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Passive Assistive Pedaling Device

A Major Qualifying Project Report

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by

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Abstract

Cycling for post-stroke rehabilitation usually occurs indoors on a stationary bicycle designed for a user with equal leg strength. Cycling training could be improved if it could occur outdoors and account for the weakness of the user’s affected leg due to hemiparesis. This MQP develops a drivetrain for an adult tricycle to allow for rehabilitative and recreational use. The drivetrain was designed so that each crank rotates on a fixed axle at a speed relative to the size of the chainring. Each chainring is connected to separate sprockets on the rear axle with a gear ratio of 2:1. The drivetrain has the potential to be set up so that the patient can pedal with their affected leg on the smaller chainring for more repetition, or on the larger chainring for more strength training. Testing indicated that users can adapt to the irregular pedaling pattern and that the potential for adjustability would make the design suitable for post-stroke rehabilitation.

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1. Introduction

Strokes are the third leading cause of death in the United States, affecting approximately 795,000 people each year. The effects of a stroke can lead to severe impairment or even death. Approximately 140,000 people die from strokes each year, but that leaves 655,000 people on average every year who need some form of rehabilitation. From 1995 to 2005, the stroke death rate decreased by 30%, which means the need for post-stroke rehabilitation has increased. Unfortunately, rehabilitation and other post-stroke costs are high; 36.5 billion dollars are spent each year in the United States alone on healthcare services, medication, and work missed due to strokes (Stroke Facts, 2014).

Most people who have had a stroke exhibit some level of hemiparesis, in which the muscles on one side of the body are weakened. Rehabilitation can help redevelop the muscle control and strength that is lost due to a stroke. Damage begins the moment the stroke takes place, although the stroke may not be detected until a full twenty four hours later (NINDS Know Stroke Campaign - Post-Stroke Rehabilitation, 2013). During this time the affected muscles can begin to deteriorate. It has been found that repetitive motion, such as cycling, can be beneficial in rehabilitating affected leg muscles. Persons with stroke often exhibit some level of hemiparesis. Activities that provide repetitive motion can help diminish the effects of hemiparesis over time, so for these people, pedaling a tricycle combines recreation and rehabilitation. Ideally, the affected leg would be moving from the flexed position to the extended position.

2. Literature Review

When designing a device for the rehabilitation of hemiparesis, it is important to investigate how the stroke affected the person. It is also imperative to understand what causes hemiparesis as well as common methods of rehabilitation for this condition, such as cycling.

2.1 The Basics of Strokes

Over 795,000 strokes happen each year in the United States alone. This high rate of strokes is due to the wide range of causes, including high blood pressure, smoking, high fat, poor diet, lack of physical activity, high bad cholesterol, diabetes, excessive drinking, stress, and heart disorders (Smith, 2010). As one ages, these causes become more common, so the risk of having a stroke doubles after age 55 and three-quarters of all strokes occur in people over the age of 65. Although all strokes have negative consequences, some strokes are more severe than others. There are two types of strokes, ischemic and hemorrhagic. Hemorrhagic strokes are more severe since they are caused by a blood vessel rupturing and leaking into the brain, which can be fatal. Ischemic strokes, caused by a blood clot slowing or stopping the blood flow to the brain, are more common than hemorrhagic strokes, accounting for 9 out of every 10 strokes. Ischemic strokes are less severe and easier to treat than a ruptured blood vessel.

Even with their differences, both types of strokes can cause extreme damage to the human body, even if treated quickly. For both types, blood flow to brain cells is disrupted, causing the cells to die due to lack of oxygen. As these cells and brain tissue die, the body loses control of the corresponding body parts leading to long term disabilities. Drugs are available to treat strokes in an attempt to curb the damage, but once it has occurred the cells cannot be rejuvenated.

A common result of strokes is partial paralysis called hemiparesis. While paralysis is a total loss of muscle function and sensation in an area, hemiparesis is a weakness or loss of muscle function that can be recovered. This weakness can cause balance issues, difficulty walking, and a decrease in fine motor skills. Fortunately, rehabilitation allows muscle strength and control to be restored through improved posture, range of motion exercises, and strength exercises (Harris et al., 2001).

2.2 Rehabilitation

After a stroke occurs, rehabilitation is necessary. However, most people who have had strokes are not healthy enough to do so right away. The average time spent on therapeutic activities in a hospital or rehabilitation center was only 20% of their day while an additional 28% of their time was just sitting. This means that for the average person, more time is spent sitting around than in rehabilitation. However, this 20% of time doing therapy involves rehabilitative exercises incorporating balance, reaching, walking, biking, and constraint-induced movement therapy, which have strong results for fewer repetitions (Huijben-Schoenmakers et al., 2009).

All this time inside means less fresh air and limited exercise (Huijben-Schoenmakers et al., 2009). Especially for the elderly, fresh air is important since it is good for the body’s natural ability to function. Fresh clean air helps digestion and the immune system, which are both weaker in the elderly, especially those who are recovering from a stroke. Fresh air also helps improve blood pressure and heart rate and cleans the lungs (6 Important Health Benefits of Fresh Air, 2012).

2.2.1 The Rehabilitation Process

There are rehabilitation procedures that attempt to repair damage from the stroke in order to restore the stroke patient’s prior health. According to the NINDS Know Stroke Campaign

(2013), this rehabilitation helps stroke survivors relearn skills that are lost from partial brain damage and learn new ways of performing tasks to accommodate for any new disabilities. In order for this rehabilitation to have its full effect, it must start within twenty-four hours of the stroke. With carefully directed, well-focused, repetitive practice, one can start to restore balance, range of motion, and muscle strength.

This therapy is not an easy task. It is expected that many hours will be put into rehabilitation of each specific muscle and that exercises are used to help improve muscle strength and coordination for motor skills. Depending on the severity of the injury, mobility training may also be necessary, where one must learn to use walking aids, such as canes or braces, to stabilize and assist the knees and ankles or to support the user's body weight while they relearn how to walk. It is also important to work on the patient's range of motion since some of that may have been lost while sitting still after the stroke. Stretches, exercises, and other treatments are used to loosen the muscles and regain a normal range of motion. A technique that is also used is constraint-induced therapy, where the unaffected limb is restricted and the patient is forced to move the injured limb, therefore regaining some normalcy of use. (Stroke Rehabilitation: What To Expect As You Recover, 2011).

It is vital that these exercises start as soon as possible to prevent further damage from occurring. A large issue faced by patients recovering from a stroke is muscle atrophy. Muscle atrophy occurs when muscles start to weaken or the muscle tissue starts to break down due to disease or lack of exercise of the affected limb. This can be recovered, to an extent, through range of motion exercise, both passive and active; however, one can only build muscle strength when doing exercises on his or her own by voluntarily moving the muscle. This is because muscle strength can only be built up by active movement of the muscles, having someone else move the patient’s leg will help recover range of motion, but not muscle strength (Carmichael, 2011).

2.2.2 Rehabilitative Leg Motion Research

There have been many studies done in recent years regarding post-stroke rehabilitation techniques for correcting hemiparesis. One such study by Malone and Bastian (2013), completed as a collaboration between the Kennedy Krieger Institute and Johns Hopkins University, focused on how asymmetries in gait affect patient adaptation to split-belt treadmill training. This study involved the use of a custom-built treadmill with two belts, one for each leg, driven by independent motors, which allowed for the belts to be “tied” at the same speed or “split” at different speeds.

The results of the study showed that participants who had had a stroke adapted just as much as the healthy participants in the spatial and temporal domains of walking, except more slowly. The study found a relationship between the baseline asymmetry and adaptation plateau of the participants, which was that they were likely to adapt toward their asymmetric baseline. “The adaptation plateau was defined as the average of the last 30 strides of split-belts, while the after-effect was the average of the first 5 strides in de-adaptation (tied belts)” (p. 5). The results also showed that different after-effects from the same split-belt adaptation will occur depending on the initial asymmetry of the participant. The analysis of the results led the researchers to hypothesize:

> “We think that training patients with an error-augmenting split-belt technique (i.e., increase initial asymmetry early in adaptation), is the best way to use the adaptive learning process for rehabilitation. It results in stroke patients exhibiting more symmetric after-effects, when belts are tied following adaptation. This would allow them to practice a symmetric walking pattern that they produce themselves—not

> one driven by the treadmill. Recent studies have demonstrated that stroke patients can maintain this more symmetric pattern for up to 3 months post-training" (p. 10).

The study suggests that different types of baseline asymmetries require different configurations of a split-belt treadmill in order to effectively use "error-augmenting training" (Table 1).

Table 1. Predicted Split-Belt Protocols for "Error-Augmenting" Training Given Different Baseline Asymmetries (Malone and Bastian, 2013)

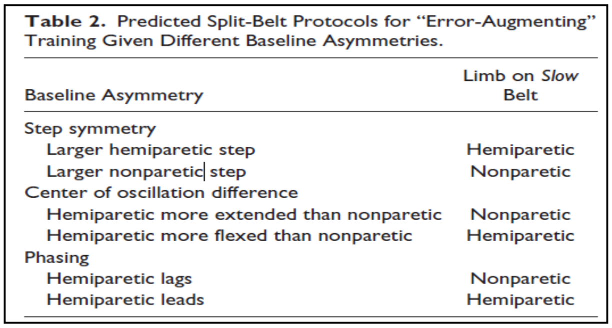


Table 2. Predicted Split-Belt Protocols for "Error-Augmenting" Training Given Different Baseline Asymmetries.

Baseline Asymmetry	Limb on *Slow* Belt
Step symmetry	
Larger hemiparetic step	Hemiparetic
Larger nonparetic step	Nonparetic
Center of oscillation difference	
Hemiparetic more extended than nonparetic	Nonparetic
Hemiparetic more flexed than nonparetic	Hemiparetic
Phasing	
Hemiparetic lags	Nonparetic
Hemiparetic leads	Hemiparetic

The study concludes that split-belt treadmill training can adapt both spatial and temporal coordination to improve the asymmetrical gait of patients who have post-stroke hemiparesis. The concept of the split-belt treadmill used in this study can serve as a basis for the creation of a passive assistive pedaling device for an adult tricycle, as both devices are aimed at correcting post-stroke hemiparesis.

Another similar study done by Kinetic Muscles Incorporated shows that physical therapy can help rewire the patient's brain to help regain normal motor function. In this study, measurements were taken before and after therapy to determine the percent improvement seen by the patients participating in the study. This therapy involves repetitive task practice to help the patient realize their full potential for movement by avoiding non-use of muscles as well as increasing the amount of regained motion by forming new neurological pathways. This study specifically focuses on retraining the brain through the use of tasks the patient would not normally do, or exaggerating tasks the patient would do to train their brain to do more extreme tasks, so that normal tasks are less challenging in comparison (Kinetic Muscles Incorporated, 2012).

Medical Staff

Many people are involved in the post-stroke rehabilitation process, including physicians, nurses, and various therapists. While the physicians and nurses are concerned with the overall health of the patient, they are also trained to assist the patients in rehabilitating themselves to get back into their daily lives. This includes helping them relearn how to pick things up and move around. The physical therapists continue by treating any motor function disabilities using repetitive motion and practicing coordination and balance to retrain the muscles. Occupational and recreational therapists are also involved with the physical therapists in helping the patient make accommodations for their daily lives such as swapping Velcro for a hook and helping them come up with ideas for physical activity and recreation. This rehabilitation could occur in a hospital, outpatient facility, nursing home, or in the patient's home (NINDS Know Stroke Campaign - Post-Stroke Rehabilitation, 2013).

Evaluation

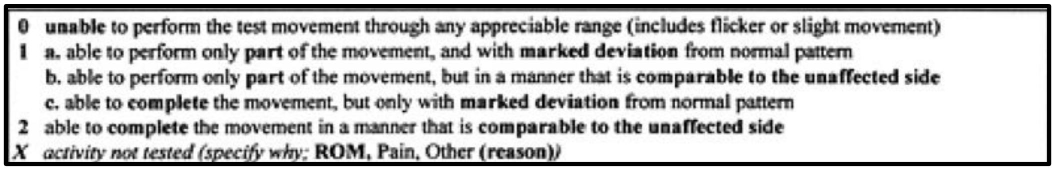
Tests and measurements conducted by medical staff are important tools in the rehabilitation of people who have had a stroke. Since strokes can vary so much, it is important for these evaluations to be quantitative and qualitative. The International Classification of Function, which is a classification of the health components of functioning and disability, should be used for testing (Hill et al., 2005). A full test should be conducted, even if only one area seems to be affected.

Tests have been developed specifically for measuring the ability of a person who has had a stroke. The tests presented are widely used and tested for reliability and validity in a stroke population (Hill et al., 2005). The tests reflect impairments, disabilities and restrictions in participation; what the person cannot do. The International Classification of Function system involves two types of tests: self-reporting and physical. The participant in the these kinds of tests can either answer questions about how they are feeling and what their capabilities are in terms of their disability, or they can be physically-tested by a therapist (Domholdt, 2000).

Tests regarding body function and activity are presented in ordinal scales. The tests are standardized in relation to the rating of the scores. It is important that the tests are evaluated according to the standardization in order to get as few measurement errors as possible in the test procedure. All involved in the testing procedure should be well acquainted with the tests and, if possible, the same individual should perform the test at baseline and at follow-up testing intervals in order to avoid different interpretations of the scoring (Langhammer, 2013).

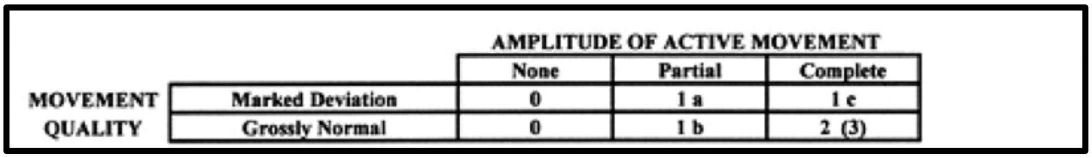
Assessment of Movement (STREAM)

The Stroke Rehabilitation Assessment of Movement (STREAM) assessment tool was developed to provide a quick and simple means to evaluate motor functioning post-stroke. The STREAM contains 30 items divided equally into 3 subscales: 1) voluntary motor ability of the upper extremity, 2) voluntary motor ability of the lower extremity and 3) basic mobility. This project will focus on the second subscale of lower extremity motion. The test begins with the participant in supine position, progressing to a seated position and ending in an upright, standing position. Items on the lower extremity subscales are scored on a 3-point ordinal scale ranging from 0 to 2. This subscale is further explained in Figure 1, with an example in Figure 2, (Salter et al., 2012).



0 **unable** to perform the test movement through any appreciable range (includes flicker or slight movement)
1 **a.** able to perform only **part** of the movement, and with **marked deviation** from normal pattern
b. able to perform only **part** of the movement, but in a manner that is **comparable to the unaffected side**
c. able to **complete** the movement, but only with **marked deviation** from normal pattern
2 able to **complete** the movement in a manner that is **comparable to the unaffected side**
X activity not tested (specify why: **ROM,** Pain, Other **(reason)**)

Figure 1. Breakdown of Evaluation Scoring (Salter et al., 2012)



		AMPLITUDE OF ACTIVE MOVEMENT		
		None	Partial	Complete
MOVEMENT QUALITY	Marked Deviation	0	1 a	1 c
	Grossly Normal	0	1 b	2 (3)

Figure 2. Example of Evaluation Scoring (Salter et al., 2012)

Total raw scores for the STREAM range from 0-70 (20 for each of the upper and lower extremity subscales and 30 for the mobility subscale, respectively). Total and subscale scores may be converted to a percentage score, and taken as an average, to accommodate missing scores on some items (Daley, 1999). There are other methods such as the Sodring Motor Evaluation Scale (Sodring et al. 1995) and the Rivermead Motor Assessment (RMA) (Lincolnet al. 1979) but STREAM is related to the motion of legs more than any other common testing method.

2.2.3 Products on the Market for Rehabilitation

There are many products on the market that aim to aid in the rehabilitation of the legs of stroke patients. Each one has its own unique way of assisting in rehabilitation of legs. Some devices like Kickstart by Cadence Biomedical and AlterG Bionic Leg are orthotics that attach to the users leg to assist in walking until the user’s gait is returned to normal. Some orthotics use robotics and others use mechanical devices to assist in this motion, but both aid the motion of the knee. Another similar device called Biomove uses electrical signals from the user’s leg and amplifies them to restore natural movement. Other products like the SRF Bicycle Pedal Adaptor (Figure 3) assist in making rehabilitation easier by adapting normal devices to make then more useful for rehabilitation (Scheiman Rebuild Fitness, Inc., 2013). Unfortunately, all of these products focus purely on rehabilitation, therefore a stroke patient who is in need of recreation and time outdoors, doesn't get the full benefit of their time rehabilitating.

Figure 3. SRF Bicycle Pedal Adaptor (Scheiman Rebuild Fitness, Inc., 2013)

2.2.4 Bicycles in Therapy

Although many different tools are available to rehabilitate legs, one of the most important and effective ways to do so is simply by walking. Unfortunately, this task is not as easy as it sounds for those who have become hemiparetic and no longer possess the strength to walk on their own without extensive assistance. The ability to use stationary bicycles or tricycles to avoid the balance issue makes cycling a reasonable alternative while adding an extra benefit of normalcy. This is because these two forms of exercise both have similar kinematic patterns. A study by Lo et al. (2012) explains that "both walking and cycling exercise are cyclic and require the alternate muscle activation of antagonists of lower extremities in a well-coordinated manner" (p. 506). Since the patient is seated while bicycling, the amount of physical activity and intensity levels can be controlled by changing the resistance levels while still improving the functional mobility of stroke patients. This repetitive motion has also been reported to increase the range of motion and reduce stiffness in hypertonic joints of stroke patients. Lo et al. (2012) notes that “studies also suggest that cyclic leg movement may provide a potential therapy for reducing hypertonia, one of the factors that prevent functional activity in stroke patients” (p. 506).

Although scientists have deemed walking as the best way to recover one’s overall mobility, cycling has many other additional benefits that makes it the better alternative to a long-lasting recovery. Although strength can be recovered through regular exercise, endurance is much harder to regain. Low impact cardiovascular activities are the best way to recover these muscles while building up the ability to withstand fatigue. Walking has higher impact on the knees than cycling strength training which allows for the continuous motion of pedaling without significant stresses on the knees (Cluett, 2013).

When compared to other exercises, cycling is a relatively knee-friendly activity that is useful for leg and knee rehabilitation. Some of the benefits of cycling are that it is non-weight bearing, low impact, provides a reasonable range of motion needed in one’s daily life, a controlled motion, variable resistance, and a stable position. It also forces symmetry which helps the user regain a more asymmetrical gait. While cycling can be as intense or as relaxed as the user chooses, it is also a good workout as it works several muscle groups. It works the quadriceps as the leg generates power by pushing the pedal down, and the hamstrings to re-bend the knee. The amount of work done by either set of muscle groups can also be varied to make the exercise easier or harder. A simple strap can be used to secure the foot, which then makes the hamstring work harder to pull the pedal up instead of having the quads work harder to push the pedal down (Cycling for Knee Rehabilitation, 2009). A study by Holt et al. (2001) proved that a stroke patient can increase his or her walking speed, endurance, and walking symmetry by riding a stationary bicycle. Cycling is also a cardiovascular aerobic activity which increases overall health. Since this is very much an activity that uses normal leg ability, the leg must have at least

100 degrees of flexion before a patient can use a normal bike (Figure 4). A bike properly adjusted to the user's height and leg length will move the knee from 30 degrees to 110 degrees flexion (Cycling for Knee Rehabilitation, 2009). The patient's physical therapist will work with them in other methods until they have this range of motion.

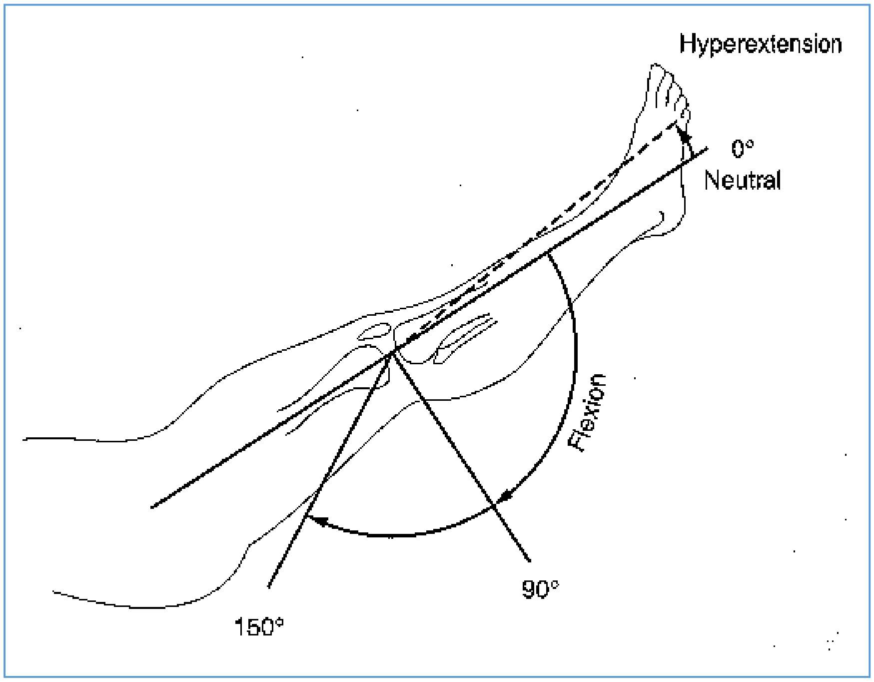


Figure 4. Knee Joint Range of Motion (P11011 / public, 2013)

Benefits of Cycling for Rehabilitation

Cycling as rehabilitation for stroke patients has been shown to be beneficial by many case studies. These case studies explain how cycling helps stroke patients reduce asymmetries in gait and strengthen the muscles and force output of their affected leg.

Cycling has been used for the rehabilitation of stroke patients, including those who have waited a long period of time before starting rehabilitation therapy. To determine the effects of cycling on the recovery of stroke patients, Holt et Al. (2001) conducted a study in which none of the participants had any therapy prior to joining the study. One patient was a 55 year old male who joined the study 18 months after his stroke and was severely hemiparetic on his right side.

On his own, he had been able to walk short distances with a cane or stick, but was still considered severely disabled. This program spanned eight weeks, alternating 2 or 3 sessions a week on a static bike. These 40 minute sessions helped make his walking pattern more symmetrical. Holt et al. (2001) found that his footprint data showed that “the reciprocal action of pedaling could improve the activity of stepping by reinforcing a more symmetrical bilateral activity of the lower limb” (p. 260). This study shows that cyclical motion can be an effective form of rehabilitation not only immediately after the stroke, but also after several months have passed.

A Stanford University study by Brown et al. (1996) focused on lower limb movement deficits in particular by investigating “the timing and amplitudes of EMG activity in seven muscle groups as 15 subjects with hemiplegia and 12 healthy, elderly control subjects pedaled a modified bicycle ergometer at a constant velocity (40 rpm) and constant workload (120J)” (Figure 5). The results illustrated significant differences in timing of muscle activity of control subjects compared to subjects with hemiplegia. It was concluded that lower limb movement deficits in people who have had a stroke are caused by hyperactive stretch reflexes, improper muscle timing, and prolonged muscle activity (Brown et al., 1996).

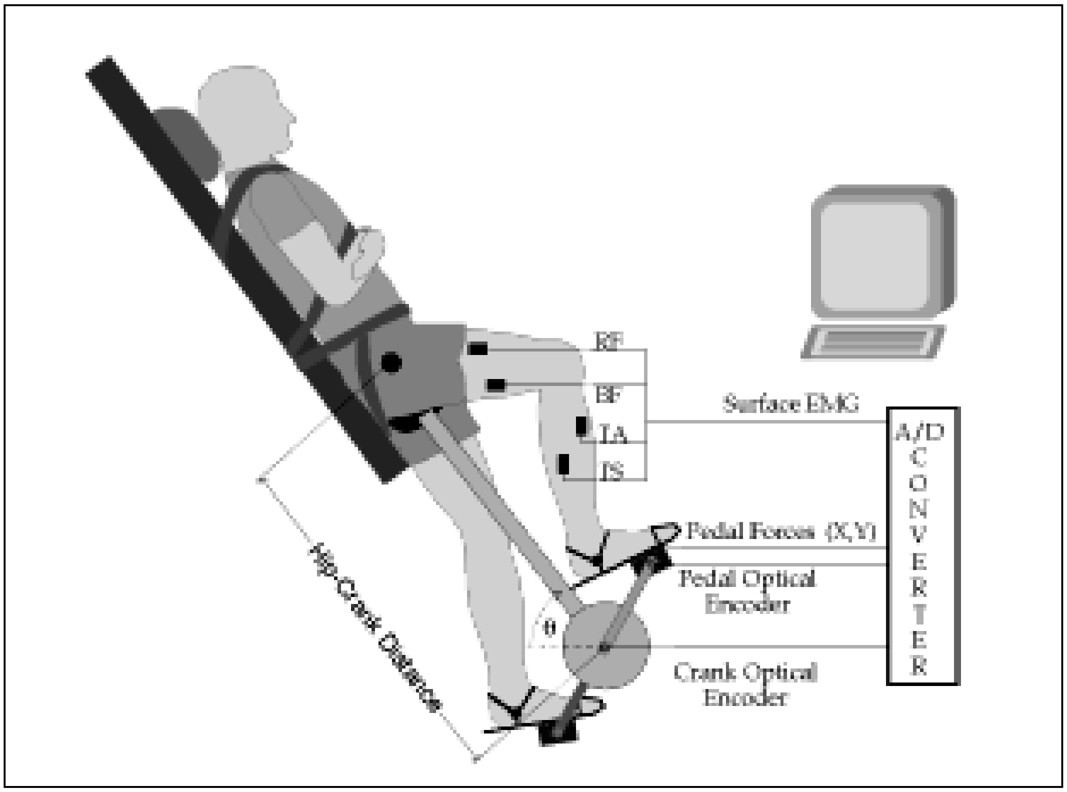


Figure 5. Setup of Bicycle Ergometer (Brown et al., 1996)

A controversial theory exists claiming that heightened activity levels should be avoided in post-stroke rehabilitation because it will exacerbate impaired motor performance. A study by Brown and Kautz (1998) tested the validity of this theory by determining what effect, if any, an increased workload had on motor performance of people with post-stroke hemiplegia. The subjects pedaled a modified bicycle ergometer while pedal force output and EMG activity in seven muscles were measured at different workloads and speeds. Brown and Kautz (1998) found that "the net mechanical work done by the plegic leg increased as workload increased in 75 of 81 instances without increasing the percentage of inappropriate muscle activity." This study provides evidence that increased levels of exercise during post-stroke rehabilitation does not exacerbate impaired motor performance.

All of these studies show that cycling can be beneficial to the rehabilitation process even long after the stroke has occurred, can be used to focus on strengthening the affected leg, that cycling can target the abnormal muscle pattern activity caused by strokes, and that exertional pedaling has positive effects on rehabilitation.

2.3 Biomechanics of Cycling

In order to understand the benefits of cycling as rehabilitation, it is useful to know the biomechanics of pedaling based on the type of motion involved. There are many different pedaling motions that can be used, including cyclical, elliptical, and reciprocating. Cyclical pedaling involves the legs forcing the pedals to move in a circular motion, which is the traditional motion used for bicycling. Elliptical pedaling involves the legs forcing the pedals to move in an elliptical motion, which is a motion used extensively in exercise machines that may be used for rehabilitation. Reciprocating pedaling involves the legs forcing pedals to move in a translational fashion, and it is less common than cyclic pedaling.

2.3.1 Cyclical Motion

The biomechanics of cyclical pedaling can be explained using a clock diagram showing the muscle sequence (Figure 6). During the Power Phase, the hip extensors start off providing all the power needed to push the pedals down, until a point when the knee extensors share the production of power for a while. Then the knee extensors take over completely for a brief period, followed by the ankle plantar flexors sharing power production until the end of the phase. During the Recovery Phase, the ankle dorsiflexors start off by pulling the toes up to level the foot out, until the knee flexors pull the lower leg upwards, followed by the hip flexors pulling the knee up to complete the cycle (Roberts, 2012).

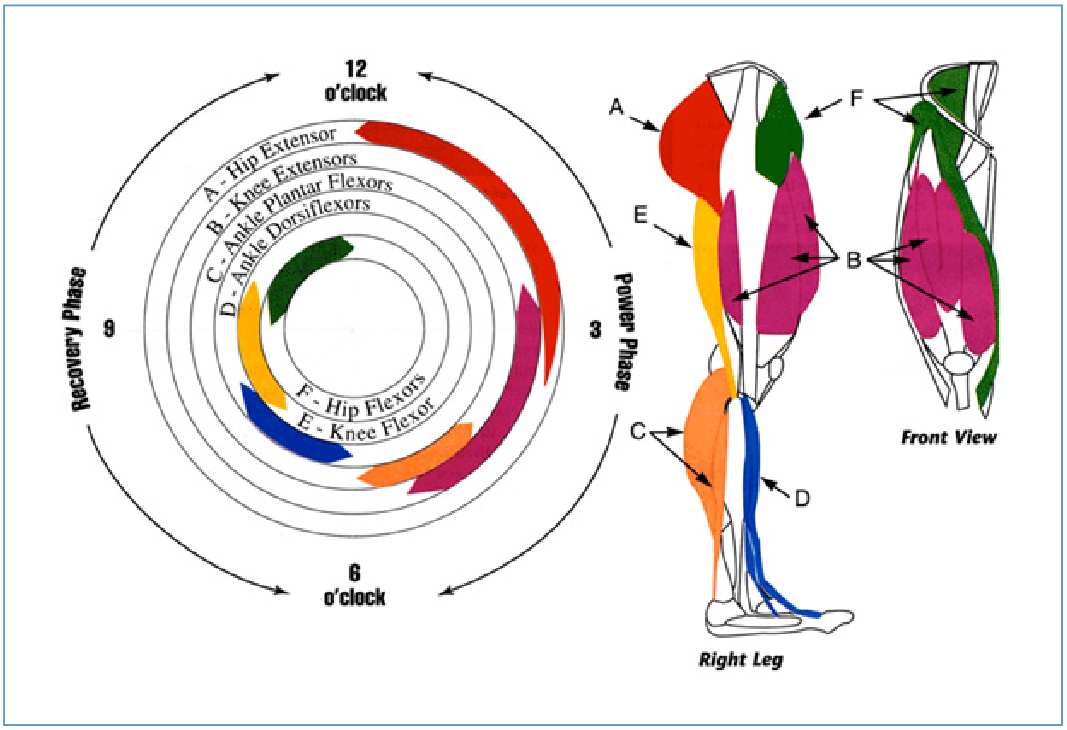


Figure 6: Biomechanics of Cyclical Pedaling (Roberts, 2012)

2.3.2 Elliptical and Reciprocal Motion

There are differences in the biomechanics of elliptical versus reciprocating pedaling. This was shown by a study of twenty college students tested on a trainer that has an elliptical and stair stepper setting. Kinematic data were collected and analyzed via a computer program. The results, (Figure 7), showed that reciprocating motion involves higher knee joint moments than elliptical motion. Elliptical motion involves greater peak hip joint moments than reciprocating motion. Both elliptical and reciprocating motion showed similar moments for the hip, knee, and ankle. There are tradeoffs when it comes to choosing between reciprocal and elliptical pedaling motion in terms of use of the most muscles and moments as seen in Figure 7 (Rogatzki et al., 2012).

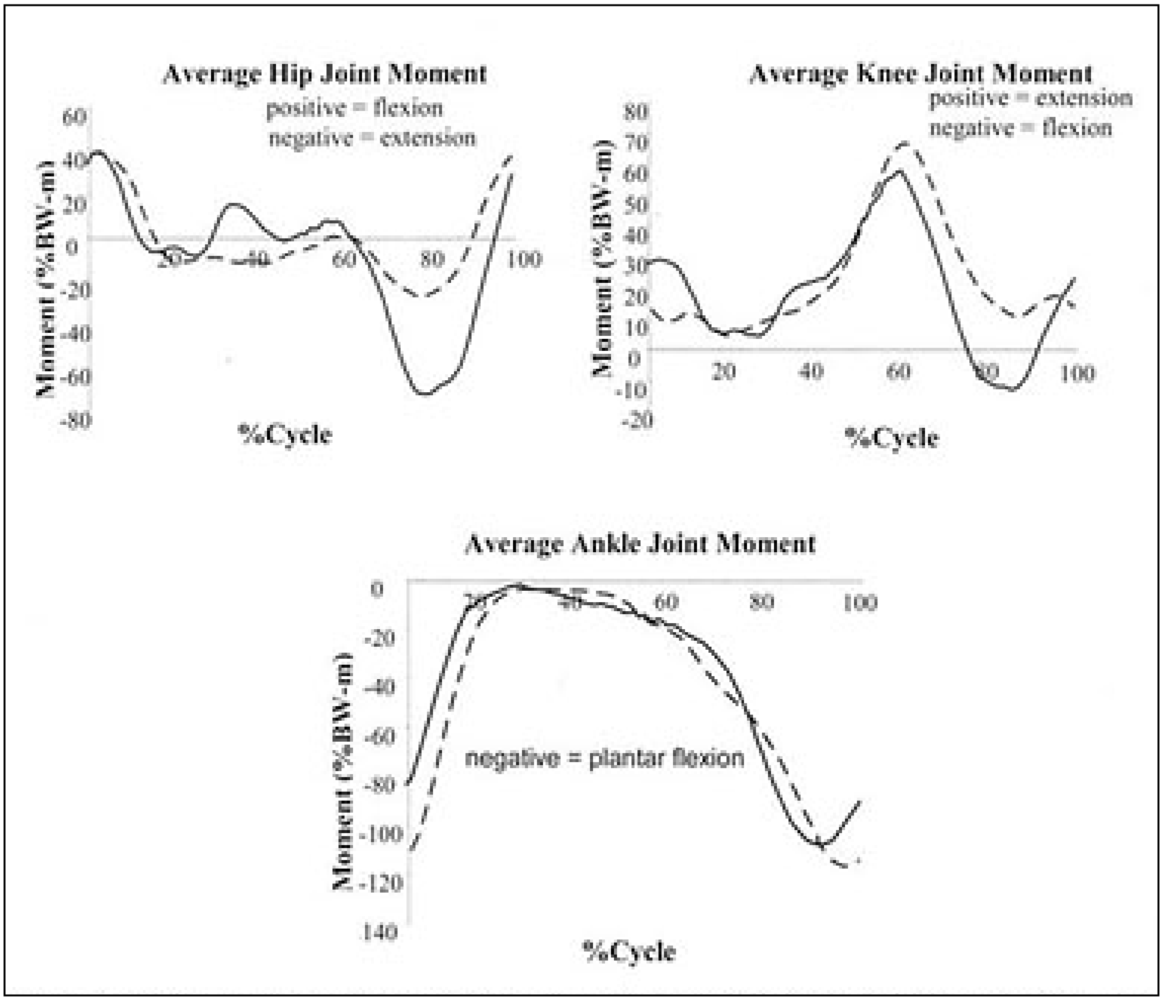


Figure 7. Average Moments Normalized to the Percentage of the Movement Cycle (% Cycle) Reciprocating = Dashed Line, Elliptical = Solid Line (Rogatzki et al., 2012)

2.4 Adult Tricycles

Although cycling has been shown to help aid the rehabilitation process, it also has its difficulties. One of these challenges is that people with hemiplegia are typically constrained to the use of stationary bicycles because of their lack of ability to balance on a standard bicycle. Tricycles compensate for this issue by allowing the user to pedal without worrying about balance.

A standard adult tricycle (Figure 8) involves the rider sitting on a seat and pedaling below themselves, similar to a standard bicycle. Unlike a standard bicycle, a standard tricycle has two rear wheels with the rear axle, chain, and rear sprocket located between them. There is only one driven rear wheel on a standard tricycle to allow for the rear wheels to rotate at different speeds while cornering. In addition, coasting is integrated into the drivetrain through a freewheeling hub (Gunderson, 2010). The cost of a standard adult tricycle is typically around a few hundred dollars.

Figure 8. Example of a Standard Tricycle (Schwinn Meridian, 2014)

A recumbent tricycle (Figure 9) involves a rider sitting in a bucket seat and pedaling in front of themselves. A system of chains links the chainrings attached to the cranks at the front of the recumbent tricycle to the rear sprocket. Recumbent tricycles can either have one rear wheel and two front wheels or two rear wheels and one front wheel. A recumbent tricycle is similar to a standard tricycle in that only one wheel is driven and coasting is integrated into the drive train through a freewheeling hub. The cost of recumbent tricycles is often $1,000 or more.

Figure 9. Example of Recumbent Tricycle (HP Velotechnik, 2012)

The team decided to purchase a standard tricycle to serve as the base for the drivetrain prototype. A standard tricycle was chosen over a recumbent tricycle due to its lower cost and higher availability.

2.4.1 Drive Train Components

When modifying a drive train for a tricycle, one must be knowledgeable of the components that will be affected. It is also important to understand how much power the user must put into the system for propulsion.

Drive Train

Children's tricycles usually have a direct connection from the pedals to the front wheel, which is not always the case for adult tricycles. There are some adult tricycles that are built as front wheel drive, such as recumbent tricycles and those without gears, where the cranks and pedals are directly attached to the axle of the front wheel. Most adult tricycles have a chain from the pedals to the rear wheels so gear ratios can be implemented to increase ease of use. One problem that must be accounted for in the tricycle design is that the outer wheel must rotate faster than the inner wheel when the tricycle turns. The inner wheel does not have to rotate as quickly as the corner is taken since it has less distance to cover in the same amount of time. One type of modification involves the rear sprocket being connected to only one of the rear wheels, while the other wheel rotates freely. This free wheel modification can either be done by inserting a bearing within the connection or by attaching it much like the front wheel which rotates freely on the Bottom Bracket (SQ Engineering – Trike 4 – Construction, 2012). Another way to account for this difference is a differential method; two separate axles are connected by a differential in the middle, which splits the input torque in two, allowing for the output rotation of each wheel to be at different speeds. This is the same method that a car uses, except instead of the more complicated automotive drivetrain system, tricycles use a chain directly connected to the differential (Nice, 2000).

Gears and Derailleurs

On a standard bicycle or tricycle there are two derailleurs, rear and front, circled in red in Figure 10. When a rider shifts gears, the shift levers adjust the cable connected to the derailleur, which determines the position of the chain on the sprocket. When shifting, the derailleur pulls the chain out and around to the next gear. Depending on which way the rider shifts, they can either increase or decrease the ratio. With a high ratio, which occurs when the chain is on the biggest sprocket in the front and the smallest in back, the bike will go faster than the same pedaling speed at a lower ratio. At the lowest ratio, which occurs when the chain is on the smallest sprocket in front and the biggest in back, it is easier to pedal.

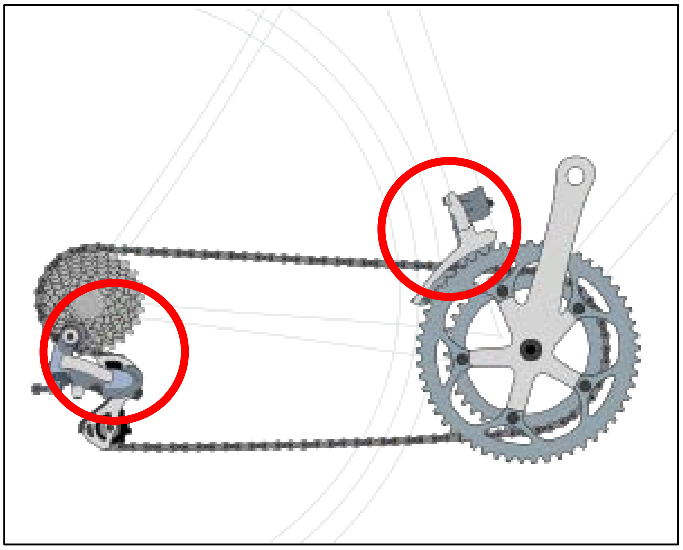


Figure 10. Front and Rear Derailleurs (Bicycle Gears, 2013)

The two derailleurs have different purposes. The rear derailleur keeps the chain in tension no matter which gear is engaged by moving closer or farther from the gears. For example, when the user changes from a large gear to a small gear, the derailleur makes up for the slack in the chain by changing its distance from the gears. The front derailleur moves the bottom of the chain from sprocket to sprocket when the user shifts gears. The top of the chain transmits the force from the front sprockets to the rear sprockets since it remains in tension when pedaling. The bottom of the chain however, is kept in light tension so the derailleur can maneuver it to change gears (Nice, 2001).

Besides the normal derailleur of a bicycle there are other options for transferring between gears. One of these options is internal-gear hubs, which work on the principle of planetary gearing, Figure 11. According to Sheldon Brown's Bicycle Glossary (2008), "a planetary gear train consists of a stationary "sun" gear, surrounded by several (usually 3 or 4) identical "planet" gears which mesh with it. The planet gears, in turn, mesh with a hollow "gear ring" which has teeth on the inner surface. The gear ring rotates faster than the planet gears." Sheldon Brown's Bicycle Glossary (2008) further explains that "if the drive sprocket is connected to the gear ring, and the cage that holds the planet gears is used to turn the wheel, the wheel will turn slower than the sprocket, thus providing a lower gear, compared with a simple hub driven by the same-sized sprockets. If the drive sprocket is connected to the planet cage, and the gear ring drives the wheel, the result is a higher gear. Most three-speed internally-geared hubs use these two configurations, along with the direct drive to provide the three speeds." There has been a decline in popularity of internal gear hubs since the 1970s, which means they are not commonly seen in modern bicycle and tricycle models today (Sheldon Brown's Bicycle Glossary, 2008).

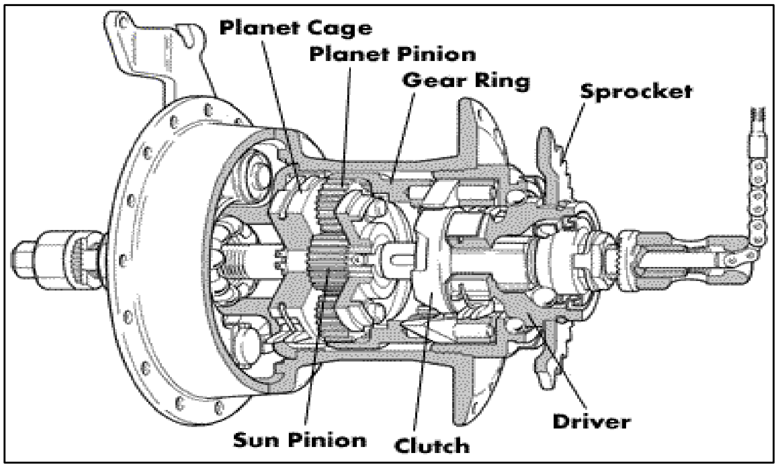


Figure 11. Internal Gear Hub (Sheldon Brown's Bicycle Glossary, 2008)

3. Goal Statement

A majority of people who have had a stroke are affected by hemiparesis, which is a weakness on one side of the body. This condition makes it difficult for them to ride a standard bicycle or tricycle, which requires an equal amount of input pedaling force by each leg. The goal of this project is to modify a drivetrain of an existing tricycle to passively assist the user's hemiplegic leg in pedaling for rehabilitation.

4. Design Specifications

The group developed design specifications, which were divided into three categories. The categories include rehabilitation, recreation, safety, maintenance, prototype construction, and user requirements. Rehabilitation and recreation were the main objectives of the design; therefore, they were more heavily weighted when compared to the other design specification categories.

Rehabilitation

1. This device must only be powered by human input.
    - In order to maximize the rehabilitative effect, the user must provide all of the force required to power the device.
2. This device must be able to adjust for different power inputs from leg to leg.
    - In order to account for the potential difference in strength of the user’s legs due to a stroke, the device must be adjustable. This is not only for the ease of pedaling for the affected person, but also to allow for the rehabilitation of the weaker leg.
3. It would be beneficial if the input torque could be adjusted along the drivetrain to change the output torque.
    - It would be preferable if the user is to be able to select the difficulty level of pedaling, similar to the resistance levels on a stationary bike or the different sized gears on traditional bikes, so that the tricycle can be used throughout all stages of rehabilitation. This would also allow the user to realize their progression in rehabilitation once they are physically able to input more power to the pedals.
4. It would be beneficial if the device allowed the user to pedal one-legged.

    - It would be preferred if the device allowed for the user to rest one leg on a stationary pedal while pedaling with the other if needed so the tricycle is usable at all stages of rehabilitation, including the very beginning when the user may not have adequate strength, endurance or range of motion in the affected leg.

Recreation

5. The device must allow for the user to be able to ride the tricycle along a 0.25 mile stretch of a rail trail.
6. The device must allow the user to ride the tricycle on a maximum grade of 3%.
7. The device must allow the tricycle to move at a constant speed of 3 miles per hour.

Safety

8. The device should conform to the Consumer Product Safety Commission Standards for bicycles.
9. The device should not intrude into the user's space within the area of the frame between the seat and the handle bars.
    - Volume of the device added onto the tricycle should not intrude the user's space while pedaling to avoid safety issues.

Maintenance

10. The device should be able to be maintained by a local bicycle shop.
    - The modifications to the tricycle should not compromise the ability for the tricycle itself to be maintained by a bicycle mechanic.

Prototype Construction

11. This device must be able to be built with the given budget of $480.

12. The device will not modify the weight (64 pounds) of the tricycle by more than 20%, preferably by less than 10%.
    - The weight limit is necessary to keep the applied pedaling force to a minimum.
13. The device should be able to be manufactured by the team using the available tools and resources of the WPI machine shop.
    - Mass manufacturability should be considered while designing and building this prototype, however main focus is on the ability to create the prototype.
14. The device must be constrained by the dimensions of the tricycle used for the creation of the prototype.
    - The tricycle consists of one front wheel with two rear wheels. The left rear wheel is directly connected through the drivetrain to the pedals, and the right wheel is free to rotate independently.
    - It would be preferred for the device to be adaptable to Worksman's Options, Schwinn, and Kent tricycle models.

User Requirements

15. The user must have a range of motion at the knee of 108 degrees to 37 degrees (where full extension is 0 degrees), at the hip of 63 degrees to 110 degrees (the angle between the torso and the thigh) and at the ankle of at least 20 degrees of combined flexion and extension.
    - These ranges of motion are necessary to ride a typical bicycle.
16. The user must have a leg length range of 26 to 30 inches.
    - The user must meet these leg length ranges in order to properly fit on the tricycle, which has a 17 inch frame size.

- The average leg length to height ratio is 45%, which means that the height range corresponding to the leg length range would be 4 foot 9 inches to 5 foot 6 inches.

17. The user must weigh less than 300 lbs.
    - There is no published source for the maximum user weight specification of the 1973 Schwinn Town & Country tricycle, however, modern Schwinn tricycles have a maximum user weight specification of 300 lbs.
18. The user must be at the recovery testing level required by physical therapists to prove that they have the ability to pedal a tricycle and would see improvements in their range of motion or strength through repetitive cyclical motion.
    - The user must be able to complete the movement, but only with marked deviation from the normal pattern.
    - It is important that the device is accommodating to the needs of someone who has had a stroke and is in the recovery process.

5. Selection of Design

The team developed multiple preliminary concept designs which were narrowed down to the top three that best satisfied the design specifications. These three designs were then evaluated further to refine the designs. These top three designs were then compared to the design specifications again to select the final design.

5.1 Preliminary Design Concepts

The eight preliminary design concepts were two reverted compound gear train designs, a flywheel design, two reciprocal pedal designs, a design to change the crank length, a design incorporating a differential, and a non-circular chainring design.

5.1.1 Reverted Compound Gear Train

Preliminary Design 1

This idea has two gears on each side of the tricycle with a chain connecting the front and rear of each side, Figure 12.

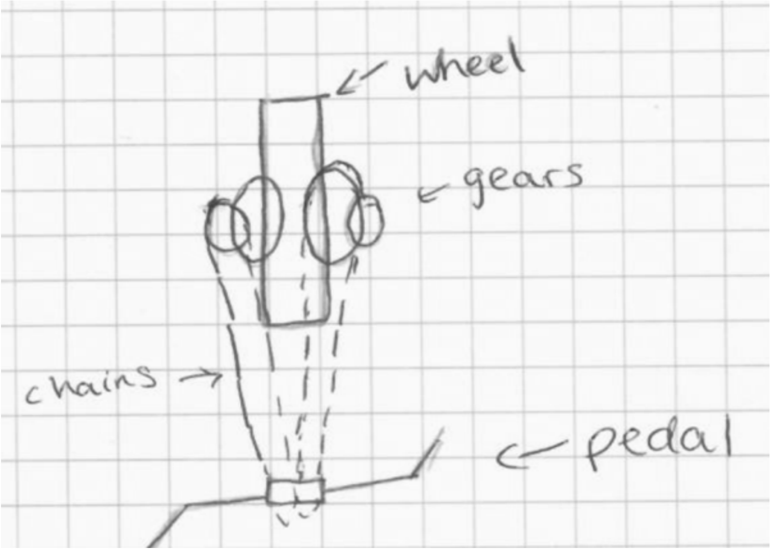


Figure 12. Design Idea 1

Preliminary Design 2

This idea involves two drivetrains and therefore two chains. The arrangement of the gears is such that the drivetrains are inverses of each other, Figure 13.

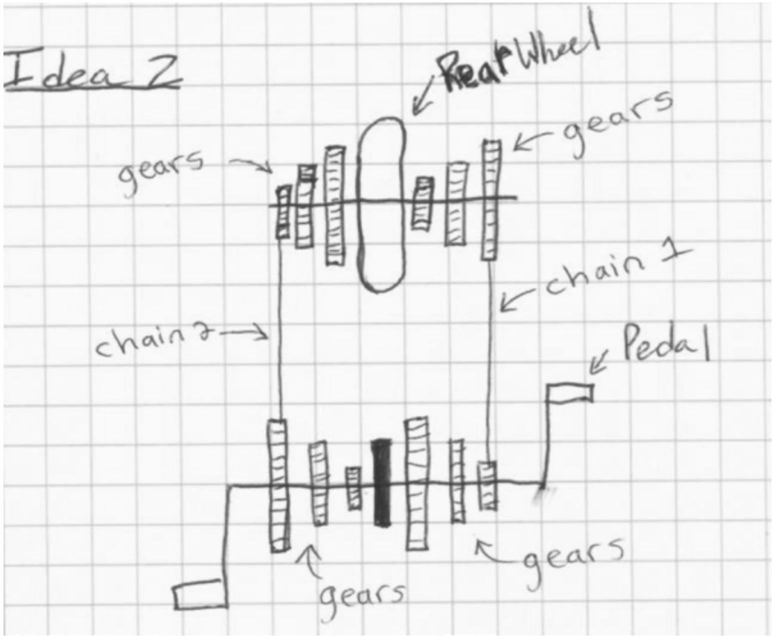


Figure 13. Design Idea 2

Reverted Compound Gear Train Design

(Includes both original design 1 and design 2**)**

An example of a dual chain drive system is the reverted compound gear train design. After combining designs 1 and 2, Design 1.1 is described as a chain and sprocket reverted compound gear train. Instead of gear 1 meshing with gear 2 and gear 3 meshing with gear 4 (Figure 14), a chain, (shown in pink in Figure 15) connects gear 1 to 2 and another chain (shown in yellow in Figure 15) connects gear 3 to 4.

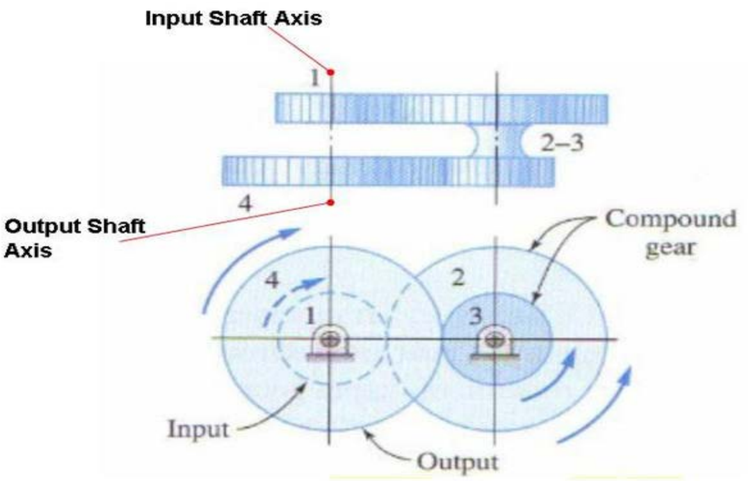


Figure 14. Reverted Compound Gear Train (What are Gear Trains?, 2010)

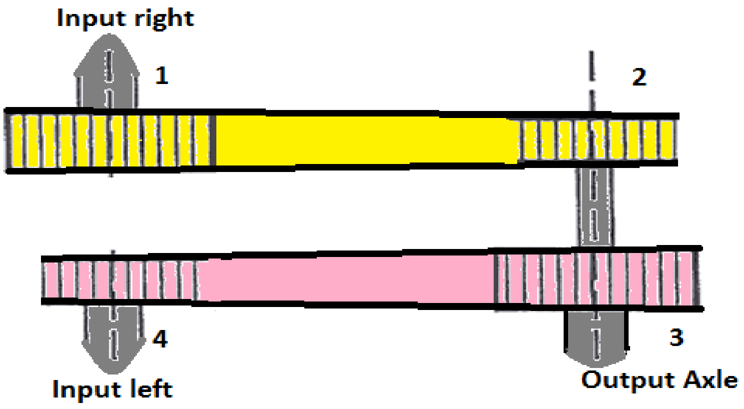


Figure 15. Chain and Sprocket Reverted Compound Gear Train

In a traditional reverted compound gear train, the input and output gears rotate in the opposite direction of the compound gears since there is direct contact between the gears. For the chain and sprocket reverted compound gear train, the chain connection forces the input and compound gears to rotate in the same direction. Gear 1 is rigidly attached to the right-side crank and gear 4 is rigidly attached to the left-side crank. Gears 2 and 3 are rigidly attached to the rear axle that drives the rear wheel. Often reverted gear trains are used as seen above in Figure 14, where the input gear 1 and output gear 4 are along the same axis, however, for a chain and sprocket reverted gear train, gear 4 is a secondary input gear. Since the user pedals with both legs at the same time, gears 1 and 4 are both used as inputs and gears 2 and 3 are outputs. For a traditional tricycle gear train, when one leg rotates, the other leg rotates at the same rate. For the chain and sprocket reverted compound gear train, gears 1 and 3 are the same size, but are larger than gears 2 and 4, which are the same size as each other. Therefore, gear 1 would make fewer revolutions than gear 4 in any given time period. Due to this gear ratio, less force would be required to pedal the crank attached to the smaller input gear. This gear train would be customizable for the user, depending on their physical abilities and the advice of a physical therapist.

5.1.2 Flywheel

Preliminary Design Idea

The initial design idea (Figure 16) for incorporating a flywheel into the drivetrain of the tricycle involved connecting the flywheel to the rear sprocket.

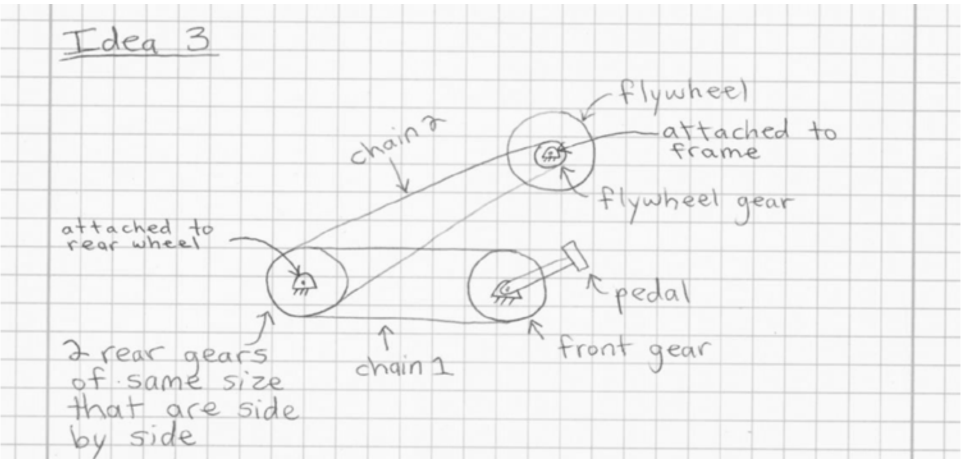


Figure 16. Design Idea 3

Flywheel Design

Design Idea 3 involves applying a flywheel to the drivetrain of the tricycle (Figure 17). The flywheel would be connected to the front chainring so that the pedaling of the cranks applies torque to the flywheel to give it rotational velocity and to store energy. The user can control the ratio of the flywheel compared to the drivetrain by operating a continuously variable transmission (CVT) attached to the front chainring. The user speeds up the flywheel by pedaling when the gear ratio is such that the flywheel rotates more than the front chainring over a given period of time. The user can get a boost from the flywheel by changing the gear ratio so that the flywheel rotates the same amount as or less than the front chainring over a given period of time, thereby, transferring energy from the flywheel to the cranks.

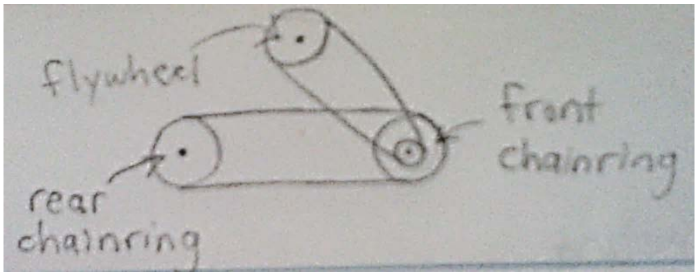


Figure 17. Flywheel Added to Tricycle Drivetrain

The benefit of adding a flywheel to the tricycle is that it allows for an increase in velocity without the user adding more power. It also functions like a normal tricycle so the user would not need to adapt to a new pedaling style. A flywheel would be beneficial for a user who has post-stroke hemiparesis because the user could increase the ratio of the flywheel to the drivetrain when they need a boost to help their affected leg rotate the crank. A negative aspect of the flywheel is that it would force the pedals to keep moving and, therefore, force the user's legs to move. This would be less rehabilitative than if the user moves their legs under their own power in order to rotate the cranks. Unfortunately, this design idea is much more expensive than many other ideas. The costs would include the flywheel itself and a CVT, both of which the team cannot easily make on its own, and additional materials to attach the flywheel to the tricycle and incorporate it into the drivetrain. This design also adds much weight to the tricycle making it harder to pedal.

5.1.3 Reciprocal Pedals

Preliminary Design Idea 4 Reciprocal Pedals

This design involves reciprocating pedals instead of the traditional rotary pedals, Figure 18. It works like a crank slider mechanism with the pedals as the slider moving a connecting rod to rotate the rotary system.

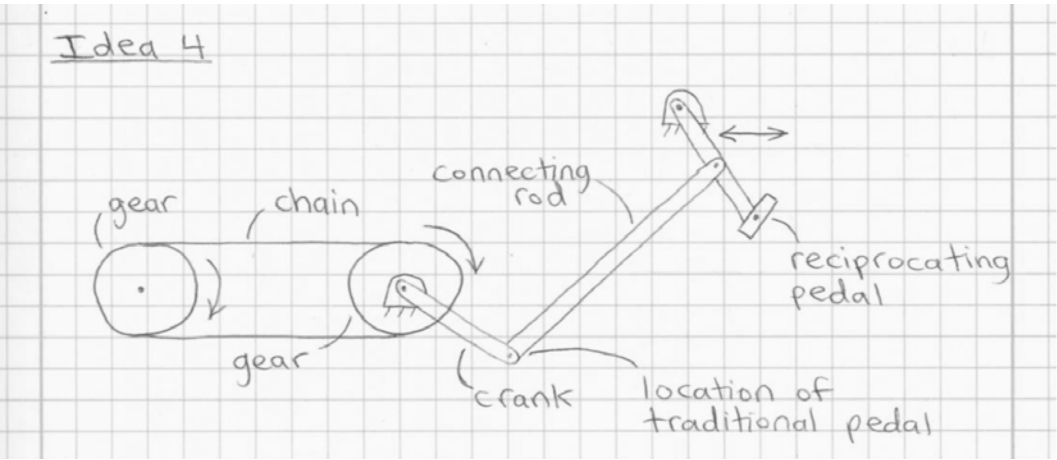


Figure 18. Design Idea 4

Preliminary Design Idea 5

This design would work similarly to design idea 4, but instead of the rider driving the crank-slider mechanism with his or her feet, the rider would use their hands to provide power, Figure 19.

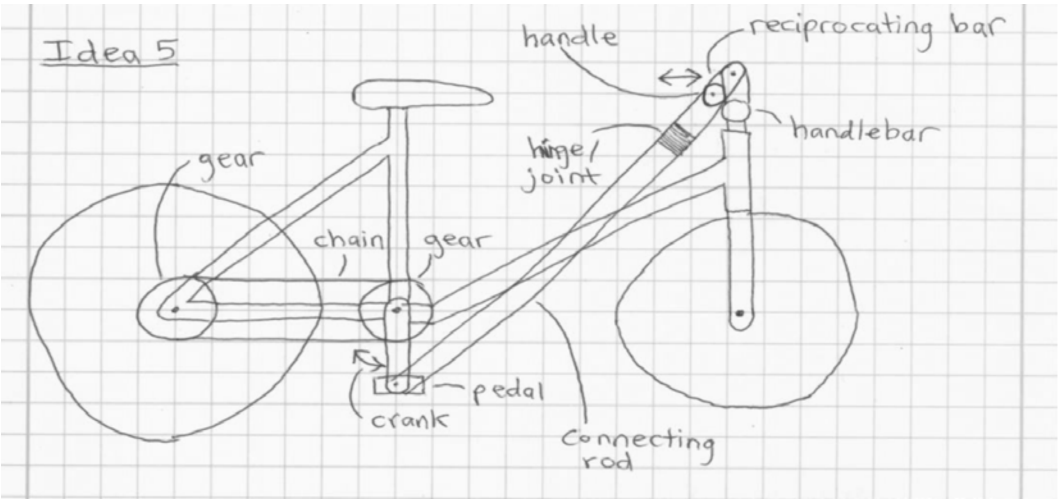


Figure 19. Design Idea 5

Reciprocal Pedal Designs

Both designs 4 and 5 are reciprocal pedaling devices that operate as crank sliders. For both designs, the pedals are used in a crank-slider setup to connect added reciprocal pedals to the existing gear train of the tricycle. The existing cranks are about 6 inches long, however, one of the existing cranks could be shortened or lengthened in order to differentiate the force of each leg to pedal. Due to the limitations of space, connection lengths between the cyclical cranks and the reciprocal cranks are limited to 2-3 ft.

In both of these designs, whether the feet are driving the cyclic pedals or the reciprocal pedals, the linkages must be setup to avoid a quick return. The cyclic pedals must move at a constant angular velocity in order to keep the tricycle moving at a constant speed, so any quick returns in the system would make one set of pedals or another move at a non-constant speed.

Reciprocal Leg Pedals (Design 4)

The benefit of reciprocal leg pedals is that it allows for two different leg motions so the user can change their positioning to exercise different leg muscles. It would also be easy to learn how to use the pedaling system. It might be awkward to try to maneuver between the cyclical and reciprocal pedals and the additional pedals might intrude into the user's space. The addition of a bucket seat to the tricycle would help with the balance issue of changing between the different pedaling systems.

Reciprocating Hand Pedals (Design 5)

The benefits of the hand pedals, similarly to the foot pedals, is that it is relatively easy to manufacture and provides an option for the user to use their arms to help their legs provide the force necessary to pedal the tricycle. This design makes the tricycle difficult to steer since the user has to let go of the hand pedals and grab onto the handlebars in order to steer.

5.1.4 Adjustable Crank Lengths

Preliminary Design Idea 6

This idea involved adjustable crank lengths, which allow for variable pedaling force depending on how the lengths are adjusted, Figure 20.

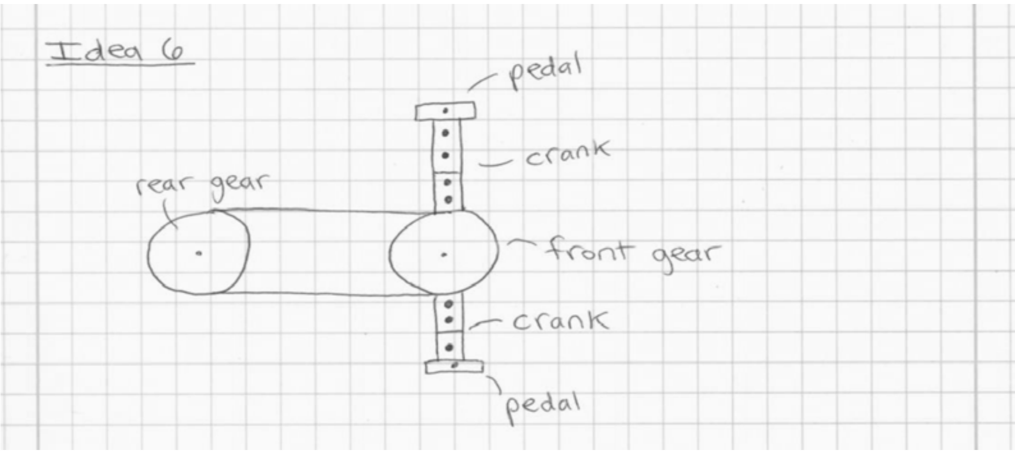


Figure 20. Design Idea 6

Adjustable Crank Length (Design 6)

The adjustable cranks design (Figure 20) will accomplish the main goal of differing the power input required by each leg, however, there are many issues associated with this design.

Increasing the crank length decreases efficiency and could have negative impact on the knees and joints by increasing the flexion required at the hip, knee, and ankle. Shortening the crank length decreases the range of motion, but increases the amount of work the user must do.

By adjusting the crank length, it is easier for one leg to pedal than the other. Since the cranks would have different lengths, the amount of force required to pedal each crank will differ. Since the torque is equal to force times the distance, if the crank is 6 inches long it will take twice as much force to get the same torque as a 12 inch lever.

One issue with increasing crank length is that while it decreases the force required to rotate the crank, it increases the range of motion, which would be an issue if the user's affected leg is unable to achieve that range of motion. (Achieving Optimal Power Through your Bike Fit Part 4: Crank Length, 2013).

5.1.5 Differential

Preliminary Design Idea 7

This design would involve installing a differential in between the cranks, Figure 21. This would allow the cranks to rotate at different speeds relative to each other.

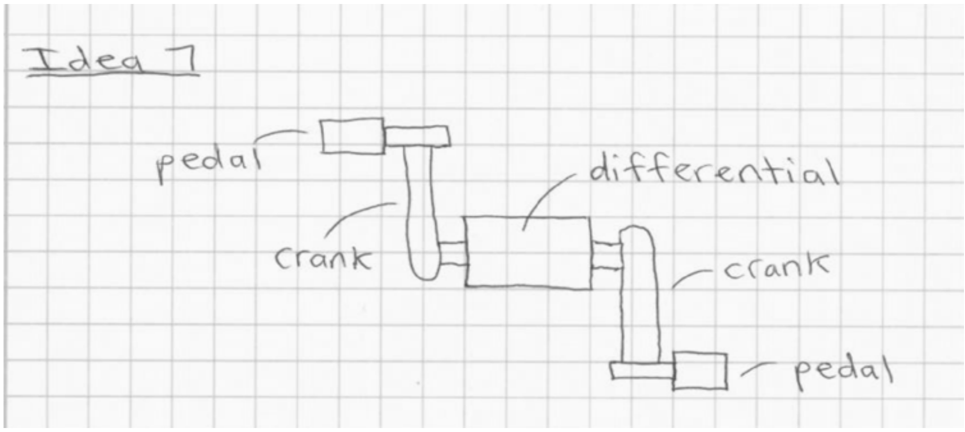


Figure 21. Design Idea 7

Differential (Design 7)

A differential is a set of gears that connects two axles and allows them to rotate at different speeds or one to rotate while the other is stationary (Figure 22 and Figure 23). An input torque turns the ring gear and carrier (blue). The carrier (blue) is connected to the sun gears (red and yellow) by way of the planet gear (green). Torque is transmitted through the planet gear to the sun gears. The planet gear revolves around the axis of the carrier and pushes against the sun gears, forcing them to rotate. If the resistance of both sun gears is equal, the planet gear revolves around the axis of the carrier without spinning about its own axis, which means both sun gears can rotate at the same rate (Figure 22).

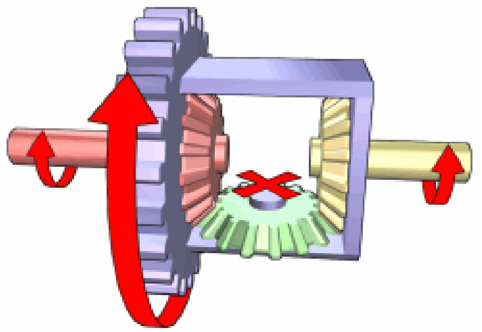


Figure 22. Differential with Both Sun Gears Rotating at Same Speed (Differential, 2013)

If there is resistance on the left sun gear (red) so that it slows down or stops spinning, the planet gear (green) will spin on its own axis in addition to revolving about the carrier's axis and continue driving the right sun gear (yellow) (Figure 23).

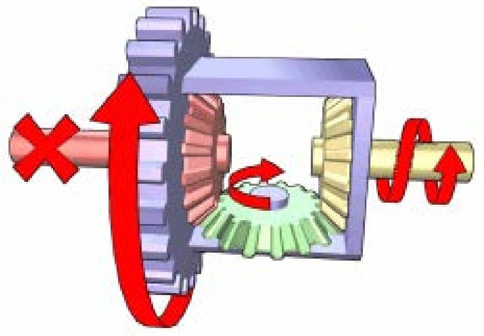


Figure 23. Differential with One Stationary Sun Gear (Differential, 2013)

For Design 7, a differential would be modified to connect the cranks of a tricycle. This would allow the cranks to turn at different rates. The benefit of this design is that it allows the user to pedal at different speeds and is infinitely adjustable. The differential allows both pedals to move independent of each other, however this means the cranks would return to the bottom dead center position as their resting position, which would make it difficult to start pedaling. This also means that the affected leg does not have to pedal, but the intention for this device is to keep the affected leg moving.

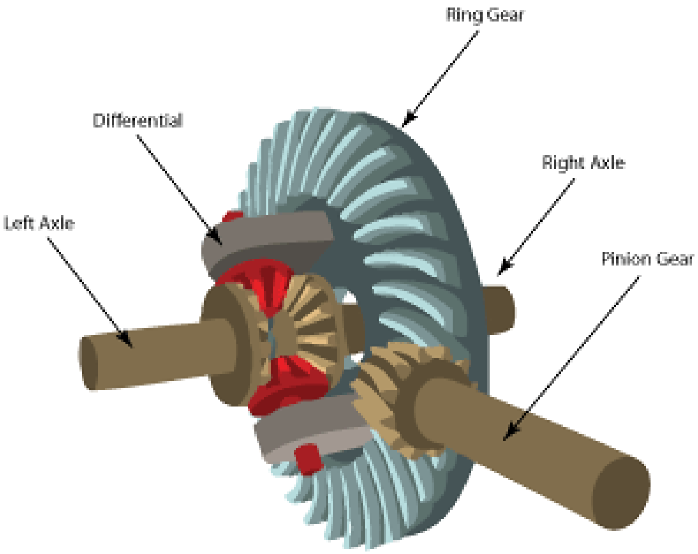


Figure 24. Differential with Pinion Gear (The Science of Differentials, 2008)

Usually there is a pinion gear that drives the ring gear (Figure 24), however, a pinion gear would not work for a differential between the cranks of a tricycle. The rotation of one of the cranks must be the driver of the ring gear in order to maintain the normal pedaling motion of the tricycle. A differential between the cranks would look similar to Figure 25.

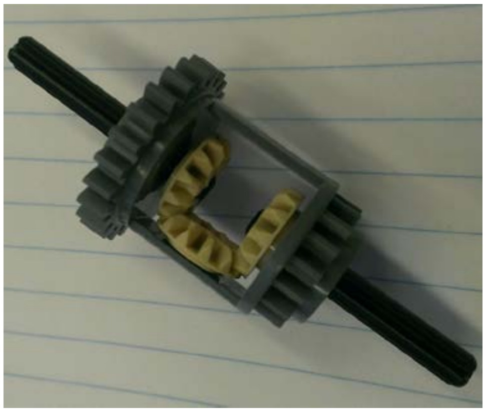


Figure 25. Model of Differential

With this configuration, the ring gear and carrier will still rotate when one of the cranks stops rotating. This configuration also allows one crank to rotate at a different speed compared to the other crank while the ring gear and carrier maintain a constant speed.

5.1.6 Non-Circular Front Chainring

Design 8

This design changes the shape of the front chainring, Figure 26. Replacing the front chainring with an oval shape would constantly change the gear ratio as the cranks rotate.

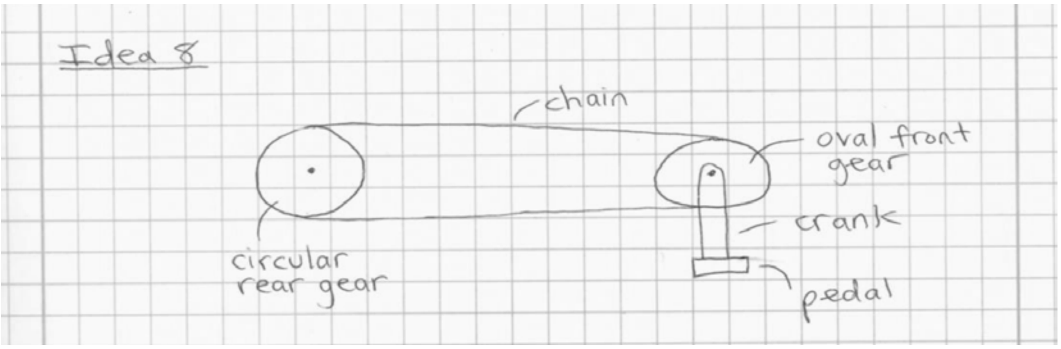


Figure 26. Design Idea 8

Non-Circular Gears (Design 8)

An oval front chainring allows for a changing gear ratio during the rotation of the cranks. The angular velocity ratio of the front chainring to the rear chainring changes as the oval rotates. The pivot would be offset to one side of the oval rather than centered. This offset pivot means that when one leg is pushing the larger side of the oval through the down stroke, the other leg is pulling up on the smaller side of the oval on the upstroke.

This design allows for continuous changes in the input ratio for each leg, however, it is difficult even for professionals to get cadence with oval gears, so someone who is relearning to cycle would have difficulty figuring it out (Malfait, Storme, and Derdeyn, 2012). They would also need to pedal with a non-continuous angular velocity in order to move the tricycle at a continuous speed.

5.2 Selection of Best Three Concepts

A decision matrix (Table 2) was used to rank the eight preliminary designs in order to narrow down to the best three concepts. The eight preliminary designs were ranked in Table 2 with each category based on a design specification. The design specifications were given a weight based on their priority. Primary design specifications that were listed as a “must” were weighted as 10% and secondary design specifications that were listed as "should" were given 5% weight.

Table 2. Decision Matrix for Preliminary 8 Designs

#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15-17	
Design Specification	Only Human Input	Variation in power in legs	Torque ratio adjustable	One legged pedaling	.25 mile rail trail	Works at 3% gradient	Allows for 3mph	Follow safety standards	Constrained to trike dimentions	Not intrude on the users space	Within budget	Weight must not be more than 20%	Manufacturable at WPI	Maintained at bike shop	Confined to user requirements	Score
Weight	10%	10%	5%	5%	5%	5%	10%	5%	5%	5%	10%	5%	5%	5%	10%	**100%**
Reverted Compound Gear Train	5	4	5	1	5	5	5	5	5	5	5	4	5	5	5	**4.65**
Flywheel	3	1	3	1	5	5	5	5	5	5	1	1	1	2	5	**3.15**
Reciprocal Leg Pedals	5	3	2	1	5	5	3	4	5	2	3	2	3	4	4	**3.45**
Reciprocal Hand Pedals	5	1	2	1	5	5	3	3	5	2	3	2	3	3	4	**3.15**
Adjustable Crank Lengths	5	3	1	1	5	5	5	4	5	2	5	5	5	4	5	**4.15**
Differential	5	5	5	5	5	5	5	5	5	5	1	4	1	4	5	**4.3**
Non Circular Gears	5	3	1	1	5	5	5	5	5	5	4	5	5	5	5	**4.3**

Based on the given scores of the decision matrix, the best three designs selected were the reverted compound gear train, differential, and non-circular gear. These three designs were then further investigated and refined.

5.2.1 Reverted Compound Chain and Sprocket

For a traditional tricycle drivetrain, when one leg pedals, the other leg pedals at the same rate. In contrast, the Reverted Compound Chain and Sprocket drivetrain (Figure 27) allows for the pedals to move at different speeds relative to each other.

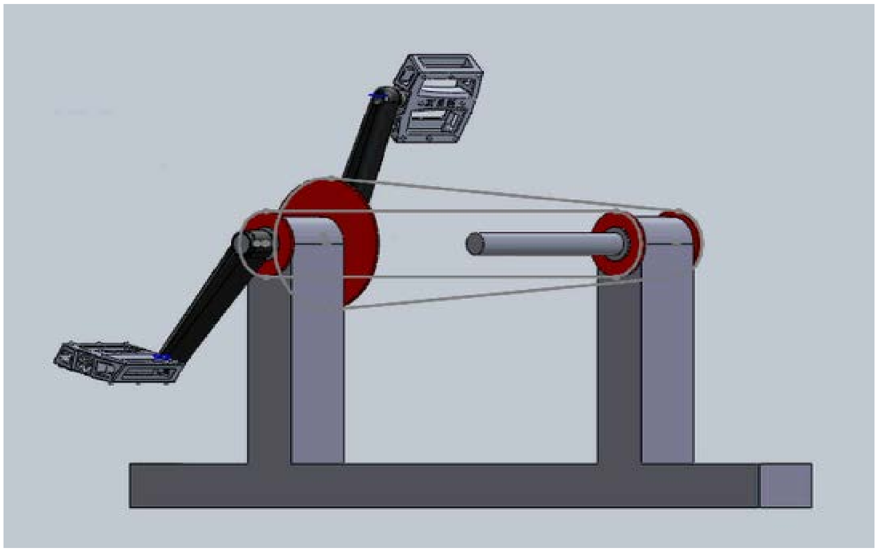


Figure 27. CAD Model of Reverted Compound Chain and Sprocket

For this drivetrain design, gear 1 and gear 4 stay the same size as the standard Schwinn Town & Country tricycle obtained for the prototype (gear 1 = 3 inches, gear 4 = 6 inches), and the additional gears (2 and 3) would be the same size as gear 1 (3 inches) (Figure 28). This would cause the left leg to make twice as many rotations as the right leg.

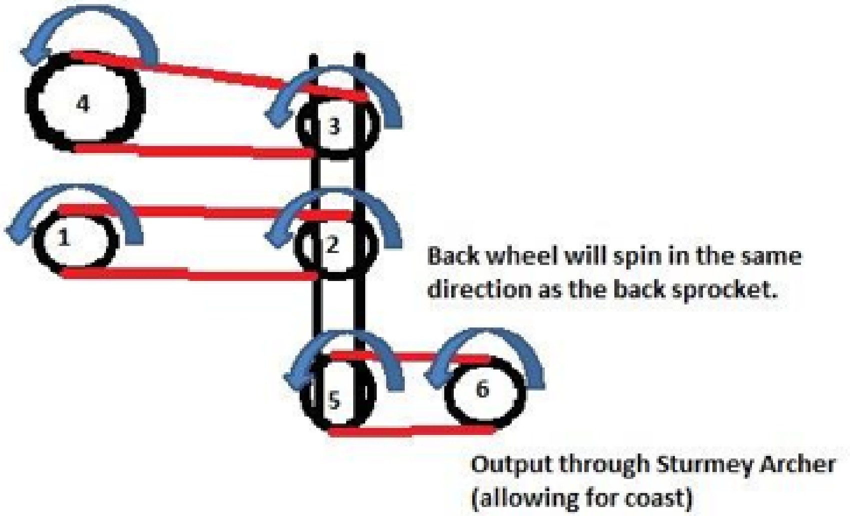


Figure 28. Reverted Compound Chain and Sprocket

Due to this gear ratio, less force would be required to pedal the crank attached to the smaller input gear. In addition to the reduced force, the leg pedaling the crank attached to the smaller input gear will make twice as many rotations as the other leg in a given time span. The user's affected leg could pedal either the smaller or the larger input gear depending on the user's physical ability and stage of rehabilitation. In most patients, the affected leg loses 50% of its strength (Weakness and strength training in persons with post-stroke hemiplegia, 2004). The Reverted Compound Chain and Sprocket compensates for the weakness of the affected leg by allowing the user to either pedal with less force and more rotations or pedal with more force and fewer rotations.

5.2.2 Differential

This design idea involves the use of a differential to connect the cranks of the tricycle instead of an axle (Figure 29). The cranks would be rigidly attached to the axles of the two planetary gears (blue). The sun gear (green) would be attached to the carrier (gray), but can spin freely on its axis. The front chainring (red) would be rigidly attached to the carrier (gray). The user's input rotation of the cranks causes the planetary gears (blue) to rotate, causing the sun gear (green) to rotate, causing the carrier (gray) to rotate, causing the front chainring (red) to rotate, causing the chain to move, causing the rear chainring to rotate, causing the wheels to rotate. The differential allows the user to pedal the cranks at different angular velocities, or to pedal one crank while the other remains stationary, while maintaining a constant linear velocity of the tricycle. By differentiating the amount of input force required by each leg to rotate the cranks, the tricycle is better suited than a standard tricycle for the use of a person who has post-stroke hemiparesis.

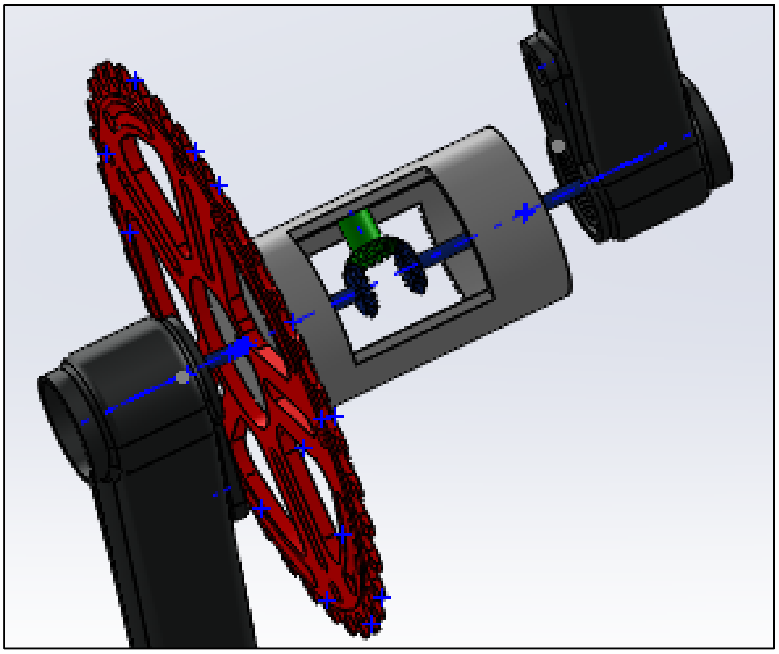


Figure 29. CAD Model of Differential Connecting Cranks

The gear ratio of one crank compared to the other crank is continuously variable since any pedaling speed is possible in the design (Figure 30). This would be more natural for the user since they could pedal each leg at a comfortable pace of their choosing. The differential allows the user to achieve milestones in their rehabilitation by being able to increase the input force from their affected leg as they gain strength.

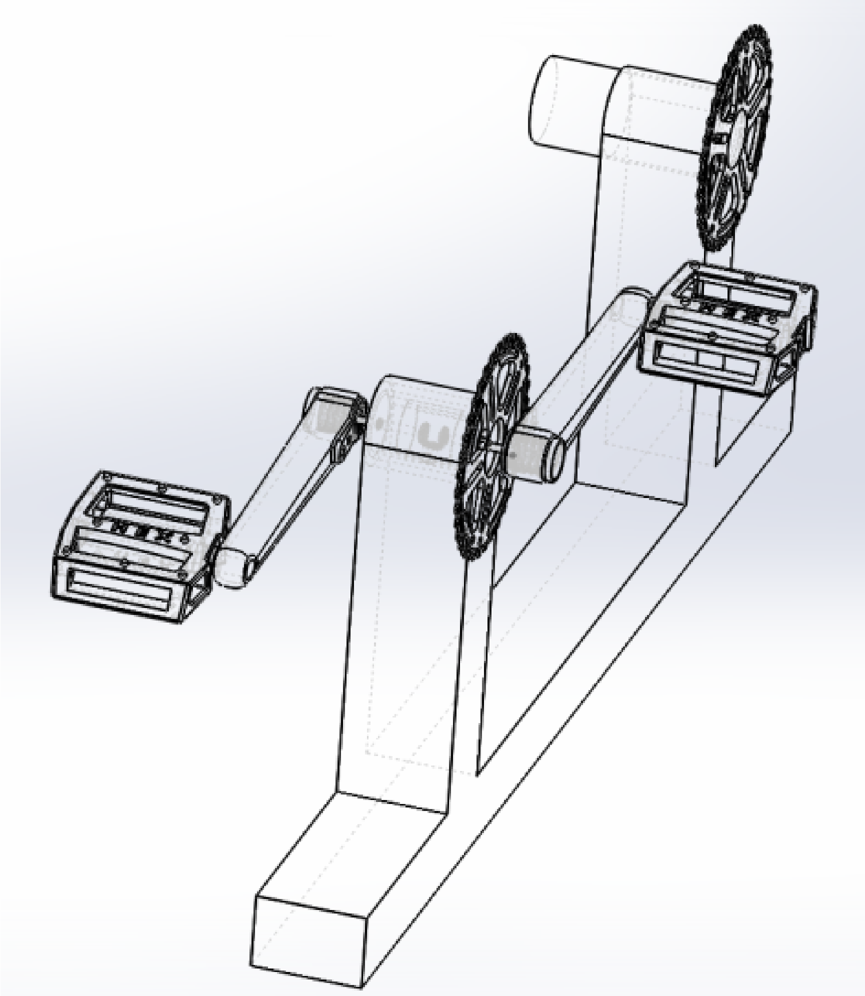


Figure 30. CAD Model of Differential Incorporated with Drivetrain

While there are many positive aspects to this differential design idea, there are also some issues. Since the cranks are independent of each other, they would rest at the bottom dead center position due to the force of gravity, which would make it difficult for the user to start pedaling from rest. The independence of the cranks also means that the affected leg is not forced to pedal, unless the user chooses to, which could take away from the rehabilitative aspect of the design. Another issue with this design is manufacturability because the parts would have to be custom-made to fit the existing tricycle.

5.2.3 Non-Circular Front Chainring

An oval front chainring allows for a changing gear ratio during the rotation of the cranks. The angular velocity ratio of the front chainring to the rear chainring changes as the oval rotates. The pivot would be offset to one side of the oval rather than centered. This offset pivot means that one leg pushes the larger side of the oval through the down stroke, and the other leg pushes through the smaller side of the oval on its down stroke. This device changes the amount of force needed to the pedal from leg to leg needed to maintain constant linear velocity of the tricycle, due to the continuous changes in input ratio.

Unfortunately, in order to move the tricycle at a constant speed, the pedals would have to have a non-continuous angular velocity. This means that the user would have to pedal faster with one leg than the other to maintain a constant speed. Although it is assumed that affected leg would naturally move slower than the other, extending the radius length of the chainring would make it harder for the other leg to move, meaning the non-affected leg would have to do twice as much work to make up for the difference in speed as well as the larger radius.

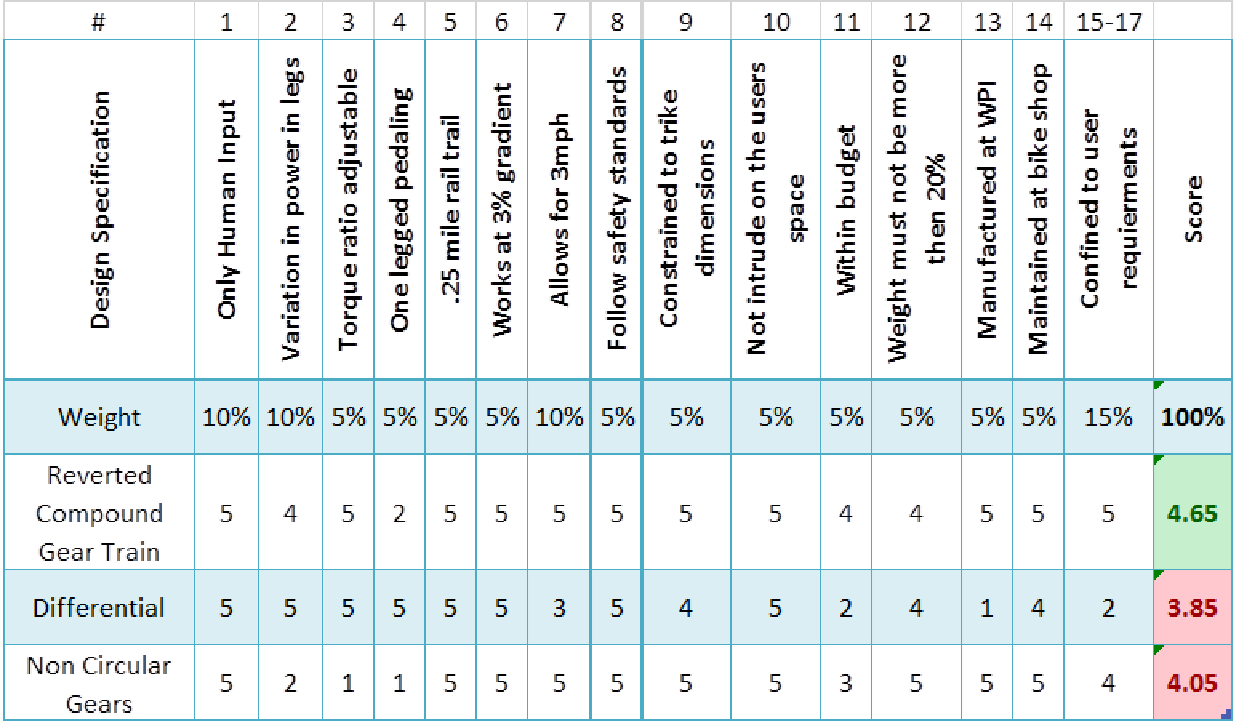
This device would also require that the amount of slack in the chain is adjustable in order to keep the chain on the chainring, and this would not guarantee that the chain will fit snugly on the chainring. The shape needed should not have sections that are too abrupt because it could cause the chain to derail from the chainring. Another concern is the space available. The frame of a typical tricycle angles out from where the cranks connect to where the rear axle connects, which limits the maximum size of the radius of the chainring to avoid collisions of the chainring with the frame itself.

5.3 Final Design

After refining the selected best three concepts, the team re-evaluated the designs by determining the positive and negative aspects of each design (Appendix A).

Using the table of the positive and negative aspects of each design, another decision matrix (Table 3) was created to rank the top three designs. Again the designs were ranked based on the design specifications, however the scores received for each category were modified after refining the designs. The criteria were rated by the team on a scale of one to five, with five meaning that the design meets the design specifications completely, and 1 meaning it does not cover all aspects of the design specification. After this final decision matrix, the team decided the Reverted Compound Chain and Sprocket was the best option of the three designs (Table 3).

Table 3. Decision Matrix for Final Three Options



#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15-17	
Design Specification	Only Human Input	Variation in power in legs	Torque ratio adjustable	One legged pedaling	.25 mile rail trail	Works at 3% gradient	Allows for 3mph	Follow safety standards	Constrained to trike dimensions	Not intrude on the users space	Within budget	Weight must not be more then 20%	Manufactured at WPI	Maintained at bike shop	Confined to user requierments	Score
Weight	10%	10%	5%	5%	5%	5%	10%	5%	5%	5%	5%	5%	5%	5%	15%	**100%**
Reverted Compound Gear Train	5	4	5	2	5	5	5	5	5	5	4	4	5	5	5	**4.65**
Differential	5	5	5	5	5	5	3	5	4	5	2	4	1	4	2	**3.85**
Non Circular Gears	5	2	1	1	5	5	5	5	5	5	3	5	5	5	4	**4.05**

5.3.1 Design Refinement

Once the final design (Figure 31) was chosen, the next step was to plan on how to make the Reverted Compound Chain and Sprocket a reality. Since the tricycle obtained was a vintage model from 1973, the sprocket sizes that would fit in the rear axle housing as well as the front connection were limited. Based on the standard diameters of chainrings on the market, it was decided that the maximum number of teeth for the front chainring would be 48, in order to fit the constraints of the tricycle's frame. If a 48 tooth large front chainring was chosen, the small front chainring would have to be 24 teeth due to the desired 2:1 gear ratio and the two rear sprockets would also have 24 teeth (Figure 32).

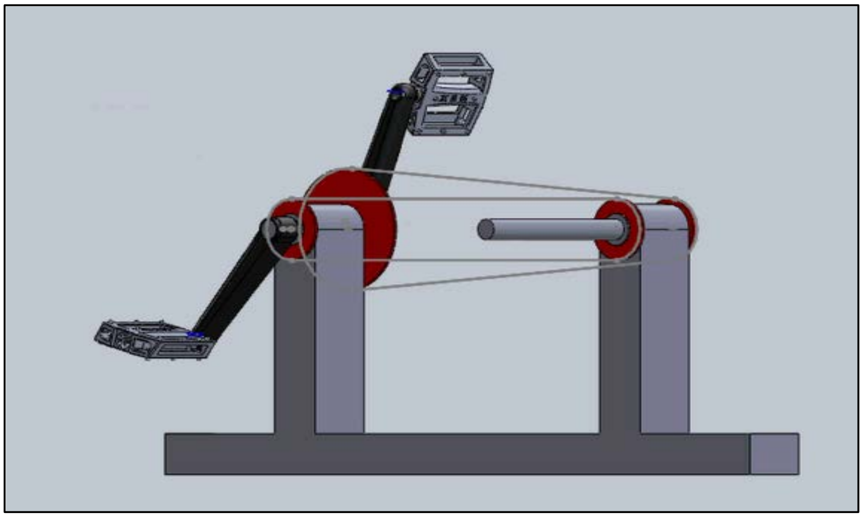


Figure 31. CAD Model of Reverted Compound Chain and Sprocket

The cranks that could be used for the design would have to have the same specific bolt center diameter (BCD) as the chainrings. Using the plans shown in Figure 32, the team visited a local bicycle shop, Bike Alley, and discussed options with one of the bicycle mechanics, who had experience restoring vintage bicycles. After this discussion, the team purchased spider cranks with an inner and outer BCD of 64mm and 104mm, along with three 22-tooth 64mm BCD chainrings and one 44-tooth 104mm BCD chainring.

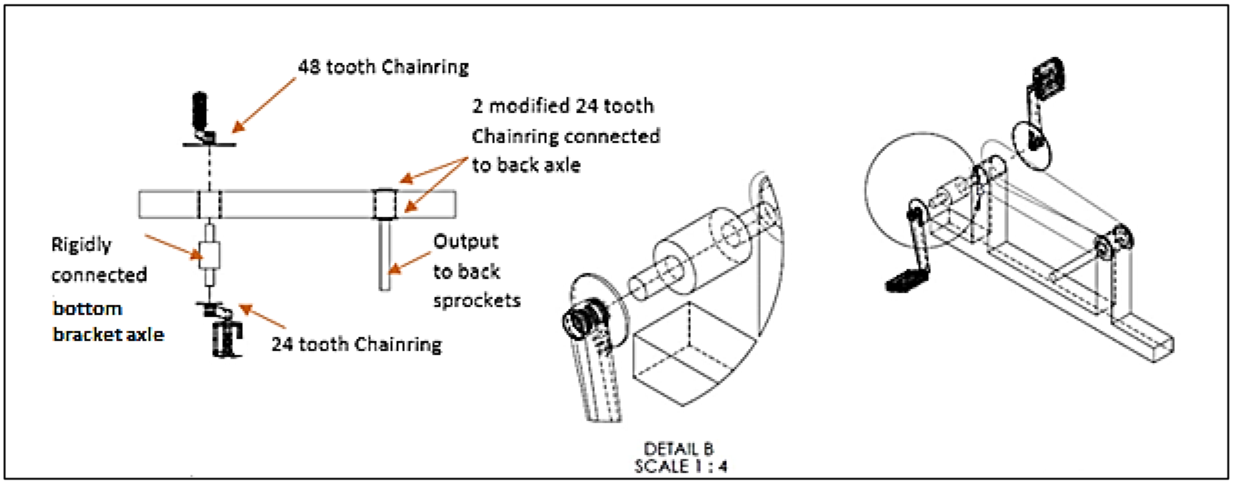


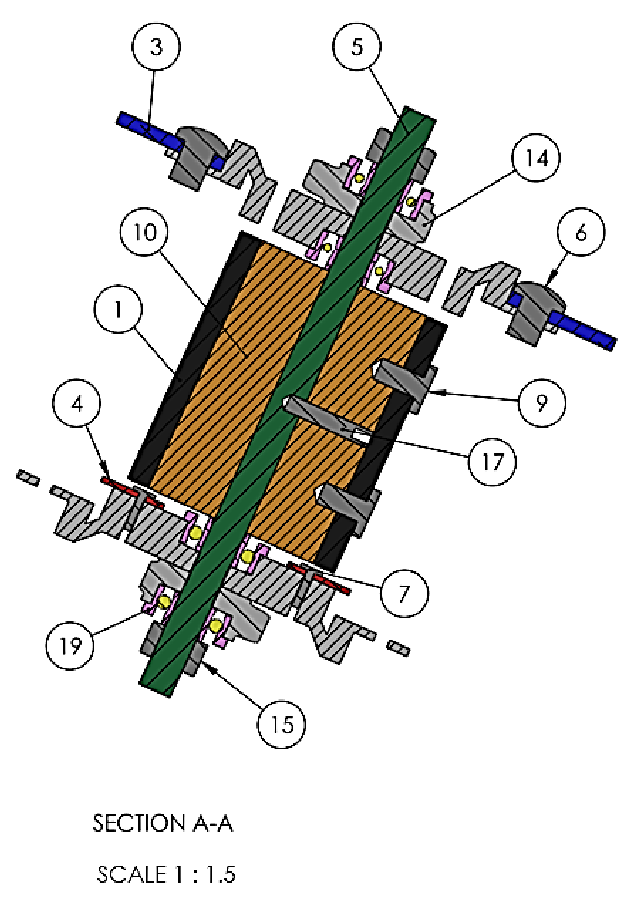
Figure 32. Preliminary Version of Final Design

Another thing that had to be considered was how the cranks were going to connect to the frame and rotate while not being rigidly attached to each other. After further discussion, a rigid axle was chosen as the connection between the cranks and bearings between the crank and rigid axle would allow the cranks to rotate. The cranks would have to be modified to allow for the bearings to be attached. Most cranks have a top hole that is either star-shaped or rectangular, but for the Reverted Compound Chain and Sprocket, the hole would need to be drilled out so that it is circular. It was decided that bearings would be press-fit into this circular hole in the cranks to allow for better motion and less friction over the fixed axle.

Since the design calls for press fitting the bearings into the cranks, the team had to determine the largest-sized holes that could be drilled into the cranks without compromising the strength of the remaining material. It was determined that the maximum diameter of the hole for the bearing was 1 inch, which would leave about 1/8 inch material surrounding the hole, following the machining rule of thumb for minimizing the risk of tearout (Appendix B). With this diameter constraint in mind, the team researched the available bearings on the market and discovered that the closest standard-sized outer diameter for the ball bearing was 7/8 inch. Ball bearings only come in standard combinations of inner and outer diameters, which constrained the size of the bottom bracket axle as it corresponds to the inner diameter of the bearing. The team decided on a flanged double-sealed steel ball bearing for 3/8" shaft diameter, 7/8" outer diameter, 13/32" width, 1” flange outer diameter, and 1/16” flange thickness. This bearing has a dynamic load capacity of 325 lbs. and a maximum speed of 3000 rpm, which is more than sufficient for its use on the tricycle.

The design of the bottom bracket axle assembly, which is located at the bottom of the frame where the cranks attach to the frame, was updated to reflect the decision to use a 3/8 inch diameter bottom bracket axle, based on the 3/8 inch inner diameter of the bearings. The original design called for a solid 3 inch diameter steel rod, of which each end was machined down to a smaller diameter to serve as the fixed bottom bracket axle, as shown in Figure 32. The team decided that machining the axle out of a larger diameter rod would reduce the strength of the axle and that a design modification was needed. The bottom bracket axle design was revised to be an assembly of two pieces, a 3 inch outer diameter cylinder with a 3/8 inch hole through the center and a long 3/8 inch diameter rod that fits through the larger cylinder and protrudes on either side. Once the bottom bracket cylinder and axle combination were finalized, the fasteners, involved in ensuring that the assembly is fixed, had to be determined as shown in Figure 33.

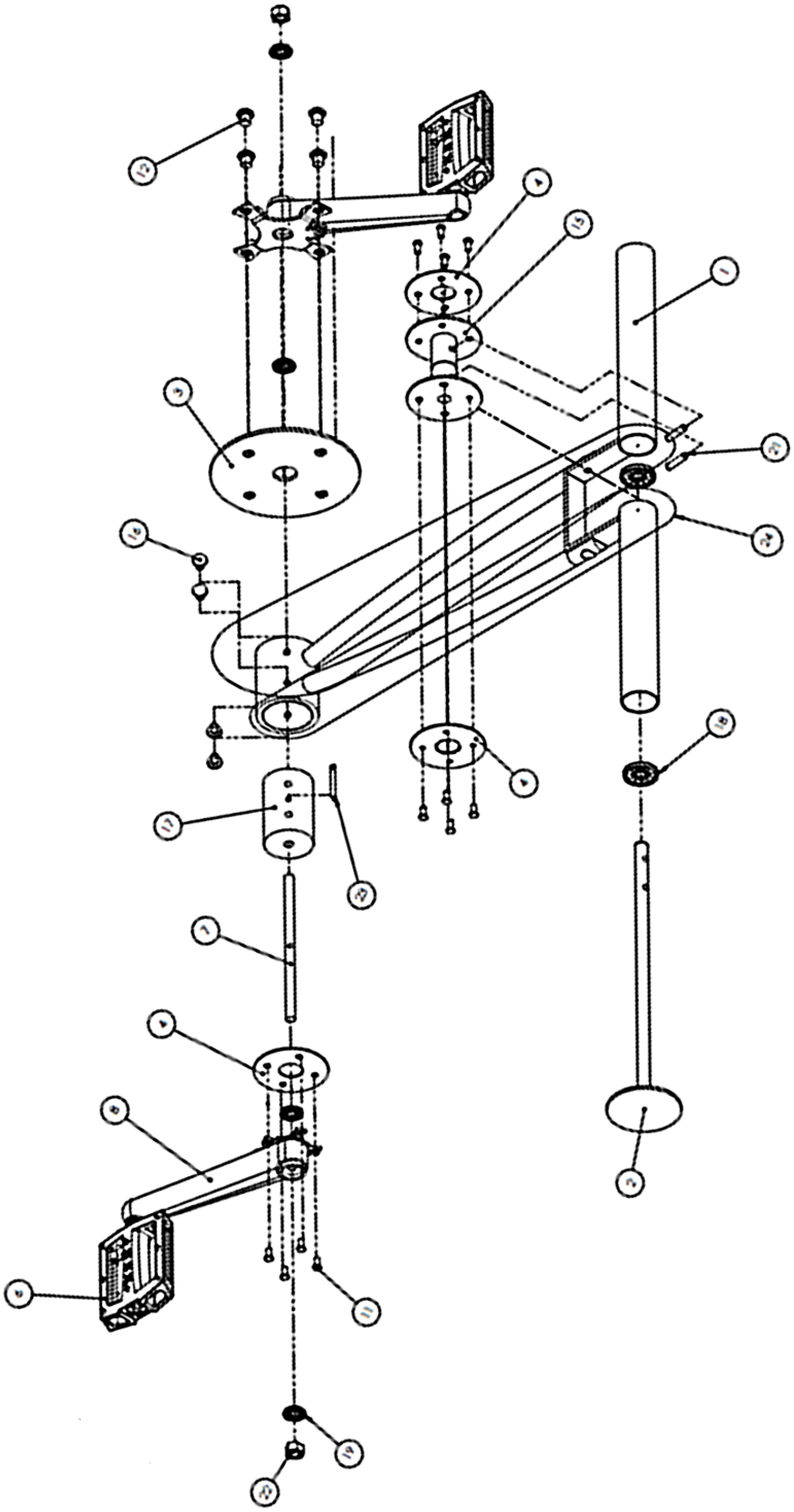
While the fixed bottom bracket cylinder was a tight fit inside the cylindrical cutout of the frame, it was also secured in place with two bolts that go through the frame and into the cylinder. The bottom bracket axle slides through the hole in the center of the cylinder and was fixed in place with a set screw that goes through the cylinder and into the surface of the axle.

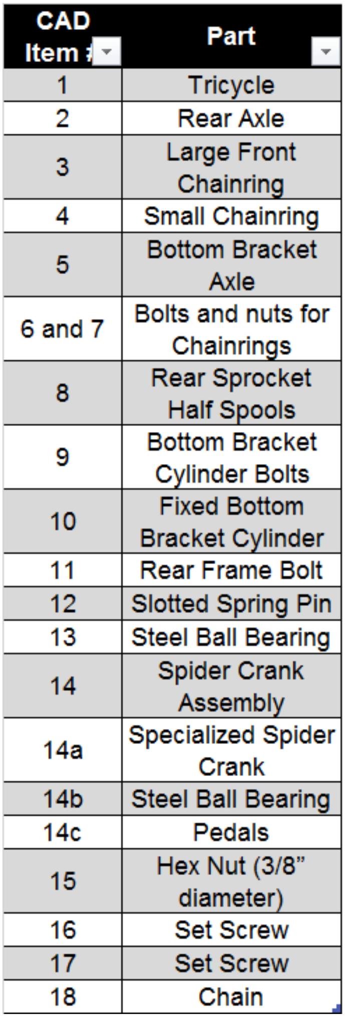


ITEM NO.	PART NUMBER	QTY.
1	Partial Tricycle Frame	1
2	Rear Axle	1
3	Large Front Chainring	1
4	Small Chainring	3
5	Bottom Bracket Axle	1
6	Large Chainring Bolt	4
7	Small Chainring Bolt	12
8	Rear Sprocket Half Spool	2
9	Bottom Bracket Cylinder Bolt	2
10	Bottom Bracket Cylinder	1
11	Rear Frame Bolt	2
12	Rear Sprocket Spool Pin	2
13	Rear Axle Bearing Assembly	2
14	Crank Assembly	2
15	Bottom Bracket Axle Nut	2
16	Rear Sprocket Half Spool Set Screw	2
17	Bottom Bracket Axle Set Screw	1
18	Chain	1
19	Crank Bearing Assembly	4

Figure 33. Cross Section View of Bottom Bracket Axle Assembly

The team originally planned on machining a spool-shaped part to connect the rear sprockets to the rear axle. The plan changed when the team realized the difficulty of machining a solid spool and the limitations it places on the positioning of the rear sprockets if they are both attached to one spool. It was decided that half spools were the best option due to their manufacturability and adjustability. All of these design decisions brought the team to the final design (Figure 34).





CAD Item #	Part
1	Tricycle
2	Rear Axle
3	Large Front Chainring
4	Small Chainring
5	Bottom Bracket Axle
6 and 7	Bolts and nuts for Chainrings
8	Rear Sprocket Half Spools
9	Bottom Bracket Cylinder Bolts
10	Fixed Bottom Bracket Cylinder
11	Rear Frame Bolt
12	Slotted Spring Pin
13	Steel Ball Bearing
14	Spider Crank Assembly
14a	Specialized Spider Crank
14b	Steel Ball Bearing
14c	Pedals
15	Hex Nut (3/8" diameter)
16	Set Screw
17	Set Screw
18	Chain

Figure 34. Exploded View of Entire Assembly

6. Analysis of Selected Design

Once the final design was selected and refined, the design had to be analyzed to verify the correct materials and sizes were used for all parts. The cycles of life for axles within the design also had to be calculated to ensure the design was safe and would endure use. All equations used were from Norton's Machine Design textbook (Norton, R., 2010).

6.1 Stress Analysis

The team completed stress analysis calculations of the bottom bracket assembly, rear axle assembly, and rear sprocket bolts. These calculations ensure that the selected materials and dimensions for the major parts of the design would endure the applied loads without failure over the long term operation of the tricycle. The calculations in their entirety can be found in Appendix E, F, and G.

6.1.1 Stress Analysis of Bottom Bracket Axle

The bottom bracket axle assembly is shown above in Figure 33. For the analysis of this assembly, the bottom bracket axle was simplified as two cantilever beams as seen in Figure 35. For these calculations, it was assumed that $x = 0$ is located at the point where the bottom bracket cylinder (blue) and the bottom bracket axle (red) intersect. W_1 is the force of the crank as a distributed load, W_2 is the weight of the cantilevered section of the bottom bracket axle as a distributed load, R is the reaction force at the support, and M is the reaction moment at the support. In the following calculations, only one side of the system is analyzed since both sides are symmetric.

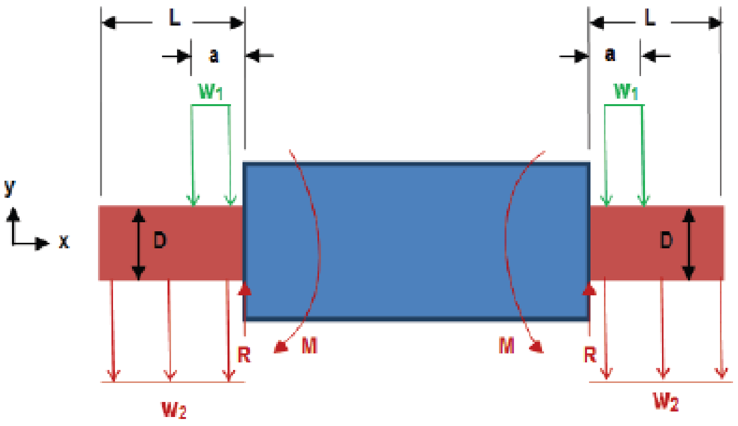


Figure 35. Bottom Bracket as Two Cantilever Beams

Given the loading, the team solved for the shear, moment, slope, and deflection of the bottom bracket axle (Figure 36).

Loading Function:

$$q(x) := R_{Ay}\cdot S(x,0)\cdot(x-0)^{-1} - w_1\cdot S(x,0)\cdot(x-0)^{0} + w_1\cdot S(x,a)\cdot(x-a)^{0} - w_2\cdot S(x,0)\cdot(x-0)^{0} + M_A\cdot S(x,0)\,(x-0)^{-2}$$

Shear Function:

$$V(x) := R_{Ay}\cdot S(x,0)\cdot(x-0)^{0} - w_1\cdot S(x,0)\cdot(x-0)^{1} + w_1\cdot S(x,a)\cdot(x-a)^{1} - w_2\cdot S(x,0)\cdot(x-0)^{1} + C_1$$

Moment Function:

$$M(x) := R_{Ay}\cdot S(x,0)\cdot(x-0)^{1} - \frac{w_1}{2}\cdot S(x,0)\cdot(x-0)^{2} + \frac{w_1}{2}\cdot S(x,a)\cdot(x-a)^{2} - \frac{w_2}{2}\cdot S(x,0)\cdot(x-0)^{2} + M_A\cdot S(x,0)\,(x-0)^{0} + C_1\cdot x + C_2$$

Slope Function:

$$\theta(x) := \frac{1}{E\cdot I}\cdot\left[\frac{R_{Ay}}{2}\cdot S(x,0)\cdot(x-0)^{2} - \frac{w_1}{6}\cdot S(x,0)\cdot(x-0)^{3} + \frac{w_1}{6}\cdot S(x,a)\cdot(x-a)^{3} - \frac{w_2}{6}\cdot S(x,0)\cdot(x-0)^{3} + M_A\cdot S(x,0)\,(x-0)^{1} + \frac{C_1}{2}\cdot x^{2} + C_2\cdot x + C_3\right]$$

Deflection Function:

$$\delta(x) := \frac{1}{E\cdot I}\cdot\left[\frac{R_{Ay}}{6}\cdot S(x,0)\cdot(x-0)^{3} - \frac{w_1}{24}\cdot S(x,0)\cdot(x-0)^{4} + \frac{w_1}{24}\cdot S(x,a)\cdot(x-a)^{4} - \frac{w_2}{24}\cdot S(x,0)\cdot(x-0)^{4} + \frac{M_A}{2}\cdot S(x,0)\,(x-0)^{2} + \frac{C_1}{6}\cdot x^{3} + \frac{C_2}{2}\cdot x^{2} + C_3\cdot x + C_4\right]$$

Figure 36. Shear, Moment, Slope, and Deflection Equations for the Bottom Bracket Axle

These functions were then plotted (Figure 37, Figure 38, Figure 39, and Figure 40) to depict the critical section of the bottom bracket axle.

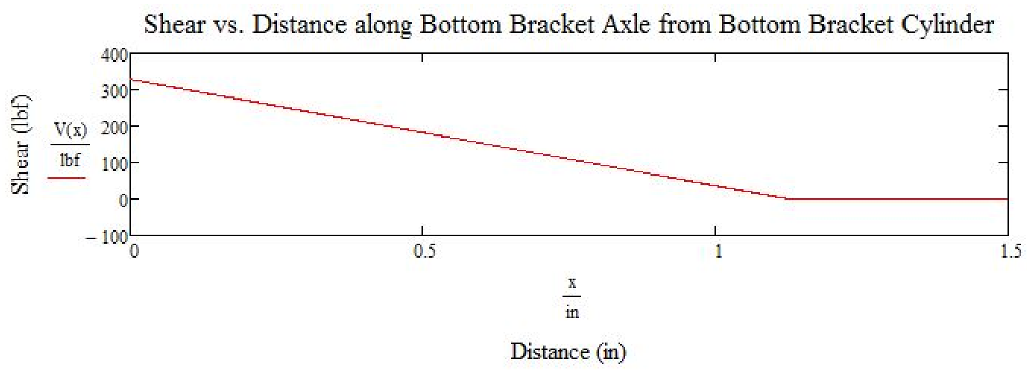


Figure 37. Plot of Shear vs. Distance along Bottom Bracket Axle from Bottom Bracket Cylinder

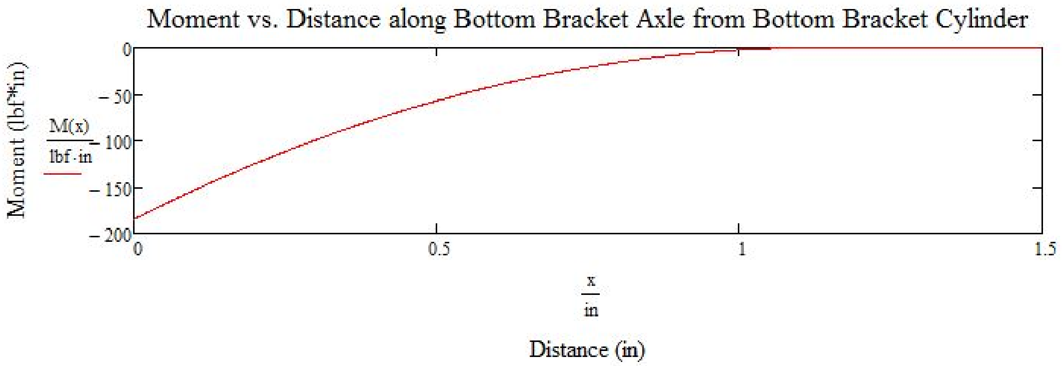


Figure 38. Plot of Moment vs. Distance along Bottom Bracket Axle from Bottom Bracket Cylinder

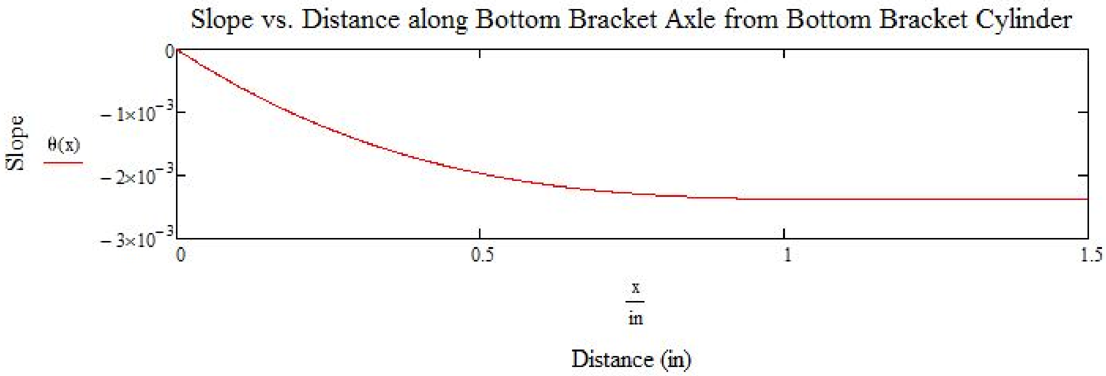


Figure 39. Plot of Slope vs. Distance along Bottom Bracket Axle from Bottom Bracket Cylinder

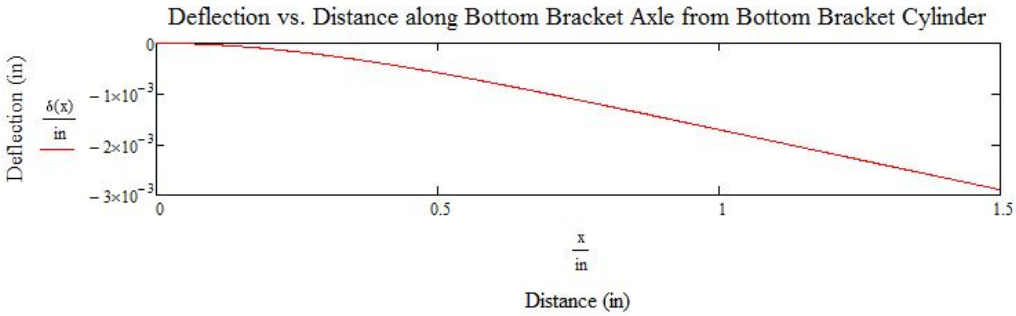


Figure 40. Plot of Deflection vs. Distance along Bottom Bracket Axle from Bottom Bracket Cylinder

The critical section of a cantilever beam is the location of the maximum shear and moment. Based on the plots in Figure 37 and Figure 38, the critical section of the bottom bracket axle is located at x = 0 inches, the interface between the cylinder and the axle. The plot in Figure 40 shows that the maximum deflection is located at the end of the axle and is minimal at 0.003 inches.

The estimated cycles of life, N, for the bottom bracket axle were calculated using the equations in Figure 41. N was determined based on S_e, the endurance limit: the stress level below which the material can be cycled infinitely without failure, and S_m the strength of the material under loading.

$$b := \frac{1}{z} \cdot \log\left(\frac{S_m}{S_e}\right)$$

$$a := \frac{S_m}{\left(10^3\right)^b}$$

$$S_n = a \cdot N^b$$

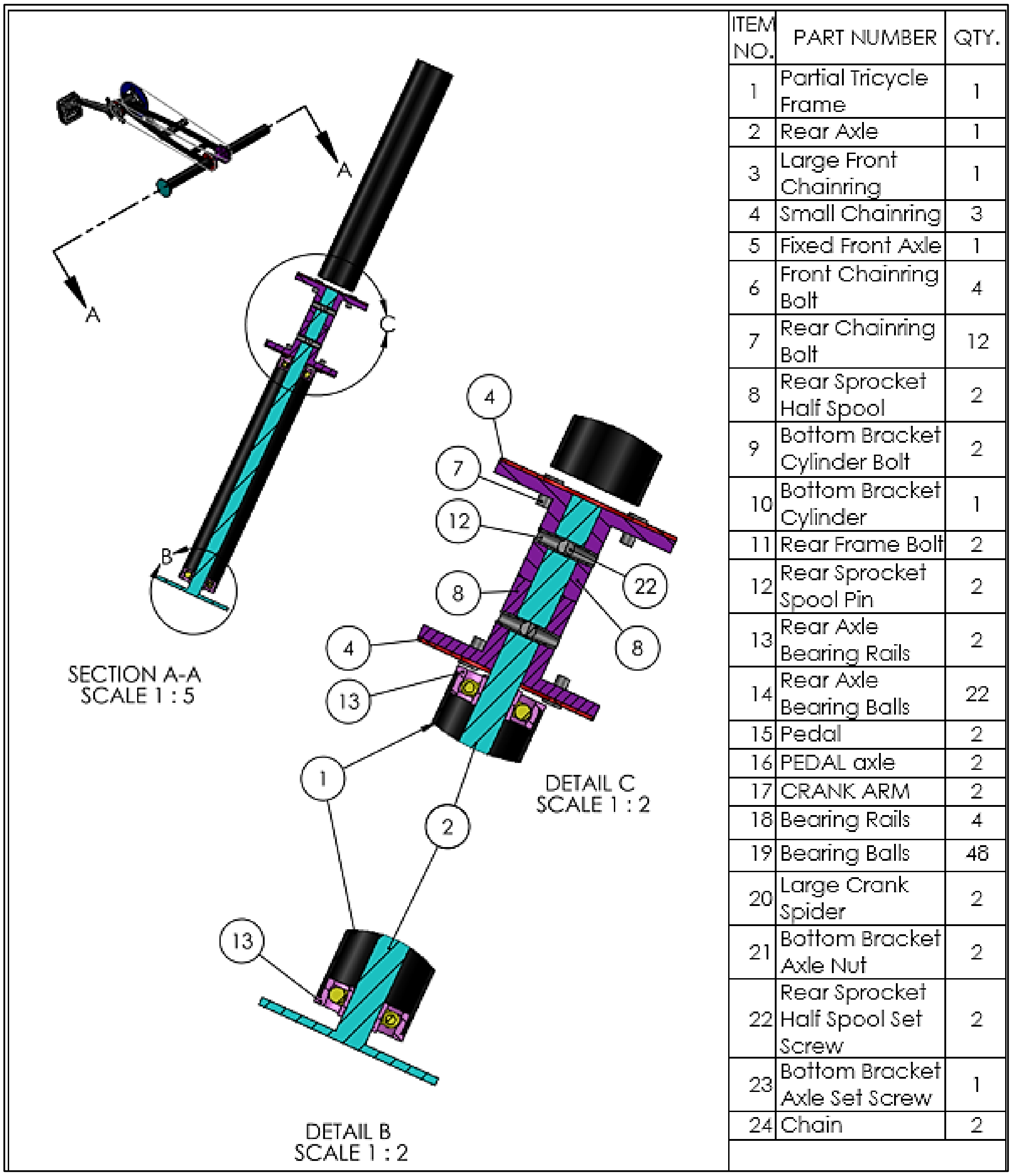
$$N := 10^{\frac{\log(S_n) - \log(a)}{b}}$$

Figure 41. Equations to Calculate Estimated Cycles of Life, N, for Bottom Bracket Axle

The results of the calculations (Appendix E) suggest that the Bottom Bracket Axle will be able to support the applied load of 328 pounds (twice the load of the average user). The cycles of life (Figure 41) of the bottom bracket axle were calculated to be approximately 18 million cycles for a machined surface. Given the tricycle will be used for rehabilitation, the tricycle cranks will only complete 756,000 cycles within its typical life which is less than the calculated life of the axle. The estimated number of cycles the axle will endure was calculated assuming a rehabilitative use of the tricycle for half an hour rehabilitation sessions 5 times a week, for 5 years. Given that the estimated cycles of the cranks is less than the calculated cycles of life for the axle, the chosen material of AISI 4140 steel will be more than sufficient for the bottom bracket axle of a tricycle drivetrain than the typical aluminum.

6.1.2 Stress Analysis of Rear Axle

The design of the rear axle assembly is shown in Figure 42.



ITEM NO.	PART NUMBER	QTY.
1	Partial Tricycle Frame	1
2	Rear Axle	1
3	Large Front Chainring	1
4	Small Chainring	3
5	Fixed Front Axle	1
6	Front Chainring Bolt	4
7	Rear Chainring Bolt	12
8	Rear Sprocket Half Spool	2
9	Bottom Bracket Cylinder Bolt	2
10	Bottom Bracket Cylinder	1
11	Rear Frame Bolt	2
12	Rear Sprocket Spool Pin	2
13	Rear Axle Bearing Rails	2
14	Rear Axle Bearing Balls	22
15	Pedal	2
16	PEDAL axle	2
17	CRANK ARM	2
18	Bearing Rails	4
19	Bearing Balls	48
20	Large Crank Spider	2
21	Bottom Bracket Axle Nut	2
22	Rear Sprocket Half Spool Set Screw	2
23	Bottom Bracket Axle Set Screw	1
24	Chain	2

Figure 42. Cross-Section View of Rear Axle Assembly

For analysis, the rear axle was simplified as a cantilever beam with bending due to the weight of the half spools and torque from the chain applied, as shown in Figure 43. For these calculations, it was assumed that x = 0 is located at the point where the rear axle (red) and the rear axle housing (orange) intersect. W_1 is the force of the cantilevered section of the rear axle as a distributed load, W_2 is the weight of the flanged part of the spool as a distributed load, and W_3 is the weight of the smaller diameter section of the spools as a distributed load. Finally, R is the reaction force at the support and M is the reaction moment at the support. Given this loading, the team solved for the shear, moment, slope, and deflection of the rear axle (Figure 44).

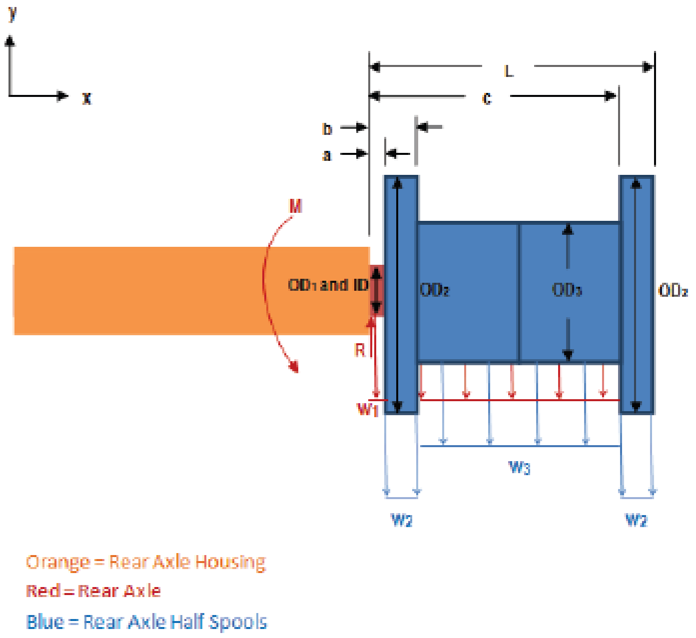
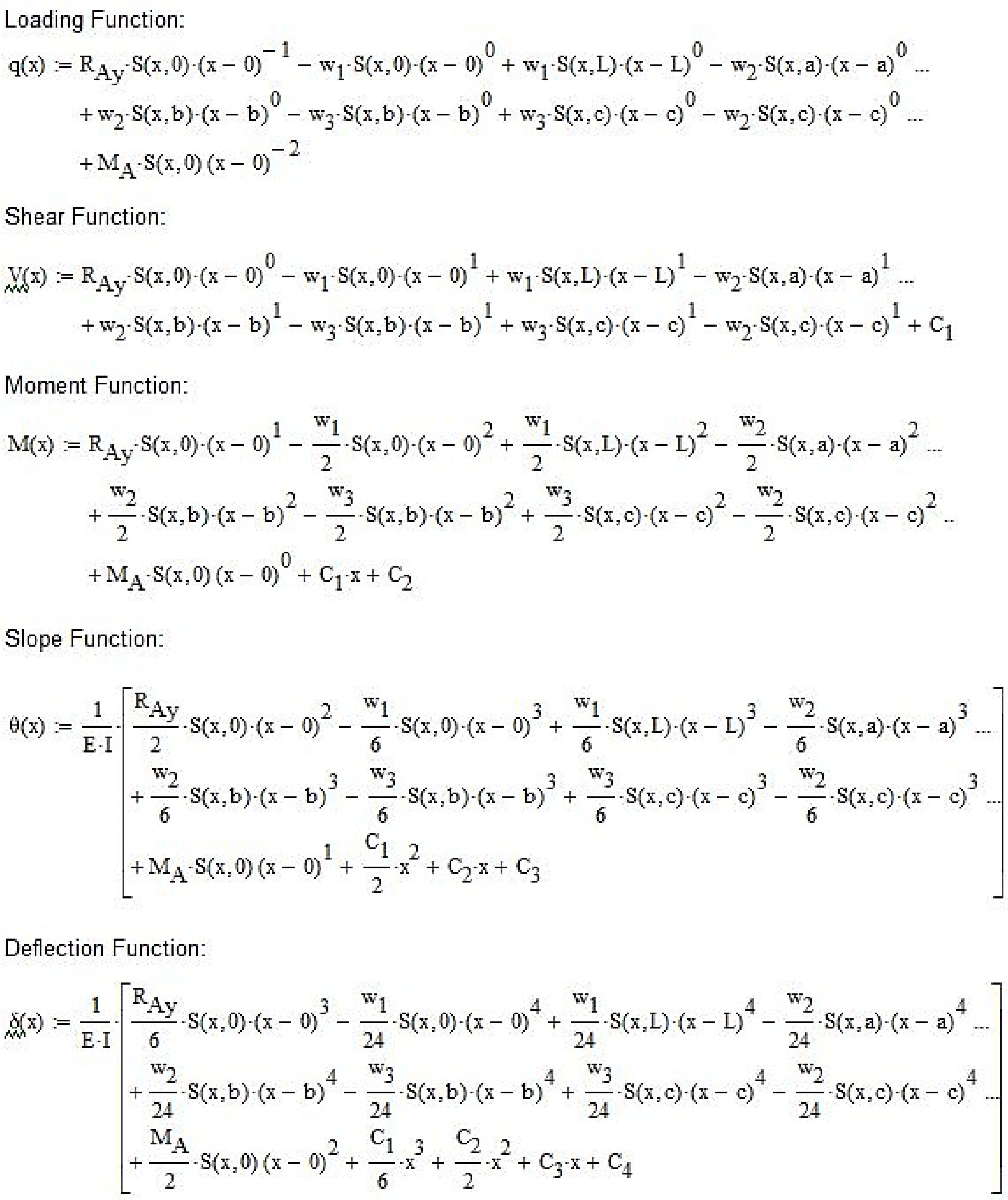


Figure 43. Rear Axle as a Cantilever Beam



Loading Function:

$$q(x) := R_{Ay}\cdot S(x,0)\cdot(x-0)^{-1} - w_1\cdot S(x,0)\cdot(x-0)^{0} + w_1\cdot S(x,L)\cdot(x-L)^{0} - w_2\cdot S(x,a)\cdot(x-a)^{0}\ \ldots$$
$$+ w_2\cdot S(x,b)\cdot(x-b)^{0} - w_3\cdot S(x,b)\cdot(x-b)^{0} + w_3\cdot S(x,c)\cdot(x-c)^{0} - w_2\cdot S(x,c)\cdot(x-c)^{0}\ \ldots$$
$$+ M_A\cdot S(x,0)\,(x-0)^{-2}$$

Shear Function:

$$V(x) := R_{Ay}\cdot S(x,0)\cdot(x-0)^{0} - w_1\cdot S(x,0)\cdot(x-0)^{1} + w_1\cdot S(x,L)\cdot(x-L)^{1} - w_2\cdot S(x,a)\cdot(x-a)^{1}\ \ldots$$
$$+ w_2\cdot S(x,b)\cdot(x-b)^{1} - w_3\cdot S(x,b)\cdot(x-b)^{1} + w_3\cdot S(x,c)\cdot(x-c)^{1} - w_2\cdot S(x,c)\cdot(x-c)^{1} + C_1$$

Moment Function:

$$M(x) := R_{Ay}\cdot S(x,0)\cdot(x-0)^{1} - \frac{w_1}{2}\cdot S(x,0)\cdot(x-0)^{2} + \frac{w_1}{2}\cdot S(x,L)\cdot(x-L)^{2} - \frac{w_2}{2}\cdot S(x,a)\cdot(x-a)^{2}\ \ldots$$
$$+ \frac{w_2}{2}\cdot S(x,b)\cdot(x-b)^{2} - \frac{w_3}{2}\cdot S(x,b)\cdot(x-b)^{2} + \frac{w_3}{2}\cdot S(x,c)\cdot(x-c)^{2} - \frac{w_2}{2}\cdot S(x,c)\cdot(x-c)^{2}\ ..$$
$$+ M_A\cdot S(x,0)\,(x-0)^{0} + C_1\cdot x + C_2$$

Slope Function:

$$\theta(x) := \frac{1}{E\cdot I}\cdot\left[\begin{array}{l}\frac{R_{Ay}}{2}\cdot S(x,0)\cdot(x-0)^{2} - \frac{w_1}{6}\cdot S(x,0)\cdot(x-0)^{3} + \frac{w_1}{6}\cdot S(x,L)\cdot(x-L)^{3} - \frac{w_2}{6}\cdot S(x,a)\cdot(x-a)^{3}\ \ldots \\ + \frac{w_2}{6}\cdot S(x,b)\cdot(x-b)^{3} - \frac{w_3}{6}\cdot S(x,b)\cdot(x-b)^{3} + \frac{w_3}{6}\cdot S(x,c)\cdot(x-c)^{3} - \frac{w_2}{6}\cdot S(x,c)\cdot(x-c)^{3}\ \ldots \\ + M_A\cdot S(x,0)\,(x-0)^{1} + \frac{C_1}{2}\cdot x^{2} + C_2\cdot x + C_3\end{array}\right]$$

Deflection Function:

$$\delta(x) := \frac{1}{E\cdot I}\cdot\left[\begin{array}{l}\frac{R_{Ay}}{6}\cdot S(x,0)\cdot(x-0)^{3} - \frac{w_1}{24}\cdot S(x,0)\cdot(x-0)^{4} + \frac{w_1}{24}\cdot S(x,L)\cdot(x-L)^{4} - \frac{w_2}{24}\cdot S(x,a)\cdot(x-a)^{4}\ \ldots \\ + \frac{w_2}{24}\cdot S(x,b)\cdot(x-b)^{4} - \frac{w_3}{24}\cdot S(x,b)\cdot(x-b)^{4} + \frac{w_3}{24}\cdot S(x,c)\cdot(x-c)^{4} - \frac{w_2}{24}\cdot S(x,c)\cdot(x-c)^{4}\ \ldots \\ + \frac{M_A}{2}\cdot S(x,0)\,(x-0)^{2} + \frac{C_1}{6}\cdot x^{3} + \frac{C_2}{2}\cdot x^{2} + C_3\cdot x + C_4\end{array}\right]$$

Figure 44. Equations for Loading, Shear, Moment, Slope, and Deflection of Rear Axle

These functions were then plotted (Figure 45, Figure 46, Figure 47, and Figure 48) to depict the critical section of the rear axle.

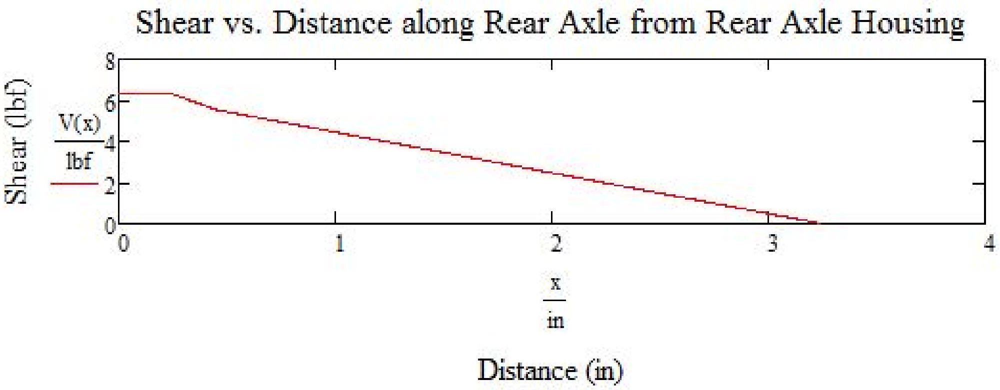


Figure 45. Plot of Shear vs. Distance along Rear Axle from Rear Axle Housing

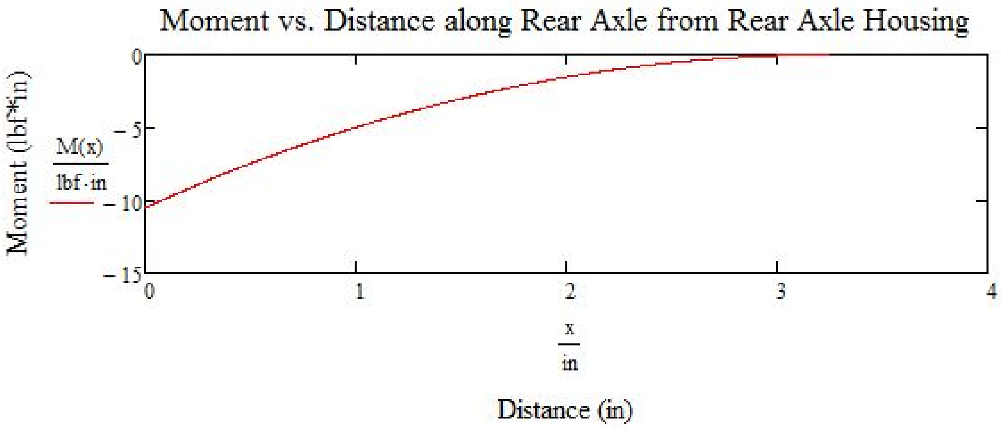


Figure 46. Plot of Moment vs. Distance along Rear Axle from Rear Axle Housing

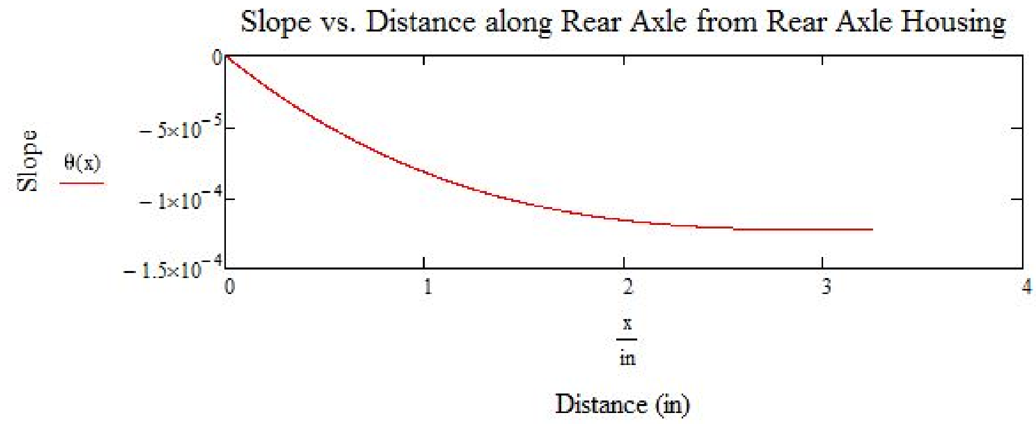


Figure 47. Plot of Slope vs. Distance along Rear Axle from Rear Axle Housing

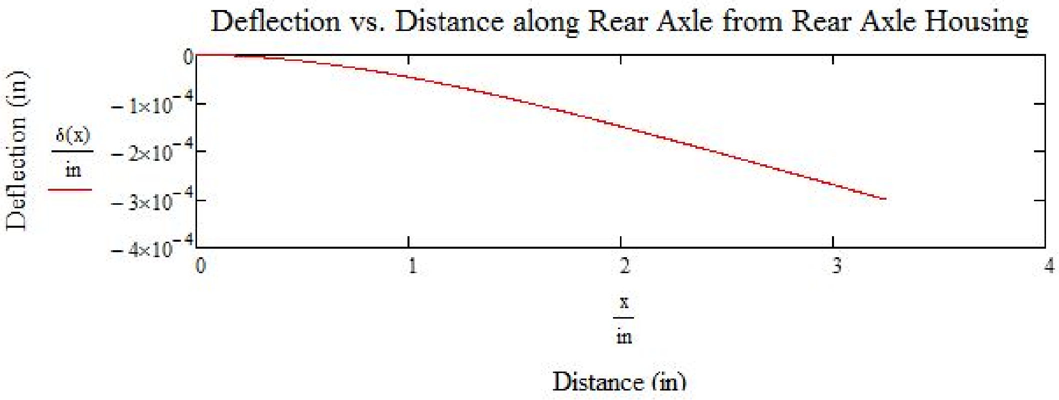
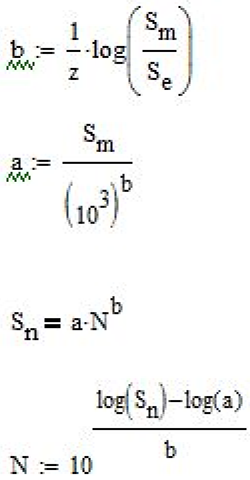


Figure 48. Plot of Deflection vs. Distance along Rear Axle from Rear Axle Housing

Based on the shear and moment plots in Figure 45 and Figure 46, the critical section of the rear axle is located at x = 0 inches, the interface between the axle housing and the axle. The plot in Figure 48 shows that the maximum deflection is located at the end of the axle and is minimal at 0.0003 inches.

The estimated cycles of life, N, for the rear axle were calculated using the equations in Figure 49. N was determined based on S_e, the endurance limit: the stress level below which the material can be cycled infinitely without failure, and S_m the strength of the material under loading.



$$b := \frac{1}{z} \cdot \log\left(\frac{S_m}{S_e}\right)$$

$$a := \frac{S_m}{\left(10^3\right)^b}$$

$$S_n = a \cdot N^b$$

$$N := 10^{\frac{\log(S_n) - \log(a)}{b}}$$

Figure 49. Equations to Calculate Estimated Cycles of Life, N, for Rear Axle

The results of the calculations (Appendix B) suggest that the rear axle will be able to support the applied load of the weight of the half spools. The cycles of life (Figure 49) of the rear axle is approximately $3*10^{28}$ cycles for a machined surface and $3*10^{12}$ cycles for a worn surface, which are beyond 10^6 cycles. The team did analysis for a worn surface to account for the edge of the bearing wearing away the surface of the rear axle. Given the tricycle will be used for rehabilitation, the rear axle of the tricycle will only complete 1,512,000 cycles within its typical life which is less than the calculated life of the axle. The estimated number of cycles the axle will endure was calculated assuming a rehabilitative use of the tricycle for half an hour rehabilitation sessions 5 times a week, for 5 years. Given that the estimated cycles of the rear axle is less than the calculated cycles of life for the axle, the weakest available type of steel, AISI 1010, will be more than sufficient for the rear axle of a tricycle drivetrain.

Shear Stress Analysis Calculations of Rear Sprocket Bolts

The chain applies a torque to the rear sprocket half spools, which is simplified as a force tangent to the half spool at a radial distance from the axis of rotation (Figure 50).

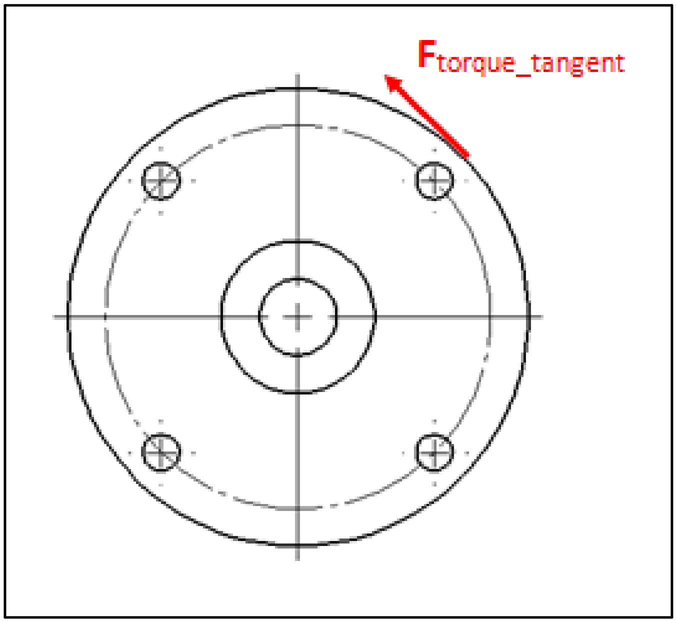


Figure 50. Side View of Rear Sprocket Half Spool including Force due to Torque

It is assumed that torque is caused by the rotation of the cranks, which causes the chain to rotate, which causes the half spools to rotate, which in turn rotates the rear axle. The tangential force due to torque acts on the rear sprocket bolts (Figure 51). This force causes shear stress in the bolts.

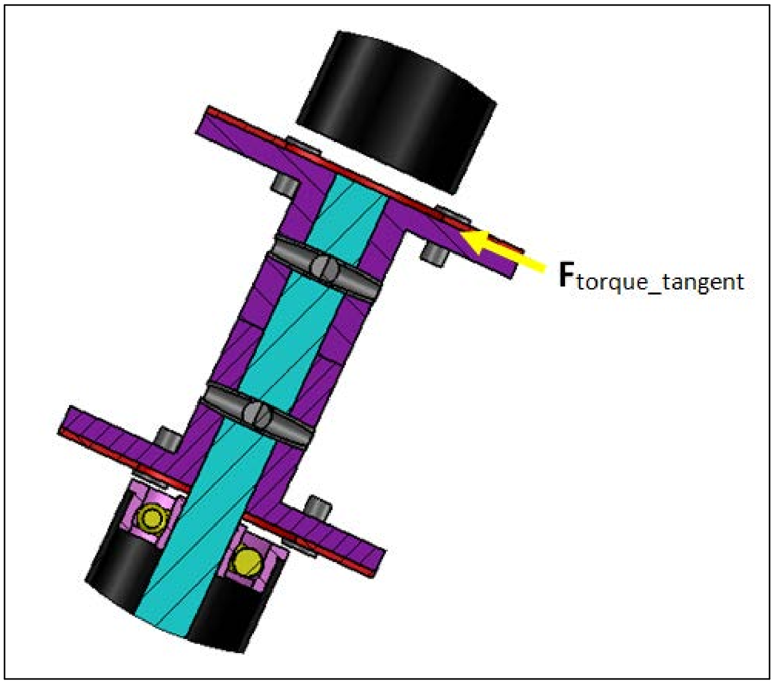
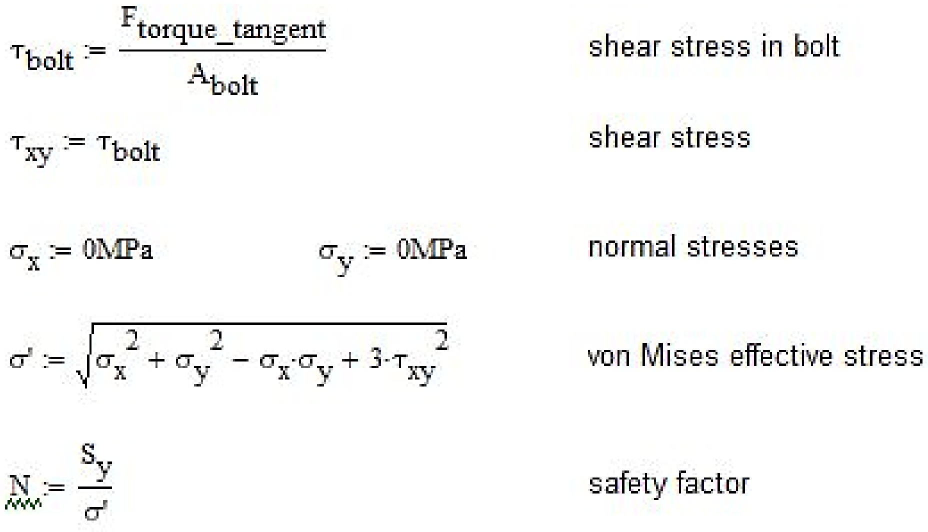


Figure 51. Cross-Section of Rear Sprocket Half Spools including the Force due to Torque

The team calculated the shear stress in the rear sprocket bolts by applying the shear stress due to torque over the cross-sectional area of a bolt and then comparing that value to the strength of the bolt material (Figure 52).



$\tau_{bolt} := \frac{F_{torque\_tangent}}{A_{bolt}}$ shear stress in bolt

$\tau_{xy} := \tau_{bolt}$ shear stress

$\sigma_x := 0\text{MPa}$ $\sigma_y := 0\text{MPa}$ normal stresses

$\sigma' := \sqrt{\sigma_x^2 + \sigma_y^2 - \sigma_x \cdot \sigma_y + 3 \cdot \tau_{xy}^2}$ von Mises effective stress

$N := \frac{S_y}{\sigma'}$ safety factor

Figure 52. Equations for Shear and Safety Factor for Rear Sprocket Bolts

The resulting safety factor of 12.025 suggests that the rear sprocket bolts will not shear under the given load and will in fact withstand loads up to 12 times the given load. These calculations can be found in Appendix C.

6.2 Equilibrium Analysis of Tricycle

The input force, F_1, at the pedal is first transferred via a chain to the rear sprocket, then along the back axle to the rear wheel (Figure 53). The tricycle can only move forward if the output force at the rear wheel, F_4, is greater than the wind and rolling resistance forces acting against the tricycle. This can be analyzed as an equilibrium equation for a standard drivetrain in an ideal scenario (Figure 53) where the input pedaling force, F_1, is constant throughout the pedal cycle. F_1 is the component of the applied pedaling force that is always perpendicular to the crank throughout the cycle.

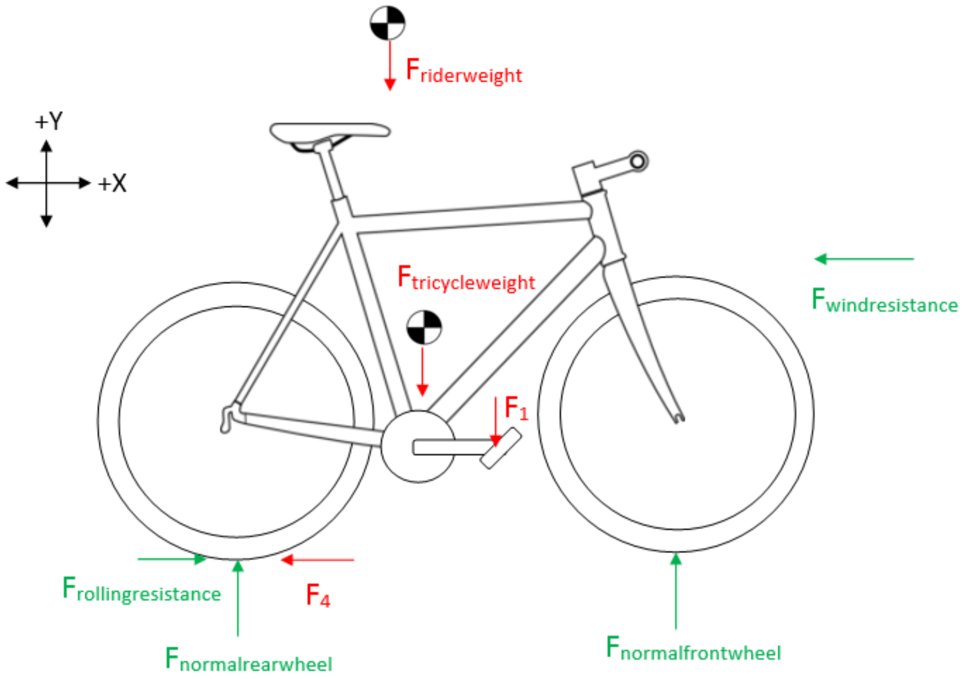


Figure 53. Free body diagram of forces involved in riding a tricycle

The average output force applied by the rear wheel to the ground was calculated using equation 6.1. F_4 is the average output force required to move the tricycle at a constant velocity of 3 miles per hour, overcoming the forces due to wind resistance and rolling resistance.

$$F_4 = F_{wind\ resistance} + F_{rolling\ resistance} \qquad (6.1)$$

The force due to wind resistance was calculated using equation 6.2, where A is the frontal area of the rider and tricycle, C_d is the drag coefficient for air, d_a is the density of air, and v is the constant velocity.

$$F_{wind\ resistance} = \frac{1}{2} * A * (C_d * d_a * v^2) \qquad (6.2)$$

The force due to rolling resistance was calculated using equation 6.3, where g is gravity, m_t is the mass of the tricycle, m_r is the mass of the rider, and C_{rr} is the coefficient of rolling resistance for asphalt.

$$F_{rolling\ resistance} = g * (m_t + m_r) * C_{rr} \qquad (6.3)$$

The output force at the rear wheel, F_4, applied through the drivetrain must be greater than the forces of rolling and air resistance acting against the tricycle and rider for the tricycle to move forward in an equilibrium state.

6.3 Force and Phasing Analysis

Free body diagrams (Figure 54 and Figure 55) were developed to show the transfer of torque through the drivetrain from the input at the pedals to the output at the rear wheel. In the free body diagrams, F_4 is the output force at the rear wheel, F_1 is the component of the applied pedaling force that is perpendicular to the crank corresponding to the large chainring, F_2 and F_3 are the forces due to the tension of the chain corresponding to the large chainring, F_6 and F_7 are the forces due to the tension of the chain corresponding to the small chainring, F_5 is the component of the applied pedaling force that is perpendicular to the crank corresponding to the small chainring, R_1 is the crank length, R_3 is the radius of the rear sprocket, R_4 is the radius of the rear wheel, and R_2 and R_5 are the radii of the large and small chainrings, respectively.

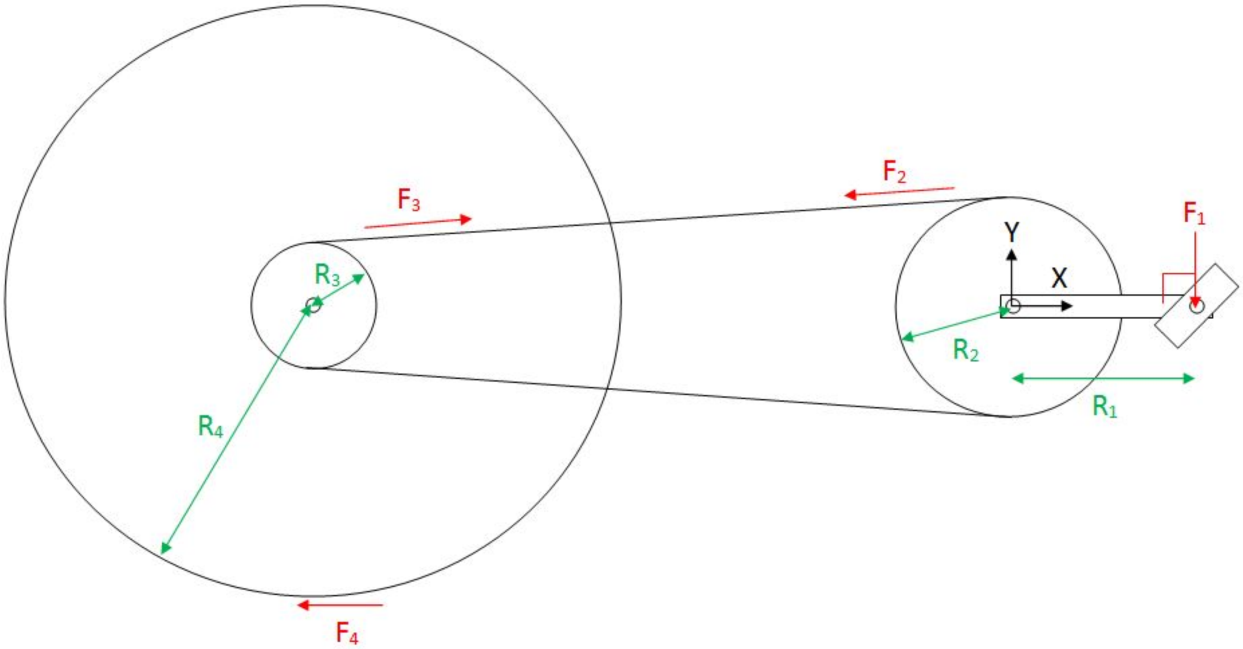


Figure 54. Free Body Diagram of Right Side of Drivetrain with Large Chainring

Assuming internal losses within the drivetrain are negligible, 6.4 and 6.5 express the relationship of torques on the right side of the drivetrain (Figure 54).

$$\boldsymbol{F_1} * \boldsymbol{R_1} = \boldsymbol{F_2} * \boldsymbol{R_2} \qquad (6.4)$$

$$\boldsymbol{F_3} * \boldsymbol{R_3} = \boldsymbol{F_{4R}} * \boldsymbol{R_4} \qquad (6.5)$$

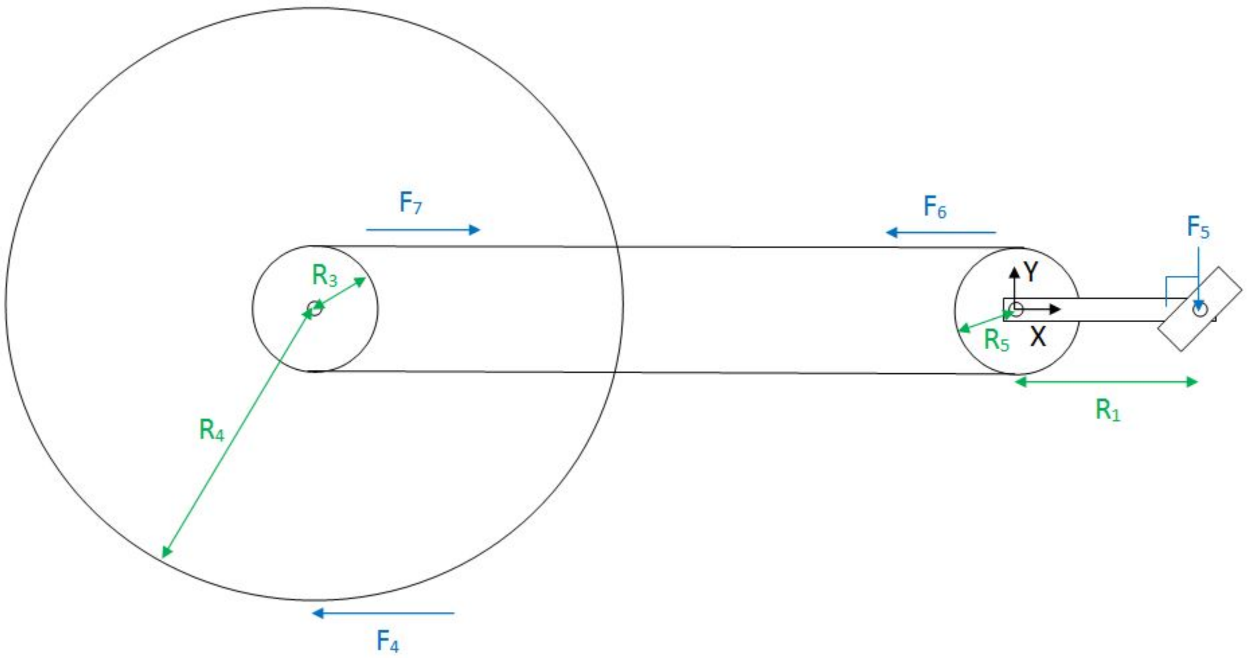


Figure 55. Free Body Diagram of Left Side of Drivetrain with Small Chainring

Equations 6.6 and 6.7 are the same as equations 6.4 and 6.5 in that they express the relationships of torques throughout the drivetrain, but for the left side instead of the right side (Figure 55).

$$\boldsymbol{F_5} * \boldsymbol{R_1} = \boldsymbol{F_6} * \boldsymbol{R_5} \qquad (6.6)$$

$$\boldsymbol{F_7} * \boldsymbol{R_3} = \mathbf{F_{4L}} * \boldsymbol{R_4} \qquad (6.7)$$

By combining equations 6.4 through 6.7, equation 6.8 was developed to express the relationship between the input pedaling forces (F_1 and F_5) and the output force at the rear wheel (F_4). Since both sprockets are fixed to the rear axle, the input forces on each pedal must be added together when calculating the transfer of torque through the entire drivetrain.

$$\boldsymbol{F_4} = \boldsymbol{F_1} * \frac{\boldsymbol{R_1} * \boldsymbol{R_3}}{\boldsymbol{R_2} * \boldsymbol{R_4}} + \boldsymbol{F_5} * \frac{\boldsymbol{R_1} * \boldsymbol{R_3}}{\boldsymbol{R_5} * \boldsymbol{R_4}} \qquad (6.8)$$

The amount of force applied to the pedal varies depending on the position of the crank along with the user's technique. It can be noted that someone with more experience will be able to apply an upward pulling force in the upstroke while someone who is less experienced may have poor technique (Figure 56), in which he or she only applies a downward pushing force (black) to the pedals. The red vectors are the resulting radial forces and the blue and green vectors are the resulting tangential forces. The yellow vectors show the effective force that causes torque.

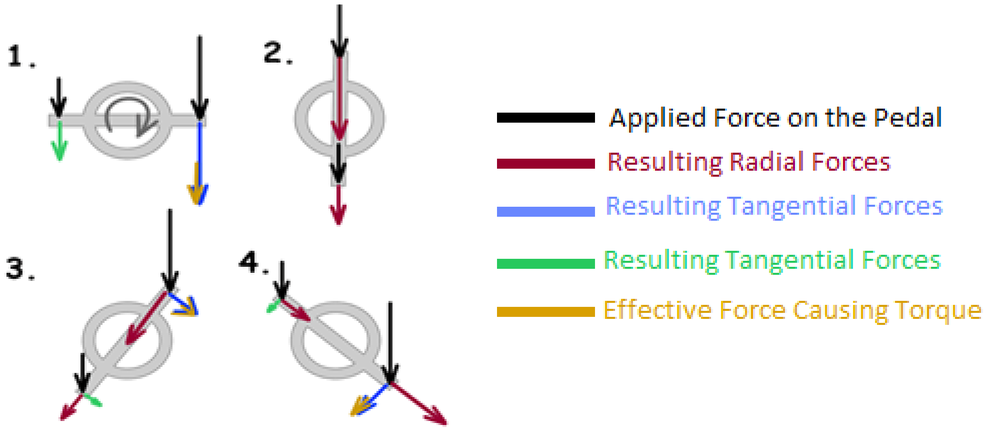


Figure 56. Poor Pedaling Technique of a Constant Downward Applied Force (Pedal Torque, 2002)

The bicycle will still move forward with poor pedaling technique, however, not efficiently. For the given tricycle, it is assumed that the upward force during the upstroke is obtained by the user pulling up on the basket pedal. Since the pedaling force is not constant throughout a cycle, equation 6.8 must be solved for numerous pedal positions to map the output force on the rear wheel for a full pedaling cycle, one rotation of the large chainring and two rotations of the small chainring.

Proper pedaling technique involves strategic application of force on the pedal to maximize the effective force that causes torque. The optimal applied force can be broken into two force components relative to the pedal and varies depending on the location of the crank within the cycle (Figure 57).

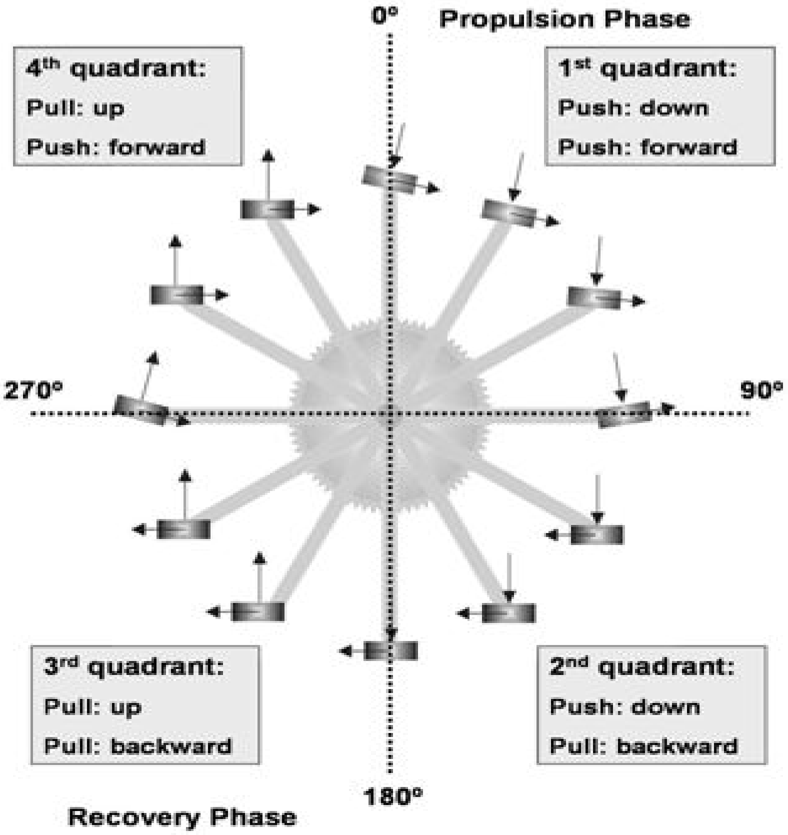


Figure 57. Pedaling Force Vector Component Directions Needed for Complete Crank Revolution (EFDeportes, 2012)

The relative force for each position in the coordinate system of the crank throughout the pedaling cycle of the tricycle was estimated based on the force vs. crank position diagram of a standard bicycle with toe clips that allow for pulling up on the pedals (Figure 58). The scale in the diagram can be used to determine the magnitude of the applied force based on the length of the vectors. Although this diagram is just an example, and the actual force varies depending on the user, the diagram (Figure 58) is a result of a study by Too, D. and Landwe, G. (2003) in which the average force at various positions throughout the cycle was measured. The original scale is in Newtons, however for comparison to calculations that were done, the scale in pounds force was added.

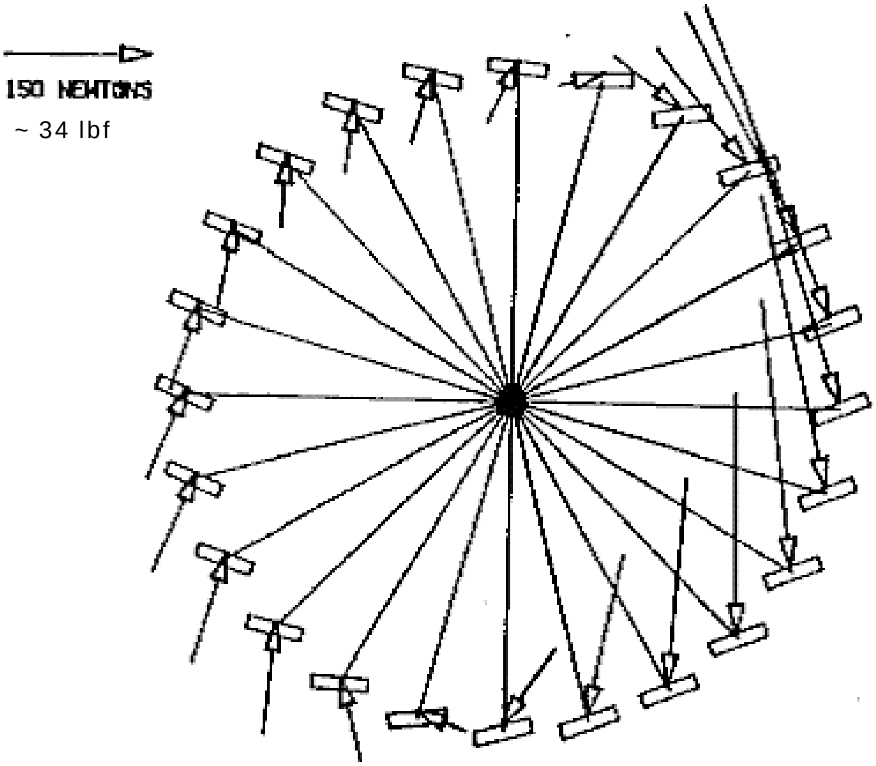


Figure 58. Applied Force Based on Crank Position for an Elite Cyclist (Too, D. & Landwe, G., 2003)

Instead of using twenty-four crank positions, the team developed a simplified version (Figure 59) with eight positions, one every pi/2 radians throughout a full pedal stroke. It is assumed that the user can pull up on the pedal on the upstroke with basket pedals similar to pulling up with toe clips. The black vectors in Figure 58, which represent the force applied by the user, were used as a scalar guideline for the black vectors in Figure 59. These black vectors are broken into two components, X (F_{ax}, red) and Y (F_{ay}, blue), given an inertial coordinate system originating at the axis of rotation of the crank. From these forces, the force perpendicular to the cranks (F_1, green), which causes torque, can be found with equation 6.9, where theta is the angle between the applied force vector (black) and the crank.

$$F_1 = F_a * sin(\theta) \qquad (6.9)$$

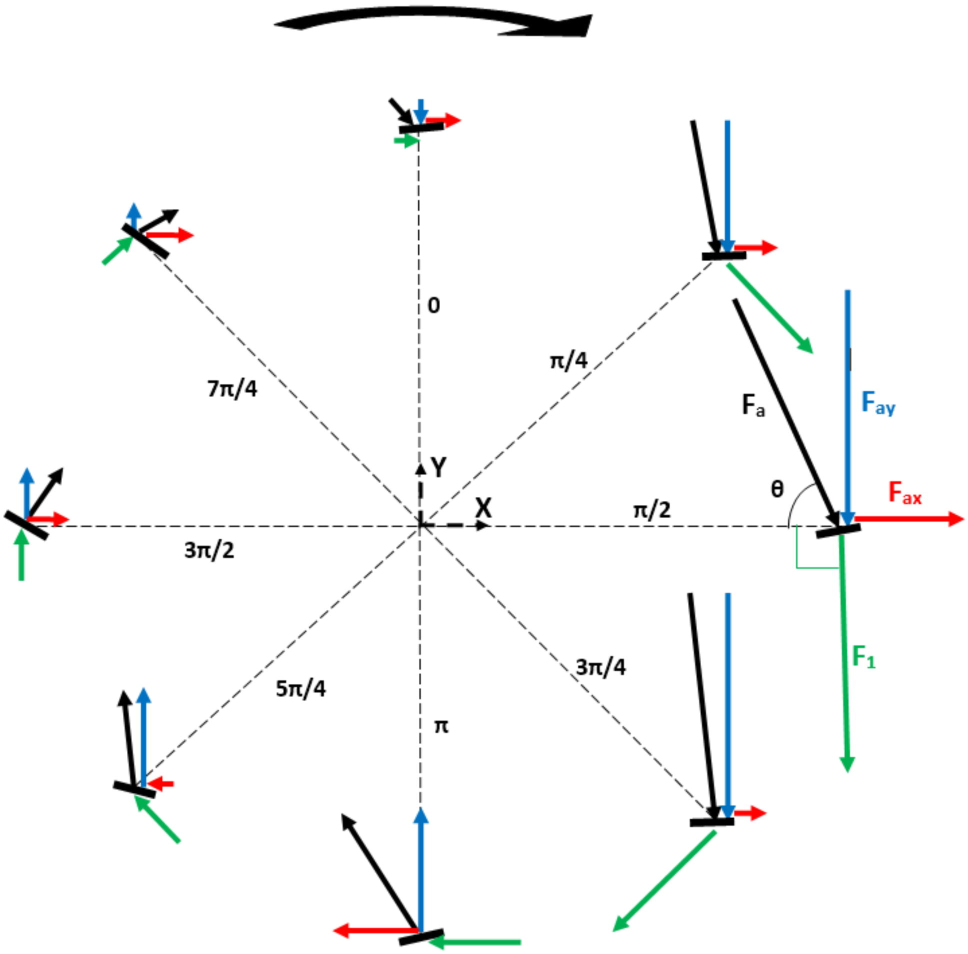


Figure 59. Simplified Relative Force Based on Position

This simplified version of the pedaling force diagram (Figure 59) was correlated with the original version (Figure 58) so that the lengths of the vectors varied accordingly throughout the cycle. The pedaling force diagrams show pi/2, the front horizontal position of the crank, as the location of the maximum force in the cycle. The team devised a scale (Table 4) based on F_1, the component of the applied force that is perpendicular to the crank. This scale ranged from one to ten, with ten being the maximum force, to demonstrate the relative pedaling forces at eight crank positions throughout the cycle.

Table 4. Approximate Scale for Relative Pedaling Forces at Eight Crank Positions

Crank Position (Radians)	Relative Force Scalar Magnitude of $F_{applied}$	Θ (degrees)	Relative Force Scalar of F_1	Percentage of Maximum Applied Force
0	1.5	135	1	10%
π/4	6	123	5	50%
π/2	11	66	10	100%
(3π)/4	10	45	7	70%
π	6	40	4	40%
(5π)/4	4	53	3	30%
(3π)/2	2.5	55	2	20%
(7π)/4	2	70	1.5	15%

Given the value of the maximum force that each of the user's legs can apply to the pedals, the relative force values at the eight crank positions can be determined using the scalars and/or percentages. A situation was considered in which the user's affected leg is on the left pedal, which corresponds to the smaller chainring, and his or her unaffected leg is on the right pedal, which corresponds to the larger chainring. Assume the left crank (blue) starts at the top dead center position, 0, while the right crank (red) starts at the front horizontal position, pi/2, (Figure 60. Right Pedal (Red) at Front Horizontal Position and Left Pedal (Blue) at Top Dead Center Position).

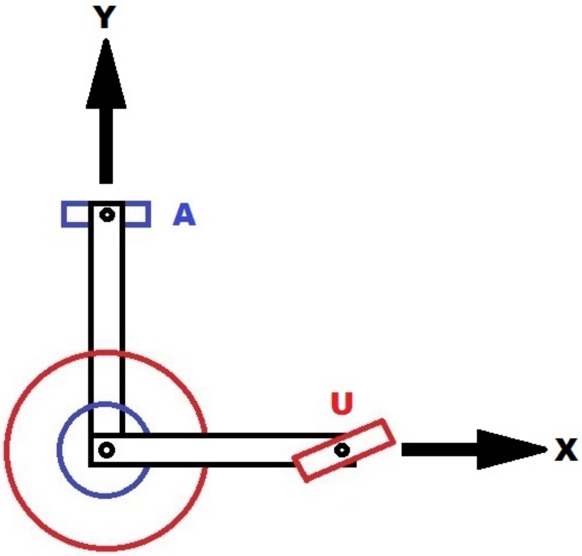


Figure 60. Right Pedal (Red) at Front Horizontal Position and Left Pedal (Blue) at Top Dead Center Position

Also, assume the user's unaffected leg can provide a maximum force of 11 lbf and therefore an effective perpendicular force of 10 lbf at the front horizontal position. Therefore, a user with an even weakness in their affected leg will able to provide a maximum effective force of 5 lbf at the front horizontal pedal position. This 10 lbf is estimated as a reasonable amount of force because a constant 5 lbf from each leg will result in a moderate pace of approximately 3 miles per hour, based on the team's previous equilibrium analysis of the drivetrain (6.2 Equilibrium Analysis of Tricycle) and the ratio of the gears in the drivetrain. These forces are also a reasonable amount of force to be applied compared to a normal healthy leg, which typically applies more than 30 lbf of effective force (Figure 58). The relative input pedaling forces for eight positions in the cycle, one rotation of the large chainring (red), and two rotations of the small chainring (blue), were determined using the scale and the given maximum force value. The input pedaling forces (F_1 and F_5) for each leg were applied to equation 6.8 to determine the output force (F_4) at the rear wheel (Figure 61).

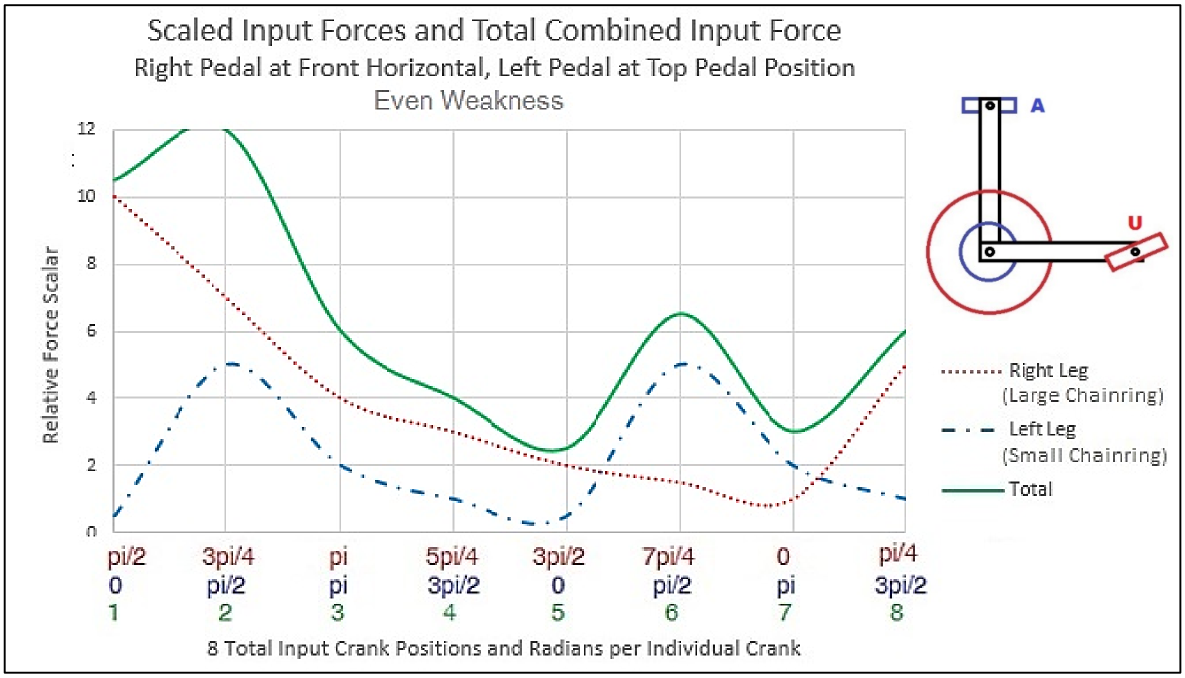


Figure 61. Input Pedaling Forces and Output Forces vs. Position

The scale of relative forces was modified for the patient conditions where their affected leg is weak in pulling (flexion), weak in pushing (extension), or even weakness, meaning they are weak in both pushing and pulling. Table 5 shows the relative force scales compared to crank position, in radians where zero is top dead center for the three specific weakness conditions. These weakness in pushing or pulling were accounted for in the relative force scale by assuming a value of zero force for the crank positions that require pushing or pulling on the pedal depending on the user’s specific condition.

Table 5. Scale of Relative Force Magnitudes for Three Conditions

Even Weakness		Can't Push		Can't Pull	
Crank Position in Radians	Crank Scalar	Crank Position in Radians	Crank Scalar	Crank Position in Radians	Crank Scalar
0	0.5	0	0	0	0.5
π/4	2.5	π/4	0	π/4	2.5
π/2	5	π/2	0	π/2	5
(3π)/4	3.5	(3π)/4	0	(3π)/4	3.5
π	2	π	2	π	0
(5π)/4	1.5	(5π)/4	1.5	(5π)/4	0
(3π)/2	1	(3π)/2	1	(3π)/2	0
(7π)/4	0.75	(7π)/4	0.75	(7π)/4	0

Since the left crank rotates twice for every one rotation of the right crank, the starting position of each crank determines when and where the cranks will meet in the cycle. In order to understand how starting position affects phasing, sixteen starting locations for the cranks were selected for analysis. The sixteen starting positions consisted of the two cranks at four possible starting positions at 90 degree rotations throughout the cycle for each crank. For each starting position, the forces for the left and right cranks were added at eight positions throughout a pedaling cycle, one rotation of the right crank and two rotations of the left crank.

For example, the cranks can be positioned such that the pedals start with the right crank at the front horizontal position, and the left crank at the top dead center position. Figure 62 is the resulting phase of the cranks with the right crank being the red curve and the left crank as the blue curve.

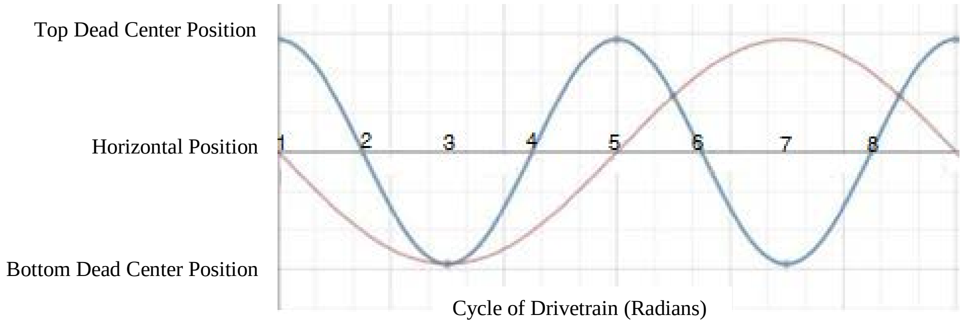


Figure 62. Position vs. Cycle for Right Front (red), Left Top (blue) Starting Position of Cranks

Using this phasing diagram, the team could determine the location of each pedal for 8 total positions within the cycle, every pi/4 radian (45 degree) rotation of the right crank and pi/2 radian (90 degree) rotation of the left crank. The appropriate force scaling was documented for each leg. These total relative force values for each leg were then added together to get a scaled score for the total force at each of the eight determined crank positions throughout a pedaling cycle (Table 6).

Table 6. Relative Force Scalars for Starting Pedal Positions at Right Front, Left Top

Relative Force Scalars Based on Crank Positions								
Crank Position Within a Full Cycle								
(Radians)	**pi/2**	**3pi/4**	**pi**	**5pi/4**	**3pi/2**	**7pi/4**	**0**	**pi/4**
Red (Right Crank)	10	7	4	3	2	1.5	1	5
(Radians)	**0**	**pi/2**	**pi**	**3pi/2**	**0**	**pi/2**	**pi**	**3pi/2**
Blue (Left Crank)	0.5	5	2	1	0.5	5	2	1
Position	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Total Relative Force Scalar	10.5	12	6	4	2.5	6.5	3	6

The total scaled values from all sixteen starting positions were then compared. These values were examined to find which starting position had the most optimal combination of desired values throughout the cycle. The optimal starting position would have a high starting force, a low variation, a low maximum force, and a high minimum force. Since the values are determined by how much force the user applies to the pedals, a high starting value indicates that the crank is starting in a position where the user will be able to initiate movement of the tricycle. The low variation, meaning a more consistent amount of force is applied throughout a full pedal stroke, is desired as the pedaling will be smoother for the user. Variation was calculated using equation 6.10 by determining the mean force value of the cycle, $\bar{x}$, and comparing each of the other force values, x, in one cycle to the mean of the set, with n being the number of forces in the set.

$$Variation = \frac{\sum(x-\bar{x})^2}{n} \qquad (6.10)$$

A low variation would have most of the forces in the set all close to the mean value, while a high variation would have more forces in the set with a greater difference from the mean value. A high minimum force and a low maximum force are also desirable to avoid spikes or dips in applied force.

For each patient condition, the relative forces vs. position for all sixteen positions were listed in a single spreadsheet. The team used acronyms for starting crank starting positions, where R stands for right crank, L stands for left crank, T stands for the top dead center position of the crank, F stands for front, meaning the crank is straight forward, D stands for the down crank position where the crank is at bottom dead center, and B stands for the back position of the crank. For example, RF LT means the starting position has the right crank starting in the forward position and the left crank starting at the top of the cycle. Recall that the right crank is attached to the large chain ring and, therefore, makes one rotation while the left crank, attached to the small chain ring, makes two rotations.

The criteria of low maximum force, high minimum force, and low variation were then added as additional columns of calculations in the spreadsheet (Table 7) while the crank starting position criteria were analyzed based on the first and second positions. The four desired criteria were analyzed such that the preferred option for each criterion was highlighted in green within the spreadsheet, with mediocre options colored orange and the worst options in red. There was a range of shading used to represent the values where a color gradient from dark green to dark red was used where dark green is the best and dark red is the worst.

Table 7. Criteria Comparison Table for Able – Even Weakness Condition

	Total Relative Force Scalars Based on Starting Crank Positions and Position in Pedaling Cycle Right Leg Able - Left Leg Even Weakness											
		Position in Pedaling Cycle										
		1	2	3	4	5	6	7	8	MAX	MIN	Variation
Starting Crank Position	RT LT	1.5	10.0	12.0	8.0	4.5	8.0	4.0	2.5	12.0	1.5	12.2
	RT LF	6.0	7.0	11.0	7.5	9.0	5.0	3.0	2.0	11.0	2.0	7.8
	RT LD	3.0	6.0	10.5	12.0	6.0	4.0	2.5	6.5	12.0	2.5	10.1
	RT LB	2.0	5.5	15.0	9.0	5.0	3.5	7.0	3.5	15.0	2.0	15.0
	RF LT	10.5	12.0	6.0	4.0	2.5	6.5	3.0	6.0	12.0	2.5	10.1
	RF LF	15.0	9.0	5.0	3.5	7.0	3.5	2.0	5.5	15.0	2.0	15.0
	RF LD	12.0	8.0	4.5	8.0	4.0	2.5	1.5	10.0	12.0	1.5	12.2
	RF LB	11.0	7.5	9.0	5.0	3.0	2.0	6.0	7.0	11.0	2.0	7.8
	RD LT	4.5	8.0	4.0	2.5	1.5	10.0	12.0	8.0	12.0	1.5	12.2
	RD LF	9.0	5.0	3.0	2.0	6.0	7.0	11.0	7.5	11.0	2.0	7.8
	RD LD	6.0	4.0	2.5	6.5	3.0	6.0	10.5	12.0	12.0	2.5	10.1
	RD LB	5.0	3.5	7.0	3.5	2.0	5.5	15.0	9.0	15.0	2.0	15.0
	RB LT	2.5	6.5	3.0	6.0	10.5	12.0	5.0	5.0	12.0	2.5	9.9
	RB LF	7.0	3.5	2.0	5.5	15.0	9.0	4.0	4.5	15.0	2.0	14.9
	RB LD	4.0	2.5	1.5	10.0	12.0	8.0	3.5	9.0	12.0	1.5	13.4
	RB LB	3.0	2.0	6.0	7.0	11.0	7.5	8.0	6.0	11.0	2.0	7.1

The comparison of these starting positions resulted in two optimal pedal alignment options (highlighted in blue in Table 7) for each patient condition. The top positions were as follows:

For a patient who is in the first stages of rehabilitation, a physical therapist is more likely to have the patient pedal their weaker leg on the faster pedal, in order to have less force and more repetition. Assuming the weaker leg is on the faster (left) crank, the following positions are better for the various conditions:

Right Leg Able, Left Leg Even Weakness

The phasing (Figure 63) resulting from the starting position of the right crank at the front horizontal position and the left crank at top dead center is beneficial for someone whose left leg has an even weakness. Since the location of maximum pedaling force is the front horizontal position, the force that the right leg is applying to the pedal at the start to compensate for the left leg's weakness when the pedals meet up at bottom dead center and pull up together, in which the unaffected leg helps the affected leg pull up. This helps get the tricycle moving and starts momentum.

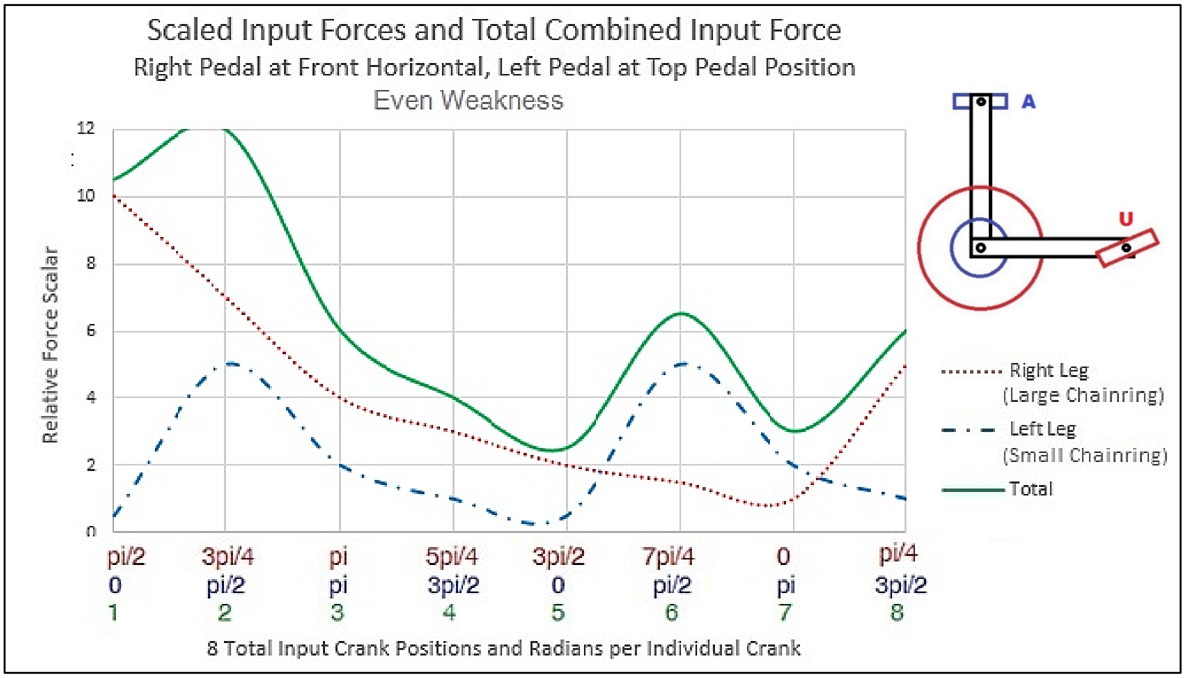


Figure 63. Force Diagram for Right Front (Red), Left Top (Blue) Starting Position

The phasing (Figure 64) resulting from the starting position of the right crank at the front horizontal position and the left crank at the back horizontal position is beneficial to someone whose left leg is weak pushing and pulling because it has an optimal starting position. Since the location of maximum pedaling force is the front horizontal position, the right leg is approaching the maximum pedaling force location as the left leg is pulling up from back horizontal. This helps maintain momentum when the left leg is pulling up and is unable to drive the tricycle by itself.

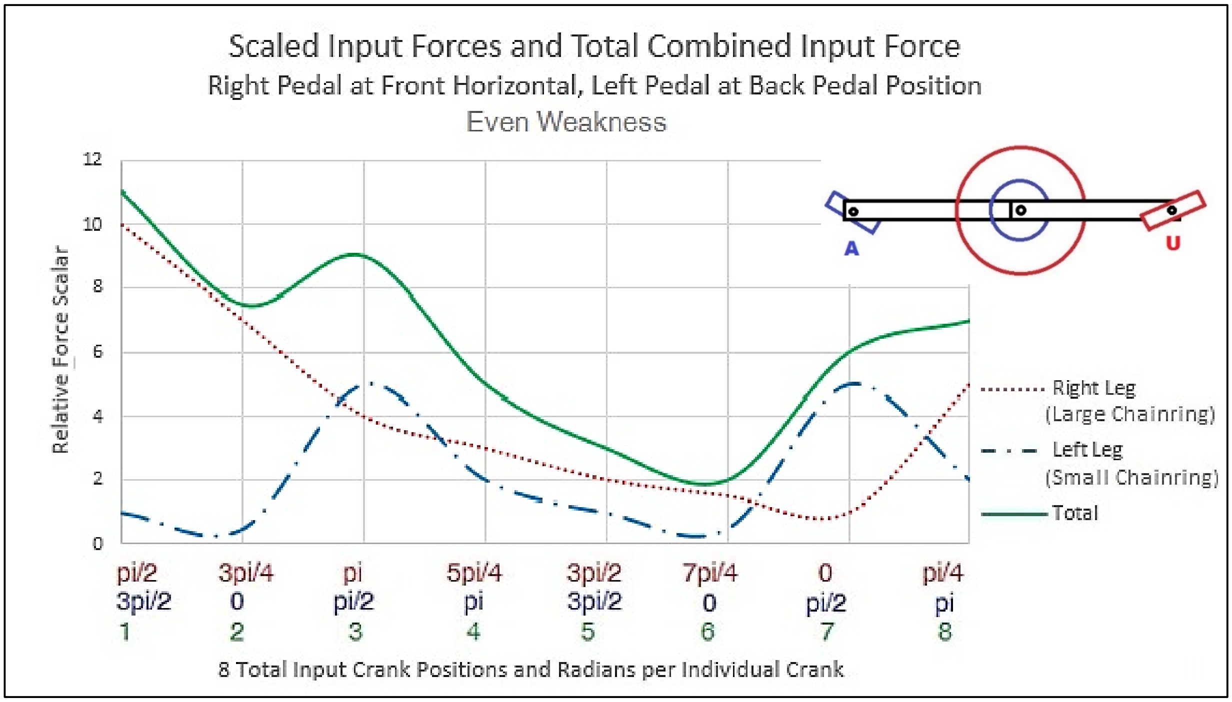


Figure 64. Force Diagram for Right Front (Red), Left Back (Blue) Starting Position

Right Leg Able, Left Leg Can't Push

The phasing (Figure 65) resulting from the starting position of the right crank at the front horizontal position and the left crank at top dead center is beneficial to someone whose left leg is weak pushing. Since the location of maximum pedaling force is the front horizontal position, the right leg is applying maximum force to the pedal at the start to compensate for the left leg's weakness in pushing the pedal down from top dead center. This helps get the tricycle moving and starts momentum.

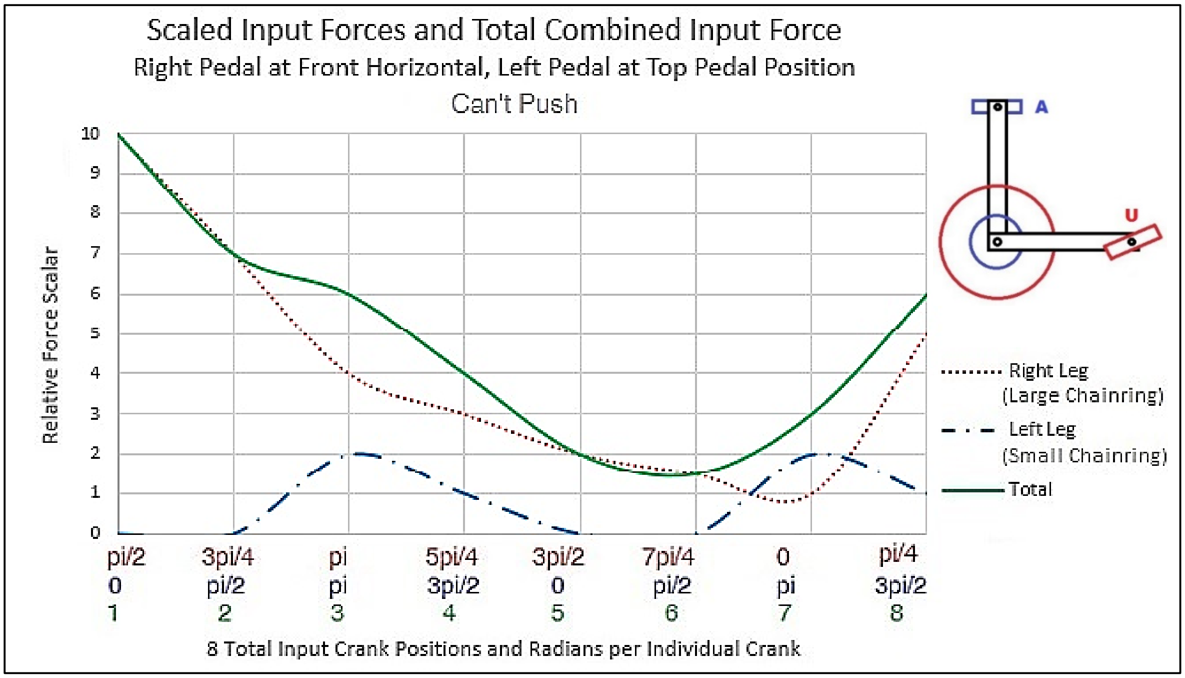


Figure 65. Force Diagram for Right Front (Red), Left Top (Blue) Starting Position

The phasing (Figure 66) resulting from the starting position of both the right and left crank at the front horizontal position is beneficial to someone whose left leg is weak pushing. Since the location of maximum pedaling force is the front horizontal position, the right leg is applying maximum force to the pedal at the start to compensate for the left leg's weakness in pushing the pedal down from front horizontal position. This helps get the tricycle moving and starts momentum.

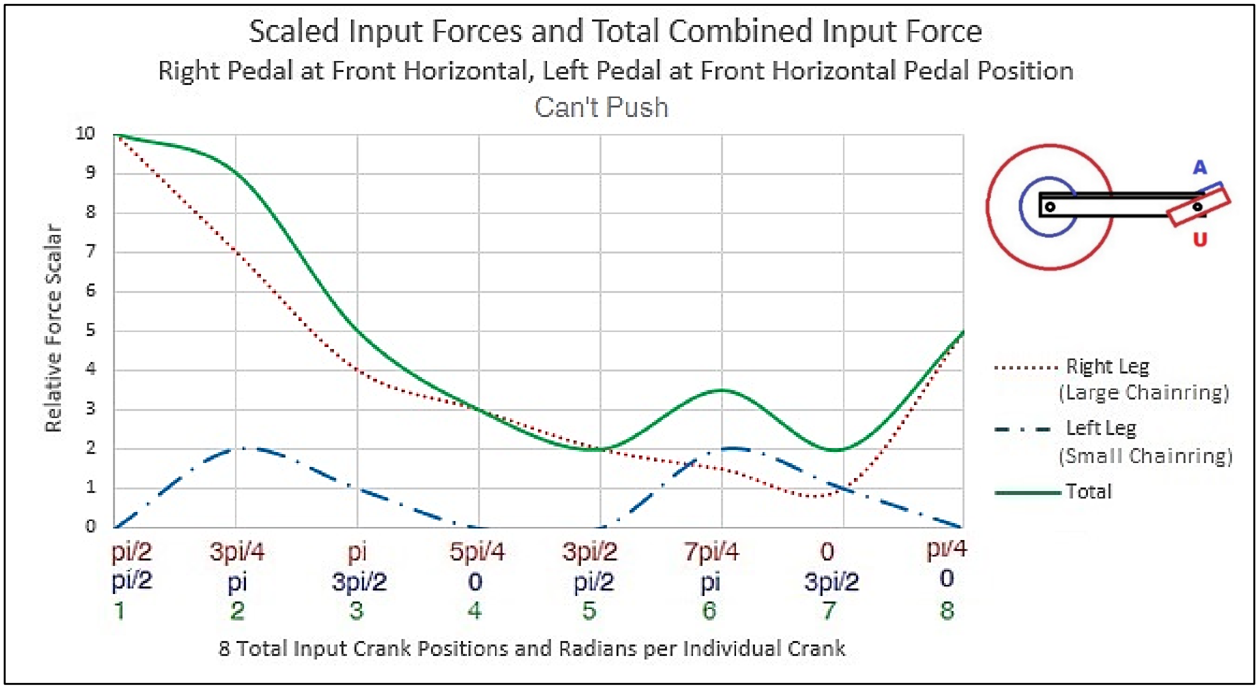


Figure 66. Force Diagram for Right Front (Red), Left Front (Blue) Starting Position

Right Leg Able, Left Leg Can't Pull

The phasing (Figure 67) resulting from the starting position of the right crank at the front horizontal position and the left crank at bottom dead center is beneficial to someone whose left leg is weak pulling. Since the location of maximum pedaling force is the front horizontal position, the right leg is applying maximum force to the pedal at the start to compensate for the left leg's weakness in pulling the pedal up from bottom dead center. This helps get the tricycle moving and starts momentum.

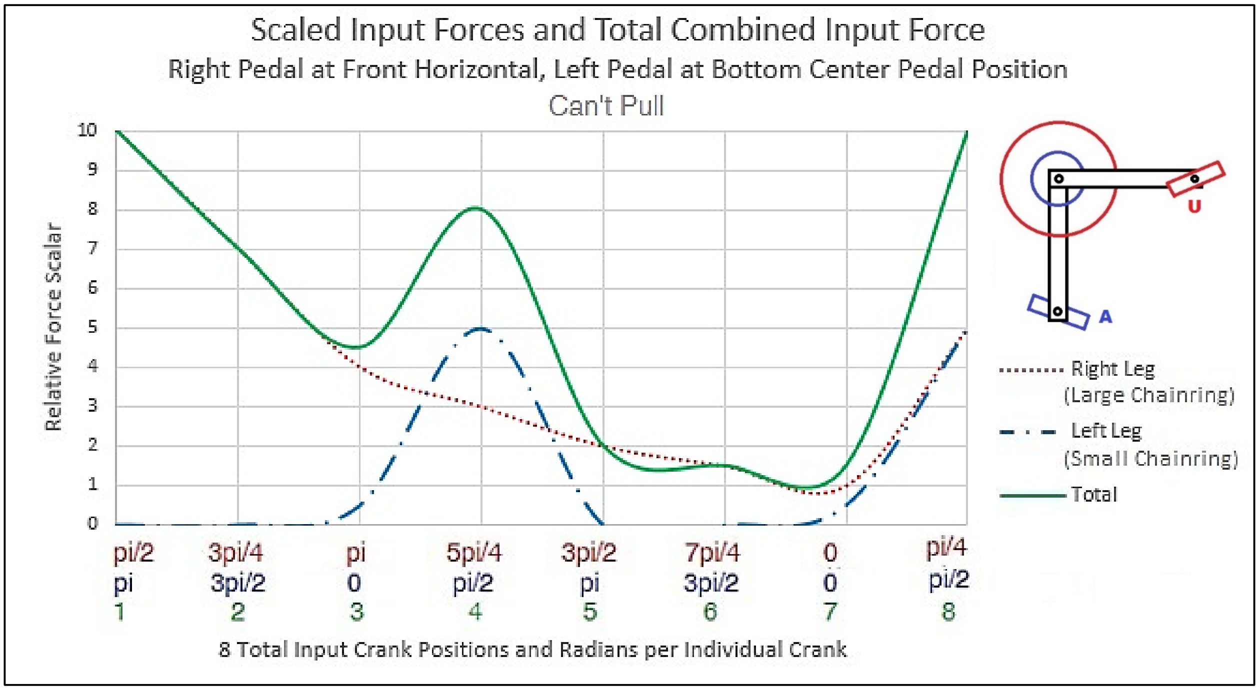


Figure 67. Force Diagram for Right Front (Red), Left Down (Blue) Starting Position

The phasing (Figure 68) resulting from the starting position of the right crank at the front horizontal position and the left crank at the back horizontal position is beneficial to someone whose left leg is weak pulling. Since the location of maximum pedaling force is the front horizontal position, the right leg is applying maximum force to the pedal at the start to compensate for the left leg’s weakness in pulling the pedal up from the back horizontal position. This helps get the tricycle moving and starts momentum.

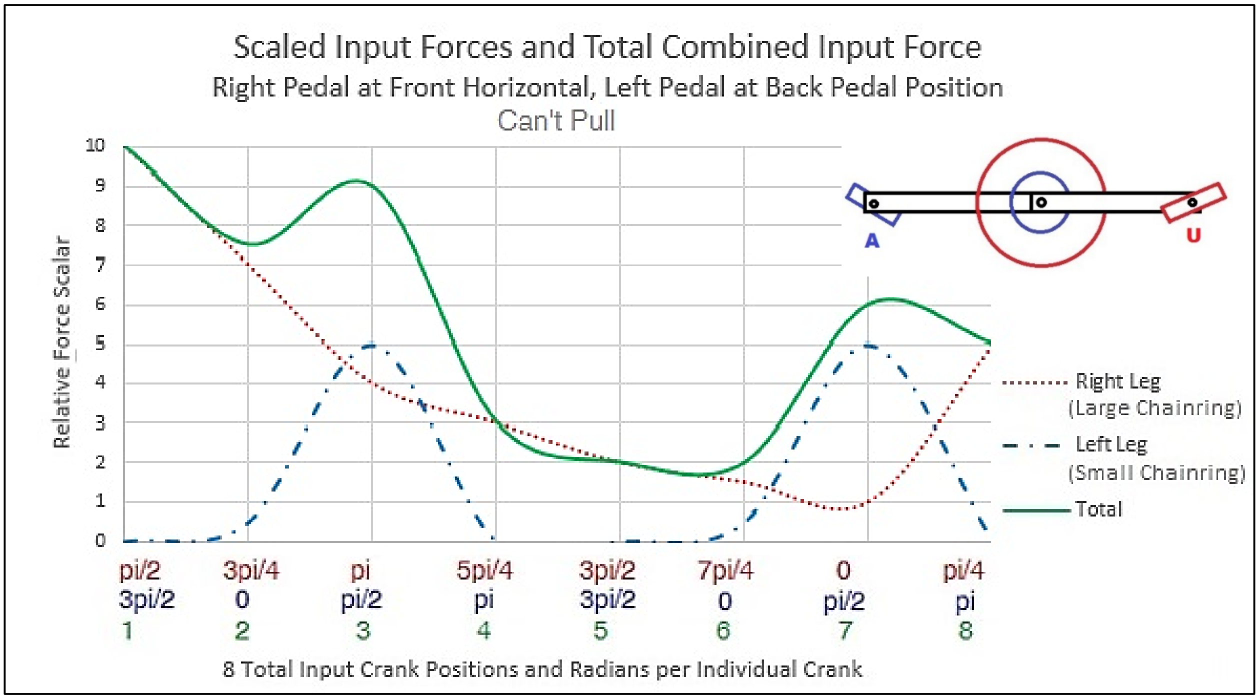


Figure 68. Force Diagram for Right Front (Red), Left Back (Blue) Starting Position

7. Manufacturing

Once the design was finalized and all parts were ordered, the manufacturing began. This started by first taking the original drivetrain apart. Reusable existing parts were salvaged and modified if needed, and other new parts were manufactured. The second step was to then assemble all of the parts. The team worked in the Rehabilitation Lab, the Washburn Labs Machine Shop, and at the local bicycle shop, Bicycle Alley, to complete the entire fabrication process.

7.1 Machined Parts

The first step in machining was to modify the rear axle housing to accommodate the new drivetrain. In order to allow for two rear sprockets to be attached to the rear axle, a part of the tubing portion of the rear axle housing, identified by the red box in Figure 69, had to be cut. To access the tubing portion of the rear axle housing, the covering that partially wrapped around the rear sprocket had to be ground off. Once this covering was removed, the team cut the tubing back so that it was flush with the angle bracket that mounts the rear axle housing to the frame. The team also cut away most of the covering, to allow for easier access to the rear axle, before welding the covering back onto the tubing. Figure 70 shows the final product of the cut and weld.

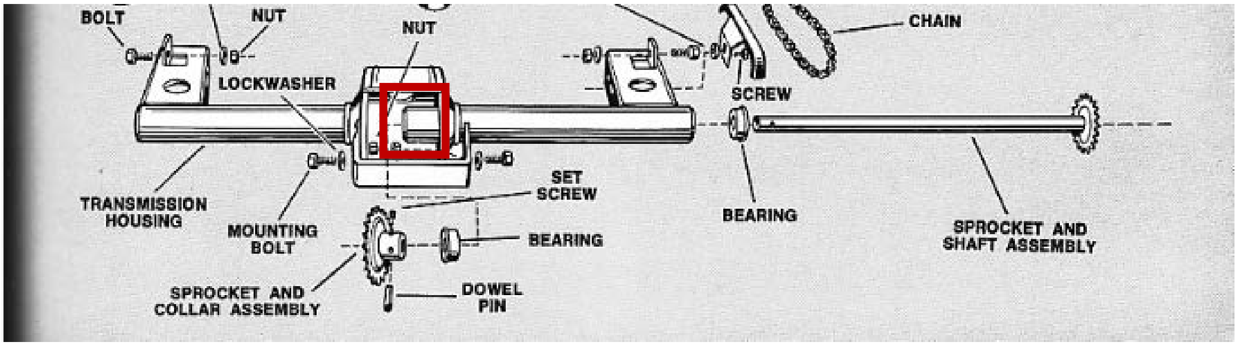


Figure 69. Rear Axle Assembly from 1973 Schwinn Town & Country Tri-Wheeler Service Manual (Schwinn Lightweight Databook, 2009)

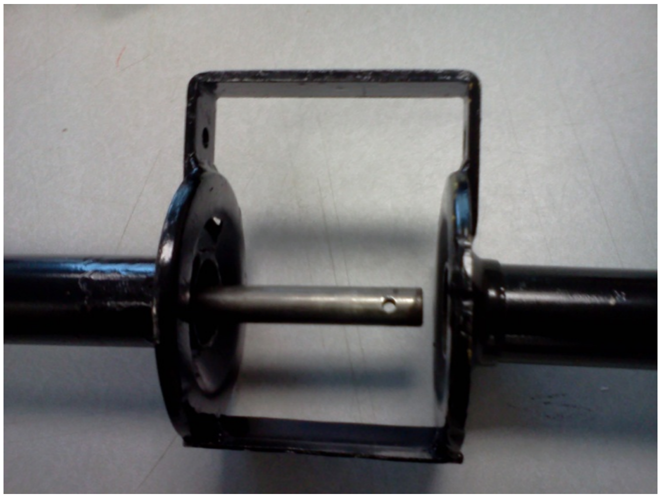


Figure 70. Modified Rear Axle Housing

Cranks

The next step in manufacturing was to machine the cranks. The team started with two regular 4-bolt spider crank arms and four flanged ball bearings. First the centers were cut out of the cranks to make room to press-fit the bearings. The bearings were then press-fit into the cranks with the flange on the inside edge of the cranks as shown in Figure 71.

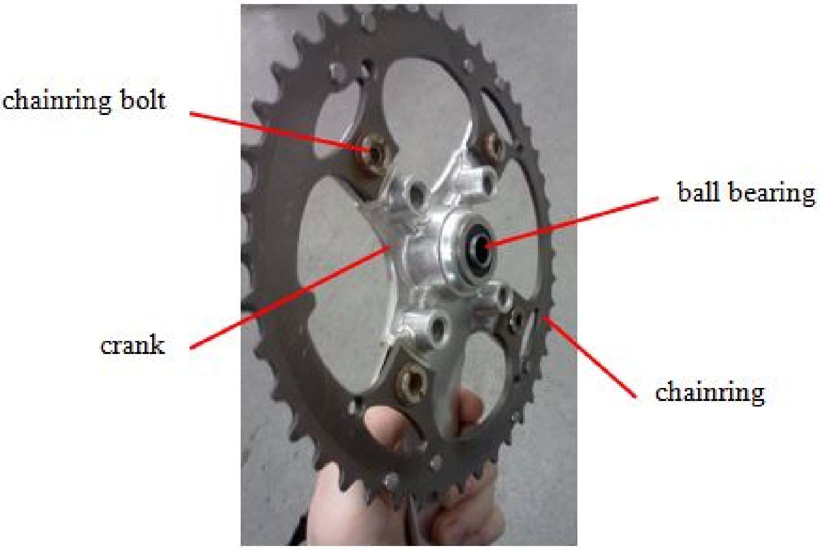


Figure 71. Ball Bearing Press Fit into Crank

One of the design decisions that was made during this manufacturing process was to purchase two right handed pedals with treads on both sides instead of re-tapping the hole in the left handed side for a left-handed pedal. The pedals were then screwed into the cranks and toe clips were then attached.

For the bottom bracket axle, the purchased rod was cut to size and then threaded. On the left side of the tricycle, the threading had to be left-handed to ensure that the bolt would not unscrew itself as the pedals rotated. This required a special left-handed tool to be purchased.

Rear Axle Assembly

Prompted by the advice of a lab assistant at the machine shop, the team decided to reduce the diameter of the bolt holes in the rear sprocket half spools. The original design called for the use of standard-sized chainring bolts, with an 8mm female threaded piece and 10mm male threaded piece, but the 10mm bolt holes in the rear sprocket half spools left very little material between the edge of the hole and the outer edge of the half spool. The lab assistant was concerned about the weakening of the half spool material from machining and the possibility of tear out of the bolt holes under load. The team chose to decrease the bolt hole diameters, and thereby increase the amount of material between the hole and the edge of the half spool, shown in Detail C of Figure 72. The team decided to reduce the bolt hole diameters to 6mm and to use shoulder screws, with an 8mm shoulder diameter and 6mm thread, in place of standard chainring bolts.

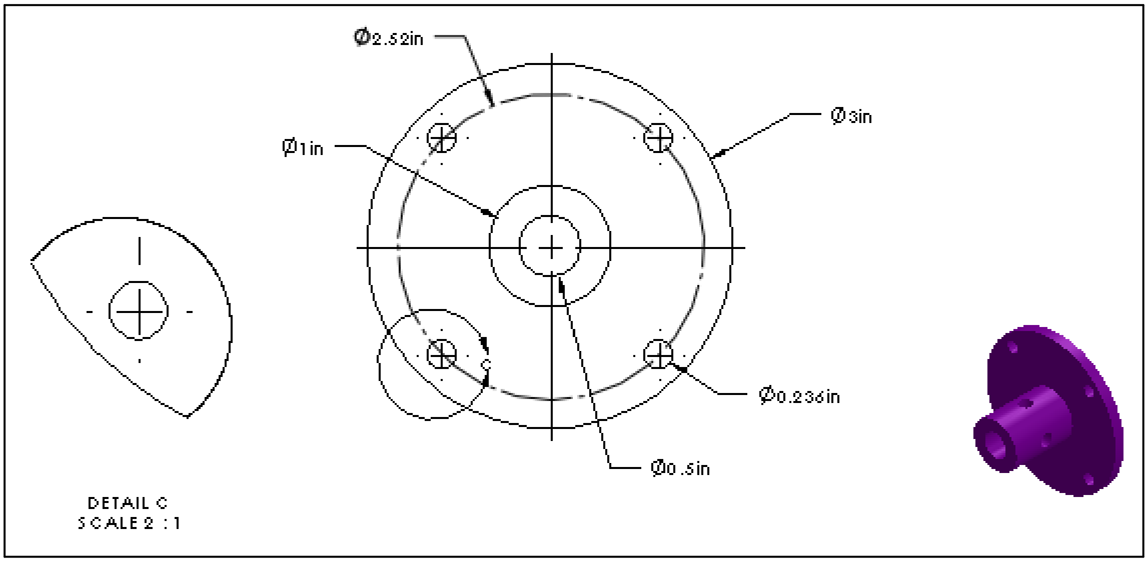


Figure 72. Drawing of Front View of Half Spool and Detail View of Revised Bolt Hole Diameter

Next, the rear axle components had to be modified. The back spool that was the pre-existing half spool did not have the correct number of teeth needed to complete the desired 2 to 1 ratio within the drivetrain. A new half spool (Figure 73) had to be created to replace the existing half spool in addition to creating another half spool to account for the addition of a second chain. These were machined on a HAAS lathe to remove material from the 3 inch rod to create the smaller diameter section, and a 5-axis HAAS milling machine to drill the holes.

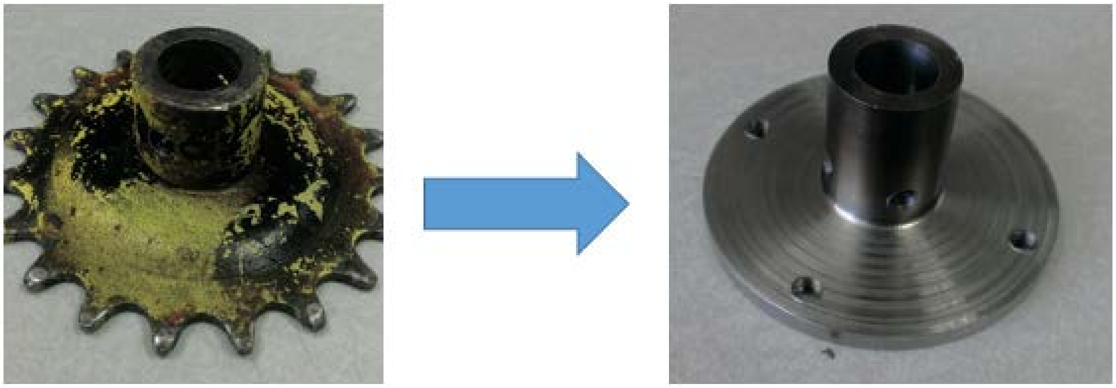


Figure 73. Original Spool and Newly Machined Spool

After both half spools were machined, the rear sprockets were attached as shown in Figure 74. The bolts used are shoulder screws where the sprocket and washers fill the depth of the shoulder and the threads grip into the threading in the machined spools as well as nuts fastened on the other side.

Figure 74. Final Rear Half Spool Assembly

After the rear sprockets were attached to the half spools, the assembly was affixed to the rear axle and the pin holes in the half spools were lined up with the corresponding holes in the axle. The set screws were then inserted to hold the half spools in place so that the spring pins could be forced through the half spool and axle to ensure a rigid connection.

Figure 75. Rear Axle Assembly

Bottom Bracket Axle Assembly

The first step was to drill holes in the bottom bracket cylinder (as seen in Figure 76) for the two ¼ inch bolts, the 10-32 set screw, and the 3/8 inch bottom bracket axle. The ¼ inch bolts hold the cylinder in the bicycle frame as well as keep the bottom bracket axle in place. These holes were drilled using a HAAS milling machine by first drilling a 3/8 inch diameter axial hole and then re-positioning the part to drill the three radial holes. For each one, the hole was first tapped, then drilled out again for a clean hole.

Figure 76. Bottom Bracket Cylinder

Next, the ends of 3/8 inch rod being used for the bottom bracket axle had to be threaded. Then, holes had to be drilled into the bicycle frame itself in order to allow for the bolts to fasten the bottom bracket cylinder in place. The bottom bracket cylinder was then slid into place along with the newly threaded bottom bracket axle, and the bolts and set screw were inserted.

Final Assembly

Once all the parts were machined, the final assembly process could begin. As mentioned above, the bottom bracket axle and cylinder were placed in the cylindrical cutout of the bicycle frame and fastened and the rear spools were assembled and affixed to the rear axle shaft. Once these were in place, the cranks could be fastened onto the bottom bracket axle. The front assembly bolts were then tightened to ensure everything is secure.

Next, the rear axle was finalized. The set screws fastening the spools to the rear axle were tightened and the pins checked for a secure tight fit. The chain was then reconnected from the Sturmey Archer to the rear axle. Next, the tricycle was taken to Bike Alley, a local bike shop, to purchase and install chains on both sides of the drivetrain. This required a special tool that ensured that the right amount of chain was used for each side.

Figure 77. Panoramic View of the Drivetrain

Before the second chain was secured, the cranks were set 180 degrees from each other (Figure 78) with the right pedal at the front horizontal position and the left pedal at the back horizontal position, to replicate the starting crank positions of a standard bicycle drivetrain. For the test trials, the team determined that the larger sprocket would be on the right side meaning the left side pedal would rotate at twice the speed; however, this could be customized to the user.

Figure 78. Front Portion of Drivetrain

Once both chains were secured and all bolts were double checked to ensure they had been tightened properly, the tricycle was fully assembled (Figure 79).

Figure 79. Entire Tricycle

7.2 Chain Alignment

Due to the locations of the chainring bolt holes on the cranks, the large front chainring is offset a greater distance from the centerline of the tricycle compared to the small front chainring. The measured offset of the chain attached to the large front chainring is 2 inches, which gives a calculated chain angle of 2.2 degrees. The measured offset of the chain attached to the small front chainring is 1-3/8 inches, which gives a calculated chain angle of 0.4 degrees. According to Van Der Plas, R., and Baird, S. (2010), a modern bicycle chain running at a slight offset is equally efficient as it is if it were to be running in a straight line (Figure 80). It has been found that a chain can have a maximum angular deviation of about 2.4 degrees while still being able to transmit 100% of the force applied to it (Van Der Plas, R., and Baird, S, 2010). Applying this information to the tricycle drivetrain, the calculated chain angles of 2.2 degrees and 0.4 degrees will not affect the efficiency of the drivetrain.

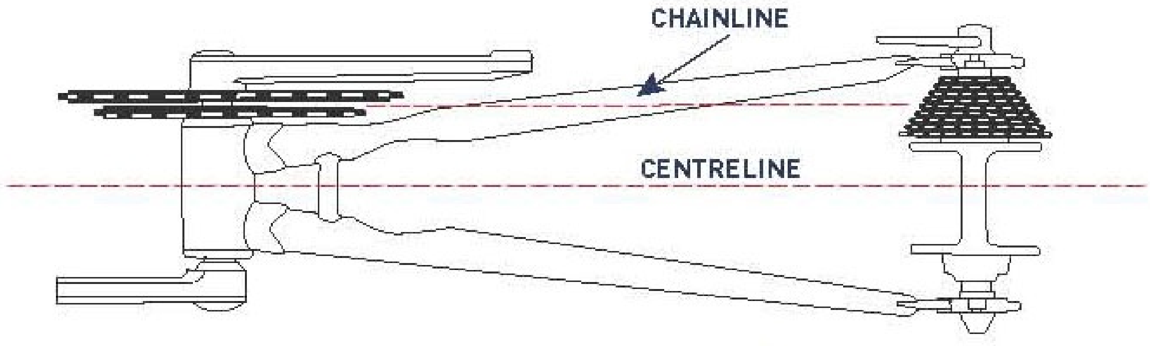


Figure 80. Bicycle Chain Alignment (How’s your chainline?, 2013).

8. Testing

Upon completing the assembly of the tricycle, the team applied four test procedures to evaluate the drivetrain and the tricycle as a whole. They were designed to verify whether or not the design specifications had been met, specifically the three categories: safety and functionality, recreation, and rehabilitation. The complete testing procedures can be found in Appendix I.

8.1 Procedure 1 – Safety and Functionality

The first evaluation procedure, determined the safety of the tricycle (Appendix I). The team evaluated the design specifications with the following results:

The tricycle must pass the Consumer Product Safety Standards (Appendix J). One of the most important of these standards is that the tricycle may not have any sharp edge that could injure the user. It also requires that all fasteners must also be secured to ensure nothing loosens breaks, or fails during testing. All bolts and other assorted fasteners were checked to verify they were tightened and in working order. Next, the standards require that pedals have treads on both sides unless they have toe clips. The pedals used for this tricycle have treads on both sides and the team added baskets to secure the user’s feet to the pedals. These requirements also state that the pedals must have 3.5 inches of clearance from the front tire before the toe clips are added. This tricycle has basket pedals instead of toe clips, but there is still 2 inches of clearance after the baskets are added. The standards also require specific tensile requirements and that the chain does not catch on any other part of the tricycle while in motion. The device requires two chains, both rotate without catching. Also, one of the chains was purchased from a local bike store and, therefore, must pass the bicycle standards tensile requirements. The second chain was the existing chain that came with the tricycle. A newer chain with a known tensile strength would be preferred for future design testing.

The team also had additional requirements that were not covered by the Consumer Safety Standards. The first additional requirement was that the device not increase the weight of the tricycle by more than 20%, and preferably not by more than 10%. It would be beneficial to minimize the added weight, since the user has to move it all with each pedal stroke. After incorporating the design changes into the prototype, the tricycle, which originally weighed 64 pounds, weighed 61 pounds. This means the design actually decreased the weight of the tricycle by 3 pounds. This weight difference is reasonable because the old steel crank assembly was denser than the aluminum assembly that replaced it, and the original rear axle assembly half spool is heavier than the one it was replaced with. The team also required that the device can not intrude into the user's space. The design does not intrude into the space between the seat and the handle bars and therefore passes this requirement.

Next, the device had to be able to be manufactured by the team using available tools and resources. Unfortunately, the Machine Shop did not have the left-handed die needed to thread one end of the bottom bracket axle, but it was purchased at minimal cost; they did have the correct-sized right-handed die to thread the other end of the axle. Design Specification Fourteen stated that the device must be constrained to the dimensions of the tricycle to prevent compromising the structural integrity of the tricycle frame and the device passed this after minimal changes. The only changes made were removing the original tricycle pedals and cranks, and replacing them with our design, and shortening the tubing portion of the rear axle housing and cutting back the rear sprocket covering. These changes, however, did not affect the structural integrity of the tricycle frame. The device also had to be able to be maintained at a local bike shop. Since most parts used in the design are obtainable at any ordinary bike shop, this design specification passes. Finally, the design had to be built within the given budget of $480. After inspecting the budget and the purchased items, the device was built under the budgeting constraints given a final total of $311.42.

8.2 Procedure 2 – Recreation

In Procedure two the team tested the ability of the device to be used in a recreational atmosphere. This started with a pre-test and was followed by testing with able-bodied users.

8.2.1 Pre-Testing

Before the testing procedures could be done, the team had to ensure that the tricycle was not only safe for use but also that the users did not have any physical limitations that could make riding the tricycle unsafe for them. The five test participants took a pre-test to ensure that they qualified for testing. A passing score consisted of all 2s. If someone did not pass the pre-test, the team did not allow him or her to participate in testing and they were asked kindly to leave. The pre-testing evaluation can be found in Appendix K.

In order to ride this tricycle, several requirements were made to ensure the user would be safe while riding. One of these (Design Specification 15) specifies that the user must have the appropriate range of motion at the knee, hip, and ankle to ensure that they don’t hurt themselves trying to ride the tricycle. Since the tricycle obtained for the prototype was a specific frame size, it was important that all test participants were in the category covered by Design Specification 16 and 17. This guarantees that the user is the correct height for the frame of the tricycle, and that the tricycle will properly support their weight. For testing, since no members of the team were certified in physical therapy, only able-bodied individuals were allowed to participate. In real use of the tricycle however, the user must have a physical therapist determine if they are at the appropriate ability level to use the tricycle with a beneficial output (Design Specification 18).

8.2.2 Testing

After the tricycle was deemed safe to ride, each of the team members rode it around the Quad on campus. Each member was successfully able to make a lap without much difficulty. After the team completed procedure one and had tested on their own, participants were then asked to ride it to test Design Specifications Five, Six, and Seven in accordance to procedure 2 (Appendix I). The first participant attempted to start riding, however, she only made it approximately twenty feet before applying force at the wrong points of the pedal cycle and causing the chain to derail. After the team realigned the chain and pedals, she attempted to continue her lap, but derailed the chain again after another ten feet. Her responses to the survey afterwards were very vague and showed that she was not able to adapt to the pedaling pattern of the tricycle. She explained that she kept trying to force the pedals to move at the normal pedaling motion and that was when the chain derailed. Participant number two then tried to ride the tricycle and experienced similar results. She was only able to move a few feet before derailing the chain and then was hesitant to try again after, afraid she would break the tricycle if she continued. These two participants showed us that the participants need to be guided in understanding the motion before they attempt to ride the tricycle.

The next three participants were much more successful. Participant number three received a more detailed explanation of how the re-designed drivetrain worked and was told more clearly what to expect from the tricycle pedaling cycle. After being well-prepared and told specifically to make sure to exert force on both pedals while riding this participant was able to pick up on the pattern quickly and was even able to speed up. He derailed the chain once while trying to maneuver the tricycle at a slower pace, but explained that he was trying to lean into the pedals maneuvering in a corner which put too much force on the slower pedal forcing its chain to derail. This showed the team that we also need to determine the test participants' bicycling history. This participant had participated in triathlons and is a very active cyclist and, therefore, was trying to lean into the pedals more on the corner which was forcing the tricycle to move more than the chain would allow.

The last two participants were less experienced bicyclists. They both were able to make their laps without derailing the chain and were able to adapt to the rhythm after receiving the same detailed explanation on what to expect. Both suggested that it was strange and awkward having the pedals both pulling up to top dead center at the same time, but were able to successfully do so after a few attempts.

Overall, this was a successful trial period. All participants made it clear that the learning curve was difficult and a sense of rhythm really helps adapt to the new pattern, but that it is very much possible to do so after a few minutes. The three participants who did not give up the first time they hit the pedal stroke where both feet pulled up at the same point eventually adjusted to the pedaling pattern and said they really enjoyed the ride. The results of the preliminary testing can be found in Appendix F.

8.3 Procedure 3 – Rehabilitation

The next stage of testing involved gaining professional insight on the device. The tricycle was brought to Worcester Physical Therapy. The team's main contact at the center was Jimmy Kakouris who is a PT, DPT, and CSCS. These abbreviations mean that he has received his Master's Degree in Physical Therapy, a Doctorate in Physical Therapy, and is also a Certified Strength and Conditioning Specialist. The CSCS certification is a written exam that not only tests the physical therapist's knowledge of the treatment of sports injuries, but also assists in proving his or her understanding of muscle strengthening after an injury. In addition to discussions with Jimmy Kakouris, we also discussed the tricycle design with Matthew Harrison, DPT. After demonstrating the tricycle's pedaling motion and explaining how the system works, both therapists rode it around the center. A few other staff members also rode the tricycle around as well and very few had difficulties adjusting to the pattern.

After they had a solid understanding of how the tricycle worked, the team asked the professionals for their opinions. When asked if he thought the device could be used recreationally by someone recovering from a stroke (Design Specifications Five, Six, and Seven), Jimmy replied that it would be fine; however being located in Worcester where there are a lot of hills and pot holes, he thought a power assist of some nature would greatly assist in the recreational quality of a design like this and suggested a local motorcycle shop that retrofits bicycles with motors. This assist would specifically be helpful for hills and in assisting the upstroke since the user's tonal deficiencies vary. He did believe it was still important to have an option for the tricycle to be powered by only human input (Design Specification 1), since the best rehabilitative effect occurs when the user is powering the motion of the device, but until the patient is strong enough to handle the hills in the local area, an assist of some nature would be helpful. Overall, the redesigned tricycle would be a great way to do rehabilitation while still being recreational.

During this discussion, Design Specifications Two and Three were mentioned and he instantly agreed that adjustability was important for a rehabilitative device. He approved of the chainrings being interchangeable as the patient progresses, since that fully utilizes error-augmented training and would be useful once the patient's affected side improves. They could then switch the gears out and start strength training. This device also allows the patient to pedal one legged (Design Specification Four), which would assist in strength training, but would not be beneficial in the earlier stages of rehabilitation. Jimmy would have liked to see a derailleur as well as the motorized assist in order to provide more adjustability for the beginning stages of rehabilitation.

This adjustability is vital for any rehabilitation device for many reasons, but primarily for the safety of the patient. In order to avoid injury to the patient, the physical therapist must ensure that the patient is not over straining themselves during their rehabilitation exercises, but they must also make sure that the patient is doing enough to make progress and recover. This discussion lead us to understand that the team could not make the decision on what sprocket ratios and pedal alignments are best for any patient’s condition. The phasing of the pedals must be fine-tuned to the patient’s individual needs. The team was able to provide an analysis of how much torque is required from each individual phasing alignment, but the information determined by the team can only be used as guidelines for the physical therapist to determine what is best for the patient.

Jimmy would like to see that this project is continued in the future and would welcome the chance to continue to be a resource for the project. The team will use the physical therapist’s advice in order to make future recommendations for the project.

8.4. Discussion

Overall, the team learned a lot through testing the device. Testing indicated that the device worked, and users would be able to adjust to the pedaling motion of the modified tricycle, when given proper explanation of the phasing motion. The next series of testing showed that physical therapists would use the device in their practice, but it also brought to light how different physical abilities would require different phasing of pedaling.

9. Conclusion

The objective for the project was to design a passive assistive modification to an existing drivetrain. This would be ridden by people who have had a stroke. A majority of people who have had a stroke suffer from hemiparesis, a weakness in one side of the body. This condition specifically makes it difficult for patients recovering from a stroke to ride a standard bicycle or tricycle. The team came up with eight preliminary design concepts that would assist with this condition. These designs were all analyzed to determine the best three concepts to refine further to select an optimal final design.

The passive assistive pedaling device that the team developed was a drivetrain that is more suitable for post-stroke rehabilitation than traditional cycling drivetrains. The drivetrain developed by the team accounts for the weakness of the user’s affected leg by creating a 2:1 gear ratio from pedal to pedal. This way, the user can have their affected leg pedal the crank attached to the small chainring for twice as many repetitions at half the force, or they could pedal with their affected leg on the larger chainring for more strength training.

The redesigned drivetrain is mounted on a standard adult tricycle instead of a stationary bicycle to allow for both rehabilitation and recreation. Since the modified tricycle can be ridden outside, the patient is not restricted to indoor rehabilitation centers and, therefore, can regain a sense of normalcy in their post-stroke lives.

Testing the drivetrain indicated that some users can adapt to the irregular pedaling pattern over time and find enjoyment in learning the new pedaling technique. When the tricycle was presented to physical therapists, the team was able to gain professional opinions on the drivetrain design. The positive commentary received from the physical therapists validated the design’s functionality and verified that a physical therapist could actually use this device with their patients. Based on the testing results and the feedback from the physical therapists, a phasing analysis of the drivetrain was done to provide a model of the variation in torque on the cranks throughout a full pedaling cycle. This torque analysis was used to define the optimal starting position of the pedals for different physical conditions being treated in post-stroke physical therapy.

Overall, the drivetrain has the potential to cater to the needs of people who have hemiparesis and are undergoing post-stroke rehabilitation.

10. Recommendations

The drivetrain designed meets the design specifications, however, there are a few additional aspects of the design that the team would have liked to pursue further or would like to do differently if given the chance to repeat this project.

An additional test that the team would have liked to have done was to experimentally test the force applied throughout the pedal stroke. This test would verify the calculated force distribution as well as to support the determination that phasing alignment is useful to vary the pedaling force for different conditions.

In addition to these supplementary tests, if repeating this project, the team would recommend making a few changes. First, it would be beneficial to use a newer model tricycle. While assembling the prototype, the team discovered that the tricycle obtained for the initial prototype had some outdated parts and sub-systems, which would therefore restrict the design so certain aspects of the design would not be compatible with a newer model. This restriction would make it difficult to manufacture these devices for sale on the market. One of these restrictions was the sizes of sprockets available. The older model sprockets and chains had a different pitch than the newer models, therefore, the gear ratios could be different. Also, the cranks and right and left pedals should be the same in future models. For the prototype, the cranks used were the same, however, the pedals used were both right-hand threaded pedals. The team was able to find two right-hand threaded pedals with threads on both sides of the pedal; they were not a matching set however that did not affect the prototype testing. A solution to this problem would be to use tandem bicycle cranks instead so that both cranks are the same left and right, but still have the spider bracket to attach a chainring.

Finally, the team would recommend a few additional aspects that should be incorporated into the system in the future. Although the original design intent specified that the tricycle be powered only by human input, through discussions with the physical therapist, it was determined that a power assist could be useful to help the user in earlier stages of their rehabilitation. The local terrain would also have to be considered for this assist. An example would be the hills in Worcester. Since the intent of the tricycle is also recreational, this assisting mechanism would help the user maneuver around outside without getting discouraged if they cannot get up a hill at first. Another future step that the team recommends after discussions with the physical therapists would be to incorporate a system of derailleurs so that each crank can be attached to either a large or small chainring. This would allow for the user to swap from mobility and repetitions, to a standard tricycle setup, or to a strength training setup as they progress through their rehabilitative process. The ability to shift gears would be beneficial for the user as he or she progress through rehabilitation. The shifting would have to be done with the positioning of the pedals in mind. For example, if shifting from a 2:1 ratio to a 1:1 ratio, the cranks must be at opposite horizontal positions when the user shifts in order to switch to the phasing of a traditional drivetrain. If shifting from a 1:1 ratio to a 2:1 ratio, the user would have to shift when the cranks are at the starting positions required for the desired phasing, based on the user’s condition and/or stage of rehabilitation.

With these recommendations, the team hopes to see the project continue in the future. The tricycle drivetrain design has room for improvement, and with the assistance of the physical therapists at Worcester Physical Therapy, the drivetrain could be made adjustable to better suit the rehabilitative needs of stroke patients.

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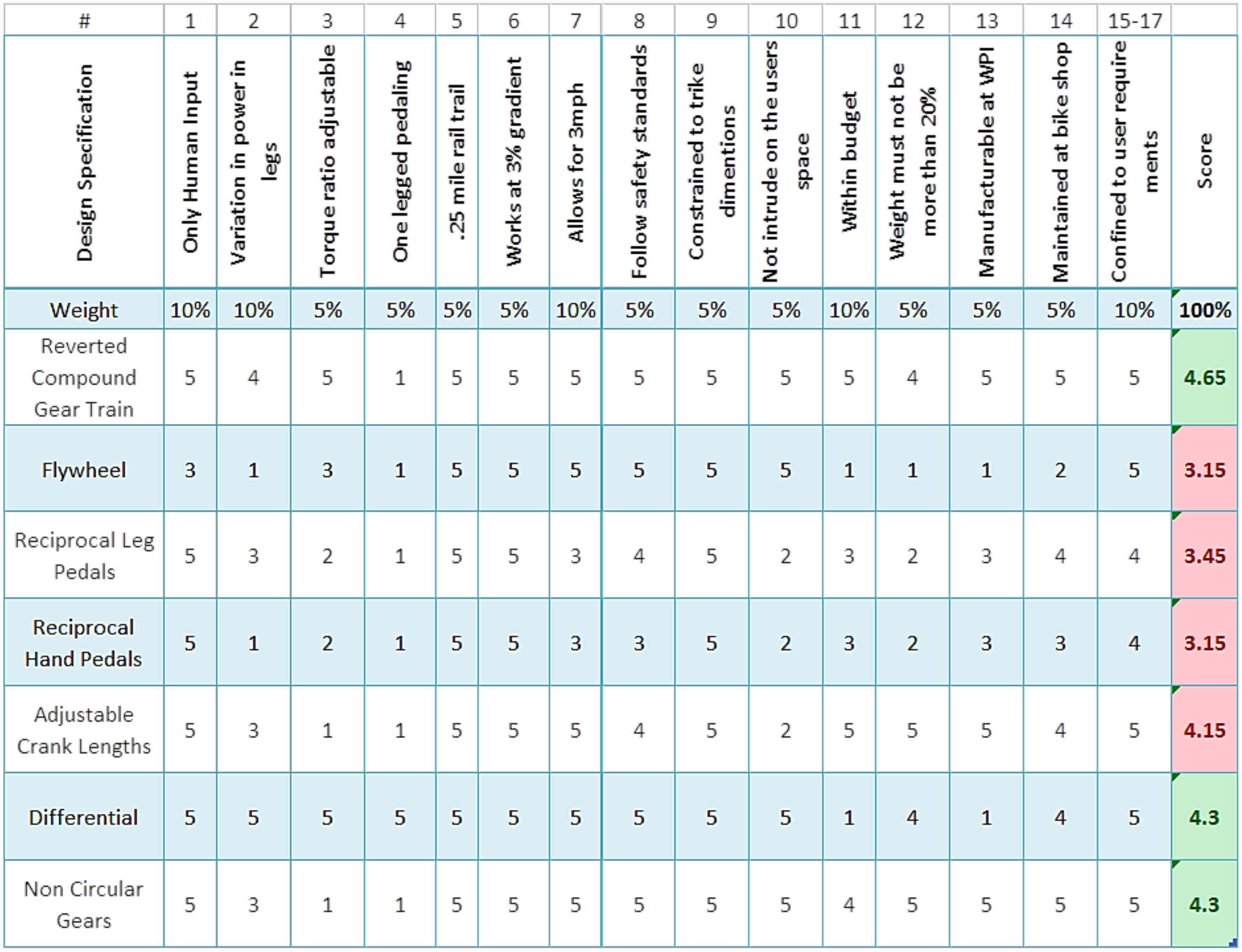
Appendices

Appendix A – Design Selection

A.1 Top 8 Design Concepts Decision Matrix



#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15-17	
Design Specification	**Only Human Input**	**Variation in power in legs**	**Torque ratio adjustable**	**One legged pedaling**	**.25 mile rail trail**	**Works at 3% gradient**	**Allows for 3mph**	**Follow safety standards**	**Constrained to trike dimentions**	**Not intrude on the users space**	**Within budget**	**Weight must not be more than 20%**	**Manufacturable at WPI**	**Maintained at bike shop**	**Confined to user requirements**	**Score**
Weight	**10%**	**10%**	**5%**	**5%**	**5%**	**5%**	**10%**	**5%**	**5%**	**5%**	**10%**	**5%**	**5%**	**5%**	**10%**	**100%**
Reverted Compound Gear Train	5	4	5	1	5	5	5	5	5	5	5	4	5	5	5	**4.65**
Flywheel	**3**	**1**	**3**	**1**	**5**	**5**	**5**	**5**	**5**	**5**	**1**	**1**	**1**	**2**	**5**	**3.15**
Reciprocal Leg Pedals	5	3	2	1	5	5	3	4	5	2	3	2	3	4	4	**3.45**
Reciprocal Hand Pedals	**5**	**1**	**2**	**1**	**5**	**5**	**3**	**3**	**5**	**2**	**3**	**2**	**3**	**3**	**4**	**3.15**
Adjustable Crank Lengths	5	3	1	1	5	5	5	4	5	2	5	5	5	4	5	**4.15**
Differential	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**1**	**4**	**1**	**4**	**5**	**4.3**
Non Circular Gears	5	3	1	1	5	5	5	5	5	5	4	5	5	5	5	**4.3**

A.2 Benefits and Shortcomings of Designs

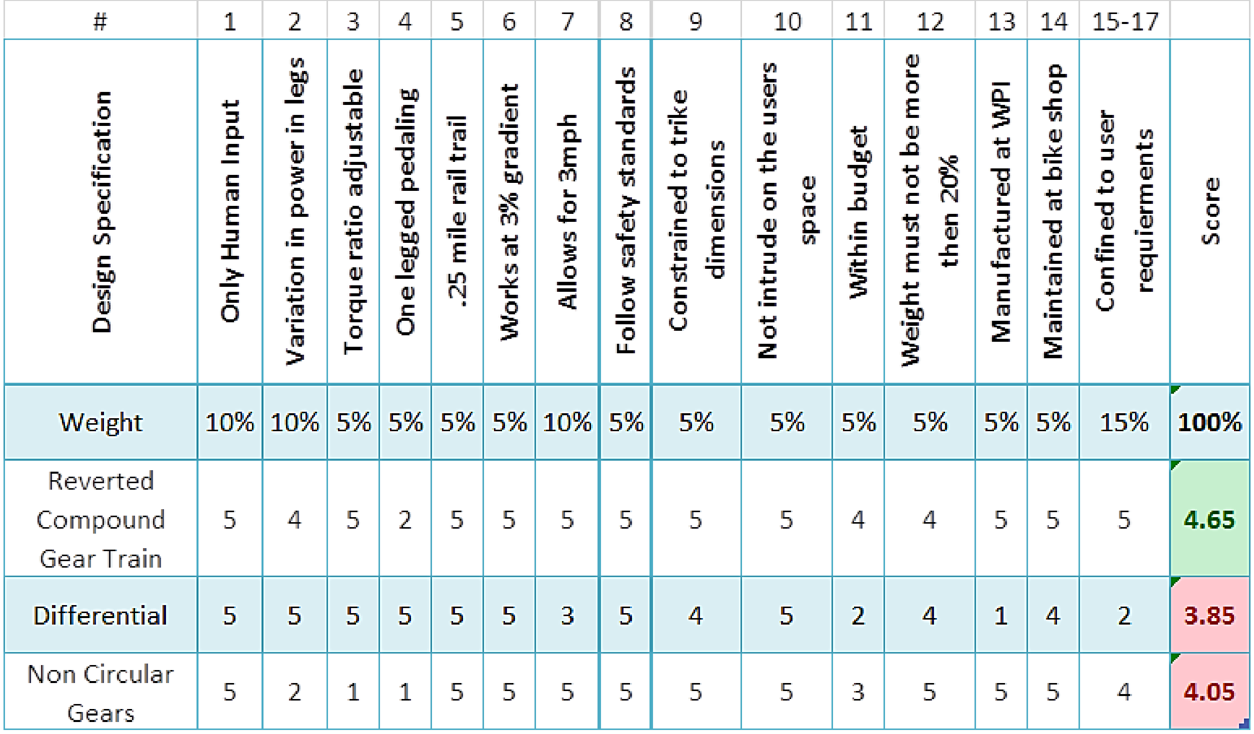
Benefits of Designs

RCGT	RCGT/Diff	Diff	Diff/Oval	Oval	Oval/RCGT	All Three
2X rotations at half the force	both have milestones (if RCGT shifts to 1:1)	Rotational freedom		continuously variable gear ratio	forces weaker leg to move	won’t be heavy
design accounts for rehabilitation of 50% loss of strength		user can choose the rate at which they pedal				differentiates the input force for each leg
gears can be exchanged for different ratios (for varying strength)		pedal with one leg				only human input
easy to build with typical bike parts (local store)		allows for natural movement of legs				

Shortcomings of Designs

RCGT	RCGT/Diff	Diff	Diff/Oval	Oval	Oval/RCGT
forces the ratio of 1:2 for leg movement - awkward	Must separate pedals	does not force both legs to move	must be custom ordered/purchased	very large torque	cant pedal one legged
if additional gears are added shifting would be weird		add springs to keep cranks in their horizontal resting position		large input forces needed	
		Very small, will shafts be strong enough to translate force? How much torque?		pedals must move at a non-constant angular velocity	
				jerky ride	
				not very user friendly	

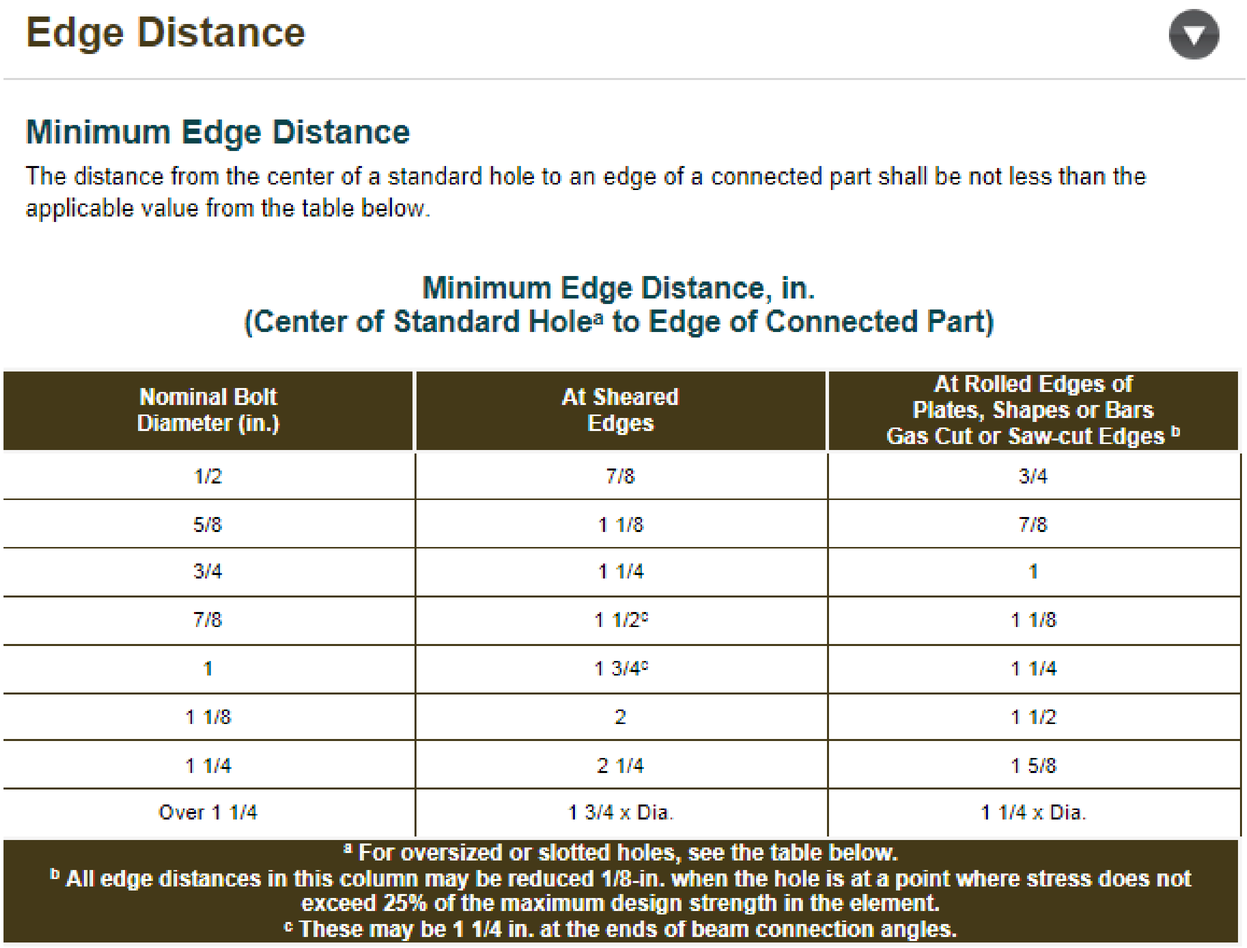
A.3 Revised Decision Matrix for Best Three Design Concepts



#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15-17	
Design Specification	**Only Human Input**	**Variation in power in legs**	**Torque ratio adjustable**	**One legged pedaling**	**.25 mile rail trail**	**Works at 3% gradient**	**Allows for 3mph**	**Follow safety standards**	**Constrained to trike dimensions**	**Not intrude on the users space**	**Within budget**	**Weight must not be more then 20%**	**Manufactured at WPI**	**Maintained at bike shop**	**Confined to user requierments**	**Score**
Weight	10%	10%	5%	5%	5%	5%	10%	5%	5%	5%	5%	5%	5%	5%	15%	**100%**
Reverted Compound Gear Train	5	4	5	2	5	5	5	5	5	5	4	4	5	5	5	**4.65**
Differential	5	5	5	5	5	5	3	5	4	5	2	4	1	4	2	**3.85**
Non Circular Gears	5	2	1	1	5	5	5	5	5	5	3	5	5	5	4	**4.05**

Appendix B

Minimum Edge Distance (Structural Steel Detailer, 2008)



Edge Distance

Minimum Edge Distance

The distance from the center of a standard hole to an edge of a connected part shall be not less than the applicable value from the table below.

Minimum Edge Distance, in.
(Center of Standard Hole[a] to Edge of Connected Part)

Nominal Bolt Diameter (in.)	At Sheared Edges	At Rolled Edges of Plates, Shapes or Bars Gas Cut or Saw-cut Edges [b]
1/2	7/8	3/4
5/8	1 1/8	7/8
3/4	1 1/4	1
7/8	1 1/2[c]	1 1/8
1	1 3/4[c]	1 1/4
1 1/8	2	1 1/2
1 1/4	2 1/4	1 5/8
Over 1 1/4	1 3/4 x Dia.	1 1/4 x Dia.

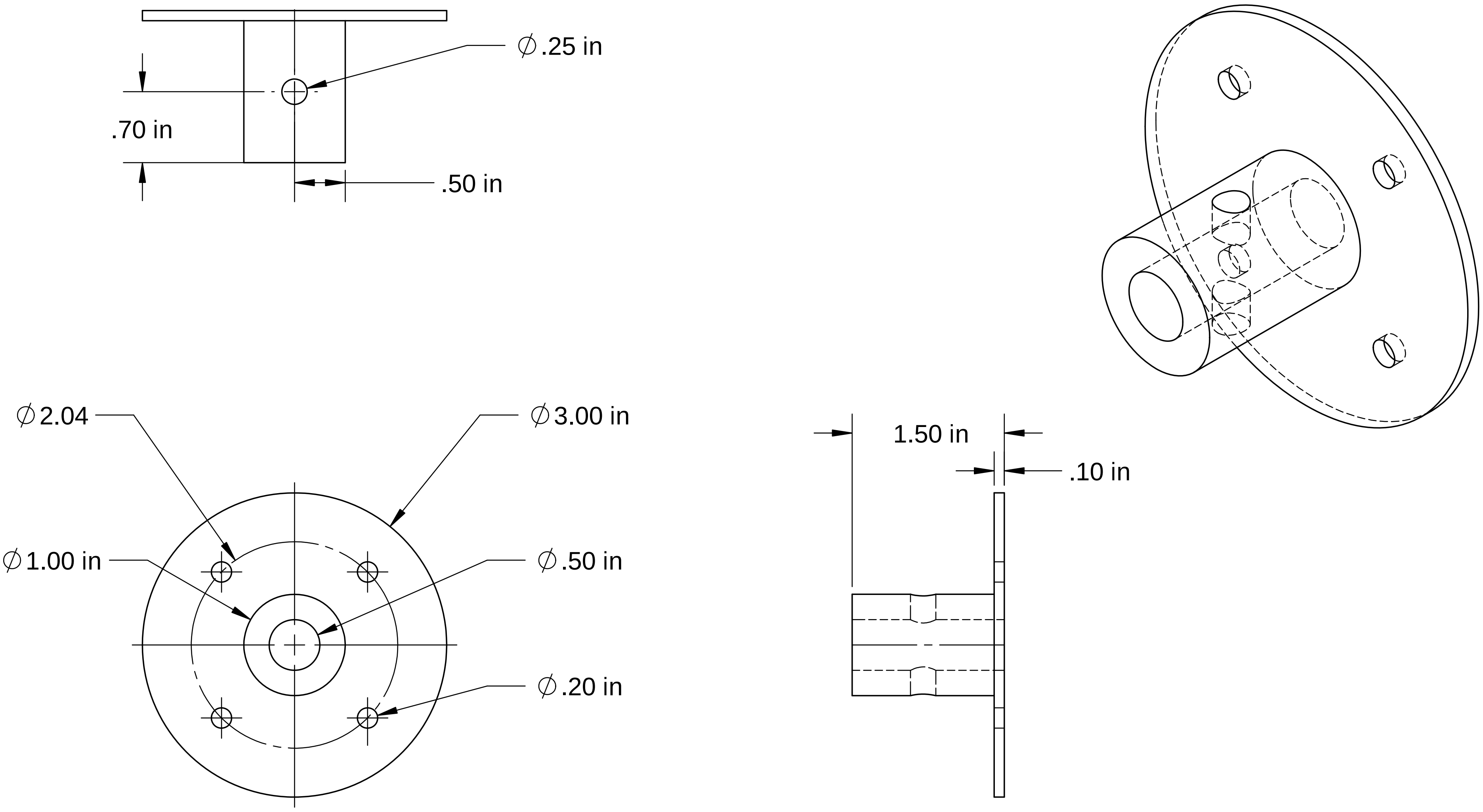
[a] For oversized or slotted holes, see the table below.

[b] All edge distances in this column may be reduced 1/8-in. when the hole is at a point where stress does not exceed 25% of the maximum design strength in the element.

[c] These may be 1 1/4 in. at the ends of beam connection angles.

Appendix C – Bill of Materials

CAD Item #	Part	Machining	Status	Vender	Cost Per Unit	Quantity	Total Cost
1	Tricycle (Partial Frame in CAD)	N/A	Purchased	Craigslist Seller	$75.00	1	$ 75.00
2	Rear Axle (Existing part from original tricycle)	To be drilled with holes for spool attachments	N/A	N/A	N/A	1	N/A
3	Large Front Chainring (110mm BCD, 44 tooth, 4 bolt)	To be bolted to right crank	Purchased	Bike Alley	$2.50	1	$ 2.50
4	Small Chainring (74mm BCD, 22 tooth, 4 bolt) (one to be bolted to the left crank and two to be bolted to the rear sprocket half spools)	N/A	Purchased	Bike Alley	$2.50	3	$ 7.50
5	Fixed Front Axle (Steel Rod 7/16" diameter and 6" length)	To be machined into fixed front axle Need to thread each end to attach nuts to hold cranks in place	Obtained from Washburn Shops, Machining Needed	mcmaster.com	1.82	1	$ 1.82
6 and 7	Bolts and nuts for Chainrings (For attaching chainrings to cranks and rear sprocket half spools)	N/A	To Be Purchased	Bike Alley	TBD	8	$ 42.42
8	Rear Sprocket Half Spools Multipurpose 4140/4142 Alloy Steel Rod (3" diameter and 4" length)	To be machined into two rear sprocket half spools	Purchased, Machining Needed	mcmaster.com	$14.01	1	$ 14.01
9	Front Cylinder Bolts (1/4" diameter and 0.5" length) (To attach front cylinder to the tricycle frame)	N/A	To Be Purchased	Howlett Lumber	0.45	2	$ 0.90
10	Fixed Front Cylinder Multipurpose 4140/4142 Alloy Steel Rod (2" diameter and 6" length)	To be machined into fixed front cylinder Need to drill holes in it for fixed front axle, front cylinder bolts, and set screw	Purchased, Machining Needed	mcmaster.com	$24.93	1	$ 24.93
11	Rear Frame Bolt		N/A	N/A	N/A	1	N/A
12	Slotted Spring Pin (1/4" diameter and 1.5" length) (To attach rear sprocket half spools to rear axle)	N/A	To Be Purchased	Hardware Barn	0.98	2	$ 1.96
13	Steel Ball Bearing (Flanged, Double Sealed for 5/8" Shaft Diameter, 1-3/8" OD, 13/32" Wide) (To replace existing bearings from original tricycle that are worn out)	To be press fit into rear axle housing	Purchased	mcmaster.com	$11.57	2	$ 24.14
14	Spider Crank Asssembly						
14a	Specialized Spider Crank (Both 110mm and 74mm BCD on each crank)	Axle holes are to be counter-bored for 7/8" Bearing Left crank threading needs to be reversed	Purchased, Machining Needed	Bike Alley	$10.00	2	$ 20.00
14b	Steel Ball Bearing (Flanged, Double Sealed for 3/8" Shaft Diameter, 7/8" OD, 13/32" Wide)	To be press fit into cranks	Purchased	mcmaster.com	$7.07	4	$ 28.28
14c	Pedals	None	Purchased	Bike Alley	$5.00	2	$ 10.60
15	Hex Nut (3/8" diameter) (To hold cranks on fixed front axle)	N/A	To Be Purchased	Hardware Barn	0.37	2	$ 0.74
16	Set Screw (1/4" diameter and 1/2" length) (To attach the half spools to the rear axle)	N/A	To Be Purchased	Hardware Barn	0.9	2	$ 1.80
17	Set Screw (10-32 thread count (3/16 diameter) and 2" length) (To attach the fixed front axle to the front cylinder)	N/A	To Be Purchased	Hardware Barn	0.9	1	$ 0.90
18	Chain (approximately 120 links needed - from both 24tooth to 48tooth and 24tooth to 24tooth)	Break into 2 lengths of chain	To Be Purchased at Bike Alley	Bike Alley	+labor	1	$ 23.75
	Shipping from McMaster-Carr						$ 16.84
	Tool for left-hand threading			mcmaster.com			$ 14.23
							$ 312.32



UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL± ANGULAR: MACH± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN		
	CHECKED		
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL 4140 Steel	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

PROPRIETARY AND CONFIDENTIAL

WPI

Passive Assistive Pedaling Device MQP

TITLE:

Rear Sprocket Spool

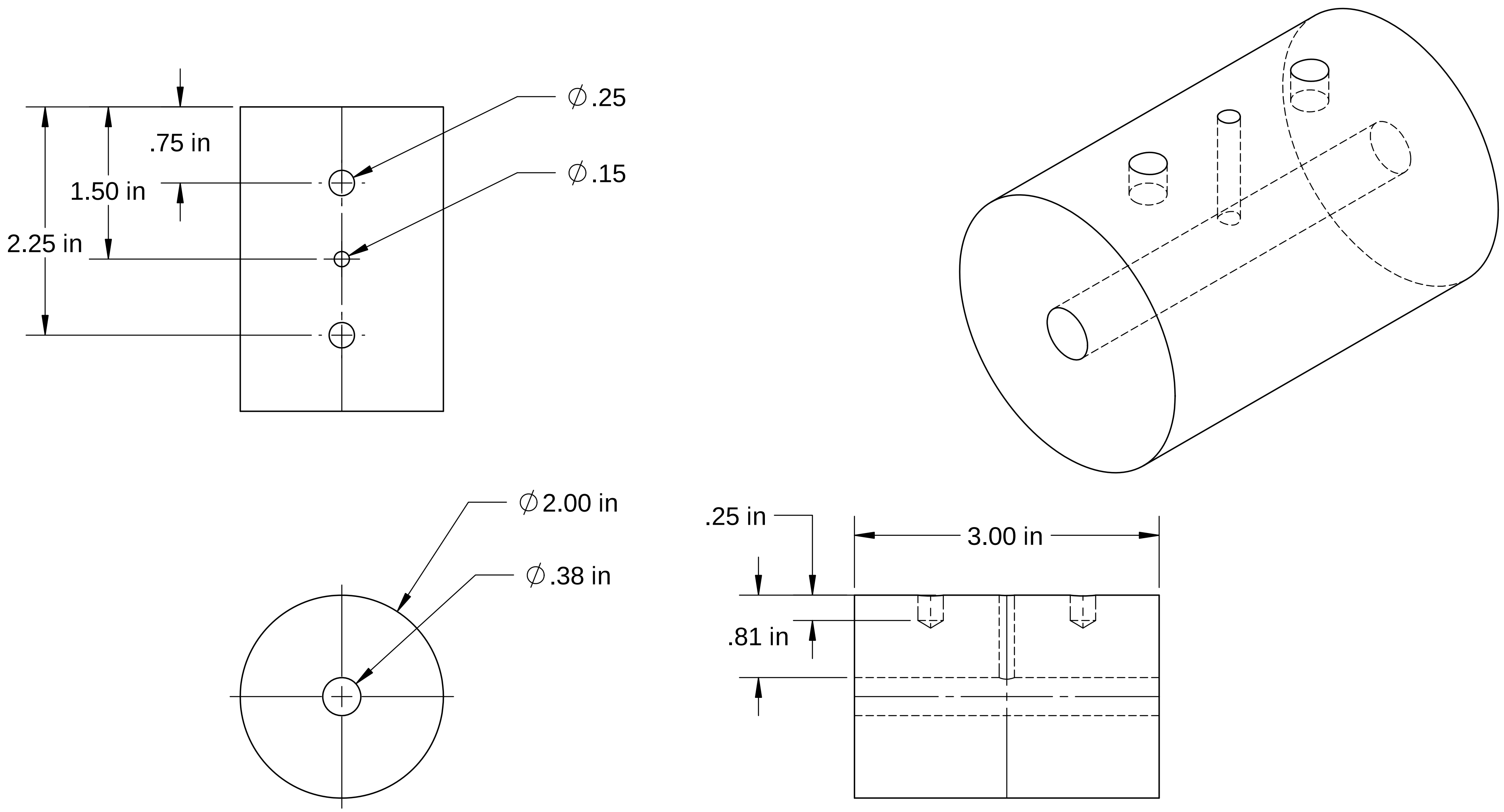
SIZE A

DWG. NO. D1

REV

SCALE: 1:1 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC
TOLERANCING PER:

MATERIAL
4140 Steel

FINISH

DO NOT SCALE DRAWING

PROPRIETARY AND CONFIDENTIAL

Passive Assistive Pedaling Device MQP

TITLE:

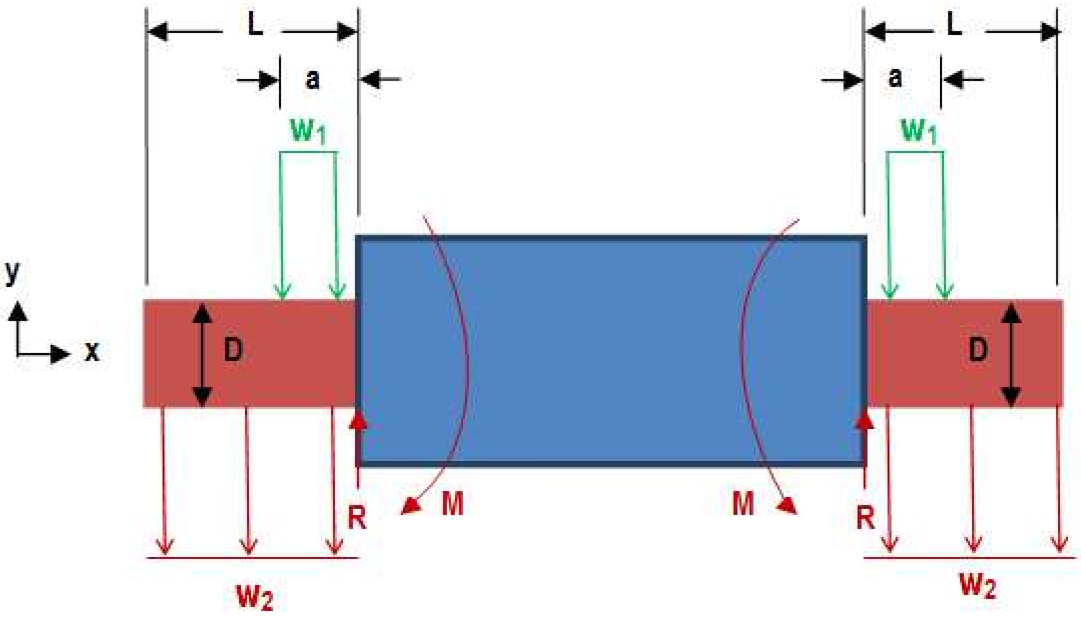
Bottom Bracket Cylinder

SIZE A
DWG. NO. D2
REV

SCALE: 1:1
WEIGHT:
SHEET 1 OF 1

Appendix E

Analysis of Bottom Bracket Axle as a Cantilever Beam



Red = bottom bracket axle
Blue = bottom bracket cylinder

$L := 1.5\text{in}$ $D := \frac{3}{8}\text{in}$ $a := 1.125\text{in}$

$F_{applied} := 328\text{lbm}\cdot\left(32.2\frac{\text{ft}}{\text{s}^2}\right) = 328.265\cdot\text{lbf}$ force due to weight of user (328lbm is an extreme value: twice the weight of the average user)

$w_1 := \frac{F_{applied}}{a} = 291.791\cdot\frac{\text{lbf}}{\text{in}}$ distributed load due to applied force on bottom bracket axle

$\gamma := 0.28\frac{\text{lbf}}{\text{in}^3}$ weight density for carbon steels (bottom bracket axle - AISI 1040)

$w_2 := \gamma\cdot\frac{\pi\cdot D^2}{4} = 0.031\cdot\frac{\text{lbf}}{\text{in}}$ distributed load due to weight of bottom bracket axle

$E := 207\cdot\text{GPa}$ for carbon steels (Fixed Front Axle - AISI 1040)

$I := \pi\cdot\frac{D^4}{64} = 9.707\times10^{-4}\cdot\text{in}^4$ second moment of mass

$C_1 := 0$ $C_2 := 0$ because $V(0^-)=0$ and $M(0^-)=0$

Solving for Reaction Forces:

Plug in $V(L^+)=0$:

$$0 = R_{Ay}\cdot(L-0)^0 - w_1\cdot(L-0)^1 + w_1\cdot(L-a)^1 - w_2\cdot(L-0)^1 + M_A\cdot(L-0)^{-1}$$

$R_{Ay} := w_1\cdot L - w_1\cdot(L-a) + w_2\cdot L = 328.311\cdot\text{lbf}$ reaction force at bottom bracket axle due to cantilever beam

Plug in $M(L^+)=0$:

$$0 = R\cdot(L-0)^1 - \frac{w_1}{2}\cdot(L-0)^2 + \frac{w_1}{2}\cdot(L-a)^2 - \frac{w_2}{2}\cdot(L-0)^2 + M_A\cdot(L-0)^0$$

$M_A := -R_{Ay}\cdot L + \frac{w_1}{2}\cdot L^2 - \frac{w_1}{2}\cdot(L-a)^2 + \frac{w_2}{2}\cdot L^2 = -184.684\cdot\text{lbf}\cdot\text{in}$ reaction moment at bottom bracket cylinder due to cantilever beam

Plug in $\delta(0)=0$:

$$0 = \frac{R_{Ay}}{6}\cdot(0-0)^3 - \frac{w_1}{24}\cdot(0-0)^4 + \frac{w_1}{24}\cdot(0-a)^4 - \frac{w_2}{24}\cdot(0-0)^4 + \frac{M_A}{2}\cdot(0-0)^2 + C_3\cdot 0 + C_4$$

$C_4 := 0$

because there is no deflection at x = 0 for a cantilever beam, $\delta(0) = 0$

$C_3 := 0$

$x := 0, 0.001\cdot L .. L$

$S(x,y) := \text{if}(x \ge y, 1, 0)$

Loading Function:

$$q(x) := R_{Ay}\cdot S(x,0)\cdot(x-0)^{-1} - w_1\cdot S(x,0)\cdot(x-0)^0 + w_1\cdot S(x,a)\cdot(x-a)^0 - w_2\cdot S(x,0)\cdot(x-0)^0 \ldots$$
$$+ M_A\cdot S(x,0)\,(x-0)^{-2}$$

Shear Function:

$$V(x) := R_{Ay}\cdot S(x,0)\cdot(x-0)^0 - w_1\cdot S(x,0)\cdot(x-0)^1 + w_1\cdot S(x,a)\cdot(x-a)^1 - w_2\cdot S(x,0)\cdot(x-0)^1 + C_1$$

Moment Function:

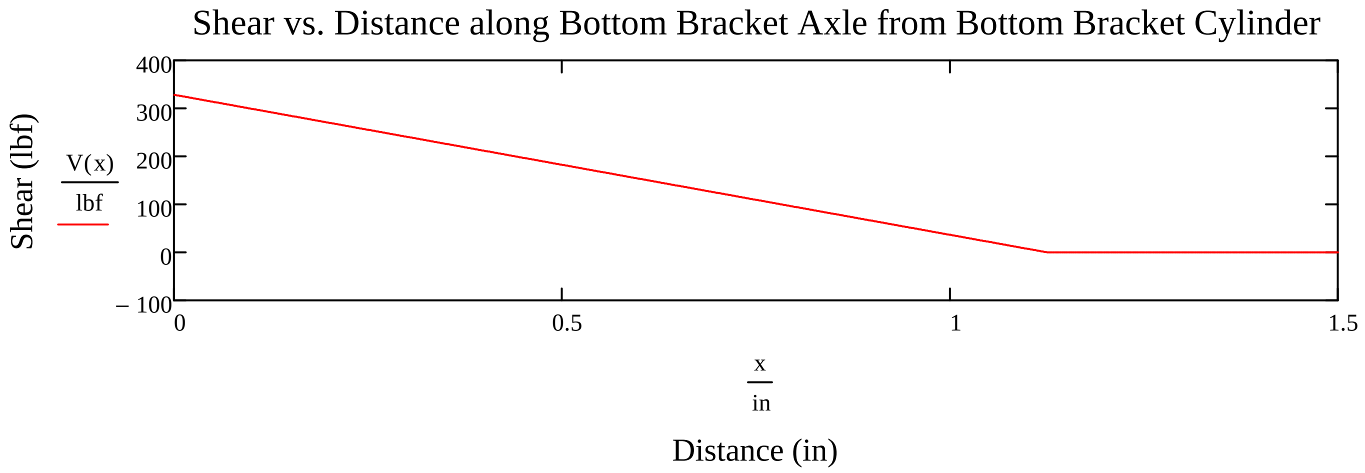
$$M(x) := R_{Ay}\cdot S(x,0)\cdot(x-0)^1 - \frac{w_1}{2}\cdot S(x,0)\cdot(x-0)^2 + \frac{w_1}{2}\cdot S(x,a)\cdot(x-a)^2 - \frac{w_2}{2}\cdot S(x,0)\cdot(x-0)^2 \ldots$$
$$+ M_A\cdot S(x,0)\,(x-0)^0 + C_1\cdot x + C_2$$

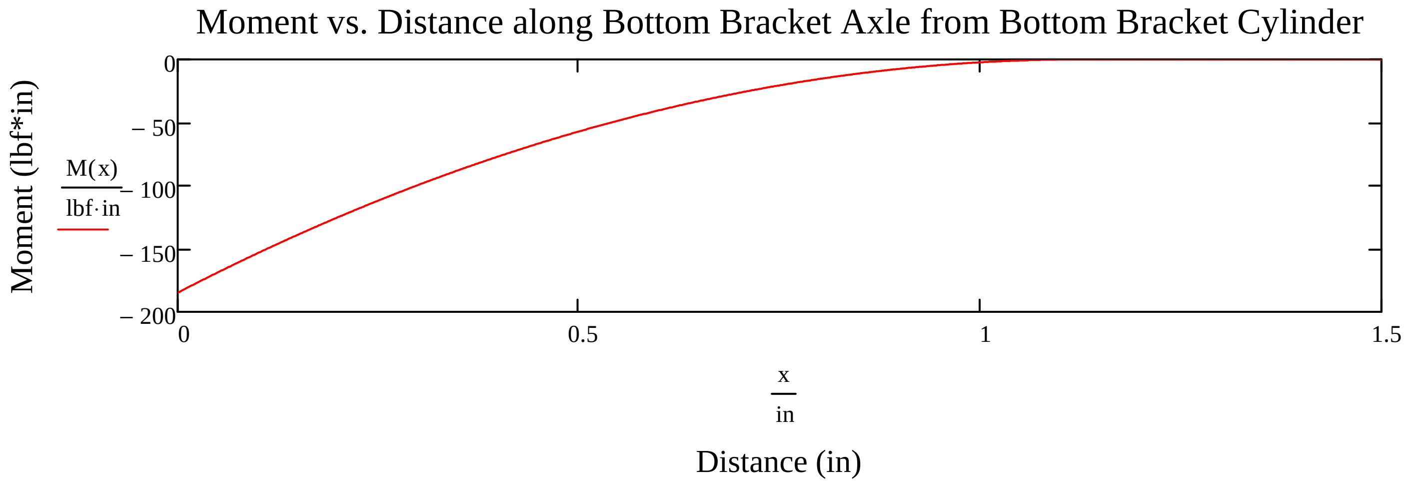
Slope Function:

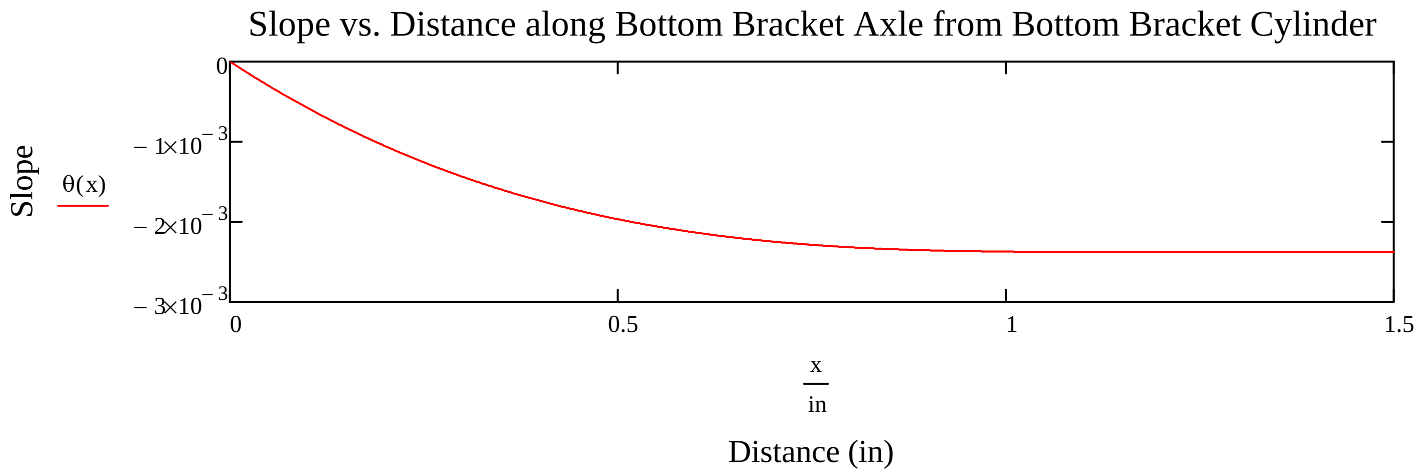
$$\theta(x) := \frac{1}{E\cdot I}\cdot\left[\begin{aligned}&\frac{R_{Ay}}{2}\cdot S(x,0)\cdot(x-0)^2 - \frac{w_1}{6}\cdot S(x,0)\cdot(x-0)^3 + \frac{w_1}{6}\cdot S(x,a)\cdot(x-a)^3 - \frac{w_2}{6}\cdot S(x,0)\cdot(x-0)^3 \ldots\\ &+ M_A\cdot S(x,0)\,(x-0)^1 + \frac{C_1}{2}\cdot x^2 + C_2\cdot x + C_3\end{aligned}\right]$$

Deflection Function:

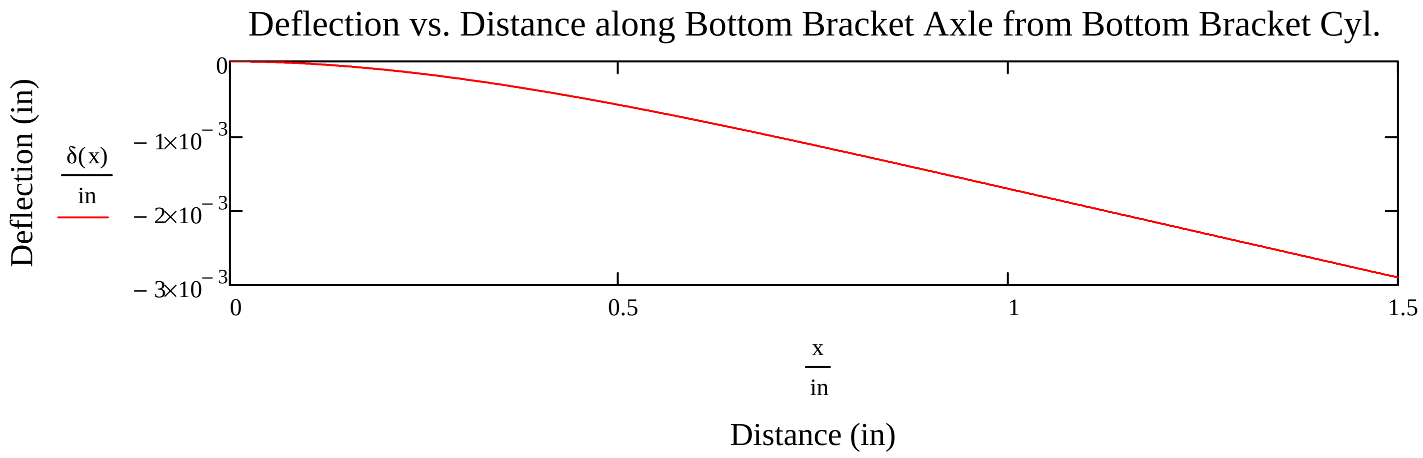
$$\delta(x) := \frac{1}{E\cdot I}\cdot\left[\begin{aligned}&\frac{R_{Ay}}{6}\cdot S(x,0)\cdot(x-0)^3 - \frac{w_1}{24}\cdot S(x,0)\cdot(x-0)^4 + \frac{w_1}{24}\cdot S(x,a)\cdot(x-a)^4 - \frac{w_2}{24}\cdot S(x,0)\cdot(x-0)^4 \ldots\\ &+ \frac{M_A}{2}\cdot S(x,0)\,(x-0)^2 + \frac{C_1}{6}\cdot x^3 + \frac{C_2}{2}\cdot x^2 + C_3\cdot x + C_4\end{aligned}\right]$$







Slope vs. Distance along Bottom Bracket Axle from Bottom Bracket Cylinder

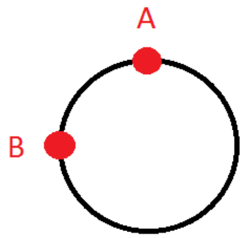


Deflection vs. Distance along Bottom Bracket Axle from Bottom Bracket Cyl.

Critical Section:

The critical section is at the location of the max V and M, which is at x = 0, the junction of the bottom bracket axle and the bottom bracket cylinder. The critical points on the critical section are A and B, as shown in the figure below.

Critical Cross-Section of Axle



Principal Normal and Shear Stresses of Critical Points at Critical Section:

Critical Point A:

$M := -M(0in) = 184.684 \cdot lbf \cdot in$

$I := \frac{\pi \cdot D^4}{64} = 9.707 \times 10^{-4} \cdot in^4$ second moment of mass

$c := 0.5 \cdot D = 0.187 \cdot in$ distance to neutral axis

$\sigma_{Ax} := \frac{M \cdot c}{I} = 35.673 \cdot ksi$

$\sigma_{A1} := \sigma_{Ax} = 35.673 \cdot ksi$ for pure tension at A due to bending

$\sigma_{A2} := 0ksi$ $\sigma_{A3} := 0ksi$

$\tau_{A13} := \frac{\sigma_{A1} - \sigma_{A3}}{2} = 17.836 \cdot ksi$

Critical Point B:

$\sigma_{Bx} := 0ksi$ $\sigma_{By} := 0ksi$

$V := V(0in) = 328.311 \cdot lbf$

$A := \frac{\pi \cdot D^2}{4} = 0.11 \cdot in^2$

$\tau_{xy} := \frac{4}{3} \cdot \frac{V}{A} = 3.963 \cdot ksi$ transverse shear stress at B

$$\sigma_{B1} := \frac{\sigma_{Bx} + \sigma_{By}}{2} + \sqrt{\left(\frac{\sigma_{Bx} + \sigma_{By}}{2}\right)^2 + \tau_{xy}^{\ 2}} = 3.963 \cdot ksi$$

$\sigma_{B2} := 0ksi$

$$\sigma_{B3} := \frac{\sigma_{Bx} + \sigma_{By}}{2} - \sqrt{\left(\frac{\sigma_{Bx} - \sigma_{By}}{2}\right)^2 + \tau_{xy}^{\ 2}} = -3.963 \cdot ksi$$

$$\tau_{B13} := \frac{\sigma_{B1} - \sigma_{B3}}{2} = 3.963 \cdot \text{ksi}$$

Safety Factors:

$S_y := 61\text{ksi}$ Tensile Yield Strength for AISI 4140 Steel

$$\sigma'_A := \sqrt{\sigma_{A1}^2 + \sigma_{A2}^2 + \sigma_{A3}^2 - \sigma_{A1} \cdot \sigma_{A2} - \sigma_{A2} \cdot \sigma_{A3} - \sigma_{A1} \cdot \sigma_{A3}} = 35.673 \cdot \text{ksi}$$

$$\sigma'_B := \sqrt{\sigma_{B1}^2 + \sigma_{B2}^2 + \sigma_{B3}^2 - \sigma_{B1} \cdot \sigma_{B2} - \sigma_{B2} \cdot \sigma_{B3} - \sigma_{B1} \cdot \sigma_{B3}} = 6.865 \cdot \text{ksi}$$

$N_A := \frac{S_y}{\sigma'_A} = 1.71$ Safety Factor of Critical Point A

$N_B := \frac{S_y}{\sigma'_B} = 8.886$ Safety Factor of Critical Point B

Endurance Limit of Machined Surface: (like Example 6-1 on pg 338 of Norton's Machine Design textbook)

$S_{ut} := 95$ ksi for AISI 4140 steel material := "steel" load := "bending"

surface := "machined" $T := 70$ deg F $R := 0.999$ $D := 0.375$ in

$$S'_e := \begin{array}{|l} \text{return } (0.5 \cdot S_{ut}) \text{ if } S_{ut} < 200 \\ (100) \text{ otherwise} \end{array} = 47.5$$

$$C_{load} := \begin{array}{|l} \text{return } 1 \text{ if load} = \text{"bending"} \\ \text{return } 1 \text{ if load} = \text{"torsion"} \\ \text{return } 0.7 \text{ if load} = \text{"axial"} \end{array} = 1$$

$$A_{95} := 0.0766 \cdot D^2 = 0.011$$

$$D_{equiv} := \sqrt{\frac{A_{95}}{0.0766}} = 0.375$$

$$C_{size} := 0.869 \cdot (D_{equiv})^{-0.097} = 0.956$$

$$A := \left|\begin{array}{l} \text{return } 1.58 \text{ if } surface = \text{"ground"} \\ \text{return } 4.51 \text{ if } surface = \text{"machined"} \\ \text{return } 4.51 \text{ if } surface = \text{"cold-rolled"} \\ \text{return } 57.7 \text{ if } surface = \text{"hot-rolled"} \\ \text{return } 272 \text{ if } surface = \text{"forged"} \end{array}\right. = 4.51$$

$$b := \left|\begin{array}{l} \text{return } -0.085 \text{ if } surface = \text{"ground"} \\ \text{return } -0.265 \text{ if } surface = \text{"machined"} \\ \text{return } -0.265 \text{ if } surface = \text{"cold-rolled"} \\ \text{return } -0.718 \text{ if } surface = \text{"hot-rolled"} \\ \text{return } -0.995 \text{ if } surface = \text{"forged"} \end{array}\right. = -0.265$$

$$C_{surf} := A \cdot \left(S_{ut}\right)^{b} = 1.349$$

$$C_{temp} := \left|\begin{array}{l} \text{return } 1 \text{ if } T \le 840 \\ \left[1 - 0.0032 \cdot (T - 840)\right] \text{ otherwise} \end{array}\right. = 1$$

$$C_{reliab} := \left|\begin{array}{l} \text{return } 1.000 \text{ if } R = 0.50 \\ \text{return } 0.897 \text{ if } R = 0.90 \\ \text{return } 0.814 \text{ if } R = 0.99 \\ \text{return } 0.753 \text{ if } R = 0.999 \\ \text{return } 0.702 \text{ if } R = 0.9999 \\ \text{return } 0.659 \text{ if } R = 0.99999 \end{array}\right. = 0.753$$

$$S_e := C_{load} \cdot C_{size} \cdot C_{surf} \cdot C_{temp} \cdot C_{reliab} \cdot S'_e = 46.122$$

$$S_m := \left|\begin{array}{l} \text{return } \left(0.75 \cdot S_{ut}\right) \text{ if } load = \text{"axial"} \\ \left(0.9 \cdot S_{ut}\right) \text{ otherwise} \end{array}\right. = 85.5$$

$$S_e = a \cdot N^{b}$$

$N_1 := 1000$ cycles N_1 is always 1000 cycles

$N_2 := 10^{6}$ cycles for a material with a knee

$z := \log(N_1) - \log(N_2) = -3$

$b := \frac{1}{z} \cdot \log\left(\frac{S_m}{S_e}\right) = -0.089$

$\log(a) = \log(S_m) - 3 \cdot b$

$a := \frac{S_m}{(10^3)^b} = 158.498$

$N := 10^6$

$S_e := a \cdot N^b = 46.122$ ksi endurance limit (stress level below which material can be cycled infinitely without failure)

$$S_m := \left| \begin{array}{l} \text{return } (0.75 \cdot S_{ut}) \text{ if load} = \text{"axial"} \\ (0.9 \cdot S_{ut}) \text{ otherwise} \end{array} \right. = 85.5$$

$S_f = a \cdot N^b$

$N_1 := 1000$ cycles N_1 is always 1000 cycles

$N_2 := 10^6$ cycles for a material with a knee

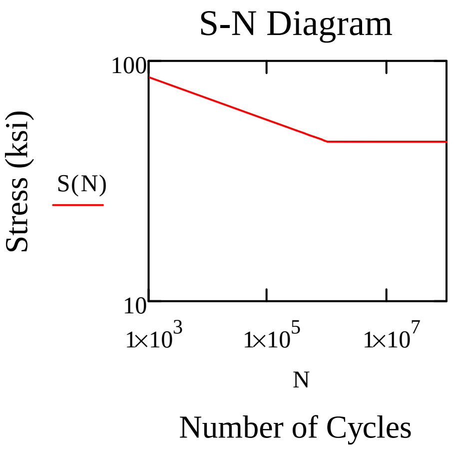
$z := \log(N_1) - \log(N_2) = -3$

$b := \frac{1}{z} \cdot \log\left(\frac{S_m}{S_e}\right) = -0.089$

$a := \frac{S_m}{(10^3)^b} = 158.498$

$$S(N) := \left| \begin{array}{l} \text{return } a \cdot N^b \text{ if } N < 10^6 \\ S_e \text{ otherwise} \end{array} \right.$$

range $N := 10^3, 10^5 .. 10^8$



$S_e := S(10^6) = 46.122$ ksi

endurance limit (stress level below which material can be cycled infinitely without failure)

Estimating Cycles of Life for Bottom Bracket Axle with Machined Surface:

$S_n = a \cdot N^b$

$\sigma_a := \sigma_{Ax} = 35.673 \cdot \text{ksi}$ σ_a = alternating stress

$S_n := \sigma_a = 35.673 \cdot \text{ksi}$

$a = 158.498$

$\log(a) = 2.2$

$b = -0.089$

$S_n := \dfrac{S_n}{\text{ksi}} = 35.673$

$\log(S_n) = 1.552$

$N := 10^{\frac{\log(S_n) - \log(a)}{b}} = 1.773 \times 10^7$ cycles of life

Endurance Limit of Material with Worn Surface (caused by bending of Bottom Bracket Axle on sharp edge of Bottom Bracket Cylinder):

$S_{ut} := 95$ ksi for AISI 4140 steel material := "steel" load := "bending" surface := "worn" $T := 70$ deg F $R := 0.999$ $D := 0.375$ in

$$S'_e := \left| \begin{array}{l} \text{return } (0.5 \cdot S_{ut}) \text{ if } S_{ut} < 200 \\ (100) \text{ otherwise} \end{array} \right. = 47.5$$

$$C_{load} := \left| \begin{array}{l} \text{return } 1 \text{ if load} = \text{"bending"} \\ \text{return } 1 \text{ if load} = \text{"torsion"} \\ \text{return } 0.7 \text{ if load} = \text{"axial"} \end{array} \right. = 1$$

$$A_{95} := 0.0766 \cdot D^2 = 0.011$$

$$D_{equiv} := \sqrt{\frac{A_{95}}{0.0766}} = 0.375$$

$$C_{size} := 0.869 \cdot \left(D_{equiv}\right)^{-0.097} = 0.956$$

$C_{surf} := 0.75$ estimated surface factor for worn material from Figure 6-26 of Norton's Machine Design textbook

$$C_{temp} := \left| \begin{array}{l} \text{return } 1 \text{ if } T \le 840 \\ [1 - 0.0032 \cdot (T - 840)] \text{ otherwise} \end{array} \right. = 1$$

$$C_{reliab} := \left| \begin{array}{l} \text{return } 1.000 \text{ if } R = 0.50 \\ \text{return } 0.897 \text{ if } R = 0.90 \\ \text{return } 0.814 \text{ if } R = 0.99 \\ \text{return } 0.753 \text{ if } R = 0.999 \\ \text{return } 0.702 \text{ if } R = 0.9999 \\ \text{return } 0.659 \text{ if } R = 0.99999 \end{array} \right. = 0.753$$

$$S_e := C_{load} \cdot C_{size} \cdot C_{surf} \cdot C_{temp} \cdot C_{reliab} \cdot S'_e = 25.638 \text{ ksi}$$

$$S_m := \left| \begin{array}{l} \text{return } (0.75 \cdot S_{ut}) \text{ if load} = \text{"axial"} \\ (0.9 \cdot S_{ut}) \text{ otherwise} \end{array} \right. = 85.5 \text{ ksi}$$

$$S_f = a \cdot N^b$$

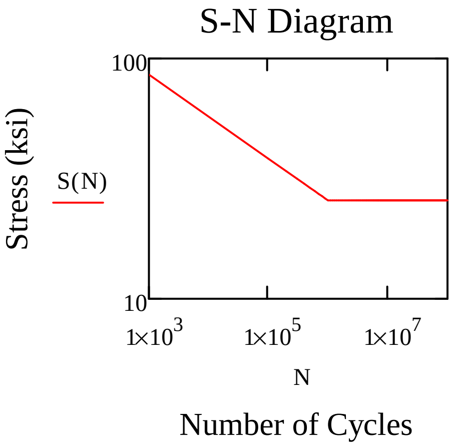
$$z := -3.000$$

$$b := \frac{1}{z} \cdot \log\left(\frac{S_m}{S_e}\right) = -0.174$$

$$a := \frac{S_m}{\left(10^3\right)^b} = 285.13$$

$$S(N) := \left| \begin{array}{l} \text{return } a \cdot N^b \text{ if } N < 10^6 \\ S_e \text{ otherwise} \end{array} \right.$$

range $N := 10^3, 10^5 .. 10^8$



$S_e := S\left(10^6\right) = 25.638$ ksi

endurance limit (stress level below which material can be cycled infinitely without failure)

Estimating Cycles of Life for Bottom Bracket Axle with Worn Surface:

$S_n = a \cdot N^b$

$\sigma_a := \sigma_{Ax} = 35.673 \cdot ksi$ σ_a = alternating stress

$S_n := \sigma_a = 35.673 \cdot ksi$

$a = 285.13$

$\log(a) = 2.455$

$b = -0.174$

$$S_n := \frac{S_n}{ksi} = 35.673$$

$$\log\left(S_n\right) = 1.552$$

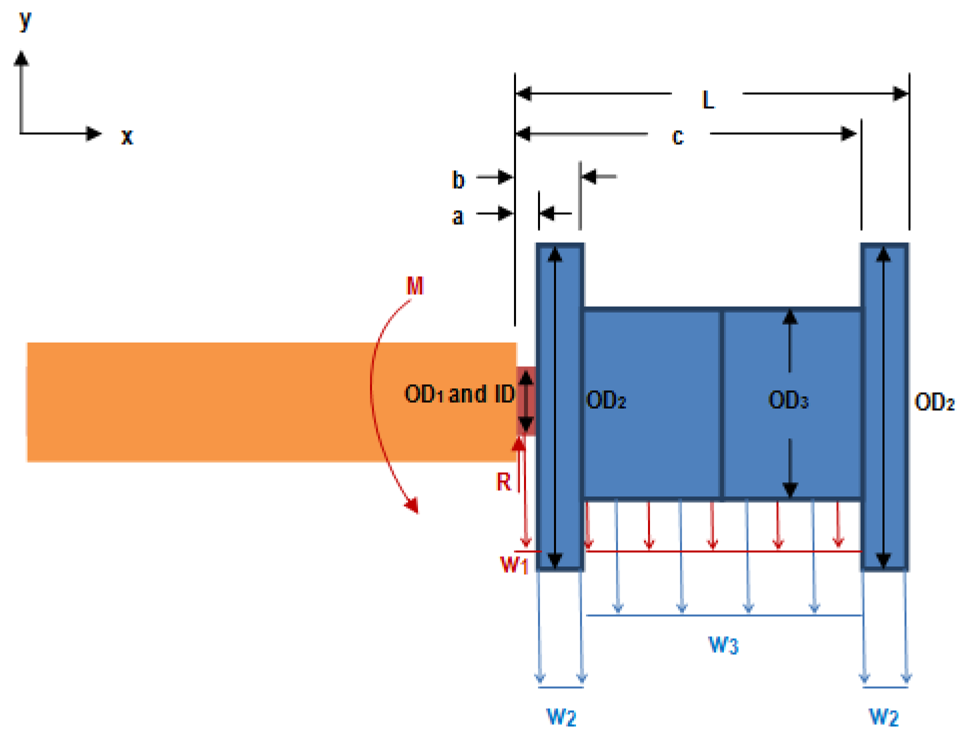
$$N := 10^{\frac{\log\left(S_n\right)-\log(a)}{b}} = 1.504 \times 10^{5}$$ cycles of life

Conclusion:

Since the safety factors are greater than 1, the Bottom Bracket Axle will be able to support the applied load. The cycles of life of the Bottom Bracket Axle are approximately 18 million cycles for a machined surface and 150,000 cycles for a worn surface. Given the tricycle will be used for rehabilitation, the tricycle cranks will only complete 756,000 cycles within its typical life which is less than the calculated life of the axle. The estimated number of cycles the axle will endure was calculated assuming a rehabilitative use of the tricycle for half an hour rehabilitation sessions 5 times a week, for 5 years. Given that the estimated cycles of the cranks is less than the calculated cycles of life for the axle, the chosen material of AISI 4140 steel will be more than sufficient for the bottom bracket axle of a tricycle drivetrain than the typical aluminum.

Appendix F

Analysis of Rear Axle as a Cantilever Beam



Orange = Rear Axle Housing
Red = Rear Axle
Blue = Rear Axle Half Spools

$a := 0.25\text{in}$ $\quad b := 0.45\text{in}$ $\quad c := 3\text{in}$ $\quad L := 3.25\text{in}$

$OD_1 := 0.5\text{in}$ $\quad OD_2 := 3\text{in}$ $\quad OD_3 := 1\text{in}$ $\quad ID := 0.5\text{in}$

$c := 0.5 \cdot OD_1 = 0.25 \cdot \text{in}$ distance to neutral axis

$E := 207\text{GPa}$ for carbon steels (Rear Axle - AISI 1010) and steel alloys (Half Spools - AISI 4140)

$$I := \pi \cdot \frac{OD_1^{\,4}}{64} = 3.068 \times 10^{-3} \cdot \text{in}^4$$ second moment of mass

$C_1 := 0$

because $V(0^-)=0$ and $M(0^-)=0$

$C_2 := 0$

$\gamma := 0.28\frac{\text{lbf}}{\text{in}^3}$ weight density for carbon steels (Rear Axle - AISI 1010) and steel alloys (Half Spools - AISI 4140)

$w_1 := \gamma\cdot\frac{\pi\cdot OD_1^{\;2}}{4} = 0.055\cdot\frac{\text{lbf}}{\text{in}}$ distributed load of force due to weight of Rear Axle

$w_2 := \gamma\cdot\frac{\pi\cdot\left(OD_2^{\;2} - ID^2\right)}{4} = 1.924\cdot\frac{\text{lbf}}{\text{in}}$ distributed load of force due to weight of larger diameter section of Half Spool

$w_3 := \gamma\cdot\frac{\pi\cdot\left(OD_3^{\;2} - ID^2\right)}{4} = 0.165\cdot\frac{\text{lbf}}{\text{in}}$ distributed load of force due to weight of smaller diameter section of Half Spool

Solving for the Reactions:

Plug in V(L$^+$)=0:

$$0 = R_{Ay}\cdot(L-0)^0 - w_1\cdot(L-0)^1 + w_1\cdot(L-L)^1 - w_2\cdot(L-a)^1 + w_2\cdot(L-b)^1 - w_3\cdot(L-b)^1 \ldots$$
$$+\,w_3\cdot(L-c)^1 - w_2\cdot(L-c)^1 + M_A\cdot(L-0)^{-1}$$

$$R_{Ay} := w_1\cdot L + w_2\cdot(L-a) - w_2\cdot(L-b) + w_3\cdot(L-b) - w_3\cdot(L-c) + w_2\cdot(L-c)$$

$R_{Ay} = 6.303\cdot\text{lbf}$ reaction force at the Rear Axle Housing due the cantilever beam

Plug in M(L$^+$)=0:

$$0 = R_{Ay}\cdot(L-0)^1 - \frac{w_1}{2}\cdot(L-0)^2 + \frac{w_1}{2}\cdot(L-L)^2 - \frac{w_2}{2}\cdot(L-a)^2 + \frac{w_2}{2}\cdot(L-b)^2 - \frac{w_3}{2}\cdot(L-b)^2 \ldots$$
$$+\,\frac{w_3}{2}\cdot(L-c)^2 - \frac{w_2}{2}\cdot(L-c)^2 + M_A(L-0)^0$$

$$M_A := -R_{Ay}\cdot L + \frac{w_1}{2}\cdot L^2 + \frac{w_2}{2}\cdot(L-a)^2 - \frac{w_2}{2}\cdot(L-b)^2 + \frac{w_3}{2}\cdot(L-b)^2 - \frac{w_3}{2}\cdot(L-c)^2 + \frac{w_2}{2}\cdot(L-c)^2$$

$M_A = -10.516\cdot\text{lbf}\cdot\text{in}$ reaction moment at the Rear Axle Housing due to the cantilever beam

Plug in δ(0)=0:

$$0 = \frac{R_{Ay}}{6}\cdot(0-0)^3 - \frac{w_1}{24}\cdot(0-0)^4 + \frac{w_1}{24}\cdot(0-L)^4 - \frac{w_2}{24}\cdot(0-a)^4 + \frac{w_2}{24}\cdot(0-b)^4 - \frac{w_3}{24}\cdot(0-b)^4 \ldots$$
$$+\,\frac{w_3}{24}\cdot(0-c)^4 - \frac{w_2}{24}\cdot(0-c)^4 + \frac{M_A}{2}(0-0)^2 + C_3\cdot 0 + C_4$$

$C_4 := 0$

because there is no deflection at x = 0 for a cantilever beam, δ(0) = 0

$C_3 := 0$

$x := 0, 0.001 \cdot L .. L$

$S(x,y) := \text{if}(x \ge y, 1, 0)$

Loading Function:

$$\begin{aligned} q(x) := {} & R_{Ay} \cdot S(x,0) \cdot (x-0)^{-1} - w_1 \cdot S(x,0) \cdot (x-0)^0 + w_1 \cdot S(x,L) \cdot (x-L)^0 - w_2 \cdot S(x,a) \cdot (x-a)^0 \ldots \\ & + w_2 \cdot S(x,b) \cdot (x-b)^0 - w_3 \cdot S(x,b) \cdot (x-b)^0 + w_3 \cdot S(x,c) \cdot (x-c)^0 - w_2 \cdot S(x,c) \cdot (x-c)^0 \ldots \\ & + M_A \cdot S(x,0)\,(x-0)^{-2} \end{aligned}$$

Shear Function:

$$\begin{aligned} V(x) := {} & R_{Ay} \cdot S(x,0) \cdot (x-0)^0 - w_1 \cdot S(x,0) \cdot (x-0)^1 + w_1 \cdot S(x,L) \cdot (x-L)^1 - w_2 \cdot S(x,a) \cdot (x-a)^1 \ldots \\ & + w_2 \cdot S(x,b) \cdot (x-b)^1 - w_3 \cdot S(x,b) \cdot (x-b)^1 + w_3 \cdot S(x,c) \cdot (x-c)^1 - w_2 \cdot S(x,c) \cdot (x-c)^1 + C_1 \end{aligned}$$

Moment Function:

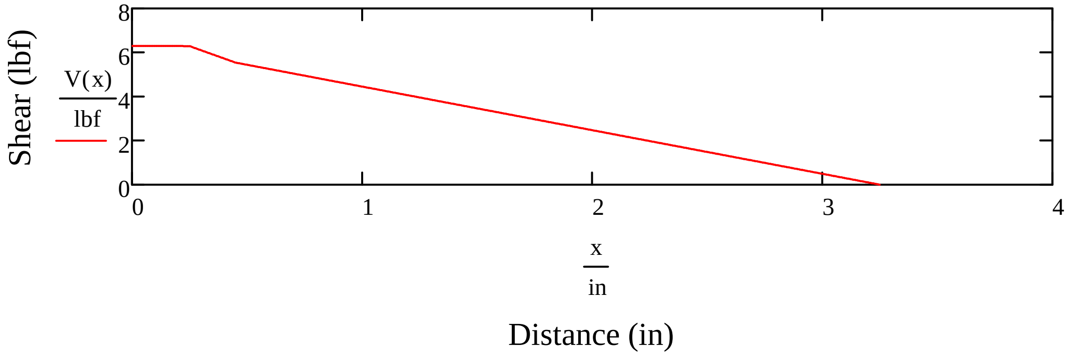
$$\begin{aligned} M(x) := {} & R_{Ay} \cdot S(x,0) \cdot (x-0)^1 - \frac{w_1}{2} \cdot S(x,0) \cdot (x-0)^2 + \frac{w_1}{2} \cdot S(x,L) \cdot (x-L)^2 - \frac{w_2}{2} \cdot S(x,a) \cdot (x-a)^2 \ldots \\ & + \frac{w_2}{2} \cdot S(x,b) \cdot (x-b)^2 - \frac{w_3}{2} \cdot S(x,b) \cdot (x-b)^2 + \frac{w_3}{2} \cdot S(x,c) \cdot (x-c)^2 - \frac{w_2}{2} \cdot S(x,c) \cdot (x-c)^2 \ldots \\ & + M_A \cdot S(x,0)\,(x-0)^0 + C_1 \cdot x + C_2 \end{aligned}$$

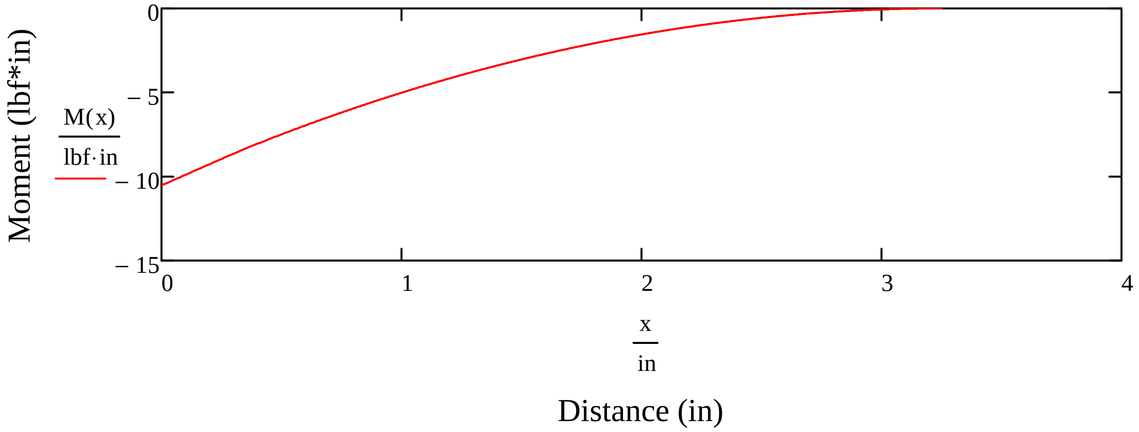
Slope Function:

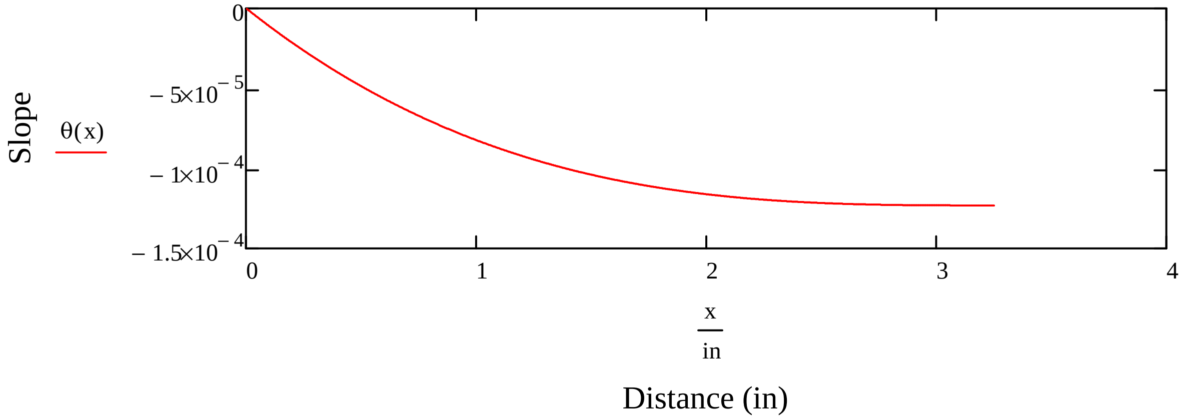
$$\theta(x) := \frac{1}{E \cdot I} \cdot \left[\begin{aligned} & \frac{R_{Ay}}{2} \cdot S(x,0) \cdot (x-0)^2 - \frac{w_1}{6} \cdot S(x,0) \cdot (x-0)^3 + \frac{w_1}{6} \cdot S(x,L) \cdot (x-L)^3 - \frac{w_2}{6} \cdot S(x,a) \cdot (x-a)^3 \ldots \\ & + \frac{w_2}{6} \cdot S(x,b) \cdot (x-b)^3 - \frac{w_3}{6} \cdot S(x,b) \cdot (x-b)^3 + \frac{w_3}{6} \cdot S(x,c) \cdot (x-c)^3 - \frac{w_2}{6} \cdot S(x,c) \cdot (x-c)^3 \ldots \\ & + M_A \cdot S(x,0)\,(x-0)^1 + \frac{C_1}{2} \cdot x^2 + C_2 \cdot x + C_3 \end{aligned} \right]$$

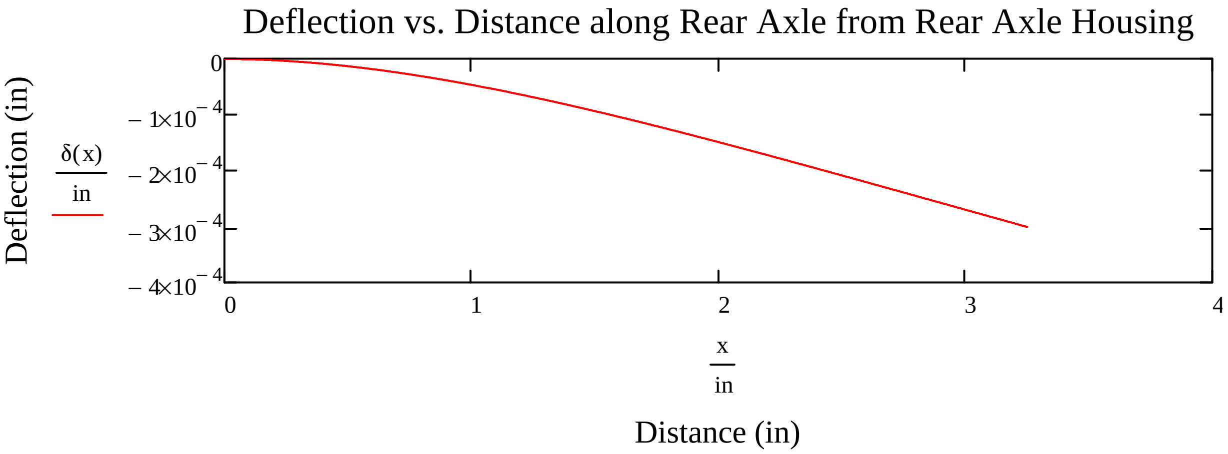
Deflection Function:

$$\delta(x) := \frac{1}{E \cdot I} \cdot \left[\begin{aligned} & \frac{R_{Ay}}{6} \cdot S(x,0) \cdot (x-0)^3 - \frac{w_1}{24} \cdot S(x,0) \cdot (x-0)^4 + \frac{w_1}{24} \cdot S(x,L) \cdot (x-L)^4 - \frac{w_2}{24} \cdot S(x,a) \cdot (x-a)^4 \ldots \\ & + \frac{w_2}{24} \cdot S(x,b) \cdot (x-b)^4 - \frac{w_3}{24} \cdot S(x,b) \cdot (x-b)^4 + \frac{w_3}{24} \cdot S(x,c) \cdot (x-c)^4 - \frac{w_2}{24} \cdot S(x,c) \cdot (x-c)^4 \ldots \\ & + \frac{M_A}{2} \cdot S(x,0)\,(x-0)^2 + \frac{C_1}{6} \cdot x^3 + \frac{C_2}{2} \cdot x^2 + C_3 \cdot x + C_4 \end{aligned} \right]$$


Shear vs. Distance along Rear Axle from Rear Axle Housing

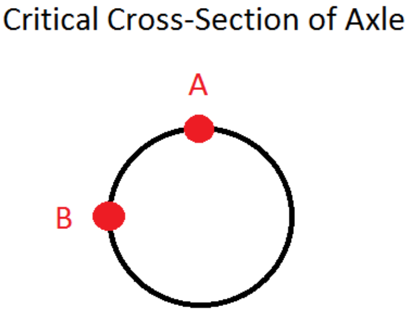

Moment vs. Distance along Rear Axle from Rear Axle Housing


Slope vs. Distance along Rear Axle from Rear Axle Housing



Critical Section:

The critical section is at the location of the max V and M, which is at x = 0, the junction of the Rear Axle and the Rear Axle Housing. The critical points on the critical section are A and B, as shown in the figure below.



Principal Normal and Shear Stresses at Critical Points of Critical Section:

Critical Point A:

$M := -M(0in) = 10.516 \cdot lbf \cdot in$

$c := 0.5 \cdot OD_1 = 0.25 \cdot in$ distance to neutral axis

$I := \frac{\pi \cdot OD_1^{\ 4}}{64} = 3.068 \times 10^{-3} \cdot in^4$ second moment of area

$\sigma_{Ax} := \frac{M \cdot c}{I} = 0.857 \cdot ksi$ $\sigma_{Ay} := 0ksi$

$P := 22.8\text{W} \qquad \omega := 17.5\text{rpm}$

$r := 0.5 \cdot OD_1 = 0.25 \cdot \text{in} \qquad J := \dfrac{\pi \cdot OD_1^{\,4}}{32} = 6.136 \times 10^{-3} \cdot \text{in}^4$ second polar moment of area

$T := \dfrac{P}{\omega} = 110.115 \cdot \text{lbf} \cdot \text{in}$ torque caused by chain (calculated using data from the team's test ride of tricycle)

$\tau_{torsion} := \dfrac{2 \cdot T \cdot r}{J} = 8.973 \cdot \text{ksi}$ torque is doubled due to use of dual chains (tricycle had one chain during the team's test ride)

$\tau_{xz} := \tau_{torsion} = 8.973 \cdot \text{ksi}$

$$\sigma_{A1} := \frac{\sigma_{Ax} + \sigma_{Ay}}{2} + \sqrt{\left(\frac{\sigma_{Ax} + \sigma_{Ay}}{2}\right)^2 + \tau_{xz}^{\,2}} = 9.412 \cdot \text{ksi}$$

$\sigma_{A2} := 0\text{ksi}$

$$\sigma_{A3} := \frac{\sigma_{Ax} + \sigma_{Ay}}{2} - \sqrt{\left(\frac{\sigma_{Ax} + \sigma_{Ay}}{2}\right)^2 + \tau_{xz}^{\,2}} = -8.555 \cdot \text{ksi}$$

$$\tau_{A13} := \frac{\sigma_{A1} - \sigma_{A3}}{2} = 8.983 \cdot \text{ksi}$$

Critical Point B:

$\sigma_{Bx} := 0\text{ksi} \qquad \sigma_{By} := 0\text{ksi}$

$V := V(0\text{in}) = 6.303 \cdot \text{lbf}$

$$A := \frac{\pi \cdot OD_1^{\,2}}{4} = 0.196 \cdot \text{in}^2$$

$\tau_{transverse} := \dfrac{4}{3} \cdot \dfrac{V}{A} = 0.043 \cdot \text{ksi}$ transverse shear stress at B

$\tau_{xy} := \tau_{transverse} + \tau_{torsion} = 9.016 \cdot \text{ksi}$

$$\sigma_{B1} := \frac{\sigma_{Bx} + \sigma_{By}}{2} + \sqrt{\left(\frac{\sigma_{Bx} + \sigma_{By}}{2}\right)^2 + \tau_{xy}^{\,2}} = 9.016 \cdot \text{ksi}$$

$\sigma_{B2} := 0\text{ksi}$

$$\sigma_{B3} := \frac{\sigma_{Bx} + \sigma_{By}}{2} - \sqrt{\left(\frac{\sigma_{Bx} + \sigma_{By}}{2}\right)^2 + \tau_{xy}^{\ 2}} = -9.016\cdot\text{ksi}$$

$$\tau_{B13} := \frac{\sigma_{B1} - \sigma_{B3}}{2} = 9.016\cdot\text{ksi}$$

Safety Factors:

$S_y := 26\text{ksi}$ Tensile Yield Strength of AISI 1010 steel

$$\sigma'_A := \sqrt{\sigma_{A1}^{\ 2} + \sigma_{A2}^{\ 2} + \sigma_{A3}^{\ 2} - \sigma_{A1}\cdot\sigma_{A2} - \sigma_{A2}\cdot\sigma_{A3} - \sigma_{A1}\cdot\sigma_{A3}} = 15.565\cdot\text{ksi}$$

$$\sigma'_B := \sqrt{\sigma_{B1}^{\ 2} + \sigma_{B2}^{\ 2} + \sigma_{B3}^{\ 2} - \sigma_{B1}\cdot\sigma_{B2} - \sigma_{B2}\cdot\sigma_{B3} - \sigma_{B1}\cdot\sigma_{B3}} = 15.616\cdot\text{ksi}$$

$N_A := \frac{S_y}{\sigma'_A} = 1.67$ Safety Factor of Critical Point A

$N_B := \frac{S_y}{\sigma'_B} = 1.665$ Safety Factor of Critical Point B

Endurance Limit of Machined Surface: (like Example 6-1 on pg 338 of Norton's Machine Design textbook)

$S_{ut} := 47$ ksi for AISI 4140 steel material := "steel" load := "bending"

surface := "machined" $T := 70$ deg F $R := 0.999$ $D := 0.5$ in

$$S'_e := \begin{array}{|l} \text{return } (0.5\cdot S_{ut}) \text{ if } S_{ut} < 200 \\ (100) \text{ otherwise} \end{array} = 23.5$$

$$C_{load} := \begin{array}{|l} \text{return } 1 \text{ if load} = \text{"bending"} \\ \text{return } 1 \text{ if load} = \text{"torsion"} \\ \text{return } 0.7 \text{ if load} = \text{"axial"} \end{array} = 1$$

Note: The rear axle is loaded in bending and torsion, but the C_{load} value will be the same for both types of loading and, therefore, will result in the same endurance limit.

$A_{95} := 0.0766\cdot D^2 = 0.019$

$$D_{equiv} := \sqrt{\frac{A_{95}}{0.0766}} = 0.5$$

$$C_{size} := 0.869 \cdot \left(D_{equiv}\right)^{-0.097} = 0.929$$

$$A := \left|\begin{array}{l} \text{return } 1.58 \text{ if surface} = \text{"ground"} \\ \text{return } 4.51 \text{ if surface} = \text{"machined"} \\ \text{return } 4.51 \text{ if surface} = \text{"cold-rolled"} \\ \text{return } 57.7 \text{ if surface} = \text{"hot-rolled"} \\ \text{return } 272 \text{ if surface} = \text{"forged"} \end{array}\right. = 4.51$$

$$b := \left|\begin{array}{l} \text{return } -0.085 \text{ if surface} = \text{"ground"} \\ \text{return } -0.265 \text{ if surface} = \text{"machined"} \\ \text{return } -0.265 \text{ if surface} = \text{"cold-rolled"} \\ \text{return } -0.718 \text{ if surface} = \text{"hot-rolled"} \\ \text{return } -0.995 \text{ if surface} = \text{"forged"} \end{array}\right. = -0.265$$

$$C_{surf} := A \cdot \left(S_{ut}\right)^{b} = 1.626$$

$$C_{temp} := \left|\begin{array}{l} \text{return } 1 \text{ if } T \le 840 \\ \left[1 - 0.0032 \cdot (T - 840)\right] \text{ otherwise} \end{array}\right. = 1$$

$$C_{reliab} := \left|\begin{array}{l} \text{return } 1.000 \text{ if } R = 0.50 \\ \text{return } 0.897 \text{ if } R = 0.90 \\ \text{return } 0.814 \text{ if } R = 0.99 \\ \text{return } 0.753 \text{ if } R = 0.999 \\ \text{return } 0.702 \text{ if } R = 0.9999 \\ \text{return } 0.659 \text{ if } R = 0.99999 \end{array}\right. = 0.753$$

$$S_e := C_{load} \cdot C_{size} \cdot C_{surf} \cdot C_{temp} \cdot C_{reliab} \cdot S'_e = 26.739$$

$$S_m := \left|\begin{array}{l} \text{return } \left(0.75 \cdot S_{ut}\right) \text{ if load} = \text{"axial"} \\ \left(0.9 \cdot S_{ut}\right) \text{ otherwise} \end{array}\right. = 42.3$$

$$S_e = a \cdot N^{b}$$

$N_1 := 1000$ cycles N_1 is always 1000 cycles

$N_2 := 10^6$ cycles for a material with a knee

$z := \log(N_1) - \log(N_2) = -3$

$b := \frac{1}{z} \cdot \log\left(\frac{S_m}{S_e}\right) = -0.066$

$\log(a) = \log(S_m) - 3 \cdot b$

$a := \frac{S_m}{\left(10^3\right)^b} = 66.916$

$N := 10^6$

$S_e := a \cdot N^b = 26.739$ ksi endurance limit (stress level below which material can be cycled infinitely without failure)

$$S_m := \left| \begin{array}{l} \text{return } (0.75 \cdot S_{ut}) \text{ if load} = \text{"axial"} \\ (0.9 \cdot S_{ut}) \text{ otherwise} \end{array} \right. = 42.3 \text{ ksi}$$

$S_f = a \cdot N^b$

$N_1 := 1000$ cycles N_1 is always 1000 cycles

$N_2 := 10^6$ cycles for a material with a knee

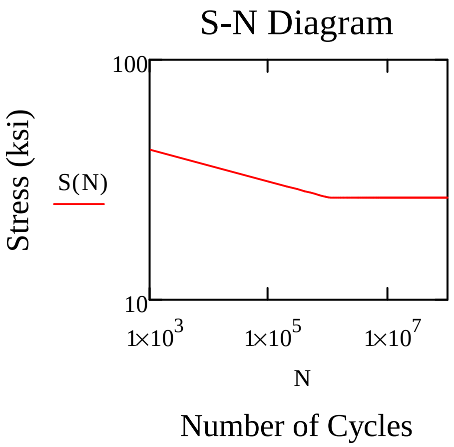
$z := \log(N_1) - \log(N_2) = -3$

$b := \frac{1}{z} \cdot \log\left(\frac{S_m}{S_e}\right) = -0.066$

$a := \frac{S_m}{\left(10^3\right)^b} = 66.916$

$$S(N) := \left| \begin{array}{l} \text{return } a \cdot N^b \text{ if } N < 10^6 \\ S_e \text{ otherwise} \end{array} \right.$$

range $N := 10^3, 10^5 .. 10^8$



$S_e := S(10^6) = 26.739$ ksi

endurance limit (stress level below which material can be cycled infinitely without failure)

Estimating Cycles of Life for Rear Axle with Machined Surface:

$S_n = a \cdot N^b$

$\sigma_a := \sigma_{Ax} = 0.857 \cdot ksi$

$S_n := \frac{\sigma_a}{ksi} = 0.857$

$a = 66.916$

$\log(a) = 1.826$

$b = -0.066$

$\log(S_n) = -0.067$

$N := 10^{\frac{\log(S_n) - \log(a)}{b}} = 3.198 \times 10^{28}$ cycles of life

Endurance Limit of Material with Worn Surface (caused by bending of Rear Axle on sharp edge of Bearing):

$S_{ut} := 47$ ksi for AISI 4140 steel material := "steel" load := "bending"

surface := "worn" $T := 70$ deg F $R := 0.999$ $D := 0.5$ in

$$S'_e := \left| \begin{array}{l} \text{return } (0.5 \cdot S_{ut}) \text{ if } S_{ut} < 200 \\ (100) \text{ otherwise} \end{array} \right. = 23.5$$

$$C_{load} := \left| \begin{array}{l} \text{return } 1 \;\; \text{if } \; load = \text{"bending"} \\ \text{return } 1 \;\; \text{if } \; load = \text{"torsion"} \\ \text{return } 0.7 \;\; \text{if } \; load = \text{"axial"} \end{array} \right. = 1$$

Note: The rear axle is loaded in bending and torsion, but the C_{load} value will be the same for both types of loading and, therefore, will result in the same endurance limit.

$$A_{95} := 0.0766 \cdot D^2 = 0.019$$

$$D_{equiv} := \sqrt{\frac{A_{95}}{0.0766}} = 0.5$$

$$C_{size} := 0.869 \cdot \left(D_{equiv}\right)^{-0.097} = 0.929$$

$C_{surf} := 0.75$ estimated surface factor for worn material from Figure 6-26 of Norton's Machine Design textbook

$$C_{temp} := \left| \begin{array}{l} \text{return } 1 \;\; \text{if } \; T \le 840 \\ \left[1 - 0.0032 \cdot (T - 840)\right] \;\; \text{otherwise} \end{array} \right. = 1$$

$$C_{reliab} := \left| \begin{array}{l} \text{return } 1.000 \;\; \text{if } \; R = 0.50 \\ \text{return } 0.897 \;\; \text{if } \; R = 0.90 \\ \text{return } 0.814 \;\; \text{if } \; R = 0.99 \\ \text{return } 0.753 \;\; \text{if } \; R = 0.999 \\ \text{return } 0.702 \;\; \text{if } \; R = 0.9999 \\ \text{return } 0.659 \;\; \text{if } \; R = 0.99999 \end{array} \right. = 0.753$$

$$S_e := C_{load} \cdot C_{size} \cdot C_{surf} \cdot C_{temp} \cdot C_{reliab} \cdot S'_e = 12.335$$

$$S_m := \left| \begin{array}{l} \text{return } \left(0.75 \cdot S_{ut}\right) \;\; \text{if } \; load = \text{"axial"} \\ \left(0.9 \cdot S_{ut}\right) \;\; \text{otherwise} \end{array} \right. = 42.3$$

$$S_e = a \cdot N^b$$

$N_1 := 1000$ cycles $\quad$ N_1 is always 1000 cycles

$N_2 := 10^6$ cycles $\quad$ for a material with a knee

$$z := \log\left(N_1\right) - \log\left(N_2\right) = -3$$

$$b := \frac{1}{z} \cdot \log\left(\frac{S_m}{S_e}\right) = -0.178$$

$$\log(a) = \log\left(S_m\right) - 3 \cdot b$$

$a := \dfrac{S_m}{\left(10^3\right)^b} = 145.056$

$N := 10^6$

$S_e := a \cdot N^b = 12.335$ ksi endurance limit (stress level below which material can be cycled infinitely without failure)

$S_m := \left| \begin{array}{l} \text{return } \left(0.75 \cdot S_{ut}\right) \text{ if load} = \text{"axial"} \\ \left(0.9 \cdot S_{ut}\right) \text{ otherwise} \end{array} \right. = 42.3$ ksi

$S_f = a \cdot N^b$

$N_1 := 1000$ cycles N_1 is always 1000 cycles

$N_2 := 10^6$ cycles for a material with a knee

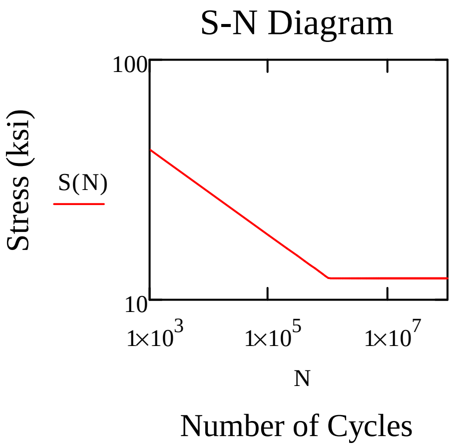
$z := \log\left(N_1\right) - \log\left(N_2\right) = -3$

$b := \dfrac{1}{z} \cdot \log\left(\dfrac{S_m}{S_e}\right) = -0.178$

$a := \dfrac{S_m}{\left(10^3\right)^b} = 145.056$

$S(N) := \left| \begin{array}{l} \text{return } a \cdot N^b \text{ if } N < 10^6 \\ S_e \text{ otherwise} \end{array} \right.$

range $N := 10^3, 10^5 .. 10^8$



$S_e := S\left(10^6\right) = 12.335$ ksi

endurance limit (stress level below which material can be cycled infinitely without failure)

Estimating Cycles of Life for Rear Axle with Worn Surface:

$S_n = a \cdot N^b$

$\sigma_a := \sigma_{Ax} = 0.857 \cdot \text{ksi}$

$S_n := \dfrac{\sigma_a}{\text{ksi}} = 0.857$

$a = 145.056$

$\log(a) = 2.162$

$b = -0.178$

$\log\left(S_n\right) = -0.067$

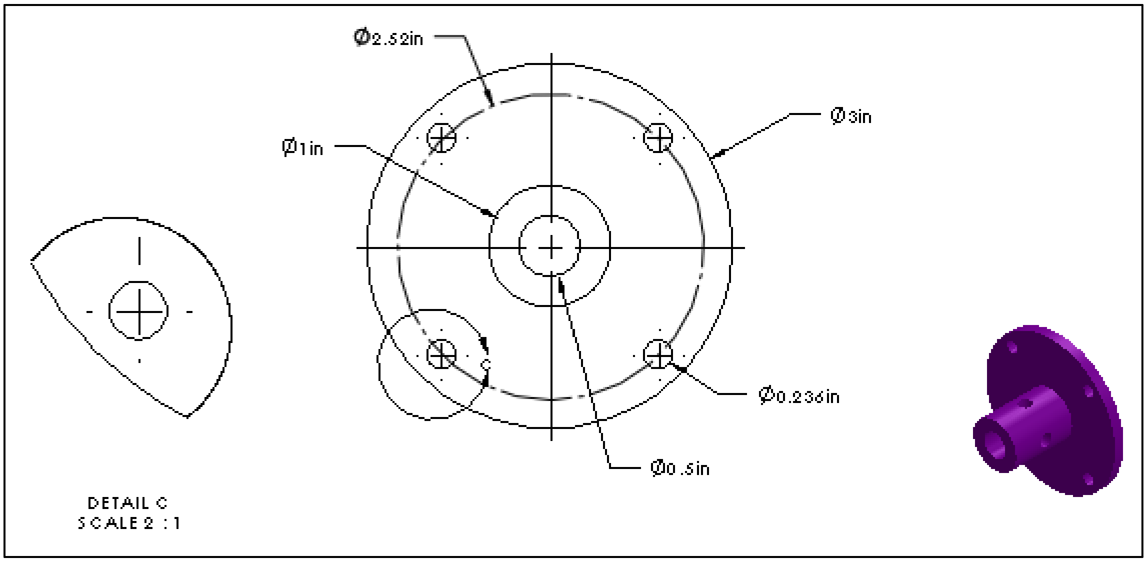
$N := 10^{\frac{\log\left(S_n\right) - \log(a)}{b}} = 3.107 \times 10^{12}$ cycles of life

Conclusion:

Since the safety factors, calculated above, are greater than 1, the Rear Axle will be able to support the applied load. The cycles of life of the Rear Axle is approximately 3*1028 cycles for a machined surface and 3*1012 cycles for a worn surface, which are beyond 106 cycles. Given the tricycle will be used for rehabilitation, the rear axle of the tricycle will only complete 1,512,000 cycles within its typical life which is less than the calculated life of the axle. The estimated number of cycles the axle will endure was calculated assuming a rehabilitative use of the tricycle for half an hour rehabilitation sessions 5 times a week, for 5 years. Given that the estimated cycles of the rear axle is less than the calculated cycles of life for the axle, the weakest available type of steel, AISI 1010, will be more than sufficient for the rear axle of a tricycle drivetrain.

Appendix G

Shear Stress Analysis of Rear Sprocket Bolts



Front View of Rear Sprocket Half Spool and Detail View of Bolt Hole

$OD_{large} := 3in$ outer diameter of flange of Half Spool

$P := 22.8W$ power (calculated from the team's test ride of original tricycle)

$\omega := 17.5rpm$ angular velocity of cranks/chainrings (calculated from the team's test ride of original tricycle)

$T := \frac{P}{\omega} = 110.115 \cdot lbf \cdot in$ torque

$F_{torque\_tangent} := \frac{T}{.5 \cdot OD_{large}} = 326.545\,N$ force tangent to Rear Sprocket Half Spool due to torque

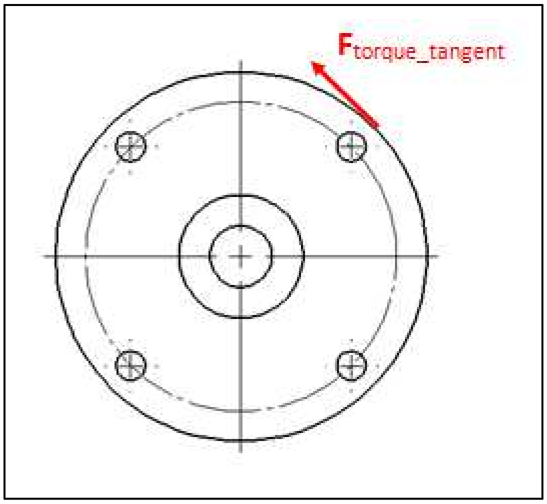
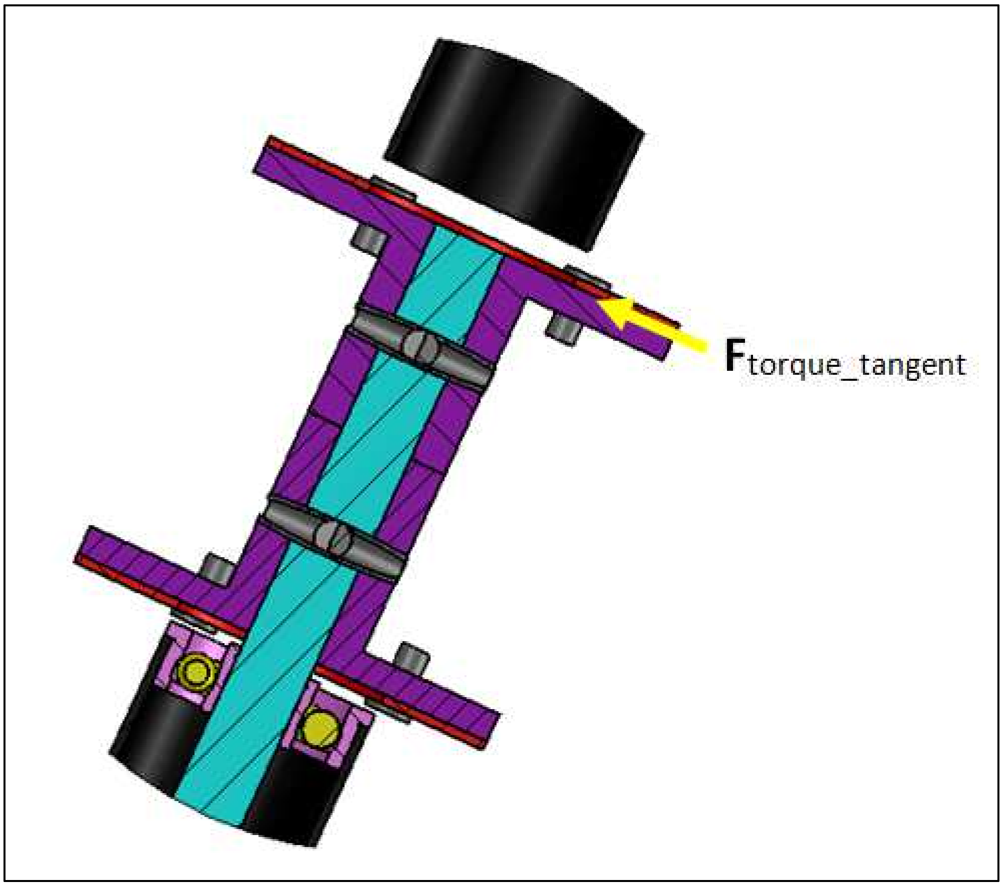


Diagram of Tangential Force on Rear Sprocket Half Spool due to Torque



Cross-Section View of Rear Sprocket Half Spools and Force Causing Shear Stress in Bolts

$S_y := 241\text{MPa}$ Tensile Yield Strength for Stainless Steel (Type 330 Annealed) Socket Cap Screw

$S_{ut} := 80\text{ksi} = 551.581 \cdot \text{MPa}$ Tensile Strength for Stainless Steel (Type 330 Annealed) Socket Cap Screw

$S_{us} := 0.6 \cdot S_{ut} = 330.948 \cdot \text{MPa}$ Shear Strength for Stainless Steel (Type 330 Annealed) Socket Cap Screw

$D_{bolt} := 0.236\text{in} = 5.994 \cdot \text{mm}$ diameter of bolt holes

$A_{bolt} := \frac{\pi \cdot D_{bolt}^{2}}{4} = 28.222 \cdot \text{mm}^2$ cross-sectional area of bolt

$\tau_{bolt} := \frac{F_{torque\_tangent}}{A_{bolt}} = 11.571 \cdot \text{MPa}$ shear stress in bolt

$\tau_{xy} := \tau_{bolt} = 11.571 \cdot \text{MPa}$ shear stress

$\sigma_x := 0\text{MPa}$ $\sigma_y := 0\text{MPa}$ normal stresses

$\sigma' := \sqrt{\sigma_x{}^2 + \sigma_y{}^2 - \sigma_x \cdot \sigma_y + 3 \cdot \tau_{xy}{}^2} = 20.041 \cdot \text{MPa}$ von Mises effective stress

$N := \dfrac{S_y}{\sigma'} = 12.025$

A safety factor of 12.025 suggests that the rear sprocket bolts will not shear under the given load and will in fact withstand loads up to 12 times the given load.

Sources:

"The shear strength of a steel fastener is about 0.6 times the tensile strength." (http://www.boltscience.com/pages/faq.htm)

"When no shear strength is given for common carbon steels with hardness up to 40 HRC, 60 % of their ultimate tensile strength is often used once given a suitable safety factor. This should only be used as an estimation." pg 2 (http://www.fastenal.com/content/documents/FastenalTechnicalReferenceGuide.pdf)

"The tensile strength of most fasteners is a common specification whereas shear strength is not." pg 12 (http://www.fastenal.com/content/documents/FastenalTechnicalReferenceGuide.pdf)

80,000 psi Minimum Tensile Strength for Stainless Steel Socket Cap Screw (SC Fastening) (http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=5&cad=rja&ved=0CEAQFjAE&url=http%3A%2F%2Fwww.scfastening.com%2Fimages%2FSocketscapalloy.pdf&ei=rw0QU4u4BefG0wGGwYCwBg&usg=AFQjCNGn2fkCvT3FcyGkfV1mVgaL80n1Dw&sig2=fX0Y8BnzwUp_3FKerT4LPg&bvm=bv.61965928,d.dmQ)

Appendix H

Force Analysis of Drivetrain

Source: http://www.real-world-physics-problems.com/bicycle-physics.html

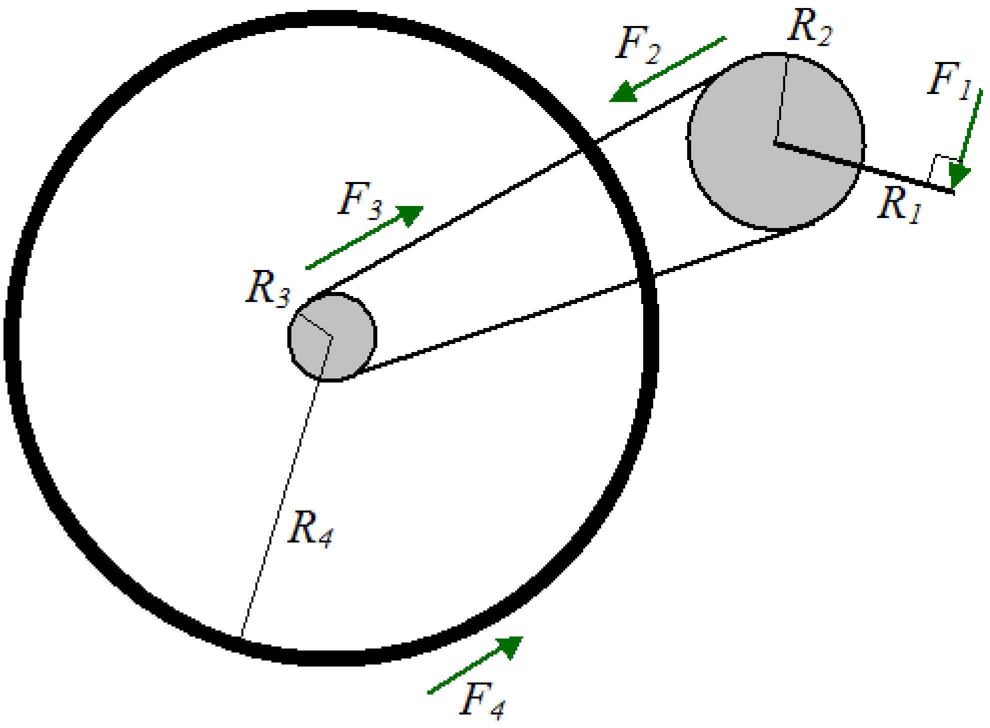


Figure 1. FBD of Right Side of Drivetrain with Large Chainring

Note: yellow highlighted variables = inputs that can vary based on user and riding location

$F_1 := 10\text{lbf}$	force applied by user's leg to the pedal attached to the large front chainring
$R_1 := 6.9\text{in}$	crank length
$R_2 := 3\text{in}$	radius of large front chainring
$R_3 := 1.5\text{in}$	radius of rear sprocket
$R_4 := 12\text{in}$	radius of rear wheel
$F_1 \cdot R_1 = F_2 \cdot R_2$ $F_3 \cdot R_3 = F_4 \cdot R_4$	assuming internal losses within the drivetrain are negligible

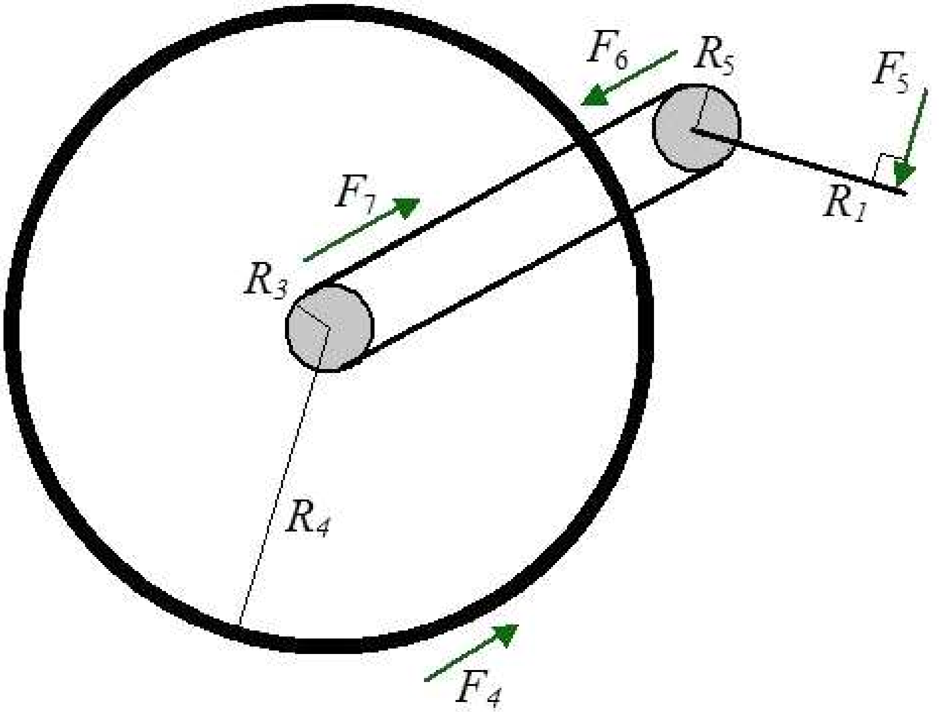


Figure 1. FBD of Left Side of Drivetrain with Small Chainring

$F_5 := 0.5\text{lbf}$ force applied by user's leg to the pedal attached to the small front chainring

$R_5 := 1.5\text{in}$ radius of small front chainring

$F_5 \cdot R_1 = F_6 \cdot R_5$

assuming internal losses within the drivetrain are negligible

$F_7 \cdot R_3 = F_4 \cdot R_4$

$F_4 := F_1 \cdot \frac{R_1 \cdot R_3}{R_2 \cdot R_4} + F_5 \frac{R_1 \cdot R_3}{R_5 \cdot R_4} = 3.163 \cdot \text{lbf}$ force causing motion

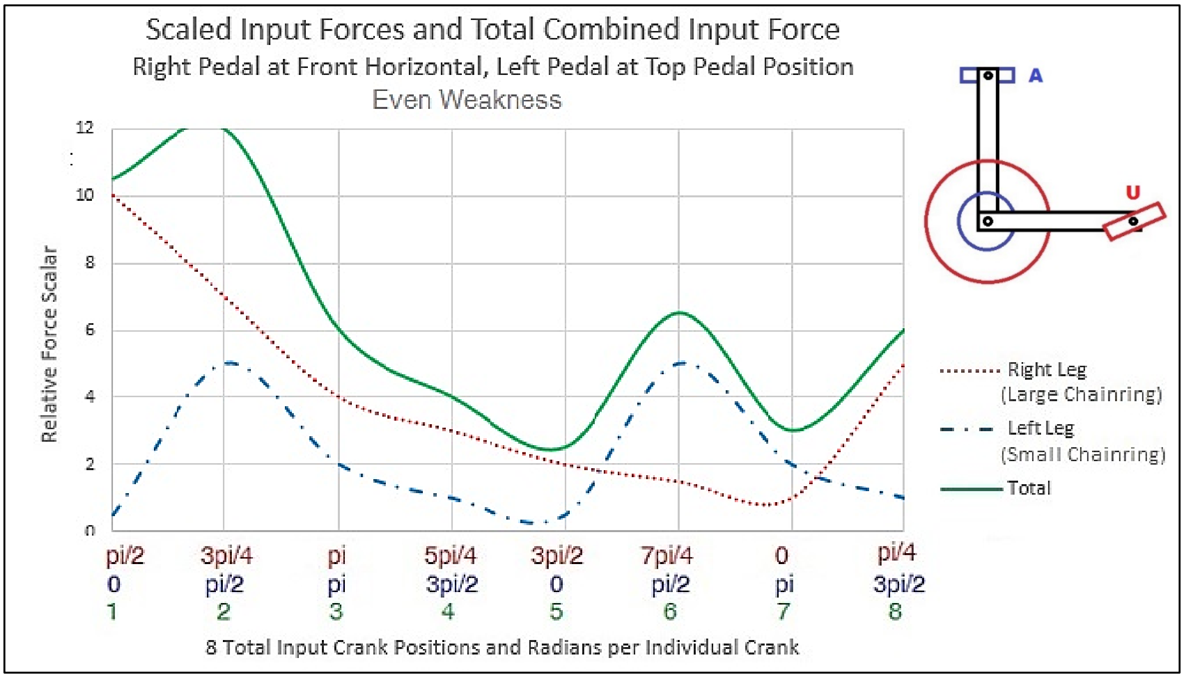
Phasing

Able – Even

	Total Relative Force Scalars Based on Starting Crank Positions and Position in Pedaling Cycle Right Leg Able - Left Leg Even Weakness											
		Position in Pedaling Cycle										
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**MAX**	**MIN**	**Variation**
Starting Crank Position	RT LT	1.5	10.0	12.0	8.0	4.5	8.0	4.0	2.5	12.0	1.5	12.2
	RT LF	6.0	7.0	11.0	7.5	9.0	5.0	3.0	2.0	11.0	2.0	7.8
	RT LD	3.0	6.0	10.5	12.0	6.0	4.0	2.5	6.5	12.0	2.5	10.1
	RT LB	2.0	5.5	15.0	9.0	5.0	3.5	7.0	3.5	15.0	2.0	15.0
	RF LT	10.5	12.0	6.0	4.0	2.5	6.5	3.0	6.0	12.0	2.5	10.1
	RF LF	15.0	9.0	5.0	3.5	7.0	3.5	2.0	5.5	15.0	2.0	15.0
	RF LD	12.0	8.0	4.5	8.0	4.0	2.5	1.5	10.0	12.0	1.5	12.2
	RF LB	11.0	7.5	9.0	5.0	3.0	2.0	6.0	7.0	11.0	2.0	7.8
	RD LT	4.5	8.0	4.0	2.5	1.5	10.0	12.0	8.0	12.0	1.5	12.2
	RD LF	9.0	5.0	3.0	2.0	6.0	7.0	11.0	7.5	11.0	2.0	7.8
	RD LD	6.0	4.0	2.5	6.5	3.0	6.0	10.5	12.0	12.0	2.5	10.1
	RD LB	5.0	3.5	7.0	3.5	2.0	5.5	15.0	9.0	15.0	2.0	15.0
	RB LT	2.5	6.5	3.0	6.0	10.5	12.0	5.0	5.0	12.0	2.5	9.9
	RB LF	7.0	3.5	2.0	5.5	15.0	9.0	4.0	4.5	15.0	2.0	14.9
	RB LD	4.0	2.5	1.5	10.0	12.0	8.0	3.5	9.0	12.0	1.5	13.4
	RB LB	3.0	2.0	6.0	7.0	11.0	7.5	8.0	6.0	11.0	2.0	7.1

Right Front Left Top (RFLT)

Relative Force Scalars Based on Crank Positions								
Crank Position Within a Full Cycle								
(Radians)	**pi/2**	**3pi/4**	**pi**	**5pi/4**	**3pi/2**	**7pi/4**	**0**	**pi/4**
Red (Right Crank)	10	7	4	3	2	1.5	1	5
(Radians)	**0**	**pi/2**	**pi**	**3pi/2**	**0**	**pi/2**	**pi**	**3pi/2**
Blue (Left Crank)	0.5	5	2	1	0.5	5	2	1
Position	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Total Relative Force Scalar	10.5	12	6	4	2.5	6.5	3	6

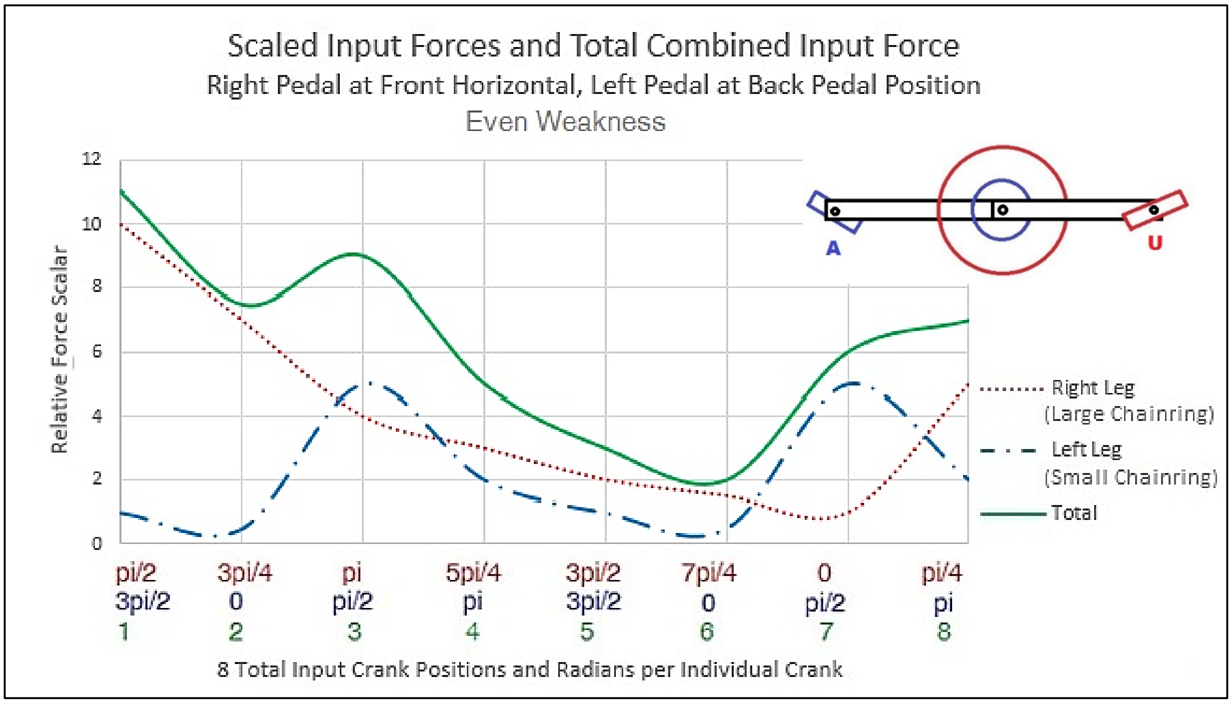

Scaled Input Forces and Total Combined Input Force

Right Pedal at Front Horizontal, Left Pedal at Top Pedal Position

Even Weakness

Right Front Left Bottom (RFLB)

Relative Force Scalars Based on Crank Positions								
Crank Position Within a Full Cycle								
(Radians)	**pi/2**	**3pi/4**	**pi**	**5pi/4**	**3pi/2**	**7pi/4**	**0**	**pi/4**
Red (Right Crank)	10	7	4	3	2	1.5	1	5
(Radians)	**3pi/2**	**0**	**pi/2**	**pi**	**3pi/2**	**0**	**pi/2**	**pi**
Blue (Left Crank)	1	0.5	5	2	1	0.5	5	2
Position	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Total Relative Force Scalar	11	7.5	9	5	3	2	6	7

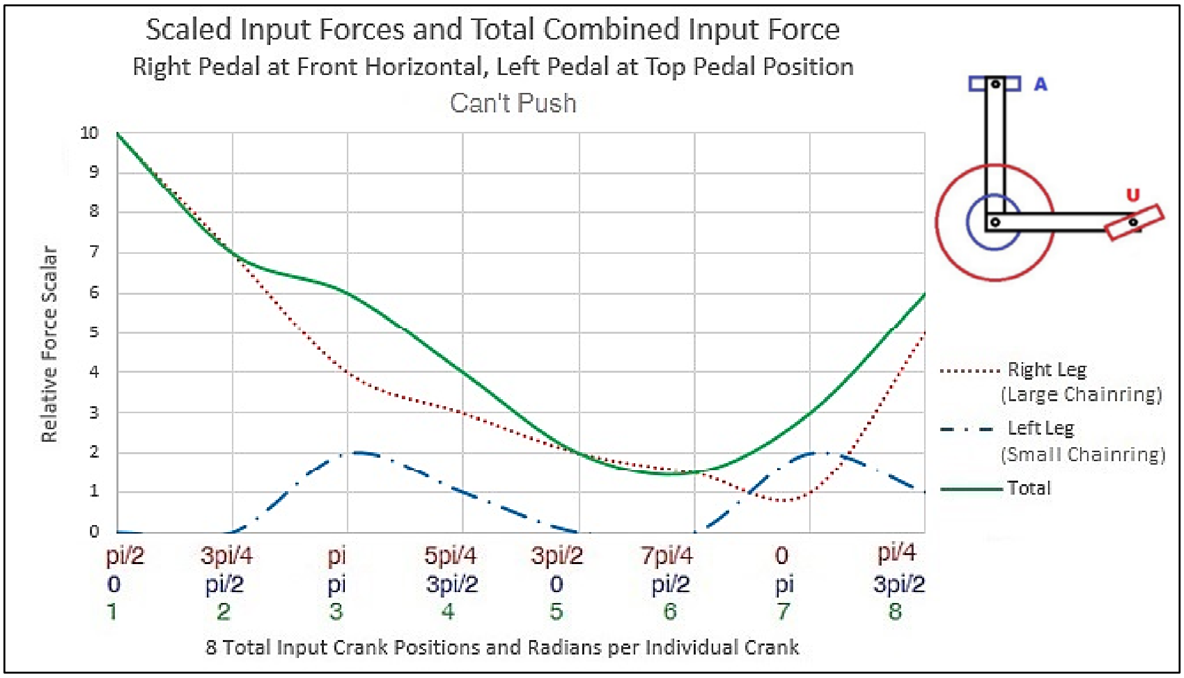


Can’t Push

	Total Relative Force Scalars Based on Starting Crank Positions and Position in Pedaling Cycle Right Leg Able - Left Leg Can't Push											
		Position in Pedaling Cycle										
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**MAX**	**MIN**	**Variation**
Starting Crank Position	**RT LT**	1.0	5.0	12.0	8.0	4.0	3.0	4.0	2.5	12.0	1.0	12.3
	RT LF	1.0	7.0	11.0	7.0	4.0	5.0	3.0	1.5	11.0	1.0	11.0
	RT LD	3.0	6.0	10.0	7.0	6.0	4.0	2.0	1.5	10.0	1.5	8.2
	RT LB	2.0	5.0	10.0	9.0	5.0	3.0	2.0	3.5	10.0	2.0	9.3
	RF LT	10.0	7.0	6.0	4.0	2.0	1.5	3.0	6.0	10.0	1.5	8.2
	RF LF	10.0	9.0	5.0	3.0	2.0	3.5	2.0	5.0	10.0	2.0	9.3
	RF LD	12.0	8.0	4.0	3.0	4.0	2.5	1.0	5.0	12.0	1.0	12.3
	RF LB	11.0	7.0	4.0	5.0	3.0	1.5	1.0	7.0	11.0	1.0	11.0
	RD LT	4.0	3.0	4.0	2.5	1.0	5.0	12.0	8.0	12.0	1.0	12.3
	RD LF	4.0	5.0	3.0	1.5	1.0	7.0	11.0	7.0	11.0	1.0	11.0
	RD LD	6.0	4.0	2.0	1.5	3.0	6.0	10.0	7.0	10.0	1.5	8.2
	RD LB	5.0	3.0	2.0	3.5	2.0	5.0	10.0	9.0	10.0	2.0	9.3
	RB LT	2.0	1.5	3.0	6.0	10.0	7.0	5.0	5.0	10.0	1.5	7.9
	RB LF	2.0	3.5	2.0	5.0	10.0	9.0	4.0	4.0	10.0	2.0	9.0
	RB LD	4.0	2.5	1.5	10.0	12.0	8.0	3.5	9.0	12.0	1.5	15.3
	RB LB	3.0	1.5	1.0	7.0	11.0	7.0	3.0	6.0	11.0	1.0	11.6

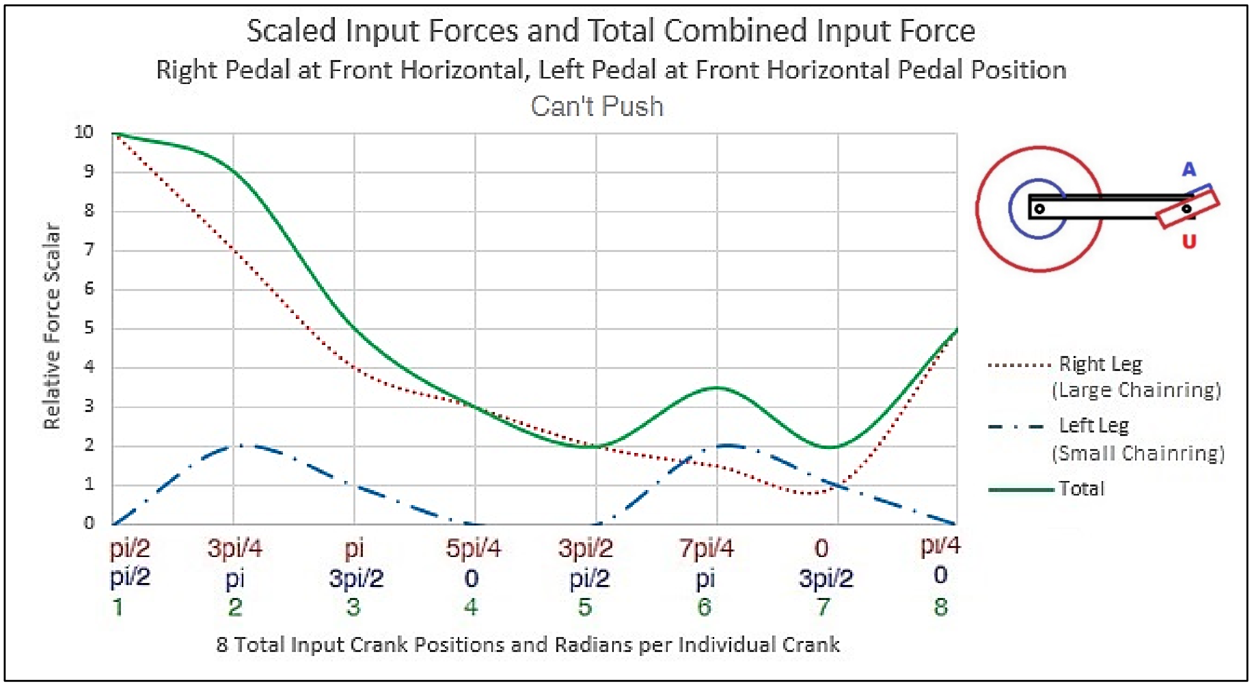
Right Front Left Top (RFLT)

Relative Force Scalars Based on Crank Positions								
Crank Position Within a Full Cycle								
(Radians)	**pi/2**	**3pi/4**	**pi**	**5pi/4**	**3pi/2**	**7pi/4**	**0**	**pi/4**
Red (Right Crank)	10	7	4	3	2	1.5	1	5
(Radians)	**0**	**pi/2**	**pi**	**3pi/2**	**0**	**pi/2**	**pi**	**3pi/2**
Blue (Left Crank)	0	0	2	1	0	0	2	1
Position	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Total Relative Force Scalar	10	7	6	4	2	1.5	3	6



Right Front Left Front (RFLF)

Relative Force Scalars Based on Crank Positions								
Crank Position Within a Full Cycle								
(Radians)	**pi/2**	**3pi/4**	**pi**	**5pi/4**	**3pi/2**	**7pi/4**	**0**	**pi/4**
Red (Right Crank)	10	7	4	3	2	1.5	1	5
(Radians)	**pi/2**	**pi**	**3pi/2**	**0**	**pi/2**	**pi**	**3pi/2**	**0**
Blue (Left Crank)	0	1	0.5	0	0	1	0.5	0
Position	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Total Relative Force Scalar	10	8	4.5	3	2	2.5	1.5	5

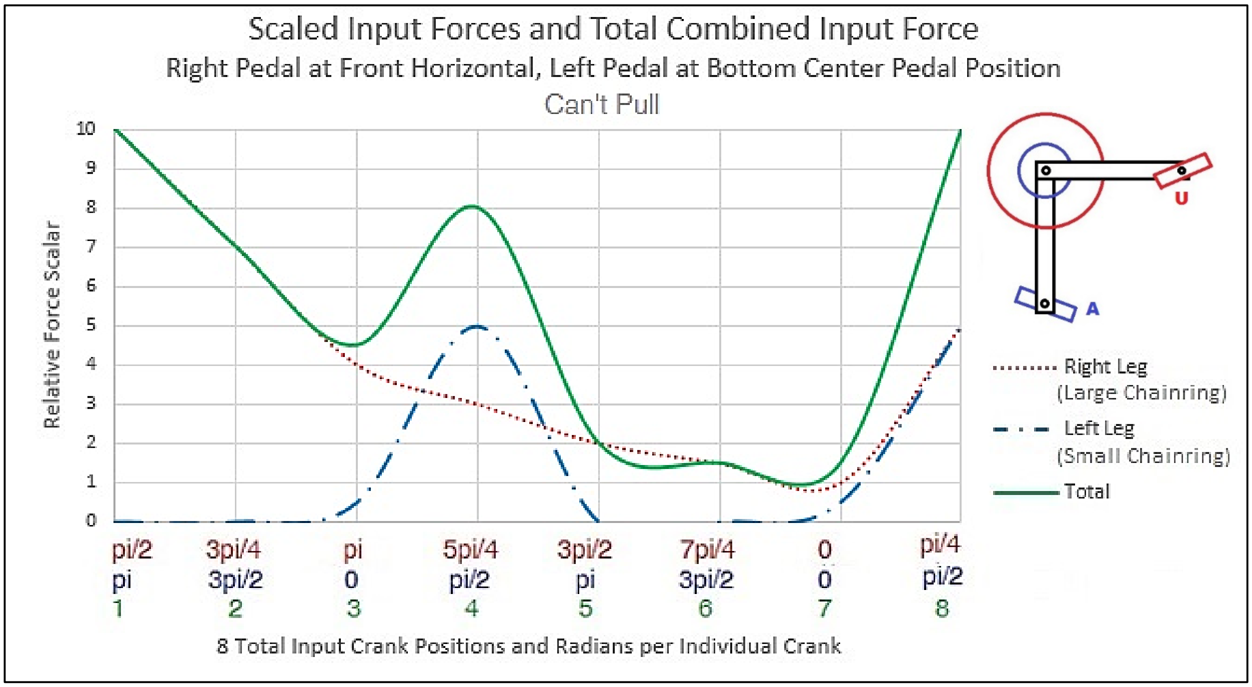


Can’t Pull

		Total Relative Force Scalars Based on Starting Crank Positions and Position in Pedaling Cycle for Right Leg Able - Left Leg Can't Pull										
		Position in Pedaling Cycle										
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**MAX**	**MIN**	**Variation**
Starting Crank Position	RT LT	1.5	10.0	10.0	7.0	4.5	8.0	2.0	1.5	10.0	1.5	11.8
	RT LF	6.0	5.0	10.0	7.5	9.0	3.0	2.0	2.0	10.0	2.0	8.5
	RT LD	1.0	5.0	10.5	12.0	4.0	3.0	2.5	6.5	12.0	1.0	13.3
	RT LB	1.0	5.5	15.0	7.0	4.0	3.5	7.0	1.5	15.0	1.0	17.2
	RF LT	10.5	12.0	4.0	3.0	2.5	6.5	1.0	5.0	12.0	1.0	13.3
	RF LF	15.0	7.0	4.0	3.5	7.0	1.5	1.0	5.5	15.0	1.0	17.2
	RF LD	10.0	7.0	4.5	8.0	2.0	1.5	1.5	10.0	10.0	1.5	11.8
	RF LB	10.0	7.5	9.0	3.0	2.0	2.0	6.0	5.0	10.0	2.0	8.5
	RD LT	4.5	8.0	2.0	1.5	1.5	10.0	10.0	7.0	10.0	1.5	11.8
	RD LF	9.0	3.0	2.0	2.0	6.0	5.0	10.0	7.5	10.0	2.0	8.5
	RD LD	4.0	3.0	2.5	6.5	1.0	5.0	10.5	12.0	12.0	1.0	13.3
	RD LB	4.0	3.5	7.0	1.5	1.0	5.5	15.0	7.0	15.0	1.0	17.2
	RB LT	2.5	6.5	1.0	5.0	10.5	12.0	3.0	4.0	12.0	1.0	13.3
	RB LF	7.0	1.5	1.0	5.5	15.0	7.0	3.0	4.5	15.0	1.0	17.3
	RB LD	2.0	1.5	1.5	10.0	10.0	7.0	3.5	9.0	10.0	1.5	12.9
	RB LB	2.0	2.0	6.0	5.0	10.0	7.5	8.0	4.0	10.0	2.0	7.2

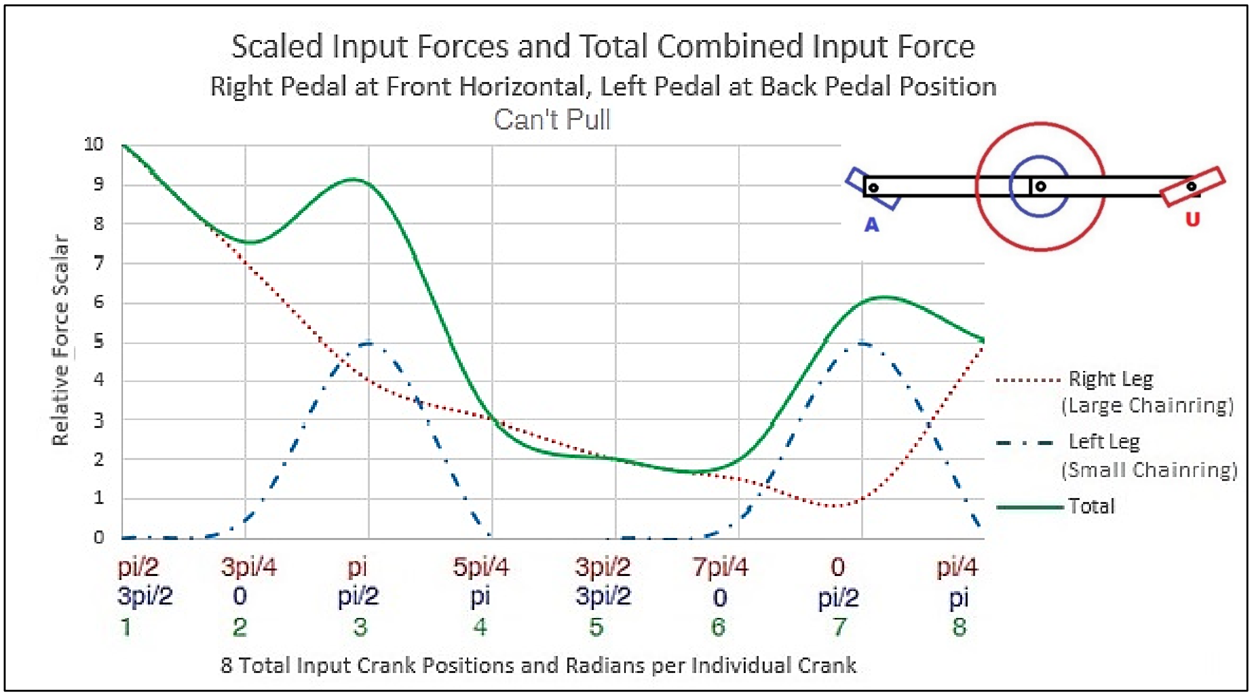
Right Front Left Down (RFLD)

Relative Force Scalars Based on Crank Positions								
Crank Position Within a Full Cycle								
(Radians)	**pi/2**	**3pi/4**	**pi**	**5pi/4**	**3pi/2**	**7pi/4**	**0**	**pi/4**
Red (Right Crank)	10	7	4	3	2	1.5	1	5
(Radians)	**pi**	**3pi/2**	**0**	**pi/2**	**pi**	**3pi/2**	**0**	**pi/2**
Blue (Left Crank)	0	0	0.5	5	0	0	0.5	5
Position	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Total Relative Force Scalar	10	7	4.5	8	2	1.5	1.5	10



Right Front Left Back (RFLB)

Relative Force Scalars Based on Crank Positions								
Crank Position Within a Full Cycle								
(Radians)	**pi/2**	**3pi/4**	**pi**	**5pi/4**	**3pi/2**	**7pi/4**	**0**	**pi/4**
Red (Right Crank)	10	7	4	3	2	1.5	1	5
(Radians)	**3pi/2**	**0**	**pi/2**	**pi**	**3pi/2**	**0**	**pi/2**	**pi**
Blue (Left Crank)	0	0.5	5	0	0	0.5	5	0
Position	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Total Relative Force Scalar	10	7.5	9	3	2	2	6	5



Appendix I

Testing and Evaluation Procedures

Evaluation: 1. Safety and Functionality

Design Specification: 8 – Consumer Safety Standards

- A bicycle may not have unfinished sheared metal edges or other sharp parts that may cut a rider's hands or legs. Sheared metal edges must be rolled or finished to remove burrs or feathering.
- Screws, bolts, and nuts used to fasten parts may not loosen, break, or fail during testing.
- Pedals must have treads on both sides. However, pedals that have a definite side for the rider to use only have to have a tread on that side. Pedals intended to be used only with toe clips do not have to have treads as long as the toe clips are firmly attached to the pedals. However, if the clips are optional, the pedal must have treads.
- A chain must operate over the sprocket without binding or catching, and must have a tensile strength of 1800 lbf (1400 lbf for sidewalk bicycles).
- Bicycles without toe clips must have pedals that are at least 3 ½ inches from the front tire or fender when the front tire is turned in any direction.

7 – The device will not modify the weight (64 pounds) of the tricycle by more than 20%, preferably by 10% only to reduce the excess force need.
9 – The device should not intrude into the user's space within the area of the frame between the seat and the handle bars.
10 – The device should be able to be manufactured by the team using the available tools and resources of the WPI machine shop.
11 – The device must be constrained by the dimensions of the tricycle used for the creation of the prototype.
12 – The device should be able to be maintained by a local bicycle shop.
13 – This device must be able to be built with the given budget of $420.

Method: The team will inspect the tricycle in the Testing Lab before Evaluation 3.

Each design spec will be evaluated on a pass/fail basis to determine if the design will be able to move forward to field testing. If any of the design fails to meet any of the critical design specifications, the team will reevaluate the design to ensure safety and function.

This will allow the team to identify any problems before physical testing.

Precautions:	The team must watch for sharp edges
Special Conditions/ Limitations:	N/A
Equipment/ Facilities:	Testing Lab, Tricycle, tensile testing results will be acquired from chain manufacturer
Data Recording:	Report will be written on the inspection of each of the design specifications with a pass/fail with further comments

Evaluation: 2. Recreation

Design Specifications: **6 –** The device must allow for the tricycle to be used for recreational purposes, such as riding around a 0.25 mile stretch of a rail trail of 3 percent at a minimum speed of 3 miles per hour.

Method: Ten participants will take a pre-test to solidify that no one will be injured while testing. A passing score will consist of all 2s. If someone does not pass the pre-test they will not be asked to test the tricycle.

The official test of the tricycle will be done by the rider doing 2 laps around the Quad. The first lap will be a test lap for the person so they can understand the motion of the tricycle. They will be told to casually ride the tricycle to get used to the motion in this lap.

After this first lap, they will then be equipped with a GPS device that will keep track of their time and speed. Each participant will be asked to ride around the quad once maintaining a speed of at least 3 miles per hour. (Participants will be told to pedal at a comfortable speed at their own discretion. The MQP team will find the average speed of the participants who are healthy, able-bodied, young adults. Since the typical person who has had a stroke loses 50% of the strength in their affected leg, we can hypothesize weather or not the intended user of the tricycle would be able to reach a speed of 3 miles per hour based on the average speed of the participants in the testing.) They can monitor their speed using the GPS device provided.

At the end of the lap the time of the lap will be recorded and the MQP team will calculate the average speed and record the data collected from observing the lap.

The user will then be asked to complete a survey answering questions about their ride along with any opinions or comments they may have.

Precautions: Helmets will need to be worn.

Special Conditions/ Limitations: Snow may affect the conditions.

Equipment/ Facilities: Helmet, the tricycle, the Quad

Data Recording: The test survey will be collected and all data will be tabulated into a findings report.

Evaluation:	3. Rehabilitation
Design Specifications:	1 – This device must only be powered by human input in order to maximize the rehabilitative effect. 2 – This device must be able to adjust for different power inputs from leg to leg. 3 – The device must allow for repetitive circular pedaling motion with the knee range of motion of 108 degrees to 37 degrees (where full extension is 0 degrees), the hip range of motion of 63 degrees to 110 degrees (the angle between the torso and the thigh) and ankle range of motion of at least 20 degrees (the angle between the lower leg and foot). 4 – It would be beneficial for the input power to propulsion ratio of the device to be adjustable. 5 – It would be beneficial if the device allowed the user to pedal one-legged.
Method:	Contact Professionals at Worcester Physical Therapy to discuss the use of the tricycle and how it would benefit or assist in rehabilitation of a patient recovering from a stroke. The team must first contact and schedule a meeting time with a rehabilitation therapist or medical professional who is knowledgeable of stroke rehabilitation methods. Next the team will bring the modified tricycle to the physical therapy center. The team will explain a study of error augmented training on a split belt treadmill. They will then demonstrate how the design works for the professional and then interview them for their opinions on how the design works and if they think it would aid the rehabilitative process.
Precautions:	N/A
Special Conditions/ Limitations:	Access to the facility and professionals
Equipment/ Facilities:	Worcester Physical Therapy
Data Recording:	The contact with the professional will be conducted in an interview format with two teammates talking and the third recording notes of the professional’s opinions.

Appendix J

Consumer Product Safety Commission Standards

This section is directly from (CPSC – Bicycle Requirements, 2002)

Bicycle Requirements Business Guidance

AUGUST 01, 2002

What is the purpose of the requirements for bicycles?

What is the purpose of the requirements for bicycles?

This regulation increases the safety of bicycles by establishing, among other things, requirements for assembly, braking, protrusions, structural integrity and reflectors. Bicycles that fail any of the requirements are banned under the Federal Hazardous Substances Act.

Where can I find the requirements for bicycles?

The requirements are in the Code of Federal Regulations (CFR) in Title 16, Part 1512.

What is a bicycle?

A bicycle has two wheels. The rear wheel drives the bicycle, using only the power of the rider. The bicycle requirements cover two different types of bicycles. Those with a seat that is more than 25 inches above the ground when the seat is adjusted to its highest position must meet all of the requirements. Sidewalk bicycles – those with a seat height of 25 inches or less – are exempt from some of the requirements or have other alternative requirements. These exemptions and alternatives are marked in bold type in this summary.

Are any bicycles exempt from the requirements?

Yes. Track bicycles designed and intended for use in competition that have tubular tires, a single crank–to wheel ratio, and no freewheeling feature are exempt and so are one-of-a-kind bicycles made to the order of an individual without assembling stock or production parts.

How are bicycles tested in general?

Assembled bicycles must meet the requirements of the regulation in the condition in which they are offered for sale. Unassembled or partially assembled bicycles must meet the requirements after assembly according to the manufacturer’s instructions.

Figure J1. Bicycle Standards (CPSC – Bicycle Requirements, 2002)

Are there any general requirements that bicycles must meet?

Yes.

(1) Adults of normal intelligence and ability must be able to assemble a bicycle that requires assembly.

(2) A bicycle may not have unfinished sheared metal edges or other sharp parts that may cut a rider's hands or legs. Sheared metal edges must be rolled or finished to remove burrs or feathering.

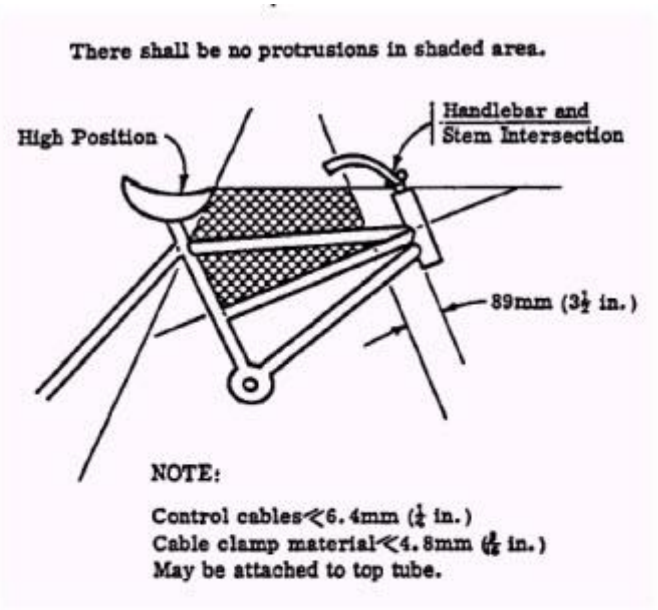
(3) When the bicycle is tested for braking and/or or road performance, neither the frame, nor any steering part, wheel, pedal, crank, or braking system part may show a visible break.

(4) Screws, bolts, and nuts used to fasten parts may not loosen, break, or fail during testing.

(5) Control cables must be routed so that they do not fray from contact with fixed parts of a bicycle or with the ends of the cable sheaths. The ends of control cables must be capped or treated so that they do not unravel.

(6) A bicycle may not have any protrusions within the shaded area of Diagram 1. However, control cables up to ¼ inch thick and cable clamps made of material not thicker than 3/16 inch may be attached to the top tube.

Figure J2. Operator Envelope (CPSC – Bicycle Requirements, 2002)



What are the requirements for brakes?

Bicycles must have front and rear brakes, or rear brakes only. Sidewalk bikes may not have hand brakes only. Sidewalk bikes with a seat height of 22 inches or more when adjusted in the lowest position must have a foot brake. A sidewalk bike with a seat height of less than 22inches need not have any brake as long as it does not have a freewheeling feature, has a permanent label saying “No brakes”, and has the same statement on its advertising and shipping cartons.

(1) Hand brakes:

(a) When tested, hand brakes may not break, fail, or have clamps that move or parts that go out of alignment. To test the brakes, push the hand lever all the way down to the handlebar or with a force of 100 pounds (lbf) and then load test the bicycle, or rock it back and forth with a 150-pound weight on the seat.

(b) Hand levers have to be on the handlebars and readily usable. The distance between middle of a hand lever and the handlebar may be no wider than 3 ½ inches (3 inches for levers on sidewalk bicycles). Unless a customer specifies otherwise, the hand lever that operates the rear brake must be on the right handlebar. The lever that operates the front brake must be on the left handlebar. A lever that operates both brakes may be on either handlebar. Please note that, if a bicycle has hand lever extensions, all tests are conducted with the extensions in place.

(c) A bicycle that only has hand brakes must stop within 15 feet when tested with a 150-pound rider riding at 15 miles per hour.

(d) When the hand lever is pushed down with 10 pounds or less applied 1 inch from the end of the lever, the brake pads must contact the braking surface on the wheel. Caliper brake pads must be replaceable and adjustable. Pads must stay in their holders without movement when a 150-pound rider rocks the bicycle forward and backward.

(e) Brake assemblies must be securely fastened to the bicycle frame with locking devices such as lock washers or locknuts, and must not loosen during the rocking test. Brake pad holders must be securely attached to the caliper assemblies.

(2) Foot brakes:

(a) Foot brakes must operate independently of any drive-gear positions or adjustments. Foot brakes must have a braking force of at least 40 lbf when 70 pounds of force is applied to the pedal.

(b) Bicycles with foot brakes must stop within 15 feet when tested with a rider of at least 150 pounds at a speed of 10-mph. A bicycle operated in its highest gear ratio at 60 pedal crank revolutions per minute that reaches a speed of more than 15 mph must stop in 15 feet when tested at a speed of 15 mph if it has a foot brake only.

(c) A foot brake must operate by applying force in the direction opposite to the force that drives the bicycle forward, unless the brakes are separate from the pedals and apply the braking force in the same direction as the drive force.

(d) When you hold a torque of 10 ft-lb at each point on the crank at which a rider can apply the brakes, that point cannot be more than 60 degrees away from the point on the crank at which the rider can start to pedal forward.

(3) Foot brake/ hand brake combinations: Bicycles with foot brake/ hand brake combinations must meet all the requirements for foot brakes listed above. If such a bicycle operated in its highest gear ratio at 60 pedal crank revolutions per minute reaches a speed of more than 15 mph, the bicycle must stop in 15 feet when tested at a speed of 15 mph using both types of brakes

What are the requirements for steering systems?

(1) The handlebar stem must withstand a force of 450 lbf (225 lbf for sidewalk bicycles) in a forward direction 45 degrees from the stem centerline when. The handlebar stem must have a permanent mark or circle showing the minimum depth that the stem must be inserted into the bicycle fork. That mark must be located a distance of at

least 2 ½ times the diameter of the stem from the bottom of the stem, and must not affect the strength or integrity of the stem.

(2) Handlebars should be symmetrical on either side of the stem. The handlebar ends should be no more than 16 inches above the seat when the seat is in its lowest position and the handlebars are in their highest position.

(3) The ends of the handlebars must be capped or covered. Grips, plugs, and other devices mounted on the ends must not come off when a force of 15 lbf is applied.

(4) When the handlebar/stem assembly is twisted with a torque of 35 ft-lb (15 ft-lb for sidewalk bicycles), it must not move or show any signs of damage. When the handlebars are twisted with the stem being held firmly, the handlebars must support a force of 100 lbf or absorb no less than 200 inch pounds of energy while bending no more than 3 inches. During this test, the handlebars must be tight enough so that they do not turn in the handlebar clamp. After the test, they cannot show any visible sign of breaking.

What requirements must pedals meet?

(1) Pedals must have treads on both sides. However, pedals that have a definite side for the rider to use only have to have a tread on that side. Pedals intended to be used only with toe clips do not have to have treads as long as the toe clips are firmly attached to the pedals. However, if the clips are optional, the pedal must have treads.

(2) Bicycle pedals must have reflectors. Sidewalk bicycle pedals do not have to have reflectors.

What are the requirements for chains and chain guards?

(1) A chain must operate over the sprocket without binding or catching, and must have a tensile strength of 1800 lbf (1400 lbf for sidewalk bicycles).

(2) Bicycles with a single front and a single rear sprocket must have a chain guard over the top of the chain and least 90% of the part of the front sprocket that the chain contacts. It 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. Past that point, the top of the guard may taper down until it is ½ inch of the chain width. The guard must 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.

(3) Derailleurs must be guarded to prevent the chain from interfering with or stopping the wheel through improper adjustment or damage.

Are there requirements for tires?

Yes. The manufacturer's recommended inflation pressure must be molded onto the sidewalls of inflatable tires in letters at least ⅛ inch high. The tire must stay on the rim when it is inflated to 110% of the recommended pressure, even when it is tested under a side load of 450 lbf. Tires that do not inflate, tubular sew-up tires, and molded wired-on tires do not have to meet any of these requirements.

What requirements are there for wheels?

A wheel must have all of its spokes and be at least 1/16 inch away from each side of the fork and from any other part of the frame as the wheel turns. When the wheel is tested with a side load of 450 lbf, the tire and spokes must stay on the rim. Sidewalk bikes do not have to meet the side load requirements.

What requirements must wheel hubs meet?

All bicycles (other than sidewalk bicycles) must meet the following requirements:

(1) Each wheel must have a positive locking device that fastens it to the frame. Use the manufacturer's recommended torque to tighten threaded locking devices. The locking devices on front wheels (except for quick-release devices) must not loosen or come off when a tester tries to take them off using a torque of 12.5 ft-lb applied in the direction of removal. Once fastened to the frame, the axle of the rear wheel must not move when it receives a force of 400 lbf for 30 seconds applied in the direction that removes the wheel.

(2) Quick-release devices with a lever must be adjustable to allow the lever to be set for tightness. Riders must be able to clearly see the levers and determine whether the levers are locked or unlocked. When it is locked, the clamping action of the quick release device must bite into the metal of frame or fork.

(3) Front wheel hubs that do not use a quick release device must have a positive retention feature that keeps the wheel on when the locking devices are loosened. To test this, release or unscrew the locking device, and apply a force of 25 lbf to the hub in the same direction as the slots in the fork.

Are there strength requirements for the fork and frame?

Yes. Clamp the front fork in the test fixture so it does not move and apply force until the fork bends 2 ½ inches. The fork shall have no evidence of fracture. The deflection at a force of 350-in-lbs shall be no greater than 2½ inches. Also, when the fork is mounted on the bicycle frame, the fork and frame assembly must withstand a steady force of 200 lbf or an impact force of 350 in-lbs, whichever is more severe, without breaking, or bending in a manner that would significantly limit the steering angle over which the front wheel can turn. These requirements do not apply to sidewalk bicycles.

What are the requirements for seats?

(1) The seat post must have a permanent mark or circle showing the minimum depth that the post must be inserted into the bicycle frame. That mark must be located a distance of at least two times the diameter of the seat post from the bottom of the post, and must not affect the strength of the post.

(2) No part of the seat, seat supports, or accessories attached to the seat may be more than 5 inches above the surface of the seat.

(3) The clamps used to adjust the seat must be able to fasten the seat to the seat post in any position to which the seat can be adjusted and prevent the seat from moving during normal use. Following testing, neither the seat nor seat post may move when subjected to a downward force of 150 lbf (75 lbf for sidewalk bicycles) or a horizontal force of 50 lbf (25 lbf for sidewalk bicycles).

Are there requirements for reflectors?

Yes. To make sure that motorists can see bicycle riders at night, bicycles (other than sidewalk bicycles) must have a combination of reflectors. Because of the complexity of these requirements, we have not attempted to include all of the tests and detail in this summary.

Generally, bicycles must have a colorless front reflector, recessed colorless or amber reflectors on the back and front sides of the pedals, and a red reflector on the rear. They must also have a reflector mounted on the spokes of each wheel, or reflective front and rear wheel rims or tire sidewalls.

The front and rear reflectors must be mounted so that they do not hit the ground when the bicycle falls over. The requirements of the regulation also include specific angles for mounting the reflectors.

The side reflector on a front wheel must be colorless or amber, and the rear wheel side reflector must be colorless or red. Reflective material on the sidewall or rim of a tire must go around the entire circumference, must not peel, scrape, or rub off, and must meet certain reflectance tests.

What other requirements must bicycles meet?

(1) A rider weighing at least 150 pounds must ride a bicycle at least 4 miles with the tires inflated to maximum recommended pressure. The rider must travel five times at a speed of at least 15 miles per hour over a 100 foot cleated course. During these tests, the bicycle must handle, turn and steer in a stable manner without difficulty, the

frame and fork, brakes, and tires must not fail, and the seat, handlebars, controls, and reflectors must not become loose or misaligned. These requirements do not apply to sidewalk bicycles.

(2) A sidewalk bicycle loaded with a weight of 30 lb. on the seat and 10 lb. on each handlebar grip must be dropped (while maintaining an upright position) one foot onto a paved surface three times in the upright position. Without the weights, the bicycle must be dropped three times on each side in any other orientation. During these tests, the wheels, frame, seat, handlebars, and fork must not break.

(3) A bicycle must be able to tilt 25 degrees to either side with the pedals in their lowest position without the pedal or any other part of the bicycle (other than tires) hitting the ground.

(4) Bicycles without toe clips must have pedals that are at least 3 ½ inches from the front tire or fender when the front tire is turned in any direction.

What requirements are there for instructions and labeling for bicycles?

(1) Every bicycle must have an instruction manual attached to its frame or included in the bicycle packaging. The manual must include operation and safety instructions, assembly instructions for complete and proper assembly, and maintenance instructions.

(2) If a bicycle is sold less than fully assembled or adjusted, any advertising material and the outside of the shipping carton must include a list of tools necessary to assemble and adjust the bicycle and a drawing showing the minimum length of the leg of a rider for whom the bicycle is appropriate. That length must allow at least one inch between the top tube and the crotch of the rider when the rider’s feet are on the ground.

(3) Every bicycle must have a permanent marking or label that shows the name of the manufacturer or private labeler and that the manufacturer or private labeler can use to identify the month and year the bicycle was manufactured. If the bicycle is privately labeled, the label must have information that the private labeler can use to identify the manufacturer of the bicycle.

Where can I find additional information?

For more information on the requirements contact the Consumer Product Safety Commission, Office of Compliance, Washington, D.C. 20207, telephone: (301) 504-7913, E-mail: sect15@cpsc.gov.

Appendix K

Pre-Testing Evaluation

With the scale given below please check the box that applies to your leg's motion for each category.

0	Unable to perform the test movement through the appropriate range
1	Able to perform only part of the movement
2	Able to complete the movement without any problems

Rating	0	1	2
Flexes hip and knee in supine (bend hip and knee so that the foot rests flat on the bed)			
Raise hips off bed into bridge from lying down with knees bent, flat feet			
Extends knee in sitting			
Flexes knee in sitting (from straight leg to 110°)			
Dorsiflexes ankle in sitting (keep heel on the ground and lift toes off the floor as far as possible)			
Plantar flexes ankle in sitting (keep toes on the ground and lift heel off the floor as far as possible)			
Extends knee and dorsiflexes ankle in sitting (straighten knee and bring toes toward the body)			
Rise to standing from sitting (asymmetry in trunk)			
Maintains standing for 20 counts			
Abducts affected hip with knee extended (while standing)			
Flexes affected knee with hip extended (while standing)			
Dorsiflexes affected ankle with knee extended (while standing)			
Places affected foot to take first step (from standing to walking)			
Takes 3 steps backwards			
Take 3 steps sideways to affected side			
Walks 10 meter indoors			
Walk down 3 stairs alternating feet			

Appendix L

Evaluation Procedure 1 Safety and Functionality

8.1 – A bicycle may not have unfinished sheared metal edges or other sharp parts that may cut a rider's hands or legs. Sheared metal edges must be rolled or finished to remove burrs or feathering.

- No additional sharp edges found. The sprockets could be considered sharp while rotating, but they are in the same configuration and they were previously. They are also covered by the chain which prevents exposed points.

8.3 – Screws, bolts, and nuts used to fasten parts may not loosen, break, or fail during testing.

- The fasteners did not create any issues during testing.

8.5 – Pedals must have treads on both sides. However, pedals that have a definite side for the rider to use only have to have a tread on that side. Pedals intended to be used only with toe clips do not have to have treads as long as the toe clips are firmly attached to the pedals. However, if the clips are optional, the pedal must have treads.

- The pedals have treads on both sides and have removable baskets.

8.6 – A chain must operate over the sprocket without binding or catching, and must have a tensile strength of 1800 lbf (1400 lbf for sidewalk bicycles).

- Chain purchased from bike alley and therefore must pass the tensile requirements.
- It does not catch or bind. It could be smoother, but it passes.

8.9 – Bicycles without toe clips must have pedals that are at least 3 ½ inches from the front tire or fender when the front tire is turned in any direction.

- Our trike has baskets, but before the baskets are attached the pedals have plenty of clearance. After attaching the baskets, the clearance is reduced to 2 inches.

9 – The device should not intrude into the user's space within the area of the frame between the seat and the handle bars.

- The device does not intrude into the users space

10 – The device should be able to be manufactured by the team using the available tools and resources of the WPI machine shop.

- We had to purchase a left hand die, however, the tool the die attaches to as well as all other tools were easily accessible

11 – The device must be constrained by the dimensions of the tricycle used for the creation of the prototype.

- The device was able to be used with the tricycle obtained for the prototype

12 – The device should be able to be maintained by a local bicycle shop.

- The device was created using materials obtainable at a local bike shop

13 – This device must be able to be built with the given budget of $420.

- The device was built costing only $311.42

Evaluation Procedure 2. Recreation

Preliminary Testing Survey

1. Do you believe this device could be used for recreational purposes, such as riding around a 0.25 mile stretch of a neighborhood on a flat road? (Did you enjoy riding the Tricycle around the Quad?)

Participant	YES	NO
1		X
2	X	
3	X	
4	X	
5	X	

Comments:
1 - It was pretty difficult
2 - The first few pedals were fun
4 – However, it was awkward when two feet where making the motion at the same time. It didn't feel like enough force
5 - Enjoyable for most of the ride except the awkward hop when both legs were pulling up

2. Did the pedaling components intrude into your personal space more than that of a normal bicycle?

Participant	YES	NO
1	X	
2		X
3	X	
4		X
5		X

Comments:
1 - My right leg was bent really close to my body while trying to pedal
3 - Not a lot of intrusion, I think it could be because of the seat orientation
(Note: Participant 3 was male, and the trike seat was designed for women)

3. Were you able to adapt to the non-traditional pedaling pattern?

Participant	YES	NO
1		X
2		X
3	X	
4	X	
5	X	

Comments:
1 - I couldn't figure it out, hard to get started
2 - I don't know
4 - But it was not comfortable
5 – Slowly, but yes

4. Would you have preferred a different gear ratio for pedaling?
(The current ratio is 1 to 2 left foot to right foot.)

Participant	Higher	Lower	Same	Unsure
1				X
2				X
3			X	
4	X			
5	X			

Comments:
1 – I'm not really sure
2 - I do not know, I could not pedal properly
4 - 1 to 3 might not line up as funny
5 - 1 to 3 might not line up as funny or 2 to 4

5. Did you feel that both of your legs were applying force to the pedals?
(Answer No if one foot was just following along the entire time without exerting any force on the pedal)

Participant	YES	NO	Unsure
1			X
2			X
3	X		
4	X		
5	X		

Comments:
1 - I'm also not sure
3 - Although it wasn't an equal force for each pedal. My dominant foot (right foot) was exerting a greater force on the right pedal than my left foot on the left pedal.
4 – At points yes
5 - Most of the time, but not all the time

6. If you answered yes to number 5:
While pedaling the tricycle with both legs, did you notice if it required more force to rotate one pedal compared to the other? If so, comment which side was easier.

Participant	YES	NO	N/A
1			X
2			X
3	X		
4	X		
5	X		

Comments:
3 - Although it wasn't an equal force for each pedal. My dominant foot (right foot) was exerting a greater force on the right pedal than my left foot on the left pedal.
4 – left
5 - right

7. Did you experience any difficulties in operating the tricycle? If so, please explain.

Participant	YES	NO
1	X	

2	X	
3	X	
4	X	
5	X	

Comments:
1 - I kept getting “stuck” and couldn’t move the tricycle
2 - I do not know, I could not pedal properly
3 - The left chain kept dislodging
4 – Learning curve
5 – Getting used to the awkwardness

8. What is your experience riding bicycles? Do you have any history?
   1 – For fun
   2 – Its been a while…
   3 – I ride bicycles frequently around my hometown, and I compete in triathlons.
   4 – Recreationally
   5 – just for fun

9. In your opinion, what made riding this tricycle different from riding a standard bicycle or tricycle?

   1 - It was a lot more difficult, it took more effort, I had to think about what I was doing
   3 - Acclimating to the abnormal rhythm of the pedals, but I assume it will be less difficult for an individual who has suffered a stroke to become accustomed to it.
   4 – Understanding how to pedal
   5 – getting used to the gear ratio