

AN ANALYSIS OF THE BICYCLE-RIDER INTERFACE FORCES IN STATIONARY ROAD CYCLING

BY

ADAM CARAHALIOS

B.S., UNIVERSITY OF PORTLAND, 2011

A thesis submitted to the  
faculty of the Graduate School of the  
University of Colorado in partial fulfillment  
of the requirement for the degree of  
Master of Science  
Department of Integrative Physiology  
2015

This thesis entitled:  
An Analysis of the Bicycle-Rider Interface Forces in Stationary Road Cycling  
written by Adam Carahalios  
has been approved for the Department of Integrative Physiology

---

Rodger Kram, Ph.D.

---

William C. Byrnes, Ph.D.

---

Alena Grabowski, Ph.D.

Date \_\_\_\_\_

The final copy of this thesis has been examined by the signatories and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

IRB protocol # 13-0537

## Abstract

Carahalios, Adam James, T (M.S. Integrative Physiology)

An Analysis of Bicycle-Rider Interface Forces in Stationary Road Cycling

Thesis directed by Associate Professor Rodger Kram

Two distinct studies were undertaken in order to examine the effects that both external weight distribution, and internal, bike-rider interface forces had on cyclists. The first section of the study looked at the bike-rider interface forces, and how they fluctuate during normal cycling; as well as how they vary with changes in rider power output, hand position, and cadence. In order to analyze these changes in isolation, three different studies were undertaken. The studies each examined 10 USAC Category 3 or better riders who were tested for 6 minute trials. Riders were tested with their hands on the tops, drops and hoods, with cadences of 60-90 RPM, and power outputs of 1-4 watts per kg. It was found that for each 1 W/kg power output increase, saddle forces decreased by 5.2 percentage points and bottom bracket forces increased by 3.3 percentage points. Cadence did not affect bike-rider interface forces. Shifting a rider's hands from the hoods to the tops and the drops increased the stem force by approximately 2 and 4 percentage points, respectively.

The weight distribution study examined the effect of different bike fitting procedures on the bike-rider system, front/rear wheel, weight distribution. The study compared 13 amateur and 14 professional riders with four different fitting techniques. It was found that the Retül Fit weight distribution was 44.7%/55.3% front/rear and the Body Geometry Fit was 32.5%/61.5% front/rear. It was also found that the professional fit and the self-fit 40.4%/59.6%, and 38.5%/61.5% respectively, are similar ( $p=.9239$ ).

## Acknowledgments

I would like to thank everyone involved in this research who has helped in some way to carry out these studies. I would like to thank Luca Viano and Alberto Fonte from *fi'zi:k* who helped with study design, materials and by funding the project in its entirety. I would like to thank my committee members Dr. Bill Byrnes, Dr. Rodger Kram, and Dr. Alena Grabowski for their time and consideration. I would like to thank Dr. Allen Lim for my initial introduction to *fi'zi:k* and his insights into cycling in general. Foremost, I would like to thank my advisor Dr. Rodger Kram for his continuous help, advice, expertise and enthusiasm for the project, without which, it would not have been possible. I would like to thank subjects, my co-researchers, Jesse Frank and Asher Straw, as well as my lab mates; particularly Arick Auyung, Erik Summerside and Alyse Kehler for their help with MatLab coding. Last but not least, I would also like to thank my parents and my girlfriend Cary, for their continual support and encouragement.

## Table of Contents:

Title Page.....	i
Signature Page .....	ii
Abstract.....	iii
Acknowledgments.....	iv
Table of Contents.....	v
Chapter 1: Bicycle-Rider Interface Forces.....	1
BRIF Study Abstract.....	2
Introduction .....	3
Hypotheses .....	8
Study 1: Power .....	8
Study 2: Cadence.....	8
Study 3: Hand Position.....	8
Methods.....	9
Overall Study Design .....	9
Subjects .....	9
Equipment.....	10
Testing Procedures .....	12
Data Collection Procedures.....	14
Data Analysis Procedures.....	14
Statistics .....	14
Results.....	15
Discussion.....	21
Hypotheses Tested.....	21
Implications and Practical Applications .....	22
Limitations .....	23
Chapter 2: The Effect of Bicycle Fitting on External, Front-Rear Weight Distribution in Road Cycling ....	25
External Weight Distribution Abstract.....	26
Introduction .....	27
Hypotheses .....	28

Study 1: Amateur Riders .....	28
Study 2: Professional Vs. Amateur Rider Comparison .....	28
Methods .....	28
Subjects .....	29
Professional Riders.....	29
Equipment and Testing Procedures .....	29
Amateur Riders .....	30
Equipment and Testing Procedures .....	30
Comparison and Statistics.....	31
Results.....	32
Professional Riders.....	32
Amateur Riders .....	32
Professional and Amateur Comparison .....	33
Discussion.....	33
Ongoing Studies .....	35
Future Studies .....	36
Conclusions .....	36
Disclaimers and Biases.....	37
Appendix 1: .....	38
References: .....	39

**Chapter 1:**  
**Bicycle-Rider Interface Forces**

## **BRIF Study Abstract**

A cycle ergometer was instrumented with 3-axis force transducers to quantify the bicycle-rider interface forces (BRIFs) at the saddle, the bottom bracket, and the handlebar stem. Three studies, each with 10 subjects and 6-minute trials, measured how BRIFs were affected by power output (1.0, 2.0, 3.0 and 4.0 W/kg), cadence (60-110RPM) and hand position (hoods, tops, drops). Prior to each experiment, the ergometer was fit to each rider, who then warmed up. A cadence sensor trigger allowed BRIFs to be compiled for each crank cycle and composite average force files were created and analyzed. In the baseline test condition (2W/kg, 90RPM, hoods), 41% of body weight (BW) was supported by saddle, 44% at the bottom bracket and 15% on the stem. Further, in the baseline test condition, the antero-posterior average BRIFs pushed backwards on the rider at the stem (12% BW) and forwards on the rider at the saddle (20% BW). From the baseline test condition, for each 1.0 W/kg increase in power, vertical saddle forces decreased by 5.2 percentage points and bottom bracket force increased by 3.3 percentage points, with the remaining force shifting from the handlebars. There were no significant changes in weight distribution with cadence changes. Vertical stem force increased by approximately 2 percentage points when the riders shifted their hands from the hoods to the tops, and by approximately 4.0 percentage points when they shifted to the drops.



## Introduction

Cycling technology has progressed rapidly over the last 15 years. The introduction of both stronger and lighter materials and components have led to large changes in the way that bikes are designed, built, and tailored to the rider. A variety of components such as handlebars, stems, and seat posts have been developed to allow for small adjustments to suit a rider's anatomy, which combined with an increase in cycling popularity have allowed the science and art of bike fitting to come a long way.

In the last 15 years, bike fitting technology has also evolved rapidly. Systematic measurement and adjustment devices have facilitated kinematics-based bike fitting protocols for riders. Bicycle fitting companies, such as Retül (Boulder, Colorado, USA), Specialized, Body Geometry (Morgan Hill, California, USA), and Guru (Laval, Quebec, CAN), have developed fitting protocols based exclusively on kinematics or anatomical flexibility. However, a number of factors are overlooked when bicycle fittings are based exclusively on kinematic data. Among these factors that have previously been overlooked are, the forces exerted onto the contact surfaces of the bike, which will be referred to henceforth as bicycle-rider interface forces or BRIFs, as well as the external weight distributions over the wheels that these fitting procedures generate.

Beginning with research by Maury Hull at UC Davis in the early 1990s, interest grew in quantifying the forces that a rider exerts on to a bike. Hull and his colleagues were some of the first to begin to quantify BRIFs. In their 1992 paper, Hull et al. discussed overuse knee issues associated with cycling; emphasizing foot loading and the forces transferred to the knee. Hull et al. also suggested that a number of anatomical variables accounted for variations in the forces

that were exerted on the bike through the foot and then the knee. Though Hull et al. described a fitting protocol that aligned the pedal spindle with the foot for cleat placement, they did not describe a fitting methodology for the rest of the rider's position on the bike. Hull et al. described variations in the forces exerted onto the pedal spindles and it seems likely that some of this variation is an effect of the differing bike fits. Because the overall fitting protocol may have an effect on BRIFs, in the present studies, a standardized fitting procedure was used for each rider, taking into account the riders' anatomy, and position on the bike.

Hull's group was also among the first to measure individual pedal forces (Hull et al., 1992). They stated that the patterns of forces could be broadly characterized as subject independent. However, Hull et al. only measured forces at the pedals. Hull et al. also stated that the maximum normal (perpendicular) pedal force occurs at approximately 100 degrees in the crank rotation and that it constitutes the majority of the force that generate torque on the bike, however, parallel (horizontal) pedal forces become meaningful when normal force is at its minimum. Hull et al. also stated that increasing cadence has the expected mechanical effect of decreasing individual forces on the pedals. Hull's group continued their research in a 1995 paper that measured cycling frame stresses. In that study, Hull et al. (1995) measured individual BRIFs for a wide variety of subjects at the pedals, seat post and stem. The riders were tested while cycling on a treadmill for three different conditions, coasting, seated uphill riding and standing uphill riding. The study did not normalize for rider weight or positioning and tested only five subjects. Hull et al. (1995) determined that the largest forces were exerted on the bottom bracket and therefore bike frames should be designed to be strongest at this point. They did not further examine these forces in terms of weight distribution, comfort, or how

these factors change during normal cycling. This rudimentary understanding of the forces exerted on the frame was all that existed for a few years.

Bressel et al. (2005) was one of the first groups to move from force-based analysis to pressure-based. They examined the changes in pressure that take place when riders rode at 118 vs. 300 +/- 82.4 watts. The study also examined the correlation between perceived stability, saddle pressure and seat post force. They found that hand position and increased power output decreased seat post force. In a subsequent study, Bressel et al. (2008) stated that "choice of saddle design should not be dictated by interface pressure alone since optimal anterior seat pressure and perceived seat stability appear to be inversely related." In other words, as pressure on the anterior portion of the seat increases (less comfort) perceived stability is higher. This study seems to suggest that additional information about the bicycle-rider interface is necessary to understand the true effects that a saddle has on a rider.

The next iteration of BRIF measurement was Wilson et al. (2007) who examined the forces that 10 riders exerted onto the saddle. The study found that 49 to 52 percent of the riders body weight was supported by the saddle at a fixed power output of 125 watts. However, their study used no formal fitting procedure, did not screen participants for their familiarity with cycling, and did not measure the forces at the bottom bracket or the handlebars.

Around the turn of the century, studies of the bicycle-rider interface changed focus to pressure-based analysis without a systematic understanding of the force-based foundations from which the pressures originate. In one saddle pressure study, Bressel et al. (2008) found

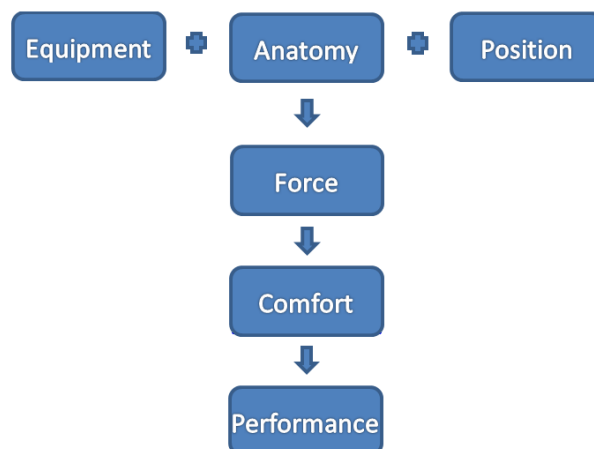
that with two different saddle shapes there were significant correlations between experience level and saddle pressure. As a riders experience level increases, the saddle pressure decreases. These findings were taken into account for the current studies and the subject pool was closely controlled so that rider experience was not a confounding variable.

Though there have been some studies that have quantified BRIFs in piecewise format, none have examined the forces systematically, or how they fluctuate during normal riding. The majority of these reference studies only examine the forces or pressure at one contact point and only in the vertical direction. The present study was crafted to examine the changes in BRIFs in response to factors that vary universally during the course of normal riding (power output, cadence and hand position).

Building upon previous studies, the present study assessed the BRIFs in all three directions at all three points of contact (saddle, bottom bracket and handlebars). Additionally, the study normalized for body weight, standardized for rider experience, cadence, hand position and the rider fit on the adjustable ergometer used for testing. The subject pool was also carefully chosen to represent competent, competitive cyclists.

The present study examined BRIFs in detail with the belief that they are particularly important because of the long duration that riders are often on their bikes. In order to simplify the complex interactions between bicycle and the rider, the conceptual diagram below in Figure 1 was developed. While traditional bike fitting is implemented at the equipment level, analysis of the forces takes place at a higher level and integrates equipment with anatomy and has the potential to generate a more comfortable ride for cyclists. It is currently difficult to quantify the

comfort of cyclist, as no widely accepted framework exists. It is hoped that one will be developed in subsequent studies. This hypothetical framework was generated under the reasonable pretense that rider comfort is quantifiable.



**Figure 1: Performance Flow Chart**

Understanding the bicycle-rider interface is complicated by the fact that the forces are continuously varying due to the cyclical nature of cycling. As a rider completes a full rotation of the crank, one full cycle, the force fluctuations and patterns that are involved change based on the rider's power output, cadence and hand position. During a race or training ride, a cyclist will change the way in which they ride countless times. As the grade of the road, the wind, the pace of riding partners, and the condition of the rider changes, a rider will change their power output, cadence, and hand positioning accordingly (Lim 2010). In order to describe and quantify these changes in isolation, three separate studies were completed so that the three factors (power, cadence and hand position) could be varied independently.

## **Hypotheses**

### **Study 1: Power**

It was hypothesized that as power output increases, the weight distribution would shift towards the bottom bracket and away from the saddle. This was hypothesized because in order to increase power, the forces on the crank must necessarily increase with power output because cadence and crank length are held constant. It is assumed that this increase in forces will come from a shift in body weight forces from the saddle and/or stem as total forces must sum to one body weight. It was also hypothesized that forces on the handlebars would increase as power output increased due to changes in rider posture on the bike.

### **Study 2: Cadence**

It was hypothesized that cadence would significantly change the magnitude of the BRIFs and the individual subject variability was expected to increase at faster pedaling cadences. This was hypothesized because at very high cadences and moderate power outputs, some cyclists exhibit visible instabilities.

### **Study 3: Hand Position**

It was hypothesized that shifting hands from the hoods to the drops would increase the vertical force on the stem while shifting the hands from the hoods to the tops would decrease the vertical force on the stem. These changes are expected from observed changes in rider torso angle that account for the changes in effective frame stack reach and height caused by the changes in hand position.

## **Methods**

### **Overall Study Design**

Three individual studies varied power, cadence and hand position separately. The first study examined BRIFs at 1.0, 2.0, 3.0 and 4.0 watts per kilogram (W/kg) at a cadence of 90 RPM and with hands on the handlebar brake hoods. The second study investigated BRIFs at 2.0 W/kg at cadences of 60, 70, 80, 90 100 and 110 RPM with hands on hoods. The final study compared BRIFs at 2.0 W/kg at a cadence of 90RPM with hands on the tops, drops and hoods. These conditions were chosen because the ranges tested were believed to be reasonable maximum and minimum values that riders could maintain for six minutes or more. Additionally the ranges appeared to be reasonable when compared to the ranges seen in normal riding for riders of this caliber.

### **Subjects**

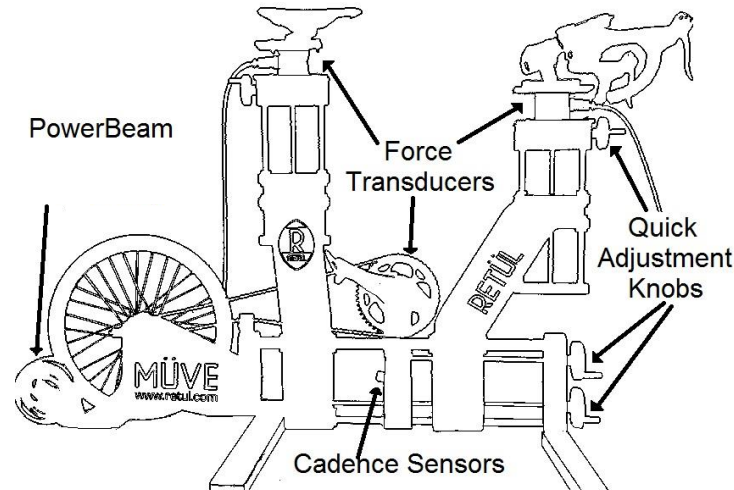
Subjects were all male, USCF Category 3 or better, bicycle racers who rode a minimum of 10 hours per week for training. Age ranged from 18 to 40 years and body mass ranged from 59 to 93 kg. This caliber of riders were thought to be able to complete the study without fatiguing and were thought to be representative of the experience level of competitive cyclists. 10 subjects were tested for each experiment with some subjects completing more than one study. All subjects provided informed consent as per the University of Colorado Boulder Institutional Review Board.

## Equipment

All of the experiments took place on a specially modified Retül Müve cycle ergometer (Boulder CO, USA). The Müve allows independent adjustment of the saddle, handlebars and bottom bracket. The reach and stack of the “frame” as well as the saddle height, offset and pitch angle are all independently adjustable. The crank arm and stem lengths are independently adjustable as well as the handlebar width and the stem angle.

For these studies, a Müve was specially modified in order to accommodate mounting points for three, 3-axis force transducers. Custom brackets were machined to allow the force transducers to be installed between stem and seat post, and the Müve’s frame. Additionally, a new bottom bracket was machined so that an additional force transducer could be incorporated. Though there were three points at which the force transducers could be attached, for the first two studies only two force transducers were available. A force transducer “blank” of the same dimensions and mountings was machined so that the vacant spot on the Müve could be filled. In order to record forces at all three measurement points, each trial was repeated twice with the stem and bottom bracket force transducer/blank swapped, while the saddle transducer stayed in place. In this way, the forces at all three points of contact could be measured for all test conditions. For each subject, the starting position of the stem/bottom bracket force transducer/blank was also randomized. For the hand position study, three force transducers were used. The force transducers were calibrated in the factory and re-zeroed for each subject, and between tests when the location of a force transducer was changed. A figure of the completed design is shown in Figure 2.





**Figure 2: Modified Retül Müve Used in Testing**

AMTI MC3-A-500 force transducers (Watertown MA, USA) were used. These transducers have the capability to measure forces and moments in all three axes. The force transducer signals were amplified using AMTI MCA-6 bridge amplifiers were fed into three National Instruments USB 6009 data acquisition units (DAQ's) (Austin TX, USA). Custom National Instruments, LabView code was then used to capture the data at 1000 Hz for 60 second windows. A total of 10 channels of data were collected for the 3 experiments. Forces in the vertical direction, the antero-posterior direction, and the medio-lateral direction were collected at each of the three bicycle-rider interface point using the force transducers. In addition, a trigger channel was recorded. The trigger channel helped in data analysis by creating a 'ping' when the left crank was near bottom dead center.

To vary the power output, a CyclOps PowerBeam (Madison WI, USA) cycling resistance trainer that was built into the Retül Müve was utilized. The PowerBeam allows for external

regulation of the power output of the rider and automatically adjusts resistance to account for small changes in cadence. The PowerBeam is guaranteed accurate to +/- 5.0 percent.

A CatEye (Osaka, Japan) cycle computer was also used to measure the cadence of the riders. The sensor was placed between the right crank and the bottom bracket and the display was placed on the handlebars of the Müve. The testing protocol relied on the riders to maintain a cadence when given feedback by the display. This was not an issue for the riders and the observed variation from the desired cadence was very small.

## Testing Procedures

Prior to each test, the riders' height, body mass and inseam were all measured. These were used to determine a standardized fit for the adjustable ergometer. A fi'zi:k Alliante (Vicenza, IT) saddle was used for all tests and the saddle was angled one degree nose down. The reach and the stack of the handlebars as well as the stem lengths, crank lengths, and handlebar widths were derived from the Felt Bikes (Irvine, CA, USA) fitting guides, as recommended by Retül. After riders received the basic bike fitting, the fit was further refined by measuring the knee angles, elbow angles and knee-pedal spindle offset as suggested by Retül. Once the bike fit was completed for each of the riders, they were allowed 10 minutes to warm up *ad libitum* at whatever power output, cadence and hand position they preferred.

For the power study, riders were asked to maintain a cadence of 90 RPM using the cadence meter. Additionally, riders were asked to keep their hands on the brake hoods during testing. Each rider performed four, 6-minute trials at 1.0, 2.0, 3.0 and 4.0 W/kg in a randomized order. 6 minute trials were chosen because it was determined in pilot testing that forces

stabilized between 4 and 5 minutes. The force graph is shown in Appendix 1. This trial order was maintained for the second series of trials in which the location of the force transducer blank was changed.

For the cadence study, a series of six trials was completed twice, with riders pedaling at cadences of 60, 70, 80, 90, 100, and 110 RPM in random order. Each of these tests was completed at a power output of 2.0 W/kg. Tests were again 6-minutes long with the last minute of data being recorded. After the six tests had been completed, the riders were allowed 10 minutes of rest while the location of the force transducer blank was changed. The subjects then completed a five minute re-warmup period and the random cadence order was repeated. The data was then compiled so that all 10 data channels were organized into a single file.

For the hand position study, riders were fit and allowed to warm up for 10 minutes as they chose. After the riders had warmed up three, six-minute tests were undertaken to measure the effects of the rider's hand position on the handlebars. Trials were completed with hands on the, tops, drops and hoods of the handlebars in a randomized order.

Six-minute trials were selected based on pilot testing in which the saddle forces stabilized between the four and five minute marks. For each test condition, riders were effectively allowed a five minute acclimatization period; and during the sixth and final minute of each trial, data was recorded.

## **Data Collection Procedures**

Data collection was accomplished using three National Instruments 6009 USB DAQs. The devices sampled amplified and zeroed data at 1,000 Hz. Up to nine channels of force data were sampled simultaneously, as well as one trigger channel. In trials where only two force transducers were used, a composite 9 data channel file was compiled between the two sets of data collection to generate 10 channel composite data files. These files were then used for data analysis.

## **Data Analysis Procedures**

Once the data had been collected from all 10 subjects for each study, they were compiled and analyzed using custom Matlab (Natick Ma, USA) code. For each test condition, (e.g. power level) the data was partitioned using the pings from the triggering channel of the captured data. Each ping delineated one complete cycle of the crank. The information from the 60 second data captures was then used to create a composite average of all of the riders for each power level, cadence, or hand position. The average forces in the vertical direction were also analyzed so that the differences between the four power levels could be more easily compared. Again, for the highest power output of the power study only, the sample was truncated to eight subjects.

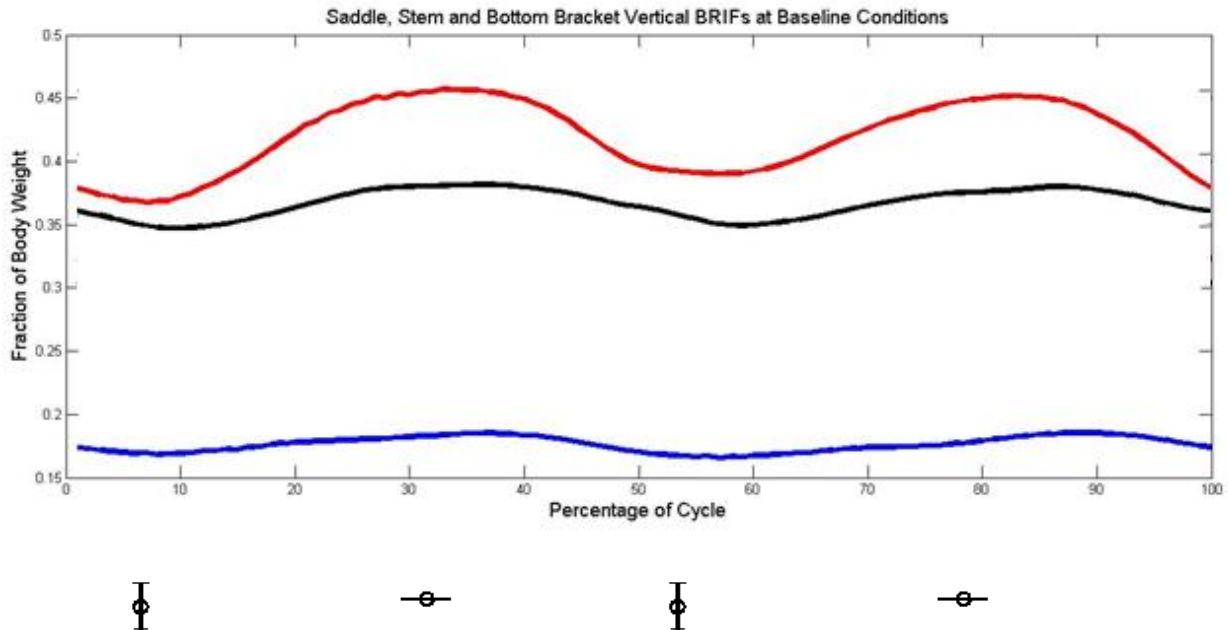
## **Statistics**

To compare the tests standard statistical methods were used with a p-value of at least .05. To compare the trends in the power and cadence studies, Pierson's correlation coefficient tests were run to determine statistical significance. Correlational tests were chosen because the power outputs and cadences seen in riders is an analogue value that varies constantly; and thus

is not suitable for binned statistic tests. Linear mixed modeling was not used because of the known interactions between the weights at the different points of contact. For all test conditions they must add up to 1.0 BW. For the hand position study several two sample t-tests were used to determine statistical significance. For this study, Bonferroni corrected p-values of .025 were used.

## **Results**

Before examining the changes that place in BRIFs caused by changes in power, cadence and hand position it is important to establish the baseline conditions. The baseline condition used in these tests is 2.0 watts per kilogram power output at a cadence of 90 rpm with the riders' hands on the hoods. This condition is believed to be a reasonable baseline for any competent cyclist. As a rider cycles at baseline conditions the bottom bracket supports approximately 41 percent of body weight. The saddle supports 44 percent of body weight and the stem approximately 15 percent. The fluctuations in these forces are shown below in Figure 3. Saddle forces are shown in red, bottom bracket forces in black, and stem in blue. Due to minor offsets in the crank position sensor compared to the bottom bracket, the cadence cycle begins at approximately 7.0 degrees before bottom dead center on the left crank arm. The graphs below show a composite average of all cyclists and all trials for each condition tested with obvious outliers removed. Outliers were determined using the two standard deviation from the mean rule.



**Figure 3: Saddle, Stem and Bottom Bracket Vertical BRIFs, at Baseline Conditions, With approximate Crank Position Shown Below**

Anterio-posterior forces at baseline conditions fluctuate with the pedal cycle. In Figure 4 below, antero-posterior forces are plotted using the same color code as Figure 3: saddle is red, bottom bracket black, and stem in blue. At baseline conditions, the saddle pushes forward on the rider with about 20 percent of body weight while the bottom bracket pushes back with about 7 percent of body weight and the stem about 12 percent. Mediolateral BRIFs were less than four percent of bodyweight at each of the three locations for all trials. Mediolateral BRIFs were insignificant in comparison to vertical and horizontal BRIFs, and thus they are not discussed further.

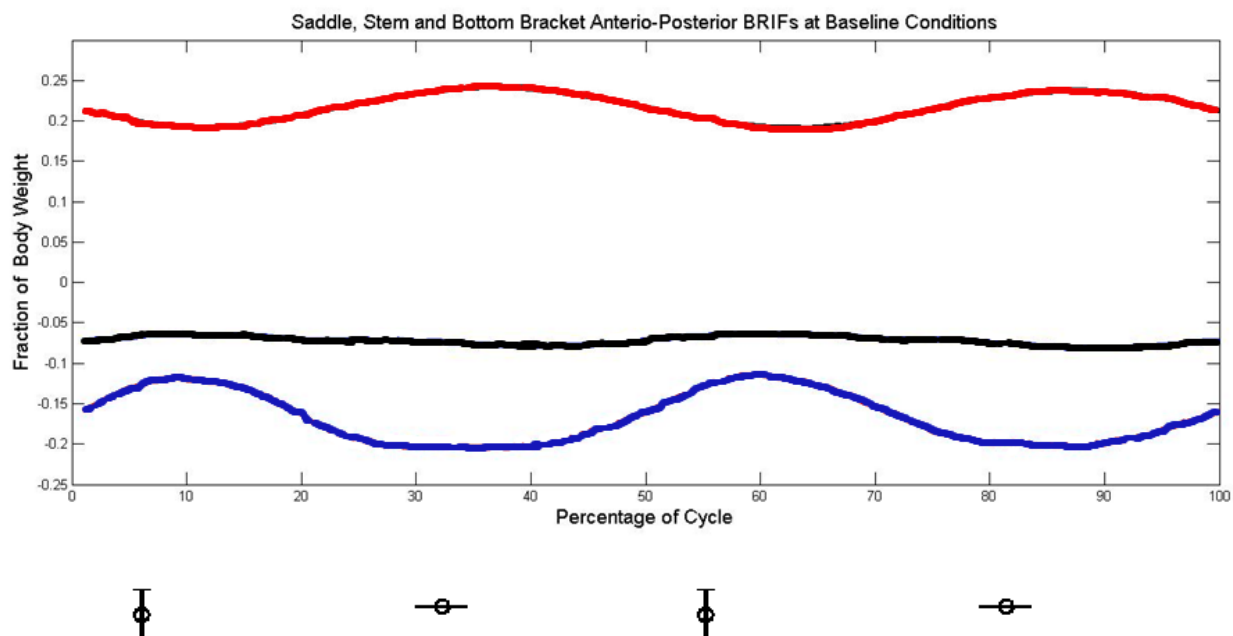


Figure 4: Antero-Posterior BRIFs at Baseline Conditions With Approximate Crank Position Shown Below

The average forces for each rider were calculated over the course of 60 to 120 complete cycles of the crank, depending on cadence. 2 standard deviation outlier tests were then run on the data and no outliers were found. The average of the forces for the 10 cyclists for each test condition were then compared to one another.

The results of the power study are shown below in Figure 5. As power output increased, the vertical forces exerted onto the saddle decreased and the vertical forces at bottom bracket increased. The vertical forces on the stem exhibited a slight but significant decrease as power output increases ( $p=.044$ ). Average vertical saddle forces decreased as power increased ( $p=.0084$ ) by 2.97 percentage points for every 1.0 watt per kilogram power output increase. Vertical forces on the bottom bracket showed a statistically significant increase ( $p=.0022$ ) of 3.85 percentage points in body weight as power output increased by 1.0 watt per kilogram. As power increased, the vertical forces transfer from the saddle and stem to the bottom bracket.

The bottom bracket force traces are shown below in Figure 4. As power increased from 1.0 W/kg (blue), to 2.0 W/kg (green), then 3.0 (yellow), and 4.0 (red), forces on the bottom bracket systematically increase without changes to the force patterns. This graph is representative of the changes in BRIFs that occur with changes in power output

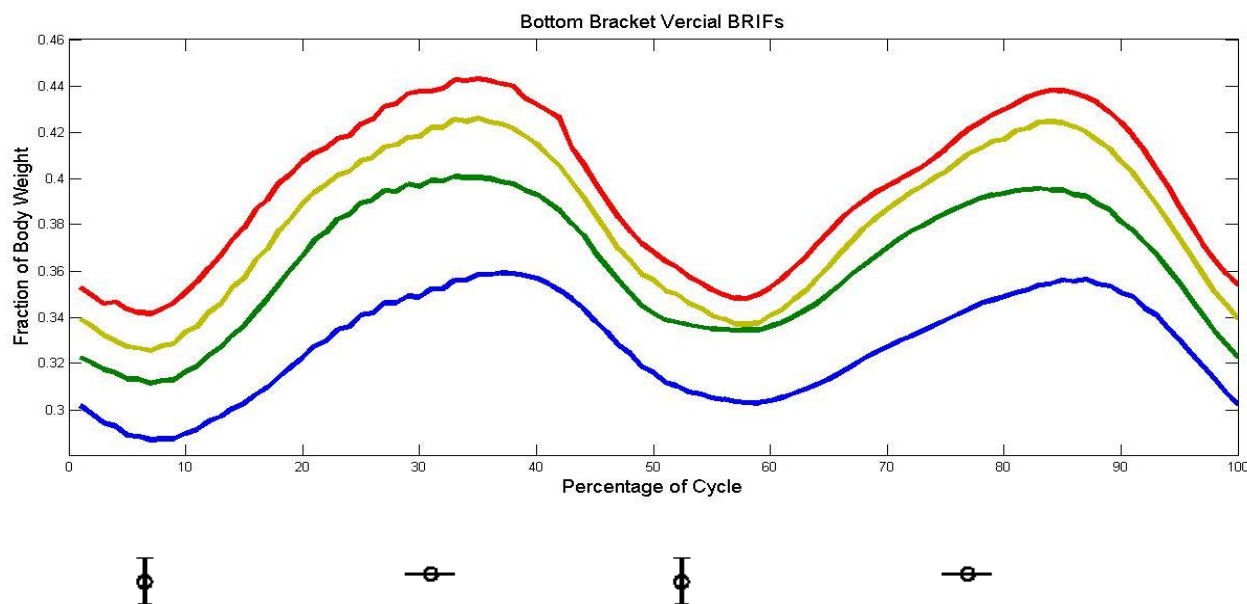


Figure 5: Vertical Bottom Bracket BRIF Changes as Power Output, With Approximate Crank Position Shown Below

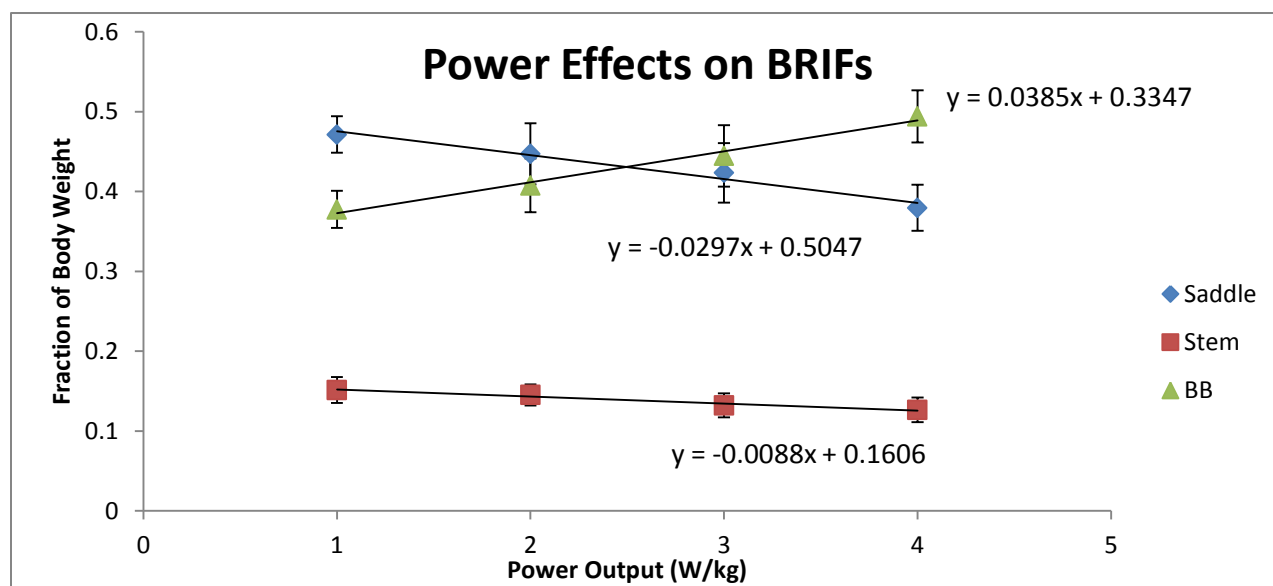


Figure 6: Power Effects on Vertical BRIFs



The effects of changes in cadence on BRIFs are depicted in Figure 7 below; there were no significant cadence effects on BRIFs. For every 10 rpm increase in cadence, the 1.4% decrease in bottom bracket BRIFs was not statistically significant ( $p=.096$ ). Vertical saddle forces increased by 1.1 percentage points for every 10 RPM increase in cadence, but again this change was not statistically significant ( $p=.118$ ). Stem forces did not exhibit a trend with cadence ( $p=.222$ )

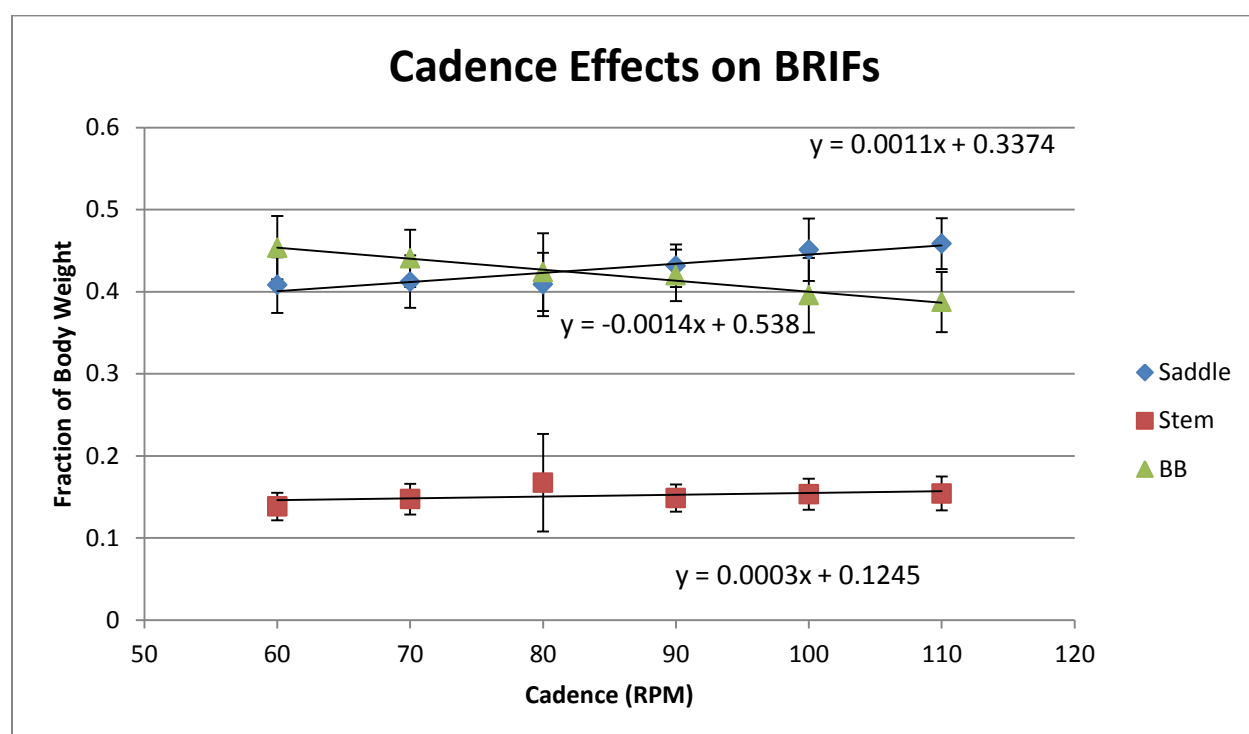
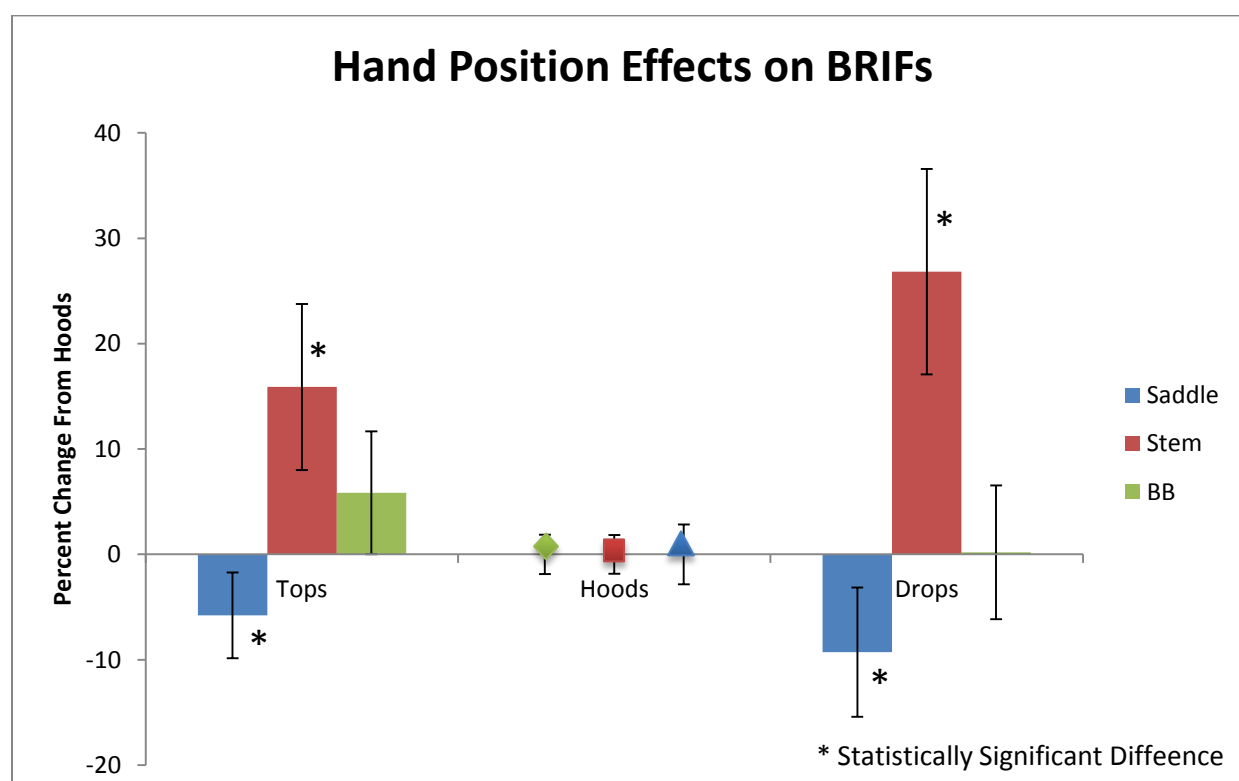


Figure 7: The effects of cadence on BRIFs

BRIFs were then compared to the baseline condition of hands on the hoods. Bottom bracket forces were not affected by hand position. As riders switched hand positions, both saddle forces and stem forces were significantly affected. As the riders shifted their hands from the hoods to the drops, vertical forces on the saddle decreased by approximately 3.0 percentage points ( $p=.001$ ) and conversely the stem force increased by approximately three

percentage points ( $p=.0009$ ). As riders shifted from the hoods to the tops, vertical stem forces increased by 2.3 percentage points ( $p=.0009$ ). Saddle forces also decreased by approximately two percent ( $p=.004$ ). All statistics were Bonferoni corrected to generate the new test statistic of  $p=.025$ . Figure 8 illustrating the effects of hand position is shown below. The baseline values of zero for the hoods are shown in the center. The error bars shown represent the inter subject variation as a percentage from the mean.



**Figure 8: The Effects of Hand Position on Vertical BRIFs**

Changes in the force patterns are shown below in Figure 9. Forces shown in magenta are for the tops hand position. The forces for the drops hand position are shown in yellow and the baseline condition forces (hoods) are shown in cyan.

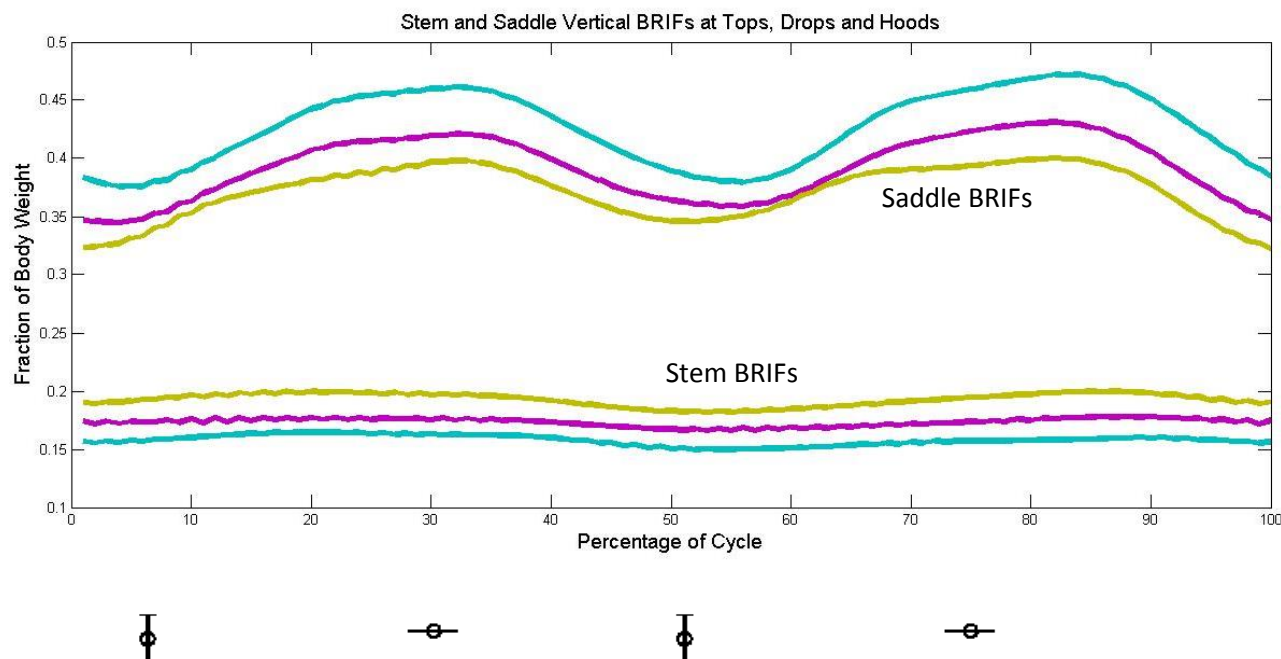


Figure 9: Stem and Saddle BRIFs at the Tops, Drops, and Hoods, With Approximate Crank Position Shown Below

## Discussion

### Hypotheses Tested

The results support Hypothesis 1 for the power study. There were statistically significant trends of increasing vertical BRIFs on the bottom bracket and decreasing vertical BRIFs on the saddle as power output increased. However, Hypothesis 2 for the power study was rejected. There was a significantly significant trend in the opposite direction from predictions. It was found that as power output increased, the riders' vertical stem BRIFs decreased. For the cadence study, Hypothesis 3 was rejected. There were no significant BRIF trends as cadence increased. For the hand position study, it was hypothesized that shifting from the hoods to the drops would increase the vertical BRIFs at the stem. This hypothesis was supported; as riders shifted from the hoods to the drops vertical BRIFs increased by 3.0 percentage points. The second hypothesis for this study was rejected. For unknown reasons, as the riders shifted their hand position from the hoods to the tops, vertical BRIFs on the stem increased by 2.3%.

## **Implications and Practical Applications**

The combination of these three studies describes the changes that take place during normal cycling as approximated by an indoor stationary cycle ergometer. The goal of this paper was to describe the changes in BRIF's that a rider would experience during a normal ride, without changing the components or their setup on their bike. Some of these changes have significant effects on BRIFs and perhaps to some extent, subjective comfort. As a rider increases their power output, BRIFs shift from the saddle to the bottom bracket. This could explain why amateur riders often complain of saddle discomfort; they are supporting significantly more weight on the saddle than more experienced riders who are consistently putting out more power.

A substantial amount of variation in cadence can be observed between riders riding together at the same speed. It appears that cadence may be simply a function of preference, or a biomechanical or muscle force-velocity physiological factor, rather than BRIFs since this study suggests that cadence does not have a significant effect on saddle, stem or bottom bracket BRIFs. As a rider increases their power output, weight shifts from both the stem and the saddle to the bottom bracket. It is interesting that vertical BRIFs shift from the handlebars to the bottom bracket. This is in contrast to the expectations behind the third hypothesis which was that as a rider increases their power output, their posture shifts forward on the bike and increases stem forces. Though many riders believe the most important contact point between the rider and the bike to be the saddle, for top tier riders with high power outputs, it may in fact be the pedals and the rider's shoes.

The hand positioning study generated one of the most unexpected findings. It was anticipated that as a rider shifted to the drops from the hoods the BRIFs at the stem would increase. It was not hypothesized that shifting from the hoods to the tops would decrease stem BRIFs. These unexpected changes may originate from one or both of two changes that take place when hand position is altered. This change in BRIFs may be due to the changes in wrist pronation that occur when switching to the tops. Although it was only observed and not quantified, the increased wrist pronation appears to change the width of the riders' elbows, possibly decreasing the arms effective reach, and shifting the torso slightly forward. Some riders also state that when riding on the hoods or the drops they feel that the spinal muscles are more active in supporting the torso, decreasing the weight supported by the handlebars. When riding on the tops, they feel that they collapse further on to the handle bars and support more weight there. Both of these kinematic changes could create BRIF changes similar to what was found in the present study. It may be possible to gain further insight into this phenomena using electromyography (EMG). Implementation of EMG is planned for future studies, and hopefully will shed more light onto this topic.

## **Limitations**

This study was designed to minimize its limitations and maximize its applicability. However, all of the testing was done inside on a stationary bike. The ergometer did not allow for riding up or down grades, and the results are only directly applicable to level riding. The ergometer also limits the medio-lateral lean, or rock, of the bike during the pedaling cycle. The effects of this limitation were minimized by only allowing riders to cycle while seated. A casual observation of seated versus standing cycling suggests that lean of the bike is minimized during

seated cycling. It is possible, however that medio-lateral forces could be higher in true road cycling. Another potential limitation of the ergometer is that in order to facilitate the fitting and adjustability elements of the bike, it is not as stiff as a traditional road bike; especially in the medio-lateral direction. This lack of stiffness did produce some amount of vibration and noise in the force transducer measurements, especially in the medio-lateral direction.

There is also the possibility that fatigue effects could have confounded some of the results. Random testing orders were used to mitigate these effects and there is no evidence to suggest fatigue effects in the results.

Stem forces were measured using an AMTI MC-3-500 force transducer. The force exerted on the handlebars in the vertical direction was well off from the center of the force transducer especially during the hand position testing. This may have caused slight distortions in the stem forces. To account for this, small corrections were made to the forces exerted on the stem. To calculate the correction, weights with an approximately similar mass to that exerted on the stem were hung from the handlebars at the locations that the forces were applied. The total corrections were very small (on average, less than .5 percent) in comparison to the forces that were exerted and were on average less than one percent. Because the total vertical body weight exerted onto the three points of contact must sum to 1.00 BW for each complete cycle, it provides a further check. Vertical forces were analyzed for each test condition and BRIFs at the three points of contact summed to nearly 100 percent, with an average error less than 1.5 percent for all test conditions.

**Chapter 2:**  
**The Effect of Bicycle Fitting on External, Front-Rear**  
**Weight Distribution in Road Cycling**

## External Weight Distribution Abstract

There is currently no published information about what the external, front/rear weight distribution is for bicyclists of any caliber. This is odd, considering the substantial handling effects that weight distribution is known to have on other wheeled vehicles (Rajamani, 2006). This study attempts to quantify the effects of different bike fits on external weight distribution. Additionally, it examines the difference between professional bike fits and those available to amateur riders. The subjects for this study were 13 amateur riders who were USCA Category 3 or better and 14 professional riders. The riders' weight distributions were measured using two force plates and a cycling trainer. All subjects used their own bikes and had their weight distribution measured with their hands on the hoods and the cranks horizontal. It was found that the Retül Fit weight distribution was 44.7%/55.3%, front/rear, ( $p=.006292$  when compared to pro fit). The Body Geometry Fit weight distribution was found to be 32.3%/67.1% ( $p=.00204$  when compared to pro fit). The most interesting result was that self-fit 38.5%/61.5% was the most similar to the professional fit 40.4%/59.6% ( $p=.9239$ ). This seems to suggest that if professional riders' weight distributions approach what is optimal, self-fit riders are naturally gravitating toward the same optimal weight distribution. It was also found that the fore-aft position of the professional riders' center of mass (body+bicycle) was, on average, 1 mm ahead of the bottom bracket center with a standard deviation of 24.3 mm.



## Introduction

The dynamics of the active bicycle and rider system are extremely complicated. The interaction of the rider, bike and road is not well understood. One of the factors that is known to affect wheeled vehicle dynamics is the distribution of weight over the wheels. Bicycles are likely affected by this as well. Although it is likely that there is a correlation between bike performance and weight distribution, very little information exists on the subject. Wilson, 2004, states that “some bicycle characteristics... can be determined by numbers... others, however, are evaluated primarily by ‘feel’. Foremost among these are aspects of comfort and handling”. This statement overlooks the difference between perceived handling and vehicle dynamics. Despite a lack of perceived changes in stability for cycling, weight distribution likely affects bicycle handling. If one extrapolates to the extremes, the difference in vehicle dynamics that weight distribution can cause in cycling becomes obvious. If 100 percent of the weight is on the rear wheel, handling and stability will suffer. Though this is an obvious exaggeration, it seems likely that these effects will exist at more reasonable weight distributions. For this reason, it seems valuable to quantify the effects of different bike fittings on weight distributions.

Bike fitting techniques currently move riders over the frame of the bike towards the front or the back based on kinematics and flexibility. The fitters who have designed the fit protocols generally have no knowledge of the effects that their fits have on external weight distribution. There is an apparent lack of information in the literature as to not only the effects of weight distribution on bike handling, but also what common weight distributions are. Bike fitters follow a systematic procedure to position riders on a bike, but none of the current common bike fitting procedures take into account external weight distribution. The goal of this

study was to determine how weight distributions vary with different fitting procedures. Weight distribution has the potential to play an additional, and important role in bike fit. Weight distributions for riders of any level were previously unknown, as are the effects of any of the widely-available fitting procedures. Additional insight into this area could prove helpful for everyone in the bike industry from frame builders to athletes to scientists.

In order to gain a more comprehensive understanding of the cyclist and rider interface, a study was designed to compare the external weight distributions of cyclists across different bike fitting procedures and proficiency levels.

## **Hypotheses**

### **Study 1: Amateur Riders**

Different fitting procedures will have a systematic effect on the external weight distribution of the bicycle.

### **Study 2: Professional Vs. Amateur Rider Comparison**

High level riders will exhibit more consistent external weight distributions on their bicycles compared to lower level riders.

## **Methods**

The bike fit procedures that were examined were the Retül Fit (Boulder, Colorado, USA), the Specialized Body Geometry fit (Morgan Hill, California, USA), professional fits, and self-fits. Self-fits are bike fits that are done by the rider to their comfort and discretion. The cyclists

ranged from USCF category 3 racers to professional level riders whose fit had been finely tuned by fitters, aerodynamicists and themselves. In addition, the fore-aft location of the center of mass for the professional riders was determined using photo-scaling.

## **Subjects**

All subjects provided informed consent as per the Institutional Review Board. All amateur subjects were healthy, competitive cyclists. For the amateur riders, data was collected in conjunction with other studies being conducted in the Locomotion Lab at University of Colorado Boulder. The professional riders sampled were on the 2014 Cannondale and BMC professional cycling teams present at the 2014 USA Pro Cycling Challenge. All data acquisition of the professional riders was completed in the days preceding the start of the race.

## **Professional Riders**

### **Equipment and Testing Procedures**

For this protocol, the riders' bicycles were briefly placed into a stationary trainer with the front and the rear wheels placed on different force platforms. The riders were asked to pedal briefly until they were comfortable on the bike with their hands on the hoods. Once the riders were comfortable, they were asked to come to a stop with their crank in the horizontal position and pause so measurements of weight distribution could be taken. The riders also had a digital photograph taken in the sagittal plane with a photo scaling block present. This allowed the location of the center of mass to be calculated using photo scaling off of the scaling block (a diagram of the test setup can be seen in figure 10). The photo scaling was verified by measuring the known lengths of the photo scaling block against one another. The error found using this technique was less than .25 percent. The results for the riders were then tabulated and

compared based on the riders fitting protocol and categorization. The number of professional riders sampled for this study was 14.



Figure 10: Professional Cyclist Data Capture Setup

## Amateur Riders

### Equipment and Testing Procedures

For the amateur rider testing, subjects stood on a single force platform and were weighed while holding their bicycle. The bicycle was then put into a trainer with the front wheel on the force platform (see Figure 11). The rider then mounted the bike and pedaled until they were comfortable with their hands on the hoods. At this point, the riders were asked to place their crank horizontal and stop pedaling momentarily. The percentage of total weight on the front wheel was then calculated by dividing the measured weight by the total weight. The riders were then surveyed about what, if any, fitting they had had done to their bike. The fitting

protocols that were observed fell into three categories: Retül fits, Body Geometry fits, and self fits, These riders' weight distributions were sampled over the course of the 2013-14 season and taken in conjunction with other tests. The number of amateur subjects sampled for this study was 13: 5 self-fit, 4 Retül Fit and 4 Body Geometry Fit.

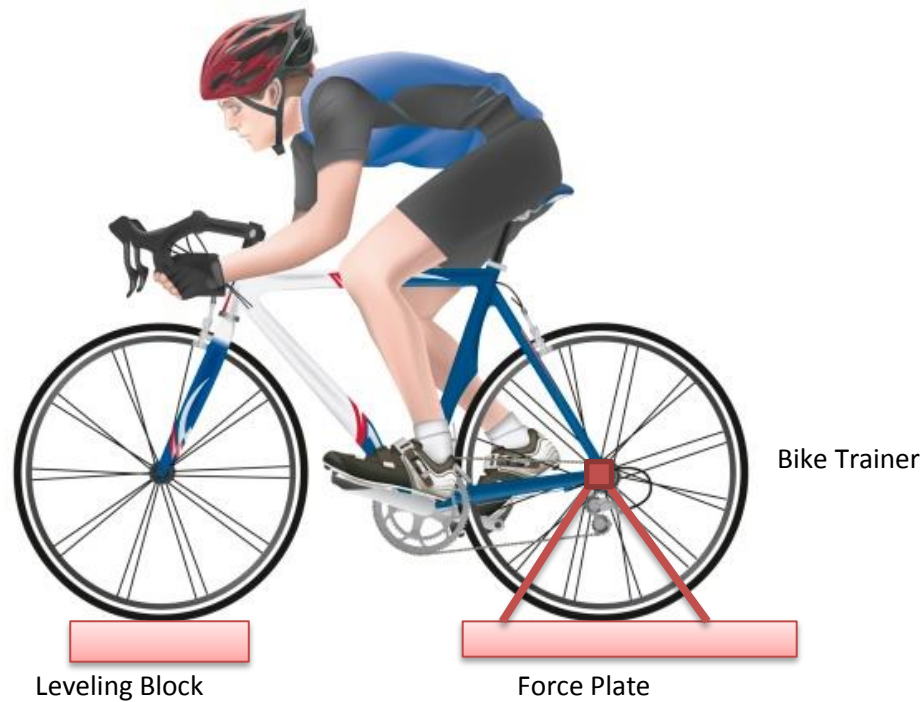


Figure 11: Amateur Cyclist Data Capture Setup

## Comparison and Statistics

To compare the weight distributions observed in the two studies, three two sample t-tests were used. Each amateur condition was compared to the professional riders' weight distributions. A Bonferroni corrected p-value of .0166 was used for all tests because of the three statistical tests being run.

## Results

### Professional Riders

The Professional riders had an overall, front/rear, weight distribution of 40.4%/59.6% (+-2%)

The spread for the professional riders was very tight with a very low standard deviation except for two riders who differed by approximately 5 percent from the average. The location of the center of mass was examined in relation to the bottom bracket. The fore-aft location of the center of mass was on average 1mm ahead of the bottom bracket with a standard deviation of 2.43 cm. Once outliers were removed, the standard deviation drops to just 11 mm. Outliers were determined by their variance of more than 2 standard deviations from the mean. The horizontal locations of the centers of mass on the bike are shown in Figure 12.

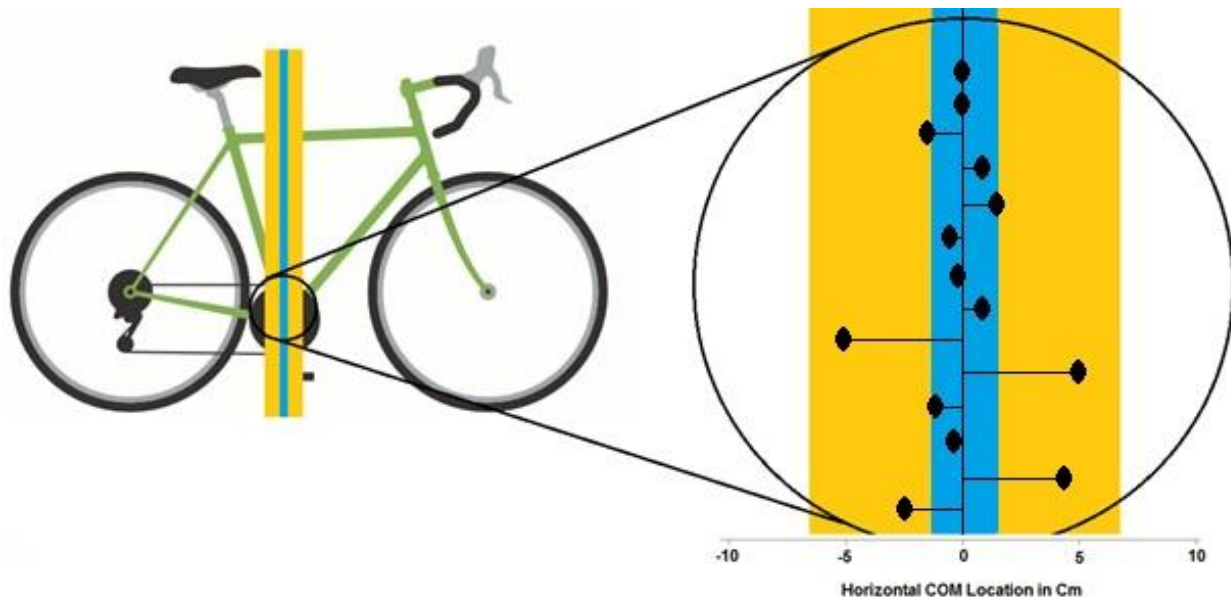


Figure 12: Professional Rider Horizontal Center of Mass Location as Measured From the Bottom Bracket for 14 Subjects

### Amateur Riders

The amateur data was divided into three different groups: Retül Fit, Body Geometry Fit, and self-fit. Self-fit data had an average front/rear weight distribution of 38.5%/61.5% (+-

4.9%). The Body Geometry fit had an average weight distribution of 32.3%/67.1% (+-2.2%), and the Retül Fit had an average weight distribution of 44.7%/53.3% (+-2.1%). These results are tabulated in Table 1 below.

Table 1: Amateur Rider weight Distributions

	Amateur Data					
	BG Fit		Self-Fit		Retül Fit	
	Front	Rear	Front	Rear	Front	Rear
Average	32.9%	67.1%	38.5%	61.5%	44.7%	55.3%
Standard Deviation	2.2%	2.2%	4.9%	4.9%	2.1%	2.1%

## Professional and Amateur Comparison

The professional rider average weight distribution, 40.4%/59.6% (+-2%) front rear, was compared to the three amateur rider conditions. Interestingly, the self-fit data most resembled the professional rider data with an average front/rear weight distribution of 38.5%/61.5% (+-4.9%). When compared using a two sample t-test, this generates a p-value of .9239. The Body Geometry fit was the most different from the professional fit with an average of 32.3%/67.1% (+-2.2%) this comparison generated a p-value of .00204. The final comparison was between the Retül fitting procedure 44.7%/53.3% (+-2.1%) and the professional riders, this test produced a p-value of .006292. These test statistics were compared to the Bonferroni corrected critical value. The analysis shows that the self-fit was not significantly different than a professional fit, however both the Body Geometry and the Retül fitting procedures were significantly different.

## Discussion

Both hypotheses were supported by the data. The bike fitting procedures showed systematic effects on the external weight distribution of the bike. Additionally, going off the

weight distributions alone, the spread of the COM position data for the professional riders was smaller than the amateur riders. The tight grouping of center of mass locations for the professional riders is also indicative of the interaction between external weight distribution and bike fit. The most notable result of this study is the similarities between the professional riders and the self-fit riders. While both the Retül and the Body Geometry fitting procedures produced statistically different weight distributions than the professional riders, the self-fit riders were almost identical ( $p=.9239$ ). This correlation may suggest that self-fit riders look for bike handling characteristics in their fit as well as bike comfort.

When conducting their fitting protocol, Retül primarily considers joint angles for fitting and the Body Geometry Fit primarily considers flexibility. A rider doing a self-fit takes into account the handling of their bike as well as their comfort on the bike; they also indirectly take into account their flexibility and joint kinematics. The small standard deviation for the professional riders' horizontal COM location relative to the bottom bracket is also interesting. The full range of the professional riders COM locations spanned just over 4.0 percent of the total bike length indicating a fairly narrow band of weight distributions.

The Retül fit seems to generally fit riders further forward on the bike. The Retül fit shifted weight approximately 5 percent forward on the bike when compared to a self-fit or a pro fit. The Body Geometry fit generally shifted the rider much further back on the bike. The BG fit moved an additional 13 percent of the rider/ bike weight onto the back wheel compared to the Retül fit. Both of these changes may affect the handling of the bike. The difference between the professional fit riders and amateur riders is substantial. It is logical to assume that the



professional riders have arrived at a near optimal state; therefore it is inferred that their weight distribution is near optimal as well. While cyclists have many other factors to consider in their bike setup, weight distribution appears to be a drastically overlooked factor.

Generally in automotive racing a 50/50 weight distribution is considered ideal, but in cycling it seems improbable that an even weight distribution would be beneficial. There is however some studies suggesting that more weight on the back wheel is optimal for vehicle dynamics under varying conditions. H. Nozaki suggests that a 40/60 front rear weight distribution is in fact ideal. This aligns nicely with the results of the study, and it again seems unlikely that this correlation appeared trivially. The ideal weight distribution for cycling performance is probably similar to the professional fit that was seen in the results for Chapter Two. This study strongly suggests that external, front rear, weight distribution is a completely overlooked element of bike fitting. Though the present study does not directly examine the effects that external weight distribution has on handling, it seems unlikely that the tight grouping of professional rider weight distributions has arisen arbitrarily.

## **Ongoing Studies**

Currently, a study is under way to examine the effects of changing stem length and height on BRIFs. The study is attempting to quantify the effects of lengthening and shortening the effective stem length by 2.0 and 5.0 centimeters. Additionally that study is examining the effects of raising and lowering the handle bars by 2.0 and 5.0 centimeters. Changing the length or angle of a bike's stem is one of the simplest and cheapest changes that a rider can make to a

bicycle to affect fit. This information could then be easily applied to fitting procedures or be used by riders to adjust their fits at home.

## **Future Studies**

The long term goal of this series of studies is to examine the factors of bike fit that affect comfort. Several more studies are planned to examine the effect of these changes in the context of a subjective comfort scale. The next study that will begin later this year will attempt to determine any correlations that exist between anatomical factors, BRIFs, rider kinematics, saddles, and subjective comfort of the subject cyclists.

## **Conclusions**

The work in Chapter One and Chapter Two has attempted to quantify the basic interactions found in cycling between the bike, the rider, and the road. These studies, the ones planned, and those in progress are part of an effort to gain additional insight into the factors that affect bike comfort. For these four studies, it seemed logical to start at the most basic elements of the rider, cycle, and road interactions, force. From there, future studies intend to build on this information and extend the understanding of cycling further into comfort and deeper into the understanding of the bike-rider interface.

Figure 13 below shows a more complete diagram of the factors believed to be involved in cycling performance. Though the aerobic conditioning of the rider is not listed in the table below it plays a substantial role in increasing a rider's performance. The combination of factors listed below can be thought of as requirements for performance. If in any of the factors below

are mismatched, the performance of the rider will suffer and there will be decrease in the riders conditioned performance.

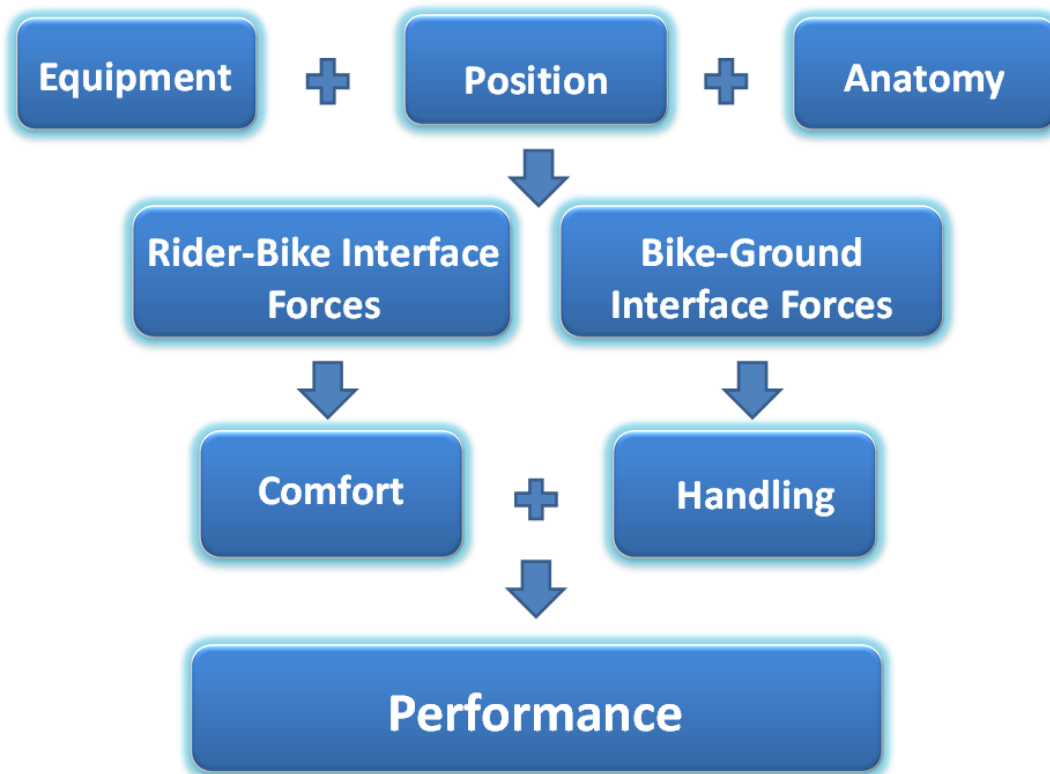


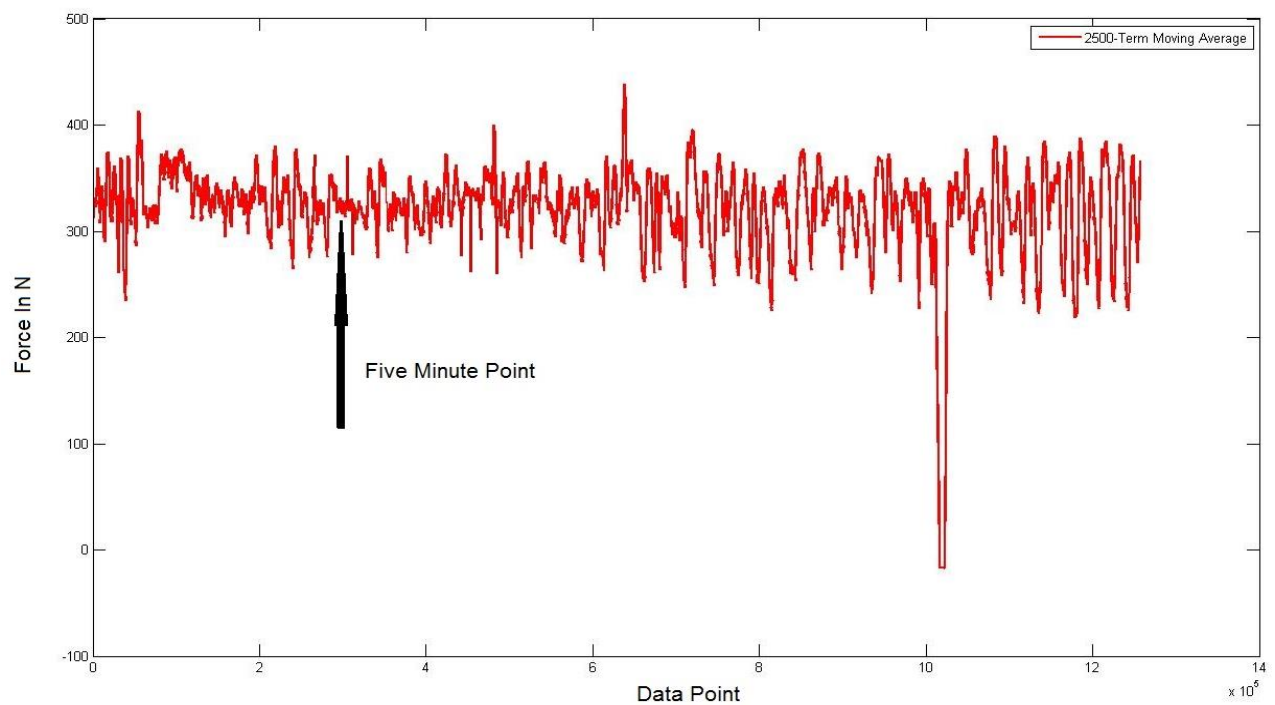
Figure 13: Performance Flow Chart for Cycling

## Disclaimers and Biases

This research is generously funded by an unrestricted grant provided to the University of Colorado Boulder by fi'zi:k, Selle Royal SPA. However, the research does not specifically apply to any fi'zi:k products and is believed to be an unbiased representation of the forces in seen in cycling.

## Appendix 1:

The figure below shows the vertical forces under the saddle for one rider during a 25 minute pilot test. The forces shown are run through a smoothing filter. By varying the filter parameters it was determined that the forces stabilized between four and five minutes. The spike at approximately 15 minutes is from the rider standing and is not relevant for testing.



## References:

1. Tom Boyd M.L. Hull, D. Wootten, An improved accuracy six-load component pedal dynamometer for cycling, *Journal of Biomechanics*, Volume 29, Issue 8, August 1996, Pages 1105-1110, ISSN 0021-9290,
2. Patricia Ruby, M.L. Hull, David Hawkins, Three-dimensional knee joint loading during seated cycling, *Journal of Biomechanics*, Volume 25, Issue 1, January 1992, Pages 41-53, ISSN 0021-9290,
3. Cal Stone, M.L. Hull, The effect of rider weight on rider-induced loads during common cycling situations, *Journal of Biomechanics*, Volume 28, Issue 4, April 1995, Pages 365-375, ISSN 0021-9290,
4. Eadric Bressel, John Cronin, Bicycle seat interface pressure: reliability, validity, and influence of hand position and workload, *Journal of Biomechanics*, Volume 38, Issue 6, June 2005, Pages 1325-1331, ISSN 0021-9290,
5. Eadric Bressel, Shantelle Bliss, John Cronin, A field-based approach for examining bicycle seat design effects on seat pressure and perceived stability, *Applied Ergonomics*, Volume 40, Issue 3, May 2009, Pages 472-476, ISSN 0003-6870
6. Chisom Wilson, Tamara Reid Bush, Interface forces on the seat during a cycling activity, *Clinical Biomechanics*, Volume 22, Issue 9, November 2007, Pages 1017-1023, ISSN 0268-0033
7. Eadric Bressel, D Nash, D Dolny, Association between attributes of a cyclist and bicycle seat pressure, *J Sex Med* 2010;7:3424–3433. Volume 7, Issue 10, pages 3424–3433, October 2010
8. Rajamani Rajesh, *Vehicle Dynamics and Control*, Springer Science & Business Media, June 4<sup>th</sup>, 2006 pp 846-852 September 2010
9. Lim Allen C, Peterman James E, Turner Benjamin M, Livingston Lindsey R, Byrnes William C,. Comparison of Male and Female Road Cyclists under Identical Stage Race Conditions, *Medicine & Science in Sports and Exercise*, 2010;
10. Nojaki, H, Effect of the front and rear weight distribution ratio of a formula car during maximum, speed cornering on a circuit, *International Journal of Automotive Technology*, 2008; Vol 9, No. 3 pp. 307-315 2008
11. Gordon D, Willson, *Bicycling science*, The MIT Press; third edition, March 19, 2004, ISBN 0262731541