle) passed on all criteria. With this, we chose to start with option 4 (modifying a balance bicycle), and potentially incorporate aspects of options 2, 3, and 5 if necessary.

4.3 Crank Length

A rider should be able to comfortably pedal a bicycle. We wanted to ensure that the client could always reach the pedal, the pedal would not scrape the ground, and her knee would not be forced to go too high. To find a comfortable crank length, the rider’s knee should be directly above the pedal when the pedal and crank are at a 3 o'clock position.

We asked the client to sit on an average 12-inch bicycle and pedal a 4-inch crank as seen in Figure 10. She was barely able to reach the pedal at its lowest position as the seat was too high, and she was mildly comfortable with the range of motion. When the pedal and crank were in the 3 o’clock position, the client’s knee was slightly offset, indicating that she would benefit from a slightly shorter crank length, but the existing crank length was sufficient if necessary.

Figure 10: Client on a 12-Inch Bicycle with a 4-Inch Crank

4.4 Handlebars

There are several potential shapes for handlebars. Handlebars can also be swapped out on certain bicycles. Based on our discussion with Finn Sinsigalli, our team believed that U shaped handlebars would have the best positioning range for the client's reach, as they can rotate along the handlebar axis and also be positioned higher and lower. Ideally, we hoped to find a frame with existing U-shaped handlebars, but, if necessary, we could change them out.

4.5 Center of Gravity

As mentioned in our literature review, people with achondroplasia have a higher center of gravity than people of average height, but a low center of gravity is preferred when learning to ride a bicycle.

To address this, our team had to identify where the center of gravity for a human on a sidewalk bicycle should be. For a human of average height, the center of gravity is just above or just below the naval, varying with gender and several other factors (center of gravity). We determined the location of the center of gravity on some of the bicycles we collected for early prototyping using the method in Appendix 1 and determined that it was often just below the saddle. As noted in our background, a children's bicycle should not exceed more than 40% of their weight. With this, we can estimate that the average child's center of gravity on a bicycle is between the saddle height and the handlebar height. This was the specification we set for the center of gravity for the client and her bicycle.

Using the method in Appendix 2 to calculate the client’s center of gravity and the method in Appendix 1 to calculate the bicycle’s center of gravity, we can use the method in Appendix 3 to calculate the overall center of gravity for the client and the bicycle together. By adding mass to the bicycle beneath the saddle, we can repeat this process until the center of gravity is within the specified range.

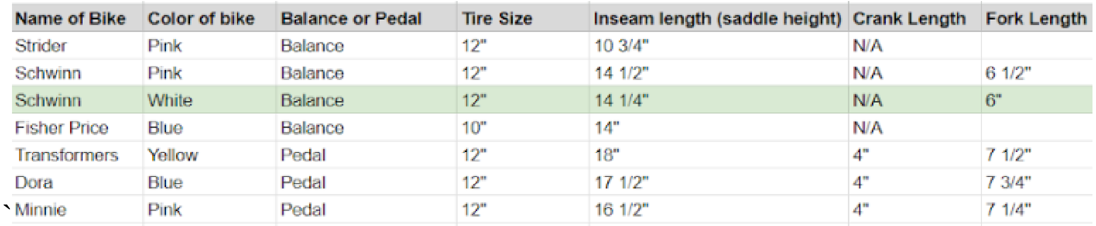
5. Detailed Design

The following is a review of a design process through Prototype 1 and into our final design with Prototype 2.

5.1 Prototype 1: Proof of Concept

5.1.1 Lowering the Balance Bicycle

Based on the evaluation of different bicycle features in the previous section, the team created the first prototype of the bicycle. First, the most ideal balance bicycle frame was chosen from 7 different children's bicycles collected from thrift stores. The 7 bicycles acquired with their specifications are shown in Figure 11 below. The frame for the first prototype was chosen because it was a 12" balance bicycle and had one of the shortest inseam measurements. The prototype 1 bicycle frame (Schwinn, white) was decided on over the pink strider bicycle even though it has a small inseam height because the pink strider bicycle had footrests. A frame with footrests was undesirable as there would not be enough room to add pedals, gears, and other functional components. However, the saddle height of the white Schwinn was still 14 ¼" in the lowest seat position, which was too high for the client's 10.5" inseam, so the bicycle had to be lowered.



Name of Bike	Color of bike	Balance or Pedal	Tire Size	Inseam length (saddle height)	Crank Length	Fork Length
Strider	Pink	Balance	12"	10 3/4"	N/A	
Schwinn	Pink	Balance	12"	14 1/2"	N/A	6 1/2"
Schwinn	White	Balance	12"	14 1/4"	N/A	6"
Fisher Price	Blue	Balance	10"	14"	N/A	
Transformers	Yellow	Pedal	12"	18"	4"	7 1/2"
Dora	Blue	Pedal	12"	17 1/2"	4"	7 3/4"
Minnie	Pink	Pedal	12"	16 1/2"	4"	7 1/4"

Figure 11: Thrift Store Bicycle Catalog

To lower the bicycle, the team replaced the front wheel from a 12" tire to a 10" tire from a different balance bicycle as seen in Figure 12. This lowered the front by 1". The balance bicycle seat was also swapped out for a smaller, shorter seat and the seat post was cut 1.5" in order to allow the seat to rest as low in the frame as possible.

Figure 12: Prototype 1 Front Tire

With the front tire swapped out, the frame was uneven and a way to lower the back of the bicycle frame had to be developed. The first method used was to incorporate 3” T-brackets from Home Depot as seen in Figure 13. These brackets were not a perfect fit, the holes needed to be grinded down using a Dremel in order to fit onto the axle of the back tire.

Figure 13: 3" T-Bracket from Home Depot

The bicycle's axle was placed on the middle hole down the base of the T while the frame was placed on one of the end holes to make it closer to the ground. Instead of having the axle resting in the back wheel frame stays, the axle sat in the bracket and a screw was added and acted as the point of contact connecting the frame to the bracket and tire. Adding this bracket successfully lowered the bicycle to the desired inseam height and was sufficient for a first prototype. Upon further reflection and discussion, it was decided that a custom bracket with a unique geometry and hole placement would be more beneficial and ensure that no extra material would stick out and potentially hurt the rider. A custom bracket would also allow for proper testing and assurance that it would withstand stresses from the rider for long-term riding.

5.1.2 Gear Mechanism

After replacing the 12” balance bicycle tire with a 12” pedal bicycle tire that had a coaster brake in the axle, a method to incorporate pedals had to be found. Pedals were an important feature in our first prototype because disfavor with balance bicycles was expressed by our client. Ultimately, we wanted our design to allow our client to learn how to ride a pedal bicycle, as that is what most children her age ride on. This was the safest way to add coaster brakes because we did not want to modify the braking system in any way. For the purpose of modularity and wanting to replicate the Prototype 1 design onto bicycles for other children with Achondroplasia, the team decided to find an existing pedaling system. This system was found by searching for modular children’s bicycle designs and balance bicycle systems. Strider, a company that specializes in balance bicycles, has a commercially available pedal kit that works on their 14” and 20” balance bicycle models. The pedal kit shown in Figure 14. had sufficient installation instructions and was deemed viable by the team to use.

Figure 14: Strider Pedal Kit

The bicycle frame we selected had a conveniently placed hole in the bottom of the seat post that was used to attach the pedal kit center assembly to. A screw was dropped down into the seat post and the pedal kit was screwed into the hole at the bottom as seen in Figure 15.

Figure 15: Pedal Kit Attachment from Bottom View

This location of the pedal kit was sufficient and had enough clearance off the floor for the pedals to rotate comfortably. The pedal to floor distance was ½ “minimum and 2 ½ “maximum with the crank length of the Strider pedal kit being 3”. Although there was enough clearance off the floor for the pedals to rotate, the tip angle did not exceed 15 degrees, 10 degrees less than the minimum tip angle required. Also, this pedal kit attachment method was not secure, as the kit could twist side to side and the seat post became deformed due to the stress put on the attachment during pedaling. The team noted that the attachment method would need to be fixed on the final prototype to be safer and more secure.

5.1.3 Client Observations

Without the chain, the geometry of the bicycle was evaluated on the client. As seen in Figure 16 below, the client's feet were flat on the floor when standing over the bicycle. This shows the balance bicycle was lowered efficiently and the inseam height allowed the client's feet to sit flat on the floor, which would be optimal for helping her learn how to ride the bicycle.

Figure 16: Client Standing Over Bicycle with Feet Flat on the Floor

The client's range of motion while pedaling without the chain was also analyzed. The client was able to reach the pedal at all points but was not as comfortable when the pedal was at the lowest point. It was also observed that the client's knee was coming up too high when her foot was at the highest point in the pedaling rotation. On a children's bicycle their thighs should remain at a downward angle even when in the highest position and should never come above the handlebars as seen in Figure 17 below (*How to Shop for a Bike for Your Kid*, 2022).

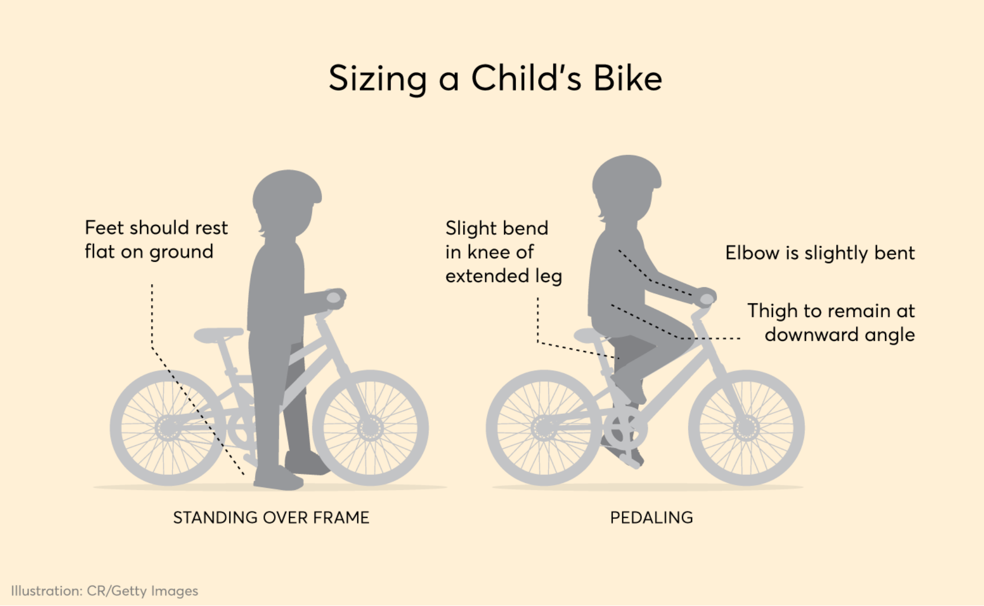


Figure 17: Sizing a Child's Bicycle

During observations with the client, her thigh was directed in an upward angle when at the highest point. When she was halfway through a pedal rotation her thigh was not in a downward angle as seen in Figure 18 below.

Figure 18: Thigh Angle during a Pedal Rotation

Although the range of motion on Prototype 1 was sufficient because her knee never became above the handlebars, it was not ideal as she would be more comfortable with her thigh angled downward when pedaling. The team decided she would benefit from a slightly shorter crank length on future prototypes.

During observations with the client, the team also rotated the angle of the handlebars inward, at a more comfortable angle for the rider. The team also noted that the seat height and handlebar angle are adjustable and could be modified in the future when the child grows.

5.1.4 Chain Interference

The chain was then added to prototype 1 to make a fully functioning bicycle. The completed Prototype 1 can be seen in Figure 19 below.

Figure 19: Completed Prototype 1

Based on the location of both gears, the chain had interference with the frame as seen in Figure 19. When pedaling with the chain on, the chain rubbed on the frame and could not ride smoothly. The team decided that for the next prototype a bicycle frame with just a chain stay would be selected to avoid this interaction.

However, Prototype 1 successfully fulfilled the goal of creating a modified bicycle for a child with Achondroplasia with materials that can be bought in store. This prototype showed that our design method was viable and would work for the client. Our team decided to create a second prototype with a new, more optimized frame that has chain clearance. In addition, the team had the time and resources to create custom brackets for the back of the frame that would better fit the bicycle to lower it, even though the T bracket method worked. This, along with other lessons learned in the first prototype helped the team to develop an improved Prototype 2.

5.2 Prototype 2: Developing the Design

Although Prototype 1 showed that our design method was viable, the team decided to move forward with a second prototype using a new frame that would have clearance for the chain and the ability to make other modifications.

5.2.1 Lowering the Frame

To lower the frame to an appropriate height, we chose our frame carefully, used a smaller front tire, and lowered the back tire using a bracket.

5.2.1.1 Frame Selection

Due to the chain interference, the team determined that the frame selected for Prototype 2 must be: a balance bicycle with 12” wheels; a frame that does not have a place to rest rider’s feet and has a singular chain stay instead of a seat stay and chain stay; an adjustable seat post that is as short or shorter than Prototype 1 (6 ¼”); and adjustable handlebars with the ability to be rotated towards the rider. Co-op Cycles REV 12 Kids' Balance Bicycle from REI was purchased in coral as seen in Figure 20 below.

Figure 20: Co-op Cycles REV 12 Kids' Balance Bicycle

The balance bicycle met all the predetermined requirements and had 12” wheels and an adjustable inseam height of 12”-17”. REI’s website says the height of the child can be 2'6"-3'3" for this bicycle making it ideal for our 2’9” client.

5.2.1.2 10 Inch Front Tire

After receiving the bicycle, initial measurements and dimensions of the bicycle were taken. With the seat in the lowest position, the distance from the floor to the seat was 13 inches.

Our client’s inseam length, however, was only 10.5 inches. The team determined that a saddle height of 12 inches was sufficient for our client with shoes on and seat compression. It was determined that in order to lower the frame and decrease the distance from the floor to the seat by an additional inch, a similar method as Prototype 1 would be followed. The biggest change from Prototype 1 to Prototype 2 was finding and purchasing a new 10” tire as well as making a custom back tire bracket specifically designed with the intent of lowering the frame. Factors that were considered when looking for a 10” tire to purchase included a complete tire assembly with spokes or a spoke equivalent, a durable material unlike the plastic 10” wheel on Prototype 1, the ability to be inflated and deflated, and a thickness that would fit in the front fork dimensions. The tire that passed the criteria was a 10” motorized scooter tire that had a thickness of 2.8”. Although this was thicker than the standard kids bicycle tire width, the tire could still fit in the front fork frame, and the tire had the benefit of adding additional weight to our design, which would lower the center of mass of the bicycle and make the bicycle more controllable for our client. Furthermore, a wider tire increases the suspension for the bicycle. One challenge of the purchased 10” tire was that the bearings on one side of the wheel protruded further out than on the other side of the wheel. To solve this problem, washers were added onto the side of the axle with the less protruded side wall until equal distances to the fork were achieved and the tire was properly centered between the front fork (see Figure 21 below).

Figure 21: 10" Tire Adaptation

5.2.1.3 Back Bracket Design

A meeting with the client was held halfway through the Prototype 2 design process to validate the dimensions of the new frame and the pedal kit position. During this meeting, the new frame with the smaller 10” tire and temporary back brackets were assessed. The temporary back wheel brackets mimicked the back brackets used in the first prototype. Two 3” T-brackets were used, with additional wire gauge wrapped around points of rotation to hold the frame steady in relation to the wheel. The temporary back wheel brackets allowed us to determine points of focus and design goals of the new back wheel brackets. The design goals of the custom back wheel brackets were to:

1. Lower the frame 1” in relation to the back tire and shift the wheel 1” away from the seat post
2. Prevent any rotation between the frame and tire from occurring
3. Reduce sharp edges
4. Minimize material
5. Reduce interaction between the bottom of the chain and the bottom of the frame stay
6. Pass a stress test with a minimum factor of safety of 3.

The design process began with measuring the existing temporary brackets and the tire’s axle, bolt diameters, and offset gear axle. The geometry was then modeled in SolidWorks. In order to minimize material, edge to hole clearance was calculated using the following principles: holes should be two times the thickness of the bracket away from edges, and six times the thickness of the bracket away from other holes (*Comprehensive Sheet Metal Guide*, n.d.). A ⅛” thick sheet of 6061 Aluminum was chosen as the material for its strength properties and weight. Edge to hole clearance was calculated as 0.25” and hole to hole clearance was calculated as 0.75”. Uniformity between the two brackets was prioritized. The first design cycle yielded the two brackets shown in Figure 22 below. The bracket on the left is for the rider’s left side of the bicycle, while the bracket on the right is for the rider’s right side of the bicycle (gear side). Note the additional hexagonal hole on the right bracket, which is intended for the offset gear. Both brackets utilize filets to reduce stress concentrations around corners and to further reduce the amount of material needed.

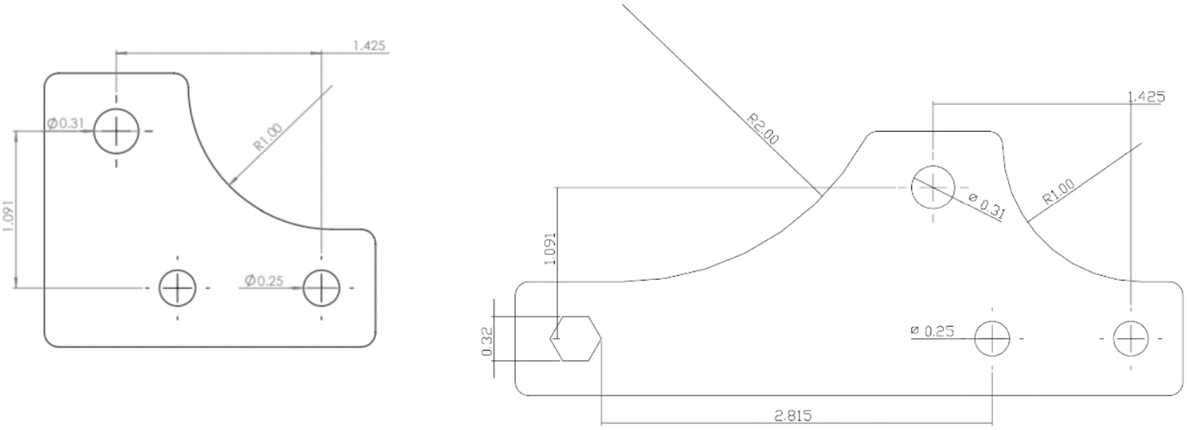


Figure 22: First Iteration Back-Wheel Bracket Design

After modeling in SolidWorks, the brackets were laser cut using ⅛” acrylic to act as a prototype and to test the fit of the holes. The acrylic brackets were observed to successfully fulfill the design goals. ANSYS simulations were run to ensure that the aluminum brackets could withstand the interaction forces from the frame and the chain. Shown below in Figure 23 are the forces applied in the ANSYS Simulation. The bolt holes in line with the frame were considered fixed, since there is a rigid connection between a washer and the frame, while the axle hole has an applied force of 60 lbf acting upward. 60 lbf was selected as the force since the bicycle is limited to a rider weight of 60 lbs. The rider applies a force down on the bracket as the tires distribute the riders’ weight, hence the reaction force from the bracket onto the axle/bicycle system is an upward force.

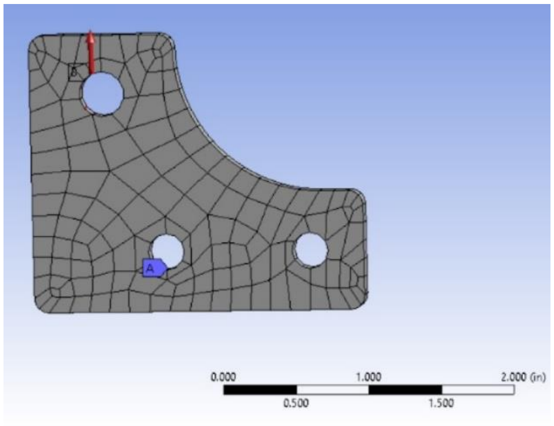


Figure 23: Applied Forces on the Left Back-Wheel Bracket

After forces were applied and the bracket was meshed in the software, Von Mises Stress and Total Deformation were simulated and run. Total Deformation for both brackets was negligible given the simulation returned values less than .005 inches. Figure 24 below shows the left back-wheel bracket with a maximum Von Mises stress of 3109.8 psi. The Factor of Safety of the brackets were then calculated using the formula:

$$Factor\ of\ Safety = \frac{\sigma_y\ (yield\ Strength)}{\sigma_{max}(\max imum\ Von\ Mises\ stress)}$$

The yield strength was defined by the aluminum sheet metal manufacturer as 35,000 psi (*McMaster-Carr*, n.d.). The left-back-wheel bracket passed with a safety factor of 11. The right back-wheel bracket passed with a safety factor of 3. A Safety factor of 3 was chosen to represent the minimum factor of safety to pass testing in accordance with Engineering Toolbox's recommendations for use with less tried and brittle materials where loading and environmental conditions are not severe (*Factors of Safety - FOS*, n.d.).

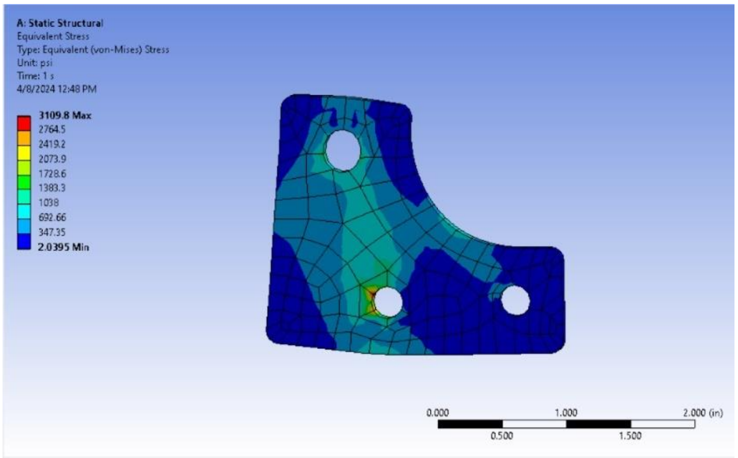


Figure 24: Maximum Von Mises Stress in Left Back-Wheel Bracket

The aluminum sheet was ordered and an appointment to use the waterjet cutters at Practice Point was made. The waterjet cutting process required minimum post processing, other than a quick sanding to remove support tabs. The brackets were then installed on the frame, as shown in Figure 25 below.

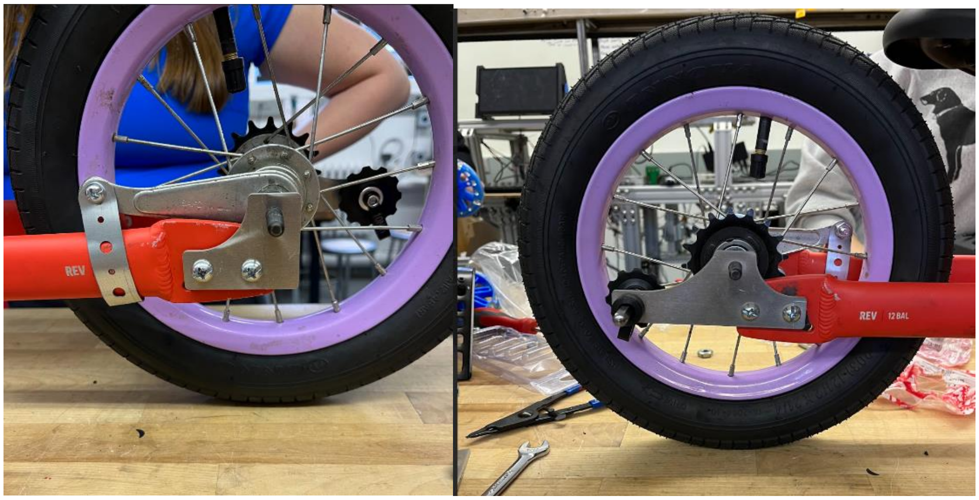


Figure 25: Aluminum Back-Wheel Brackets Assembled on Bicycle

Following the assembly of the back-wheel brackets onto the frame and adding the gear onto the back tire's gear, we noticed the chain was only interfacing with about 4 teeth on the power gear (gear that is a part of the tire assembly) at a given time. This was concerning as the likelihood of the chain slipping off the gear increases as the number of teeth interfacing with the chain decreases. Upon further research, it was found that 180 degrees of contact between a chain and gear is favorable, but the minimum contact angle is 120 degrees (*Sprockets and Chain | DUO Build System*, 2022). Because of this finding, we decided it was unsafe to proceed with the bracket design on the gear side of the back wheel. The second prototype on the gear side was designed to prioritize the contact value of at least 120 degrees between the chain and the gear. Three different possible positions were first visualized by moving the offset gear and observing how much of the chain was in contact with the gear. Images of these three positions are shown below in Figure 26.

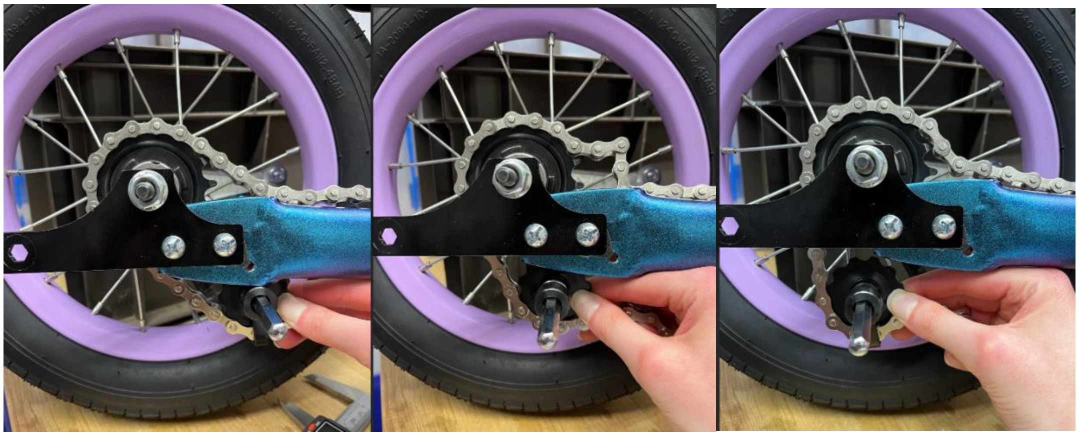


Figure 26: Possible Locations of Offset Gear to Increase Chain/Gear Contact

The third position was eliminated as a design option because there was only 90 degrees of contact between the chain and gear. We moved forward with analysis on the first and second position models, as the first position had 150 degrees of contact between the gear and chain and the second position had 135 degrees of contact between the gear and chain. Shown below in Figure 27 are the SolidWorks models for offset gear position 1 and offset gear position 2.

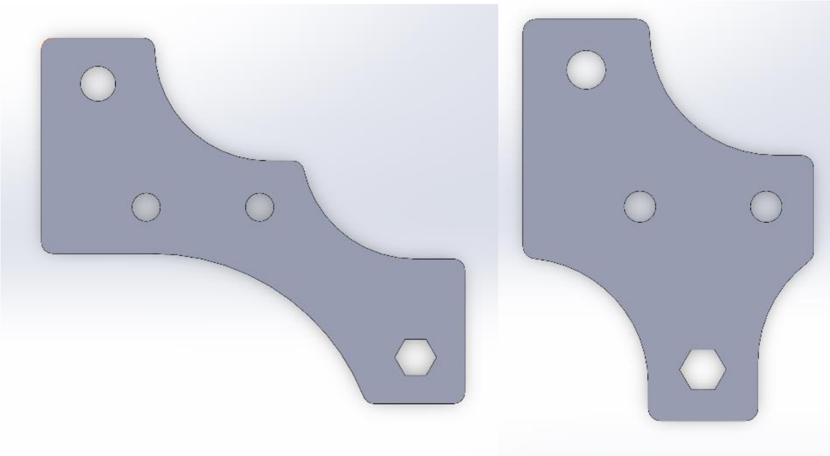


Figure 27: SolidWorks Models of Offset Gear Position 1 and 2

Once again, prototypes of the brackets were made of acrylic using a laser cutter and tested on the bicycle to ensure a proper fit and geometry that is favorable with the bicycle frame. Following successful test fitting, ANSYS Structural Analysis was run. The forces for the rear bracket on the gear side are slightly different than the forces on the non-gear side. With the added offset gear to the design, a force from the chain and a moment from the chain are added. The force acting on the hexagonal hole (offset gear hole) is an angled vector that counteracts the force experienced from the chain pulling on the offset gear. This force was calculated using the formula $F = 2Tsin\frac{\theta}{2}$, where F is equal to the overall force exerted on the offset gear, T is equal to the magnitude of each tension, and is equal to the angle in which the chain bends. The angle in which the chain bends was found by measuring the angle of change from the position where the chain enters the offset gear, to the position where the chain leaves the offset gear. This was found to be 135 degrees. The convention for the equation states that it is 180 degrees minus the overall angle, hence is equal to 45 degrees (ropebook, 2019). The tension was found by analyzing and assuming the power the client would generate while pedaling. $Power = Torque \cdot Rotational\ Speed$, where Torque applied is a function of both the force on the pedal and the crank length ($Torque = Pedal\ Force \cdot Crank\ Length$), hence the combination of the torque and rotational speed is the power a rider generates in Watts. The power generated by the client was assumed to be 100 watts, which was an overestimate based on the power levels that a human being can produce through pedaling. A person who is smaller and less well-nourished would most likely produce 50 watts if the task of pedaling occurs for hours at a time (Yadav et al., n.d.). From these assumptions, the force of the chain component was interpolated to be 30 lbf using Table 2 below that converts watts to peak newtons and kilograms of force during high pedal stroke efficiency ("Chain Tensile Strength Testing," n.d.).

Table 2: Watts to Pounds Force on Chain

Watts	Newtons of Force Chain	Kilogram Force (kgf) Chain	Pounds Force (lbf) Chain
100	133	14	30
200	266	27	60
400	533	54	120

The resultant force was then calculated to be 42.426 lbf. The resultant force was then broken into an X and Y vector using the angle of the resultant force (92 degrees) that were 1.48 lbf and 42.4 lbf respectively. The moment was calculated by applying the component 30 lbf force at a distance equivalent to the radius of the offset gear (.875 in), resulting in a negative moment of 26.25 lbf*in. The same forces were also applied to the offset gear position 2 bracket. See Figure 28 below for a visual of the forces on the offset gear bracket.

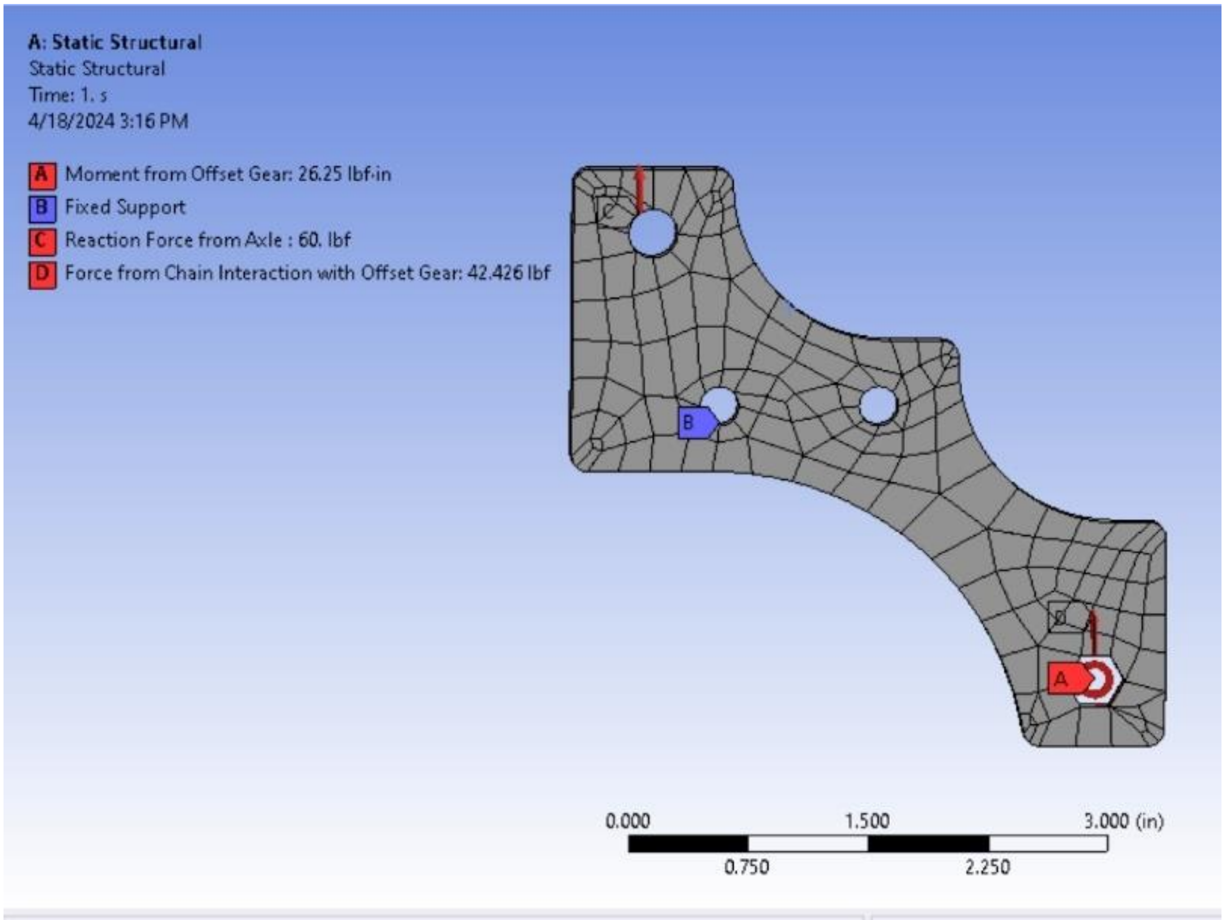


Figure 28: Applied Forces on the Offset Gear Bracket

After forces were applied and the bracket was meshed in the software, Von Mises Stress and Total Deformation were simulated and run. Total Deformation for both brackets was negligible given the simulation returned values less than .002 inches. Figure 29 below shows the offset gear position 1 bracket with a maximum Von Mises stress of 3368.8 psi. Figure 30 below shows the offset gear position 2 bracket with a maximum Von Mises stress of 4415.4 psi. The Factor of Safety of the brackets were then calculated using the formula:

$$Factor\ of\ Safety = \frac{\sigma_y\ (yield\ Strength)}{\sigma_{max}(\max imum\ Von\ Mises\ stress)}$$

The yield strength was defined by the aluminum sheet metal manufacturer as 35,000 psi (*McMaster-Carr*, n.d.). The offset gear position 1 bracket passed with a safety factor of 10 while the offset gear position 2 bracket passed with a safety factor of 7.

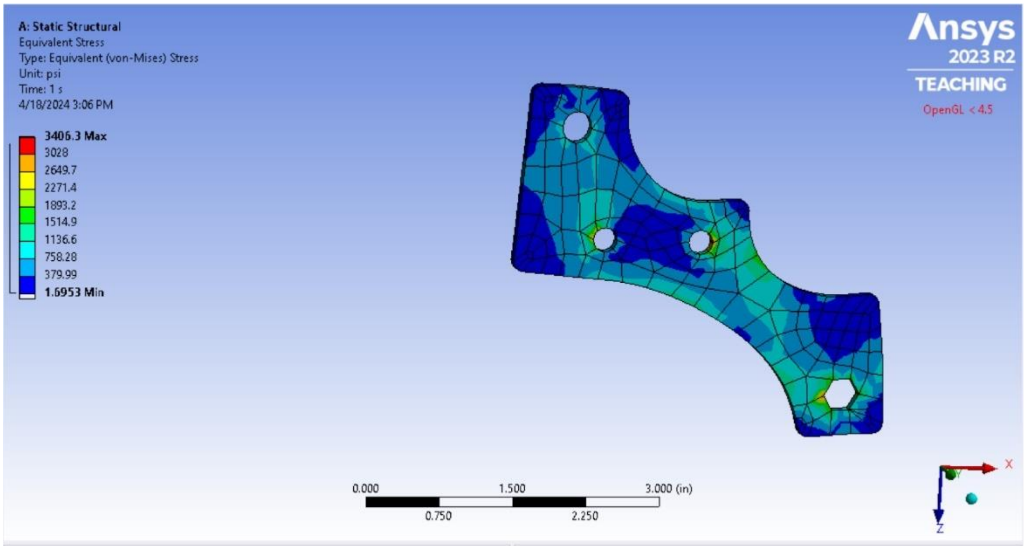

A: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: psi
Time: 1 s
4/18/2024 3:06 PM

Figure 29: Von Mises Stress of Offset Gear Position 1

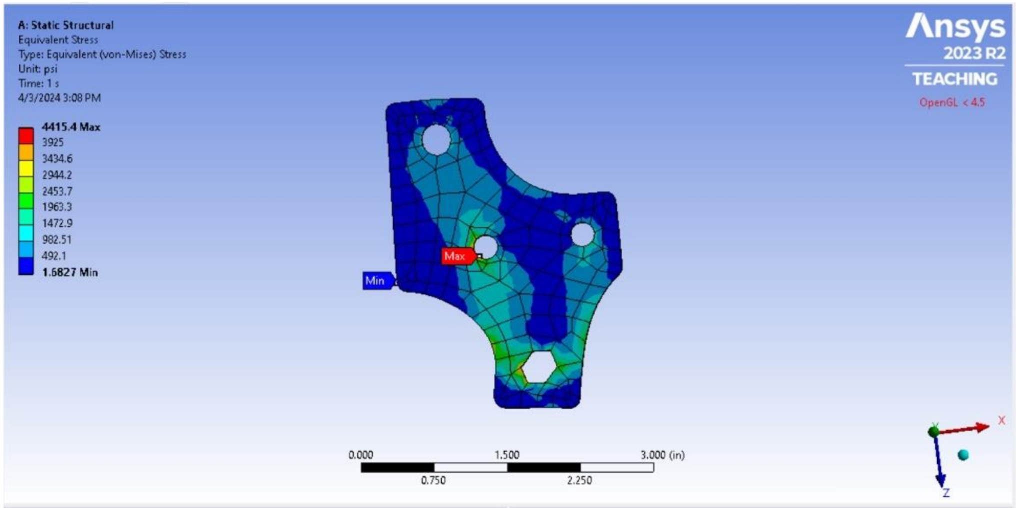

A: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: psi
Time: 1 s
4/3/2024 3:08 PM

Figure 30: Von Mises Stress of Offset Gear Position 2

After running ANSYS on the two different offset gear positions, we determined the bracket with the offset gear in position 1 was the ideal design since it had the largest factor of safety, had the most favorable geometry that reduced chain interference and affected tip angle the least. The bracket was then manufactured and installed using the waterjet cutters at Practice Point.

5.2.2 Functional Bicycle Mechanisms

After lowering the bicycle frame the remaining necessary distance, we had to incorporate functional bicycle mechanisms to convert the balance bicycle to a pedal bicycle.

5.2.2.1 Coaster Brake Implementation

To implement functional bicycle mechanisms into the balance bicycle, a 12" back tire from a pedal bicycle had to be integrated into the design. A 12" pedal bicycle tire is the smallest tire size that has a brake assembly in the tire hub.

5.2.2.2 Integration of a Pedal Kit

Through observations of Prototype 1 we determined we needed a more secure way of attaching our Pedal Kit to the bicycle. This attachment method is needed to eliminate all movements in the X, Y and Z directions. The Pedal Kit also had to be put in a location where there would be enough clearance with the ground and the pedals at their lowest position. In order to address these design requirements, we observed the components we were working with the down tube of the frame, which has an oval shaped cross section; and the center of the pedal kit, which was a circular cross section with a tangent flange. This is essentially two tubes that needed to be mounted in a perpendicular fashion. In our research we found that a double U bracket can accomplish this and ordered a standard double U bracket with the appropriate dimensions for our components. The selected double U bracket is shown in Figure 31 below.

Figure 31: Double U Bracket used for the Pedal Attachment

The pedal kit was able to be securely installed to the frame using this bracket. To increase the coefficient of friction between the bracket and the frame, we inserted rubber tape as an added precaution.

5.2.2.3 Chain and Gear Alignment

After integration of the pedal kit and back tire with a coaster brake, chain and gear alignment had to be ensured. Some slight interaction was noticeable between the chain stay and the chain. To improve this interference, an offset gear was incorporated into the back wheel bracket design to redirect the chain and lower the path from it. This method was successful and allowed the chain to be tightly fit around the whole assembly and have no interaction with the frame. Tip angle was not affected as a part of this modification, further ensuring the success of the chain and gear alignment.

5.2.3 Comfort and Ergonomics Design Prioritizations

After developing a functional bicycle, we addressed the client's comfort and ergonomics while riding. Through analysis of Prototype 1, it was determined that the client's positioning with a 3-inch crank caused discomfort in her hips and knees. In a meeting, the group tested if the client would benefit from having a shorter crank length. The team mimicked a 2” crank at the bottom of the pedal path while the rider was stationary. This was done with a 1” block to simulate where the pedal of a 2” crank would be during the lowest position of her pedal stroke. Through this test the client notified the group that she was much more comfortable with the positioning of the 2” crank. A side-by-side photo of her leg positioned at the bottom of the pedal stroke with the 3” crank and the 2” crank is shown in Figure 32. As observed, her knee was fully extended with the 3” crank compared to the 2” crank where she had a slight bend of her knee.

Figure 32: 3" Crank Compared to 2" Crank Position at Lowest Pedal Stroke

With a 2” crank providing an increase in comfort in the lower position, the team tested the comfortability of a 2” inch crank at the top of the pedal path. Another stationary test was performed in which the seat was raised up 1” to simulate a 2" crank at the top of the pedal path. The client notified us that this positioning in her knees and hips felt much more comfortable compared to the 3” inch crank. Figure 33 is a side-by-side comparison of the 3" crank and the simulated 2” crank. As observed, her hip is less stressed, and her knee holds a more natural angle than the 3” crank. From these two tests, it was decided that a 2” pedal crank would be more ideal for the client’s comfort.

Figure 33: 3" Crank vs Simulated 2" Crank Hip and Knee Locations at Highest Pedal Stroke

Following these tests, the team contacted a PLA in Washburn shops. Different methods of designing shorter cranks were discussed including machining cranks that can fit onto the existing pedal kit or cutting down the current cranks, re-tapping, and threading a new hole. The first method of machining new cranks was deemed infeasible with the machine equipment since we would have to taper the crank to fit onto the pedals as well as machine a new gear. In addition, Washburn shops limit the use of steel in the machining mills, so aluminum would have had to be used, which was less ideal for the cranks. The second method, cutting down the current cranks, re-tapping, and threading a new hole, was deemed feasible given project time and resources. There are two standard sizes of pedal screws used across all bicycles: 9/16” and 1/2". The existing crank pedal system had 9/16” pedal screws, but the team decided to use half-inch pedal screws instead as the 1/2" pedals allowed for a larger edge to hole clearance, ensuring a stronger crank. In prior visits with the client, we noticed she had a hard time keeping her foot on the existing pedals since they were long and thin. With the redesign of a smaller pedal screw, wider pedals were purchased to alleviate this discomfort experienced by our client.

As seen in Figure 34, the cranks were modeled and an ANSYS simulation was run to verify the pedal would be able to withstand the forces subjected onto the hole if a new hole were to be added an inch down from the original hole. Using the yield strength of a standard bicycle crank, 35534.2 PSI (245 MPa), (Steel ASTM A216 WCB) the safety factor of the crank was calculated by dividing yield strength by Von Mises stress obtained from the ANSYS structural simulation (Kattimani, n.d.). The safety factor of 15.7 was rounded down to 15, which is five times the required safety factor of 3 for a bicycle (*Factors of Safety - FOS*, n.d.).

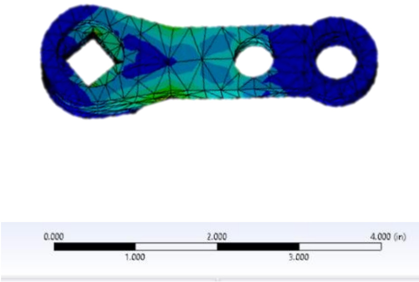


Figure 34: ANSYS of Bicycle Crank with Hole at 2"

After ensuring a 2” crank would be safe for the client, the Washburn PLA guaranteed that our crank modification method would be viable and producible given the tools available at the machine shop. A left-handed tap for the left side pedal was purchased as the thread direction is opposite for the left pedal in all bicycles. An appointment at Washburn was booked and the following tasks were completed to yield the modified crank shown in Figure 35: A gear puller removed the right-side crank from the pedal assembly, while the left side crank was removed using crowbars. The hole's location was measured and marked to ensure it was an inch lower than the existing hole and centered on the crank. Half inch holes were drilled into the marked location using a drill press. The drilled holes were then tapped (20TPI) using a left-hand tap on the left pedal, and a right-hand tap on the right pedal. The excess crank length with the old hole was cut off using a metal saw, and then edges were smoothed using a metal file. Exposed metal was painted to prevent rusting and create a clean, polished look.

Figure 35: Crank with Gear Cut Down to 2"

Final Prototype 2 can be seen in Figure 36 below.

Figure 36: Prototype 2 Final Bicycle

6. Testing: Safety First!

The first priority for the bicycle is that it is safe for our client to ride. The following tests were completed using standards from the Consumer Product Safety Commission (*Bicycle Requirements Business Guidance*, n.d.). The team only performed tests on elements of the bicycle that were created or altered, not elements that were used from pre-existing bicycles (i.e., the brackets were tested but not the frame) assuming the manufacturer ensured all components pass.

6.1 Chain Alignment Test (CPSC "chain requirements" 1)

Procedure:

1. Setup bicycle with chain positioned around back wheel gear, offset gear, and pedal kit gear.
2. Place the bicycle on the Park Tool bicycle stand so that the bicycle is positioned as shown in Figure 37 below.

Figure 37: Bicycle on Park Tool Bicycle Stand

3. Place hands on pedals to simulate pedal path movement and pedal the bicycle in the air for roughly 1 minute.
4. Listen for any "clicking" in the chain. Watch for any binding or catching in the chain.

Failure Criteria:

The test is successful if no “clicking” is heard and no binding or catching is visibly observed in the chain.

Results:

The set up of the chain alignment test can be seen in Figure 38 below.

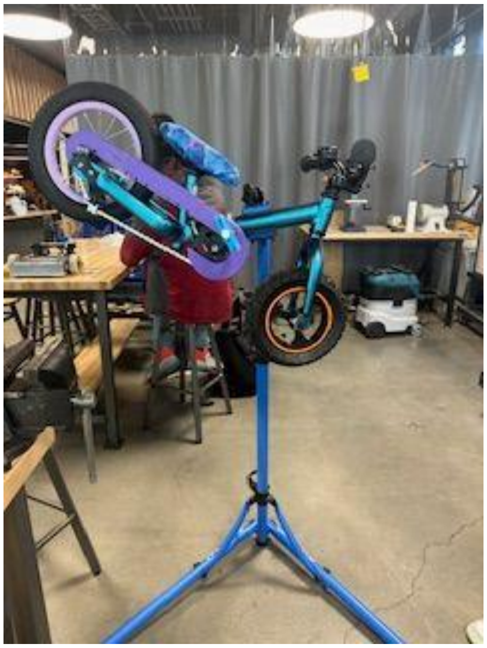


Figure 38: Chain Alignment Test Setup

The test was successful due to no “clicking” being heard and no binding, catching, or interference was visibly observed in the chain.

6.2 Bicycle Tip Angle Test (CPSC “other requirements” 3)

Procedure:

1. Put one pedal so the crank is in the lowest position and adjust the pedal to be perpendicular to the ground as shown in Figure 39 below.

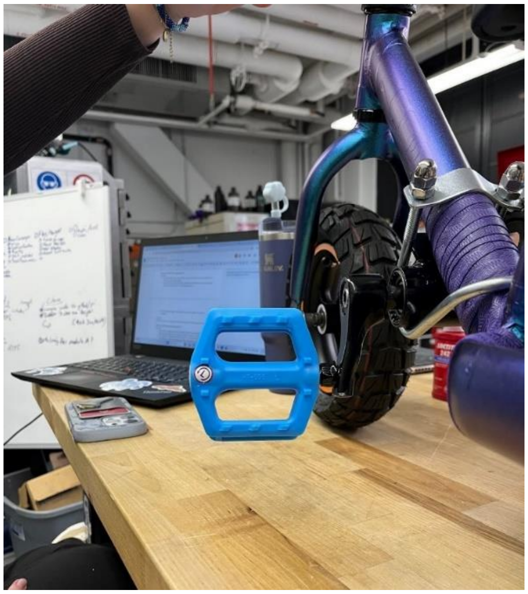


Figure 39: Pedal Positioned Perpendicular to the Ground

2. Place an iPhone parallel to the pedal using the level feature on the iPhone measure app as shown in Figure 40 below.

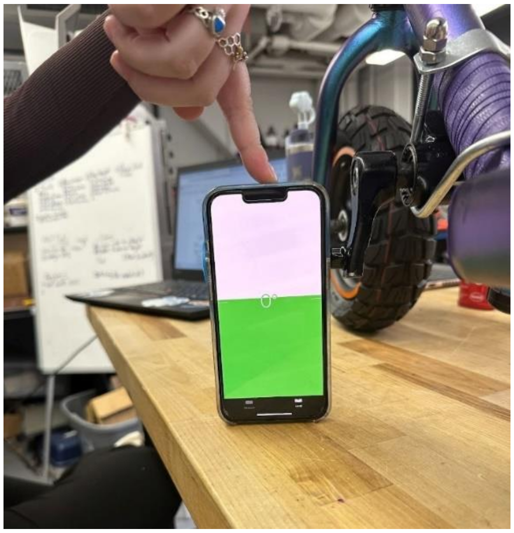


Figure 40: Phone Positioned Parallel to the Pedal with iPhone Measure App

3. Tilt the bicycle until the pedal hits the ground. Record the angle displayed on the iPhone app.
4. Repeat two additional times.

Failure Citeria:

The bicycle must be able to reach a minimum angle of 25 degrees without the pedal or any other part of the bicycle (other than the tires) hitting the ground.

Results:

The set up of the tip angle test for trial 1 can be seen in Figure 41 below.

Figure 41: Tip Angle Test Setup

Results across three trials are shown in Table 2 below.

Table 3: Tip Angle Test Result Angle (degrees) over 3 Trials

Trial	Trial 1	Trial 2	Trial 3	Average
Angle (degrees)	28°	27°	28°	27.7°

The bicycle passed the tip test as the average angle was greater than 25°.

6.3 Drop Test (CPSC “other requirements” 2)

Procedure:

1. Drop the bicycle (while maintaining an upright position) from one foot above the ground for three trials in the upright position.
2. Next, drop the bicycle from one foot above the ground for three trials on each side in any other orientation.

Failure Criteria:

If the wheels, frame, seat, handlebars, pedals, and fork do not break or shift the bicycle has passed the drop test.

Results:

The set up for the drop test can be seen in Figure 42 below with the lowest point on the bicycle (bottom of both tires) is at the 1ft mark. Results of the first trial can be seen in Figure 43.

Figure 42: Setup for the Drop Test

Figure 43: Results of 1 Trial after the Drop Test

After 3 drops in the upright position and 3 drops in any other orientation the bicycle or its components did not break and passed the drop test.

6.4 Chain Guard (CPSC “Chain Guard Requirements” 2)

In accordance with the CPSC guidelines, bicycles with a single front and a single rear sprocket must have a chain guard over the top of the chain and at least 90% of the part of the front sprocket that the chain contacts. The guard must also extend back to within at least 3.2 inches of the center of the bicycle’s rear axle. The top of the guard from the front sprocket back to the rear wheel rim must be at least twice as wide as the chain. The guard must also prevent a 3 inch long, ⅜ inch diameter rod from catching between the upper junction of the sprocket and the chain when a tester tries to insert the rod at any direction up to a 45-degree angle from the side of the bicycle that the chain is on.

The chain guard design went through eight iterations. Some design considerations that were incorporated into the process included: installation method (how we attached to the bicycle), attachment method (how we attached pieces to other pieces of the assembly), material (PLA), color (purple), manufacturing method (3D printed), limitations of the manufacturing method (3D printer bed and supports), and elimination of sharp edges.

The chain guard was modeled in four pieces. The pieces are fixed to each other and the bicycle using zip ties. It is mounted to the bicycle at two points on the pedal kit and around the back axle. Dimensions of the chain guard were determined using existing chain guards, bicycle measurements, and CPSC guidelines. An image of the final assembly is shown in Figure 44 below.

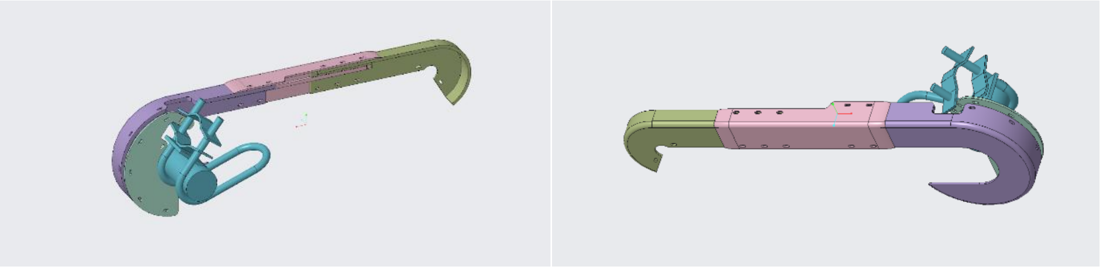


Figure 44: Chain Guard Assembly

6.5 Touch Test (CPSC "general requirements" 2)

Procedure:

1. Install chain guard securely over chain on the bicycle.
2. Run a hand over all parts of the bicycle in multiple orientations and note any locations that feel sharp. Sharp is defined as any edge or point that could pierce or cut skin or clothing.
3. Use a shoelace or sweatshirt drawstring with a knot at the end and drag against all parts of the bicycle that were modified, making sure to change the orientation and angle. Note any locations that get the shoelace or drawstring caught in between them.

Failure Criteria:

If any locations feel sharp, sand/grind the part of concern. If the string gets caught in a modified part, remove all possible open space using grip tape. Repeat the touch test after fixing any sharp locations.

Results:

After running a hand over all parts of the bicycle no sharp locations were noted. The sweatshirt drawstring setup can be seen in Figure 45 below.

Figure 45: Touch Test Setup with Sweatshirt String

After the sweatshirt drawstring was dragged against all parts of the bicycle that were modified, no locations had the drawstring get caught, even when changing the orientation and angle. The bicycle passed the touch test.

6.6 Adult Ride Test

Procedure:

1. A rider weighing at least 140 pounds rides a bicycle by sitting on the seat and placing their feet lightly on the sides of the treadmills but keeping the majority of their weight on the bicycle.
2. The rider travels at 5 miles per hour for 5 minutes checking for the durability of the assembly.
3. Next, the rider travels at 5 miles per hour for 5 minutes again while steering/leaning the bicycle minimally, checking that the bicycle can turn and steer in a stable manner without difficulty.

Failure Criteria:

During these tests, the bicycle must handle, turn, and steer in a stable manner without difficulty and the bicycle assembly must not fail. If any of these are difficult, the team must evaluate and redesign aspects of the bicycle and repeat the test again.

Results:

The set up of the adult ride test can be seen in Figure 46 below.

Figure 46: Adult Ride Test Setup, Front View (Left) & Back View (Right)

After the rider traveled 5 mph for 5 minutes checking durability and traveled another 5 mph for 5 minutes steering the bicycle, the bicycle did not have any difficulty and passed the adult ride test.

6.6 Weight Distribution Test (Not in CPSC Guidelines, necessary with bracket modifications)

Procedure:

Back-Wheel Brackets

1. Record the location of the back-wheel bracket bolts in reference to the back-wheel fork slot before testing (see image on the left in Figure 47 below as a reference).
2. Have someone greater than 60 lbs sit on the seat of the bicycle for roughly 15 seconds while the bicycle is held in place by another person.
3. Observe if there is any displacement of the back wheel bracket by re-measuring the location of the bolts in reference to the back-wheel fork slot.
4. Record the displacement value if there is any.
5. Repeat the process 2 more times for a total of 3 trials.

Pedal-Kit Bracket

1. Record the location of the pedal-kit U-bracket in reference to the seat post intersection portion of the frame before testing (see image on the right in Figure 47 below as a reference).
2. Have someone greater than 60 lbs place their weight onto the left pedal attached to the pedal kit assembly for roughly 15 seconds while the bicycle is held in place by another person.
3. Observe if the pedal-kit bracket is displaced by re-measuring the bracket's location in reference to the frame.
4. Record the displacement value for that side.
5. Repeat the process 2 more times for a total of 3 trials.
6. Repeat steps 6-10 with the right pedal.

Figure 47: Location of Back-Wheel Bracket Bolts in Reference to the Back-Wheel Fork Slot (left) and Location of the Pedal-Kit U-Bracket in Reference to the Seat Post Intersection Portion of the Frame (right)

Failure Criteria:

If displacement greater than 1 mm occurs, run the fastener test on the back wheel brackets and pedal-kit bracket and re-test the weight distribution after fastener fit has been ensured.

Results:

During the weight distribution test of the back wheel brackets, no displacement was recorded over 3 trials. When testing the pedal kit bracket, no displacement was observed for 3 trials on each of the pedals, passing the weight distribution test.

6.7 Fastener Test (CPSC "general requirements" 4)

Procedure:

1. Perform all testing procedures above and check for any broken, loose, or failure of screws, nuts, and bolts.
2. Try to unscrew all screws, nuts, and bolts without the use of tools.

Failure Criteria:

Screws, bolts, and nuts used to fasten parts may not loosen, break, or fail during any of the above testing procedures. If any screws, nuts, or bolts become loose or break, get replacements of these parts, apply more Loctite, and test these parts again.

Results:

No screws, bolts, and nuts used to fasten parts did not loosen, break, or fail during any of the other tests. During the fastener test, no screws, nuts, or bolts become loose or broken, passing the fastener test.

Based on the standards from the Consumer Product Safety Commission, this bicycle was tested for children's use. From the results of these tests, this bicycle is safe for a rider no larger than 60lbs (based on the frame maximum weight).

7. Discussion & Conclusions

7.1 Discussion

We accomplished our goal of designing, developing, and testing a method of adapting a bicycle to comfortably accommodate a child with Achondroplasia and facilitate learning. Our bicycle was ergonomically correct for our client's body, fully functional, and proven safe. We achieved this with three methods: lowering the bicycle frame, incorporating functional bicycle mechanisms, and addressing comfort.

The bicycle frame was lowered the necessary distance to accommodate our client's 11-inch inseam. Starting with a balance bicycle frame that had a 13-inch saddle height and a step through design, we lowered it the remaining necessary distance by using a smaller tire in the front and integrating a custom bracket in the back. Functional bicycle mechanisms were incorporated to convert the balance bicycle to a working pedal bicycle. Brakes, pedals, gears, a chain, and an offset gear were installed and proven functional and secure. Comfort and ergonomics were addressed with adjustable features like handlebars and crank length, and new pedals.

Limitations of this process include time, resources, and budget. This prevented us from designing, developing, and manufacturing a custom frame or more machined parts. Another major limitation of our project was the amount of space we had to work with in our design. Bicycle mechanisms exist below the saddle and far enough above the ground to maintain full clearance and reasonable tip angle. This gave us an extremely small amount of vertical space to work with, which made the process increasingly difficult.

We were also limited by our client and her family. Our client is only six years old and has no experience with bicycling. She does not know what riding a bicycle is supposed to feel like, or how to articulate her discomforts to us. Furthermore, meeting with our client and workshopping our prototypes was limited by the client's schedule, school, appointments, and their parent's time. This caused some delays as meetings had to be postponed and rescheduled on multiple occasions to accommodate the everyday lives of the family we worked with. However, these limitations did not prevent us from accomplishing our goal of providing her with a safe and comfortable first bicycle.

In conclusion, the bicycle is comfortable, can facilitate learning, and is proven to be safe for the rider. The team was able to create a bicycle that fits our specific 6-year-old client's needs and wants for a bicycle.

7.2 Future Recommendations

In the future, the team would like to create a custom pedal kit attachment. Although our attachment worked with the double U bracket, it would be more ideal to create and machine a custom attachment method. This way the pedals would be more securely attached and tailored to our specific bicycle design. This would also eliminate the need for extra rubber to fill gaps in the bracket and make it more secure while also reducing sharp interaction points of the attachment method. In the future, the bicycle would also benefit from custom hand brakes in addition to coaster brakes. Coaster brakes are standard for children's bicycles, but hand brakes could be used as an additional braking mechanism. Hand brakes would have to be modified and specifically designed for our client, as she has very small hands and low grip strength. Our team also purchased additional handlebars that can be swapped out on the bicycle when she grows and raises the seat. These handlebars are U shaped and will be able to rotate for maximum comfort. The additional purchased handlebars for future use are pictured in Figure 48 below.

Figure 48: U-Shaped Handlebars for Future Use (when the Client Grows)

With additional time, resources, and budget, the team could have approached the design method differently and went the route of designing a custom frame using BikeCAD, a software specifically designed for bicycle frame design.

7.3 Broader Impacts

Creating this specialized bicycle for a child with Achondroplasia can have significant broader impacts. First, the project promotes inclusivity and accessibility by allowing a child with this condition to participate in physical activities like cycling just like her peers. Second, this project opens the door for future innovations and solutions for bicycles for children with Achondroplasia. This bicycle is just one way to create an adaptive bicycle for a child with Achondroplasia but can be used as inspiration to make other bicycles like it. This could go a step further, moving away from bicycle adaptations and toward an off-the-shelf accessible bicycle design. Designing, developing, and producing commercially available bicycles specifically for children with Achondroplasia would be more efficient, accessible, and affordable for Little People everywhere. The total cost to produce the custom bicycle to fit a child with Achondroplasia came out to roughly $940 as seen in Appendix 4: Bill of Materials. This draws a stark contrast to being able to purchase a commercially available children’s beginner bicycle, which ranges anywhere from $100 - $400. Not only are there no options on the market for children with Achondroplasia, but the associated cost to adapt such a bicycle that functions the same way as a standard 12” pedal bike cannot be completed with a limited budget, further increasing inaccessibility to a solution that allows children with Achondroplasia to learn how to ride a bike just like their peers. This project raises awareness about the unique needs of individuals with Achondroplasia within the cycling community, advocating for more diverse and inclusive design approaches in the future.

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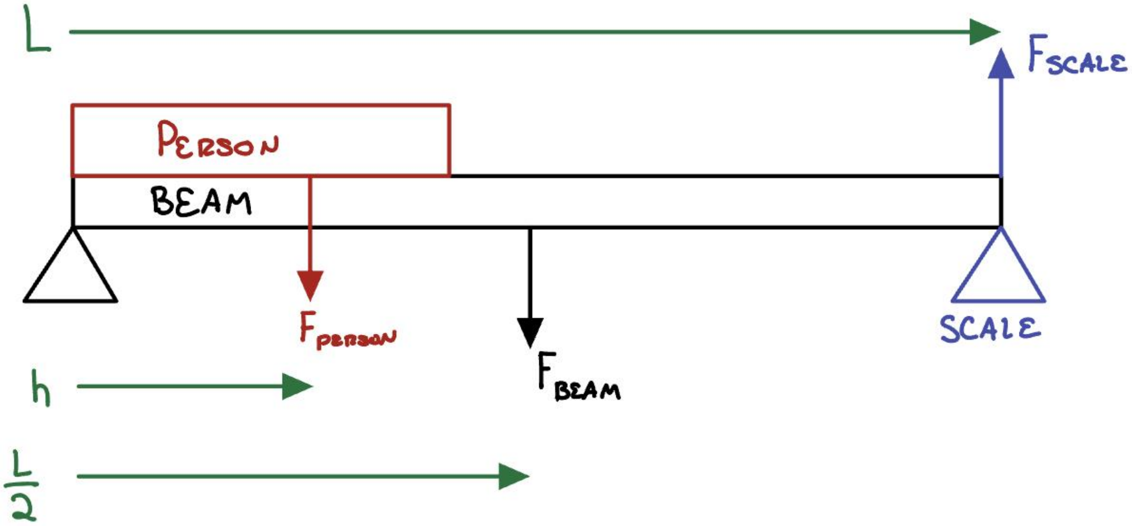
Appendices

Appendix 1: Finding Center of Gravity of a Bicycle

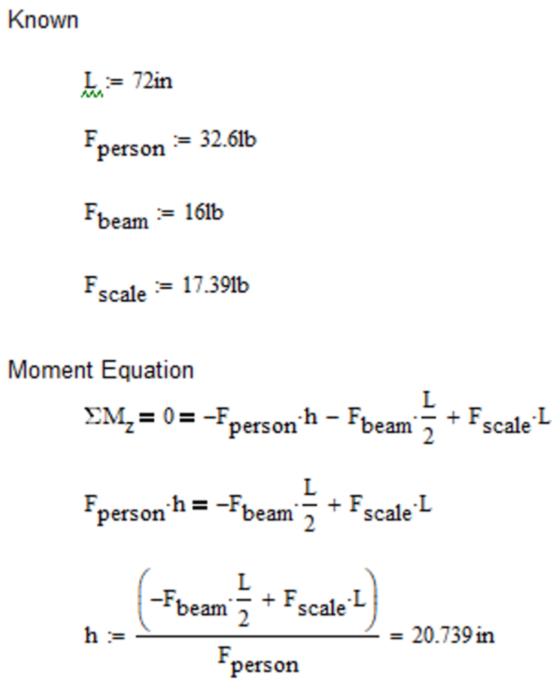
To find the center of gravity of a bicycle, we hung the bicycle from a single point and drew a vertical line down the length of the bicycle from that point. This was repeated from another hanging point, and the center of gravity is located at the intersection of the two points.

Appendix 2: Finding Height of Center of Gravity of a Human

To find the height of the center of gravity of a human, we utilized moments. Below is a free body diagram of our setup. We had the client lay horizontally with her feet at one end of a uniform beam and a scale supporting the other end of the beam. The weight of the client, weight of the beam, and length of the beam were all known. By observing the values on the scale, we were able to calculate for h, which is the height of the client's center of gravity.



The weight of the client, weight of the beam, and length of the beam were all known. By observing the values on the scale, we were able to calculate for h, which is the height of the client's center of gravity. Calculations for h are shown below.



Known

$L := 72\text{in}$

$F_{person} := 32.6\text{lb}$

$F_{beam} := 16\text{lb}$

$F_{scale} := 17.39\text{lb}$

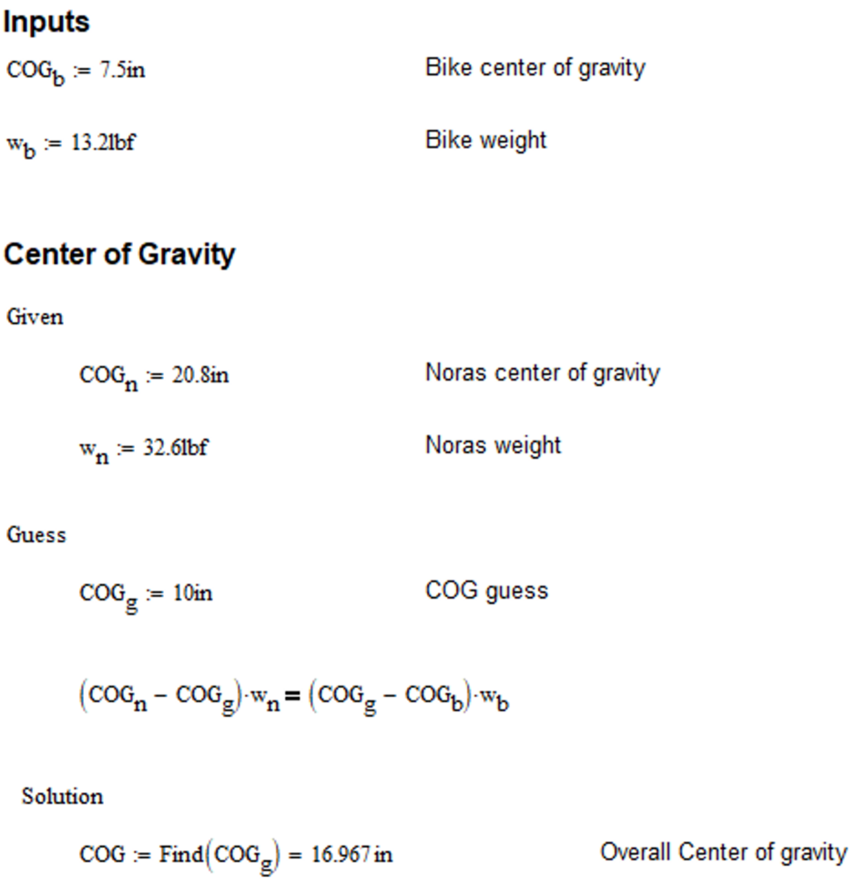
Moment Equation

$$\Sigma M_z = 0 = -F_{person} \cdot h - F_{beam} \cdot \frac{L}{2} + F_{scale} \cdot L$$

$$F_{person} \cdot h = -F_{beam} \cdot \frac{L}{2} + F_{scale} \cdot L$$

$$h := \frac{\left(-F_{beam} \cdot \frac{L}{2} + F_{scale} \cdot L\right)}{F_{person}} = 20.739\,\text{in}$$

Appendix 3: Finding Height of Center of Gravity of a Human and Bicycle together



Inputs

$COG_b := 7.5\text{in}$ Bike center of gravity

$w_b := 13.2\text{lbf}$ Bike weight

Center of Gravity

Given

$COG_n := 20.8\text{in}$ Noras center of gravity

$w_n := 32.6\text{lbf}$ Noras weight

Guess

$COG_g := 10\text{in}$ COG guess

$$\left(COG_n - COG_g\right) \cdot w_n = \left(COG_g - COG_b\right) \cdot w_b$$

Solution

$COG := \text{Find}\left(COG_g\right) = 16.967\,\text{in}$ Overall Center of gravity

Appendix 4: Bill of Materials

Level	Component	Quantity	Cost
1	REI Co-Op Balance Bike	1	$149.00
2	Strider Pedal Kit	1	$69.99
3	Pedal Kit Attachement	2	$58.88
4	Replacement Pedals	1	$14.99
5	Rubber Tape	1	$15.99
6	M8-1.25 Acorn Cap Nuts (25 pack)	1	$8.99
7	Left handed ½” -20 UNF Thread Tap	1	$13.39
7	Right Handed Thread ½”-20 UNF	1	$8.79
2	10 Inch Tire	1	$59.99
2	6061 Aluminum Sheet, 1/8" Thick, 12" x 12"	1	$37.29
2	Back Wheel Brackets Cut from Aluminum, files can be found on website page	2	$10 - $150
3	Offset Gear	1	$24.98
4	Pipe Hanger Strap	1	$9.62
5	Set Screw Shaft Collar for 3/8" Diameter	2	$4.04
6	Bike Chain	1	$14.99
6	3D Printed Chain Guard, files can be found on website page	1	$10.00
2	Bell	1	$10.99
2	Bike Seat Cover	1	$7.99
2	Additional Handlebars	1	$38.99

3	Bike Handlebar Grips	1	$6.99
6	Bolts/Nuts ¾” (8 Pack)	1	$1.38
6	Washers ⅜” (25 Pack)	1	$5.97
2	Vinyl Wrap	1	$27.90
3	Vinyl Sealing Spray	1	$19.99
7	Loctite	1	$16.99
Total Cost			$938.12