Modified Bicycle Motion

Preliminary Proposal

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October 2016

ME 476C – Section 1

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1 BACKGROUND

1.1 Introduction

This project is about modifying a bicycle to limit range of motion in the knee joint. The project was presented by our client Dr. Scot Raab, an assistant professor of Athletic Training at Northern Arizona University. Dr. Raab has suffered a knee injury that resulted in his meniscus being removed. This severely limits his range of motion in his knee making it difficult to ride a bicycle. Although there are products that accomplish this, they tend to limit torque output, making it difficult for the rider to go uphill and attain high speeds. The objective of this project is to design a device for a standard bicycle that will limit range of motion in the knee with minimal torque loss.

1.2 Project Description

Following is the original project description provided by the sponsor:

> "Modified Bicycle Motion"
>
> Problem: Cyclist (recreational or competitive) that suffer knee injuries limiting ROM (Range of Motion) must give up cycling because the top of the pedal stroke causes extreme flexion of the knee. This results in abnormal forces across the knee joint and the patellar femoral articulation causing discomfort.
>
> Current attempted solutions:
>
> 1. Raise seat height but to go too high prevents appropriate alignment at the bottom of the pedal stroke and may result in rocking left and right on the saddle resulting in low back issues or soft tissue damage to the Perineum (area of soft tissue between what cyclist refer to as the sit bones or the ischium's)
> 2. Shorten the crank arm of the pedal but this decreases torque and speed available to the cyclist or ability to climb inclines.
>
> Objective: Protect ROM (limit it) and allow cyclist to produce maximal torque using current gears available to cyclist via front or rear chain rings
>
> That last part almost allows the team to invent a new set of gears but that requires thinner, thicker, longer, or shorter chains, etc. As you add rings to the gears your chain must be thinner to fit between the gears or the hub needs to get wider and that create s wider bike, etc. The objective of this project is to limit the amount of drastic modifications to existing bikes, but provide a smaller ROM for the rider.
>
> Create a modification that can be applied to (one size, multiple sizes?) standard bikes to modify the motion of the cyclist so their knees do not bend beyond 90 degrees."

1.3 Original System

This project involves the modified design of a standard two-wheel bicycle design. A standard bicycle is composed of a frame, fork, wheels, drivetrain, handlebars, brakes, and a saddle.

1.3.1 Original System Structure

A standard bicycle frame design consists of a double diamond design and features a fork that is placed in the head tube of the frame. Bicycles can be made from steel, aluminum, titanium, or carbon fiber. Most bicycle components are made of either aluminum or carbon fiber depending on the price level of the build. The figure below is of a standard road bike and has all of the components labeled.

Figure 1: Bicycle Diagram

1.3.2 Original System Operation

A standard bicycle converts mechanical energy from the user into translational motion. This is performed via the drivetrain system containing a set of chain-driven gears. This set of gears is put in motion by the user through the pedals. The bicycle's drivetrain contains a set of adjustable gears, allowing the user to shift to a different gear ratio depending on terrain. This system is cable-operated, and adjusted manually by the user via a switch on the handlebars. This same handlebar system contains the controls for the cable-operated brakes and steering functionality [1].

1.3.3 Original System Performance

The weight of our client's road bicycle is 19 lb. and the general modern mid-range road bike weighs around 17-18 lbs. Our client generally averages about 15-16 mph on his bike rides, but can fluctuate due to head or tail winds and the amount of climbing or descent included in the ride.

1.3.4 Original System Deficiencies

The current system forces the user to bend their knee at an angle less than 90 degrees at the top of the pedal stroke, causing pain for a rider with flexural knee issues. It is currently believed that a combination of the pedal crank arm length and seat height are the primary cause of this issue. Table 1 tabulates a list of commonly manufactured crank arm lengths.

Table 1: Commonly Manufactured Lengths of Crank Arms

Crank Arm Length (mm)
165
170
172.5
175

2 REQUIREMENTS

2.1 Customer Requirements (CRs)

Our customer requirements are rated on a scale of 1 to 5, 1 being the least important. Our customer requirements are durability (4), retrofittability (5), low weight (3), maximum torque (5), low cost (3), safety (5), and aesthetics (2).

We rated retrofittablity as a 5 because our client wants a device that he can attach to his own bicycle instead of having to replace his entire bicycle. We rated maximum torque as a 5 because this is one of our main objectives and what will distinguish our design from existing designs. We rated safety as a 5 due to our engineering code ethics. We rated durability as a 4 because we desire for our design to not break in a crash and for it to withstand uneven terrain. We rated low weight as a 3 because low weight is desirable and convenient, but not necessary. We rated low cost as a 3 because we would like our product to be accessible to more cyclists. Finally, we rated aesthetics as a 2 because we value function over form.

2.2 Engineering Requirements

Engineering Requirements were derived from our customer requirements and they are listed below in Table 2. The first requirement for the design is added weight. Since our client will be using his bike for competition, the added weight should not exceed 300 grams in order to make the bike easier to ride and faster up hill climbs. The second requirement for the design is the cost, which should be less than $250 per design. The third engineering requirement for the design is to be able to sustain a falling weight of more than 50 lbs. at a height of 0.6 ft., which is the safety standard bicycles are typically designed and tested for. The fourth engineering requirement of the design is power generation. The maximum difference in power generation of our design should be within 5% of the power generated by a standard crank arm. The fifth engineering requirement for the design that the knee angle should always be greater than 90^o in order to reduce the pain our client experiences at the top of the pedal stroke.

Table 2: Engineering Requirements

Sr. no	Requirement	Condition
1	Added Weight	< 300g
2	Cost	< $250
3	Sustain Falling weight	50 lb at height of 0.6ft
4	Power generation as compared to standard cranks	Difference < 5%
5	Knee Angle	> 90°

2.3 House of Quality (HoQ)

A House of Quality is used to determine our most important engineering requirements for this project. In the table, the customer requirements are listed on the left and weighted in terms of importance on a scale of 1 to 5, 5 being the most important and 1 being the least important. The customer requirements are rated 0, 1, 3, or 9 depending upon their correlation with the engineering requirements. A 0 is no correlation, 1 is weak correlation, 3 is medium correlation, and 9 is strong correlation to the engineering requirements. The weight factor is multiplied by the correlation value and summed up at the bottom to find the absolute technical importance (ATI). The engineering requirement largest ATI number will be first in Relative Technical Importance (RTI) and RTI will continue down until the lowest ATI and that will be the last in RTI.

Table 3: House of Quality

		Engineering Requirements				
Customer Req.	Weight Factor	Added Weight <300 g	Design Cost <$250	Sustain Falling Weight ≥50 lbs At .6 ft	Power Generation <5% Difference Vs. Stnd. Cranks	Knee Angle > 90°
Durable	4	0	0	9	0	0
Retrofittable	5	1	0	0	0	0
Low weight	3	9	3	0	0	0
Max Torque	5	0	0	0	9	1
Low cost	3	1	9	0	0	0
Safe	5	0	0	3	0	0
Aesthetics	2	0	0	0	0	0
Knee Angle	4	0	0	0	1	9
Target (w/ tol.)		200 (<300) g	$160 (<$250)	55 (>50) lb at .6 ft	3 (<5) %	93°-141° (>90)
ATI		35	36	51	49	41
RTI		5	4	1	2	3
TP#						
DL#						

Our teams most import engineering requirement is the sustained falling weight. This engineering requirement won because if our design can sustain a falling weight of 50 lbs. it will be safe and durable by being able to sustain damage from a crash. Power generation and knee angle are also important engineering requirements to consider when designing our product.

3 EXISTING DESIGNS

3.1 Design Research

We researched many different existing designs that claim to help reduce forces on the knee joint and/or reduce the knee's range of motion, or the knee angle. We conducted web searches and wrote literature reviews on the existing designs we found, whether in the form of an article, a patent, or a product's website. The existing designs found are outlined and compared to customer requirements in Section 3.2.

3.2 System Level

The following section describes existing designs found and compares it to customer requirements and to the other existing designs.

3.2.1 Existing Design #1: Shortened Crank Arm (Orthopedal)

This design is a product currently on the market, called the Orthopedal. The Orthopedal is a small metal device that is attached onto a bicycle crank arm illustrated in Figure 1. It has four different slots along the crank arm to insert the pedal, thus adjusting the crank arm length. The shortened crank arm length results in a limited range of motion, causing reduced forces on the knee joint. However, it reduces torque capacity causing increased difficulty in biking uphill and reduced maximum speed. [2]

Figure 2: Orthopedal Crank Arm

3.2.2 Existing Design #2: Retractable/Extendable Crank Arm Patent

This design is a for a US patented retractable crank set for a bicycle. This crank set, illustrated in Figure 3, has a crank arm that extends and retracts depending on position. The crank shaft will be in the retracted phase at the top of the pedal stroke which will reduce the effects of patellar femoral articulation. Then the crank shaft will extend along the front side of the stroke which results in more produced torque. The crank path is illustrated in Figure 4 in orbital L. This design is similar, but is more desirable in terms of torque than the Orthopedal design described in 3.2.1. However, this design cannot be easily retrofitted onto different bicycles, like the Orthopedal. [3]

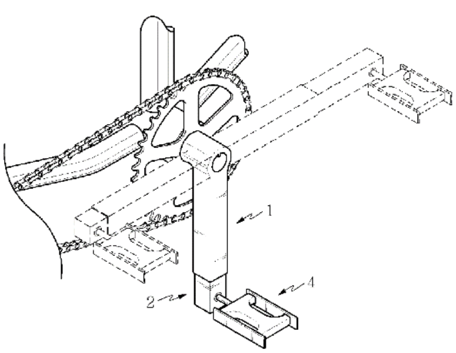

Figure 3: Extendable/Retractable Crank Arm

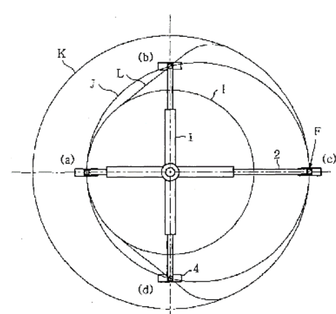

Figure 4: Pedal Path for Extentable/Retractable Crank Arm

3.2.3 Existing Design #3: CrankTip Pedal

This design is a device that is currently available on the market and is attached onto the pedal of a standard bicycle. The device has a dual swing-arm mechanism that moves the pedal in front of the end of the crank arm along the front of the pedal stroke causing increased torque. The crank arm shortens along the back of the stroke to reduce range of motion experienced by the knee at the top of the stroke. The path of the pedal for a CrankTip Pedal is compared to the pedal path of a standard pedal in Figure 5. This design can be easily retrofitted onto any bicycle and has a more desirable torque than the plain shortened crank arm design. However, it's high in cost. [4]

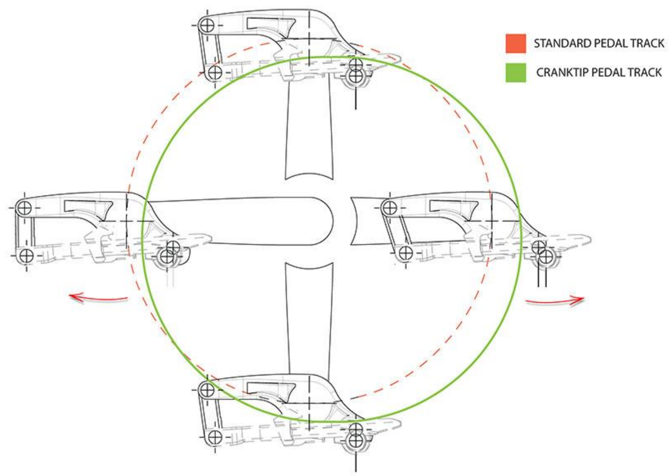

Figure 5: CrankTip Pedal Path vs. Standard Pedal Path

3.2.4 Existing Design #4: Kneesavers

This design is a small device that is currently on the market, called Kneesavers. It extends the pedals outward from the bicycle, as seen in Figure 6, reducing forces on the knee joint. This design changes the forces acting on the knee, however it does not affect the knee angle throughout the pedal stroke. [5]

Figure 6: Pedal without Kneesavers vs. Pedal with Kneesavers

3.2.5 Existing Design #5: Pivoting Crank Arm (Duke University)

This design was created by a group of students at Duke University. They were tasked with modifying a bicycle so that their client, who has limited range of motion in her left knee, can continue to bike as a hobby. Their design consists of a pivoting crank arm that pivots to shorten the crank arm, reducing the range of motion in the knee and making it more comfortable for the injured rider. This design is pictured in Figure 7 below. This design is limited due to its poor torque output which produces the same problem as the Orthopedal and the shortened crank arm. It reduces the maximum speed attainable and the ability to go uphill comfortably. [6]

Figure 7: Pivoting Crank Arm

3.2.6 Existing Design #6: Rotor Q-Rings

This design is of chain rings that are applied to standard cranks. The chain rings are elliptical in shape, shown in Figure 8, and reduce the patellar force on the knee at the top of the pedal stroke by making the chain ring size smaller. The chain ring becomes bigger along the front of the pedal stroke where the most power is produced, thus creating more torque. Although this does not directly affect the range of motion in the knee, it can be combined with a shortened crank arm to limit range of motion and increase torque output. [7]

Figure 8: Elliptical Rotor Q-Ring Chain Ring

3.3 Subsystem Level

The main function of this project is to propel the rider of the bicycle forward through the drivetrain of the bicycle. Firstly, the user applies force through the legs on to the pedals, which are attached to the end of crankset. The force from the crankset is applied to chain rings that causes them to rotate in a clockwise motion, the teeth on the chain ring pull the chain in the same direction. The chain will pull rotate the cassette (gear set located at the back of the bicycle) and the rear wheel in the clockwise direction. The content of the section below will be discussing the existing designs for (1) cranksets, (2) chains, and (3) cassettes.

3.3.1 Subsystem #1: Crankset

Force is applied through the pedals on the crank arms make them act as a lever. The chain rings are fixed to the crankset and rotate with the cranks in a clockwise motion.

3.3.1.1 *Existing Design #1:* Shimano Ultegra Crankset

The Shimano Ultegra road bicycle crankset features a four arm spider design for mounting two chain rings, capable of handling a variety of different chain ring sets, chain guide on chain rings to reduce chain dropping, made of aluminum, and works for 11 speed group sets. This product relates to our customer requirements by having optimal stiffness for power/torque transfer, durable, aesthetics, low weight (765g), and reasonably priced. [8]

Figure 9: Shimano Ultegra Crankset

3.3.1.2 Existing Design #2: Shimano XTR Trail Crankset

The Shimano XTR mountain bicycle crankset features three different four arm spider designs for mounting 1-3 chain rings (1X, 2X, or 3X), made for 11 speed group sets, and made of aluminum. This product relates to our customer requirements by providing optimal power transfer through the cranks, low weight (1X – 583g, 2X – 630g, and 3X – 656g), durable, aesthetics, and safe. [9]

Figure 10: Shimano XTR Trail Crankset (2X)

3.3.1.3 *Existing Design #3:* Campagnolo Super Record Crankset

The Campagnolo Super Record road bicycle crankset features a four arm spider design for mounting the two chain rings, step-up system on chain rings to enhance shifting performance, carbon construction, compatible with 11 speed group sets, and a simple assembly for ease of maintenance. This crankset relates the following customer requirements durable, aesthetics, no torque/power loss, and low weight (603g). [10]

Figure 11: Campagnolo Super Record Crankset

3.3.2 Subsystem #2: Chains

The chains are held in place by the toothed gears that are the chain rings and cassettes. The chain will carry the clockwise rotation of the crankset which will move the cassette and rear wheel.

3.3.2.1 *Existing Design #1:* Sram XX1 Eagle Chain

This Sram XX1 mountain bicycle chain features quiet operation, no interior square edges, increased wear resistance over previous iterations, hollow pins, and compatible with 12 speed group sets. This chain relates to the following customer requirements of being durable, low weight from the hollow pins, and aesthetics (gold colored). [11]

Figure 12: Sram XX1 Eagle Chain

3.3.2.2 *Existing Design #2:* Shimano Dura-Ace Chain

The Shimano Dura-Ace chain features hollow pins, a PTFE coating to help increase the wear resistance of the chain, and is compatible with 11 speed group sets. This product relates to our customer requirements by being low weight (243g) and having increased durability. [12]

Figure 13: Shimano Dura-Ace Chain

3.3.2.3 Existing Design #3: Muc-Off Nano Chain

The Nano Chain is a chain is not made by a bicycle component company, however it is made by company that makes chain lubricants. A chain can be chosen for the drivetrain of the purchaser's choice. The chain is hand treated and has a special lubricant applied to it to reduce drivetrain resistance and improve the chain's weatherproof capabilities. This chain meets the customer requirements of durability and improves the torque output efficiency of the drivetrain. [13]

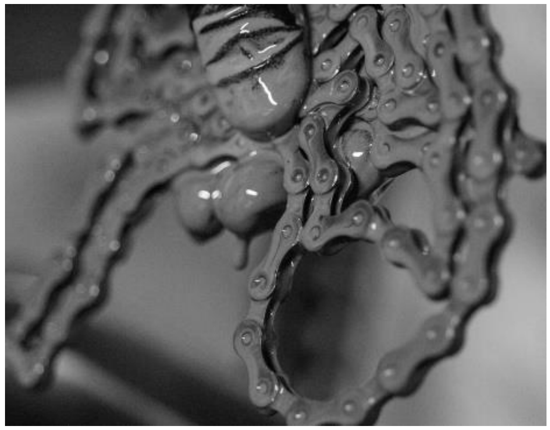

Figure 14: Muc-Off Nano Chain

3.3.3 Subsystem #3: Cassettes

The cassette the group of gears located at the rear of a bicycle and is attached to the rear wheel. The motion transferred from the chain causes the cassette to rotate clockwise and rotate the rear wheel.

3.3.3.1 Existing Design #1: Sram XX1 Eagle Cassette

Sram's XX1 Eagle Cassette is one of the only commercially available cassettes that has 12 cogs or gears on it, has a wide range of gears that are optimal for mountain biking (10-50 teeth), one of the strongest cassettes available, and has the smallest tooth available which has 10 teeth in it. This product meets the customer requirements of durability, maximum torque output from the 10 tooth cog, and aesthetics (gold colored). [14]

Figure 15: Sram XX1 Eagle Cassette

3.3.3.2 Existing Design #2: Campagnolo Super Record Cassette

The Campagnolo Super Record cassette features six titanium sprockets, has a nickel-chrome surface treatment to increase the life of the cassette, and the teeth are designed to provide maximum power transmission to the rear wheel. This design meets the customer requirements of maximum torque, durability, and lightweight (177g). [15]

Figure 16: Campagnolo Super Record Cassette

3.3.3.3 Existing Design #3: Shimano Ultegra Cassette

The Shimano Ultegra cassette features the availability to have a wide range of gears available for road cycling ranging from 11 to 32 teeth, which is better for climbing. This cassette aligns with the torque because an 11 is the general industry standard for the smallest number of cassette teeth and this design is reasonably priced. [16]

Figure 17: Shimano Ultegra Cassette

4 DESIGNS CONSIDERED

4.1 Crankset Slider

The crankset slider is a crank based concept that consists of crank with a channel machined out of it. A tension spring is attached at the top of the channel and to the pedal holder, which is the drawing on the right side of the figure below. In the 3 to 6 o'clock position of the pedal stroke the spring elongates, thus increasing the length of the crank. The crank length will be in the shortened at the top of the pedal stroke, which will allow the knee angle to open up and ease the pain in the knee. Advantages of this design is that it maximizes torque in the pedal stroke, low weight, keeps the knee at an angle greater than 90°, and is retrofittable. Disadvantages of this design is that there may be a safety and durability issue with the spring because it could break during a ride.

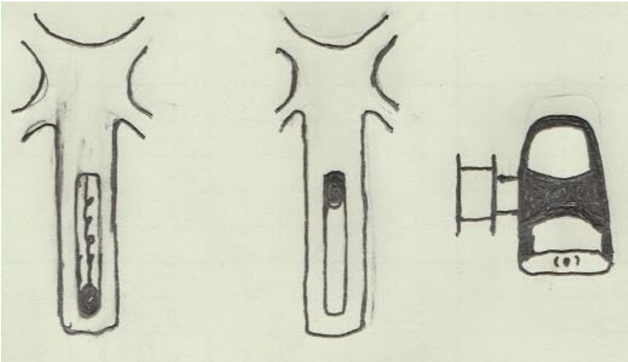

Figure 18: Crankset Slider Concept

4.2 Pedal Slider

The pedal slider design is similar to crankset slider except that it is mounted to a standard set of cranks. The design is a hollow rectangular box with an open side. A tension spring is attached to the top of the inside of the box and to the top of the pedal holder. This design screws into normally where the pedal would go and the straps on the top of it will wrap around the cranks to hold the pedal slider in place. Same as the crankset slider, the pedal slider's spring in the 3 to 6 o'clock position of the pedal stroke elongates and in the 12 o'clock position the spring will be retracted thus making the crank arm feel shorter and increasing the knee angle. Advantages of this design is that it is low weight, can be placed on any crankset with the same threading, and keeps the knee angle greater than 90°. Disadvantages of this design is there is a safety and durability issue with the spring and widens the rider's stance on the bicycle.

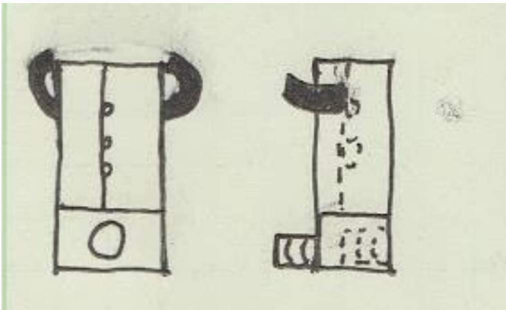

Figure 19: Pedal Slider Concept

4.3 Translating Cranks

The translating cranks is a crank based design. The design uses two vertical parallel bars that attach to the crank arms and to the pedal bar which is seen above the crank arm in the figure below. The two bars are allowed to move freely in either the left or right direction. In the lower half or 3 to 9 o'clock position of the pedal stroke the cranks will be in the extended position, illustrated by the drawing on top in the figure. This position will extend the crank length through part of the downward stroke, increasing the torque output. In the upper half of the pedal stroke or 9 to 3 o'clock position of the cranks, the cranks will be in the lower position shown in the figure. This will shorten the crank length at the top of the pedal stroke allowing for a greater knee angle. Advantages of this design is that it is retrofittable, able to maximize torque output in the pedal stroke, and keep the knee angle greater than 90^{o}. The disadvantages of this design is that the pedal bar moving freely may be difficult to adjust to and the vertical bars may break from impact forces of a crash.

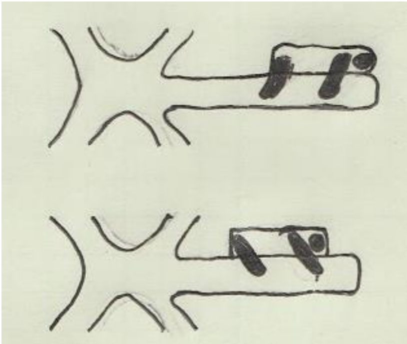

Figure 20: Translating Crankset Concept

4.4 Four Chainrings

The four chainrings design is the concept of creating a greater range of gears available to the rider. The gears would range from an extremely tall gear (55T or 54T) that can be used for fast descents or sprint finishes in a race to a small gear (30T or 32T) for steep and/or long climbs. The team recommends that this design is paired with short crank arms in order to keep the knee angle greater than 90^{o}. The advantages of this design is that the largest chairing would maximize torque output, increase the range of gears usable by the rider, and the design is durable. The disadvantages of the four chainrings is that there are no currently no commercially available cranksets, shifters, or front derailleurs that are designed to accommodate four chainrings on a bicycle.

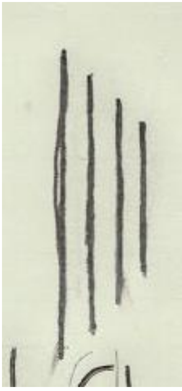

Figure 21: Four Chainrings Concept

4.5 Q-Rings / Elliptical Chainrings

Q-rings are commercially available elliptical chainrings, they are mentioned previously in section 3.2.6 of this report. The team recommends that this design is paired with short crank arms in order to keep the knee angle greater than 90º. These chainrings allow the user to produce more torque through the power phase of the pedal stroke and Q-rings reduce the force on the knee in the dead spots of the pedal, which is located at the top and bottom of the pedal stroke. The advantages of this design is that it is lightweight, durable, safe, retrofittable, and helps to produce maximal torque. The disadvantages of this design is that Q-rings drop chains more frequently than standard round chainrings, crank arm length is nonadjustable, and elliptical chainrings may take time to get accustomed to.

4.6 Gear Ratios

Adjusting the gear ratios on the client's bicycle is the simplest solution. This design involves making the chainrings larger and/or making the cassette teeth smaller in order to produce more toque through the drivetrain of the bicycle. The advantages of this design is that it is safe, durable, retrofittable, low weight, inexpensive, and simple. The disadvantages of this design is that the knee angle may be less that 90º and the torque increase in the system may be marginal.

4.7 Manually Adjustable Pedals

An issue with the current design of a shorter crank arm length is that it limits torque. This limited torque creates a disadvantage when in competitive applications. As a modification of this design, the user can adjust the crank arm length on an as-needed basis. By releasing a locking mechanism connecting the pedal to the crank arm, the user can move the pedal to several positions along the crank arm while riding. This results in a shorter effective crank arm length. In application, the rider can shorten the effective crank arm length while at cruising speeds, and lengthen it when extra torque is needed for added acceleration.

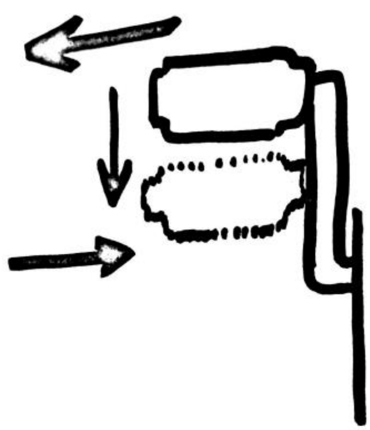

Figure 22: Manually Adjustable Pedals

4.8 CVT (Continuously Variable Transmission)

As currently designed, a CVT transmission maximizes the torque transferred from an engine to the wheels. This is done by having a large number of gear sets that seamlessly change gearing based on the input torque and rpm. These transmissions are frequently used in small (under 50cc) scooter applications. To explore the maximization of the available torque a user can utilize, the implementation of a CVT transmission may be advantageous. In application the user would not need to shift the bicycle, the gearing ratio delivering maximum torque would already be selected. This coupled with a shorter crank arm would provide the user with the maximum torque with minimal bending of the knee.

Figure 23: CVT Concept

4.9 Translating Seat

While current designs raise the seat to minimize knee bending, this causes discomfort and possible injury for the user. A different approach would be to translate the seat horizontally. This would change the angle the knees would bend without adding the unwanted discomfort. This design would be achieved by adding a horizontal post onto the seatpost. A metal pin would be inserted to lock the seat into the horizontal post.

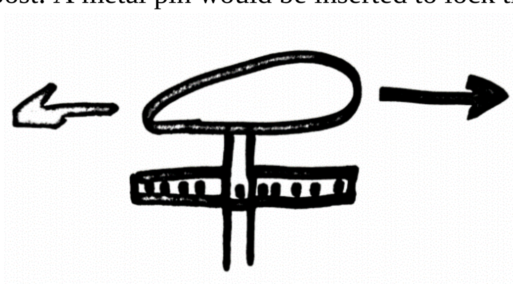

Figure 24: Translating Seat Concept

4.10 Modified Pedal Shape

In an attempt to create an adjustable crank arm length, a modification of the pedal can be utilized. In this design, the pedal would be modified to have multiple "steps" of height along its width. While this would significantly increase the width of the pedal, this would achieve an inexpensive and effective way to adjust the angle of the users' knees.

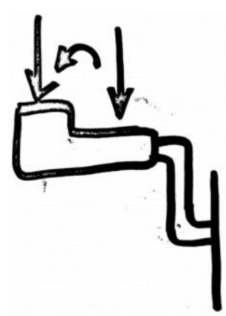

Figure 25: Modified Pedal Shape Concept

5 DESIGN SELECTED

5.1 Rationale for Design Selected

A decision matrix was used in order to decide which designs to pursue and is shown in Table 3. In the table, the customer requirements are listed on the left and weighted in terms of importance on a scale of 1 to 5, 5 being the most important. Each design is rated on a scale of 1 to 5, 5 being the design completely fulfills the customer requirement and 1 being the design doesn't satisfy the customer requirement. Each rating is multiplied by the customer requirement weighting and added together to create the total score.

Table 4: Decision Matrix

Customer Requirements:	Weightings:	Designs:									
		Crankset Slider	Translating Cranks	Pedal Slider	4 Chain Rings	Q-Rings	Adjustable Pedals	Translating Seat	CVT	Pedal Shape	Gear Ratios
Durable	4	3	4	3	5	5	4	4	3	4	5
Retrofittable	5	5	5	5	2	4	4	3	3	4	5
Low weight	3	4	3	4	3	4	3	3	3	4	4
Max torque	5	4	3	4	4	4	4	2	4	4	3
Low cost	3	3	3	3	2	3	3	3	2	3	4
Safe	5	4	3	2	4	4	3	4	4	3.5	4
Aesthetics	2	4	3	2	4	3	3	3	3	2	4
Knee angle	4	4	3	4	3	3	4	2	3	4	1
	Total Score:	122	107	108	105	119	111	93	100	114.5	116

As illustrated in Table 3, the crankset slider design, Q-rings, and improved gear ratios are the three designs that received the highest score. Due to the patented design of the Q-rings, we decided not to pursue that, but potentially add it to another design. So, the pursued designs will be the crankset slider and the gear ratios.

The crankset slider can easily be retrofitted to any bicycle, it would greatly improve torque as opposed to a standard shortened crank arm, would help the knee angle, and is safe for the rider. These benefits caused this design's high score and our selection of this design to pursue.

The improvement of gear ratios is very durable, has increased torque capacity, and can easily be retrofitted. These benefits caused its high score and our selection of this design to pursue. The design did receive a 1 in terms of knee angle, because the knee angle is unaffected. However, when paired with a shortened crank arm, it meets this requirement and increases its score.

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