Spring 1-1-2017

The Effects of Suspension on the Energetics and Mechanics of Riding Bicycles on Smooth Uphill Surfaces

Asher Hamilton Straw
University of Colorado at Boulder, asher.straw@colorado.edu

The effects of suspension on the energetics and mechanics of riding bicycles on smooth uphill surfaces.

By

Asher H. Straw

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
2017

This thesis entitled:

The effects of suspension on the energetics and mechanics of riding bicycles on smooth uphill surfaces.

written by Asher H. Straw

has been approved for the Department of Integrative Physiology

____

Rodger Kram, Ph.D

____

Thomas LaRocca, 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 # 17-0213

Abstract

Straw, Asher Hamilton (M.S., Integrative Physiology)

The effects of suspension on the energetics and mechanics
of riding bicycles on smooth uphill surfaces

Thesis directed by Associate Professor Emeritus Rodger Kram, Ph.D.

Bicycle suspension elements smooth the vibrations generated by irregularities in the road or trail surface. However, it is unknown whether the energy put into the suspension system exacts a metabolic or mechanical cost. Here, I investigated the effects of suspension systems on the energetics and mechanics of riding bicycles on smooth uphill surfaces in both the sitting and standing positions.

Chapter 1: Twelve male cyclists road at 3.35m/s up a motorized treadmill inclined to 7% grade. All subjects used the same road bike equipped with a steering tube front suspension system. Each subject completed six 5 minute trials separated by 5-minute rest periods, with the suspension system in rigid (locked) and compliant settings. I measured their metabolic rates from oxygen consumption and carbon dioxide production. I also measured their mechanical power outputs. In the sitting position, metabolic power averaged 13.10±0.54 (rigid) and 13.21±0.54 W/kg (compliant). Mechanical power averaged 2.83±0.06 W/kg in both conditions. During standing, metabolic power averaged 14.22±0.73 (rigid) and 14.17±0.81 W/kg (compliant). Mechanical power averaged 2.86±0.03 and 2.87±0.05 W/kg respectively. None of these differences were statistically significant.

Chapter 2: Eight male and four female mountain bikers rode at 2.77m/s up a motorized treadmill inclined to 7% grade. Subjects rode a dual-suspension mountain bike. Each subject completed six 5 minute trials separated by 5-minute rest periods, with the suspension set to firm and soft conditions. I measured their metabolic rates from oxygen consumption and carbon dioxide production. I also measured their mechanical power outputs. In the sitting position, metabolic power averaged 11.38±0.48 (firm) and 11.44±0.49 W/kg (soft). Mechanical power averaged 2.54±0.20 W/kg in both conditions. During standing, metabolic power averaged 12.46±0.62 (firm) and 12.63±0.90 W/kg (soft). Mechanical power averaged 2.57±0.21W/kg in both conditions. None of these differences were statistically significant.

In conclusion, suspension systems in both road and mountain bikes had no effect ($p>0.10$) on the metabolic or mechanical power required for bicycle riding on smooth uphill surfaces in either seated or standing positions.

Table of Contents

List of Tables

List of Figures

Chapter 1

Figures

Chapter 2

Figures

Thesis Introduction

Bicycles have always fascinated me. I dedicated my entire college tenure to enthusiastically studying the energetics and mechanics of riding bicycles. I conducted and published a study of the effects of shoes and pedals on the metabolic cost of bicycling (Straw et al. 2016). In addition, I studied the metabolic effects of changing the bicycle's relative crank-angles (Straw et al. 2017). More recently, I helped to refine the use of a motorized treadmill to simulate bicycling in the lab and used those methods to validate on-board power meters for a bicycle manufacturer. Overall, my passion for bicycles has led me to places I never thought possible.

The bicycle community (riders, coaches, journalists and manufacturers) has historically believed that bicycle suspension systems incur an energetic penalty and thus bicycle frames should be extremely rigid. Specifically, in road bicycles, this had led to extremely rigid frames which do nothing to reduce or damp road vibrations. But recently, road cyclists have begun venturing onto dirt and gravel roads for races and adventure only to find that rigid bicycle frames are uncomfortable and fatiguing. Thus, road bike manufacturers have begun to incorporate suspension elements into road bike frames in an attempt to improve rider comfort. However, traditionalists still question whether or not suspension systems are exacting a metabolic or mechanical cost. Research on the topic of road bike suspension systems has until this point, been non-existent.

In contrast to road cyclists, mountain bikers are much more open to the use of suspension system and the technology is far more advanced. Yet mountain bike riders still perceive that suspension systems cause their body to "bob" up and down when pedaling and thus impose a metabolic penalty. In response, manufacturers have equipped their mountain bikes with manual and automatic lock-out systems to make the bike more rigid and minimize “bobbing” during riding on smooth surfaces. Several studies have been conducted to test this notion, but unfortunately, some of the past research has been flawed. Further, none of the research has compared differences in riding position (sitting vs. standing).

In the ensuing two chapters, I focus specifically on the effects of suspension systems on the energetics and biomechanics of bicycling. In chapter 1, I present my research on a novel steering tube suspension system (Future Shock®) for road bicycles and its effects on the metabolic and mechanical power demands. In chapter 2, I present my research on mountain bicycle suspension systems and the effects on the metabolic and mechanical power demands. In both cases, my research focused on uphill riding in both seated and standing positions on a smooth treadmill surface.

I thank Specialized Bicycle Components Inc., and specifically Todd Carver for funding our many bicycle related research projects and allowing me to continue to follow my passion for cycling throughout my graduate school career.

I dedicate this thesis to all the people who have helped me along the way: my friends, my advisors, my family and most of all my fiancé Margaret.

Chapter I.

The effects of a front suspension system on the energetics and mechanics of smooth uphill road bicycling.

Introduction

Riding a modern road bicycle with a rigid frame requires mechanical power (and hence metabolic energy) to overcome aerodynamic drag, internal transmission friction, rolling resistance, and, if riding uphill, gravity. When bicycles were first invented, the dirt roads were rough and rolling resistance was a dominant factor in a rider's energy expenditure (Minetti et al., 2001). The first bicycle wheels had wooden spokes and rims with iron bands wrapped around the circumference (Wilson, 2004). Such wheels directly transmitted vibrations and shock causing great rider discomfort. In fact, one early bicycle model was known as the "bone shaker" (Hadland & Lessing, 2014). Solid rubber tires replaced the iron bands and modestly reduced vibrations from irregularities in the road (Wilson, 2004). Towards the end of the 19th century, formerly rough dirt and cobblestone road surfaces began to be paved with asphalt (macadam) which is obviously smoother (Reid, 2011). The first pneumatic (air-filled) bicycle tires were introduced in 1888 and, together with the paved roads, greatly enhanced rider comfort (Hadland & Lessing, 2014). As paved asphalt roads became prevalent in the 20th century, pneumatic tires were developed which could hold far higher pressures thus lowering rolling resistance (Hadland & Lessing, 2014). Minetti et al. (2001) have provided unique data on how the mechanical power requirements dramatically decreased over a century of bicycle evolution. But, as manufacturers worked tirelessly to maximize the efficiency of road bicycles on smooth surfaces, the sport of bicycling took a dramatic turn.

In 1970, mountain bikes were "invented" and bicycling returned to rough dirt roads and trails (Wilson, 2004). By the 1990s, bicycle manufacturers began to develop mountain bikes with forks that suspended the front wheel to reduce the shock and vibrations acting on the rider. Subsequently, dual-suspension systems (front and rear) emerged, allowing cyclists to ride even faster and more comfortably over even rougher terrain. However, suspension systems with damping elements intrinsically dissipate mechanical energy.

When riding a bicycle with a rigid frame on smooth surfaces with high pressure tires, minimal mechanical work is done to deform the frame, tires, and other components. However, when riding a bicycle with a suspension system comprising springs and/or dampers, the rider inevitably does additional mechanical work with each pedal stroke to compress the suspension elements. It does not seem feasible to recapture that energy when the suspension system rebounds to provide forward movement of the bicycle. However, on rough irregular surfaces, a suspension system might provide a net savings of metabolic energy by reducing the muscular effort and co-contractions required to control and maneuver the bicycle.

As early as the 1990s, researchers began to investigate whether riding mountain bikes with suspension increased or decreased the rider's metabolic cost. Berry at al. (1993), studied the metabolic energy expenditure of cycling on a motorized treadmill (4%, 6.5MPH) with both smooth and bumpy surfaces. They compared a dual-suspension mountain bike vs. a rigid-framed mountain bike. They found no significant difference in oxygen uptake between suspension types when riding on a smooth surface. However, when surface bumps were added, metabolic cost was 12% lower for the dual-suspension mountain bicycle. Later, MacRae et al. (1999) compared a mountain bike with a front wheel suspension to a dual-suspension mountain bike. On two different timed race courses, one dirt, and one asphalt, they reported that the bicycle with front suspension required 24.9% (dirt) and 25.8% (asphalt) less mechanical power output, but paradoxically they recorded no difference in metabolic cost between the two suspension systems. Nielens et al. (2001) used a stationary cycle ergometer to evaluate the energy savings/cost of suspension systems. They compared bikes with dual-suspension, front suspension only and no suspension at power outputs between 50 and 250W and found no significant differences in metabolic cost between any of the bicycles. Thus, overall the data have consistently reported no energetic penalty for mountain bike suspension systems on smooth surfaces.

With the success and popularity of mountain bike suspension systems, manufacturers have recently returned full circle to incorporate suspension technology on road bicycles with the goal of improving rider comfort, especially on rough dirt, gravel or cobble-stone roads. These new technologies have even begun to be incorporated into racing bicycles used in one of the world's most famous races, Paris-Roubaix which has numerous cobble-stone sections. Yet, to date, there have been no scientific studies published on the energetics or mechanics of road bikes with suspension systems.

Here, we investigated the metabolic and mechanical power requirements of riding a road bicycle with a front-end suspension system. Our purpose was to quantify if this suspension system incurs metabolic or mechanical penalties when riding uphill on a smooth surface. Further, we determined if any such penalty is exacerbated when riding in a standing position. We tested the null hypothesis that the suspension system would not significantly change either the metabolic or mechanical power required to ride at a given speed and incline.

Methods

Subjects

We tested 16 male subjects (age: 27 ± 1.3 yrs, mass: 75.05 ± 7.48 kg, mean ± SD). All subjects reported cycling more than 4 hours per week and none had current musculoskeletal injuries. Participants provided written consent as per the University of Colorado, Boulder Institutional Review Board.

Bicycle Configuration

Subjects rode a 56cm Specialized Roubaix® bicycle (Mass: 9.02kg) (Specialized Bicycle Components, Morgan Hill, CA, USA) at a velocity of 3.35 meters/second (= 7.5MPH) up an incline of 4.0° or ~7% on a large custom-built, motorized treadmill (length 3.2m, width 0.9m). The tire pressure was set to 100 PSI. The bicycle was equipped with a crank-based mechanical power meter (Quarq®, Spearfish, SD, USA). The bicycle had a Shimano® 105 component group set fitted with 52/34 tooth chainrings and an 11-28 tooth rear cassette (Shimano, Sakai, Osaka Prefecture, Japan). The rear cassette gave the riders the options of 11, 12, 13, 14, 15, 17, 19, 21, 23, 25, 28 teeth. We calculated the riders' cadences using Equation 1:

$$\text{Cadence (RPM)} = \text{Speed (m/s)} \div \text{(distance per revolution)} \cdot 60 \qquad \text{(Equation 1)}$$

where distance per revolution = (wheel circumference x gear ratio). Wheel circumference with tire was 2.09 m and tire pressure was maintained at 100psi (6.89 bar).

The suspension system (Future Shock ®, Specialized Bicycle Components, Morgan Hill, CA, USA), here abbreviated as FS, comprises a metal coil spring that has a linear stiffness (k) of ~ 30.0 kN/m up to 20mm of compression, zero pre-load and negligible damping. The spring is housed inside of a metal canister that is nested inside the bicycle's steering tube. A rigid stem clamps to the upper end of the FS and the handlebars are clamped at the other end of the stem

(Figure 1.). Essentially, the FS suspends the upper body of the rider but the frame, drivetrain and wheels are not affected by the vertical movements of the rider's hands and arms.

Figure 1. Depiction of the Future Shock®.

We calculated each factor that contributes to the total mechanical power output required to ride at the specified conditions. First, we measured the coefficient of rolling resistance (C_{RR}) for the test bicycles with a rider on the treadmill at the 4.0° incline (Figure 2). To do so, we attached a cord to the head-tube of the bicycle frame. The cord ran parallel to the treadmill deck and passed over a low-friction pulley mounted in front of the treadmill. We hung weights at the end of the cord and turned on the treadmill to 3.35 m/sec. We manipulated the amount of the hanging weight (F_{PULL}) until the freewheeling rider was in equilibrium, neither drifting forwards nor backwards. The force perpendicular (normal) to the treadmill surface (F_N) equals (M+m), where M equals the rider mass and m equals the bicycle mass multiplied by gravitational acceleration, g, 9.81 m/s^2 and the cosine of the inclination angle (Equation 2).

$$F_N=(M+m)\ g \cos(4.0°) \quad \text{(Equation 2)}$$

C_{RR} is equal to the ratio of those two forces.

$$C_{RR} = F_{Pull} / F_N. \quad \text{(Equation 3)}$$

With the C_{RR} determined, we calculated the rolling resistance force and knowing the velocity, we calculated the power (P) to overcome rolling resistance using Equation 4.

$$P_{RR} = (M + m)\ g \cos(4.0°)\ C_{RR}\ v_{treadmill} \quad \text{(Equation 4)}$$

We then calculated the vertical power required to ride up the 4.0° incline against gravity using Equation 5.

$$P_{VERT} = (M + m)\ g\ v_{treadmill} \sin(4.0°) \quad \text{(Equation 5)}$$

Finally, we multiplied the sum of the vertical and rolling resistance powers by 1.02 in order to account for drivetrain losses (Martin et al., 1998) (Equation 6).

$$(P_{VERT} + P_{RR}) \bullet 1.02 \quad \text{(Equation 6)}$$

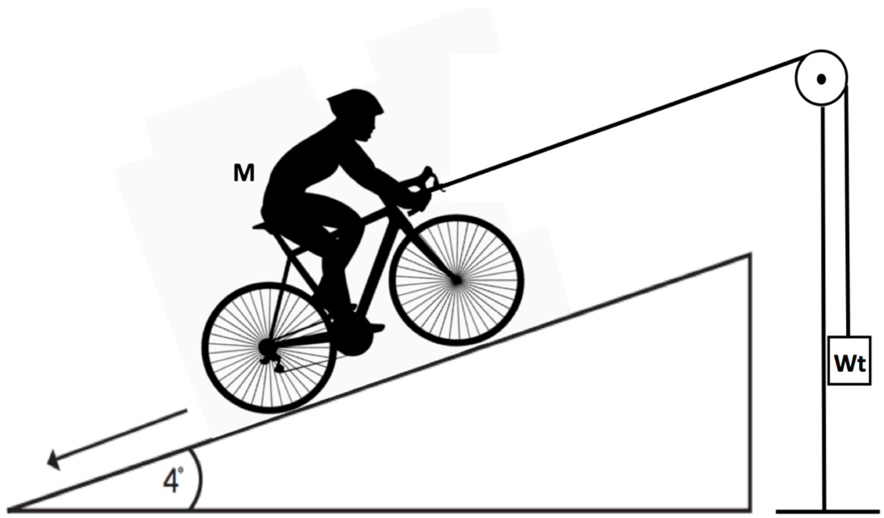

Figure 2: Diagram depicting how we measured C_{RR} on the treadmill.

Experimental Design

Each subject reported to the lab for one session, lasting up to two hours. They first practiced cycling on the uphill treadmill during two 5-minute periods with an additional 5 minutes wearing the expired-gas analysis mouthpiece and noseclip. The subjects practiced riding both sitting and standing. Following the treadmill practice, the subjects rested for 5 minutes before actual testing began. Next, subjects completed six, 5-minute experimental trials separated by 5-minute rest periods between trials. The first and last trials were baseline-seated trials with the FS locked out in a rigid configuration (R_{Sit}). These two baseline trials ("Baseline 1" and "Baseline 2") allowed us to evaluate if any parameters drifted due to fatigue, learning etc. Two of the four middle trials consisted of riding the bicycle with the FS steering tube suspension system engaged (FS_{Sit} and FS_{Stand}). In the other two middle trials (R_{Sit} and R_{Stand}), the FS was rigidly locked out by inserting a steering tube spacer. In each configuration, subjects rode a seated and a standing trial. The possible orders were counterbalanced and randomly assigned. During the trials, riders were allowed to freely choose their gear ratio for both sitting and standing trials. The gear ratio they chose for the first sitting trial had to be used for the other sitting trial and likewise for the standing trials.

During the six experimental trials, we collected each participants' expired gases and calculated the STPD rates of oxygen uptake ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) using an open-circuit expired gas analysis system (TrueOne 2400; ParvoMedics, Sandy, UT, USA). Before each experiment, we calibrated the gas analyzers and pneumotach using reference gases, and a calibrated 3-L syringe, respectively. We averaged $\dot{V}O_2$, $\dot{V}CO_2$, and respiratory exchange ratio (RER) for the last 2 minutes of each trial. We planned to exclude any participants whose RER values exceeded 1.0, but all values remained below 1.0. From the $\dot{V}O_2$and $\dot{V}CO_2$ measurements, we calculated metabolic power in watts (W) (Brockway, 1987).

We equipped the bicycle with a small, lightweight video camera (GoPro ®), mounted to the handlebars and focused on the bicycles head-tube. We marked a small dot on the head tube of the frame and one on the stem that clamped the handlebars. By measuring the change in distance between the dots with the use of Kinovea software (www.Kinovea.org), we could quantify the displacement the spring throughout each trial. By combining the displacement data with the known stiffness (k), we determined the work done and mechanical power input at the FS (Equation 6,7).

$$\text{Mechanical Energy (joules)} = \tfrac{1}{2}\, k\, (\Delta L)^2 \qquad \text{(Equation 6)}$$

$$\text{Power (watts)} = (\text{Mechanical Energy/Pedal Stroke}) \bullet (2 \bullet \text{Cadence (rev/s)}) \qquad \text{(Equation 7)}$$

Statistical analysis

We analyzed the data in MATLAB (The MathWorks, Inc., Natick, MA, USA) using multiple paired t-tests. We consider the calculated mechanical power on the treadmill to be the standard to which we related the Quarq® crank-based power meter output.

Results

We excluded the data for 4 subjects due to a substantial increase (> 3.0 %) in their metabolic cost of cycling from Baseline 1 to Baseline 2. We attribute that to fatigue.

In order to tease out differences between the rigid and FS conditions, the repeatability of both metabolic power and mechanical power measurements was crucial. For the 12 subjects analyzed, between the Baseline 1 vs. Baseline 2, we found no significant difference in metabolic power (P=0.88) (Table 1). Further, we calculated a non-significant 0.27% decrease on average for the crank-measured mechanical power (P=0.51) (Table 2). Lastly, to evaluate the accuracy of our calculated power, we compared it to the crank-measured mechanical power for the Baseline 1 trial recorded values. The calculated mechanical power averaged 2.82 W/kg and the crank-measured mechanical power averaged just 0.75% greater at 2.84 W/kg (P=0.04) (Table 2). This value was well within the expected accuracy of commercial power meters and our confidence in the assumed 2% drivetrain power loss.

Table 1: Body mass, and metabolic power (W/kg body mass) data for each subject across all conditions. Compliant is with the Future Shock® in the un-locked position and Rigid is with the Future Shock® in the locked position.

		Metabolic Power (W/kg)					
Subject	Mass (kg)	Baseline 1	Rigid Sit	Compliant Sit	Rigid Stand	Compliant Stand	Baseline 2
1	77.8	14.44	14.31	14.48	15.80	15.92	14.54
2	75.9	14.31	13.99	13.78	15.02	14.92	14.32
3	75.8	12.99	13.21	13.18	14.26	13.69	13.27
4	93.3	13.65	12.90	13.11	14.46	14.10	13.52
5	71.6	12.73	12.82	12.85	13.31	13.27	12.83
6	69.9	12.59	12.42	12.21	12.97	12.87	12.55
7	72.1	13.10	13.11	12.89	14.11	14.05	13.12
8	67.6	12.71	12.90	13.39	14.61	14.89	12.90
9	67.2	12.85	12.64	13.06	13.90	13.76	12.98
10	76.4	13.41	13.01	13.22	14.06	14.39	13.15
11	69.3	13.50	13.06	13.14	14.05	14.06	13.31
12	83.7	13.16	12.78	13.15	14.10	14.06	13.06
Mean	75.1	13.29	13.10	13.21	14.22	14.17	13.30
S.D.	7.5	0.61	0.54	0.54	0.73	0.81	0.59

Table 2: Body mass, and mechanical power (W/kg body mass) data for each subject across all conditions. Compliant is with the Future Shock® in the un-locked position and Rigid is with the Future Shock® in the locked position.

Crank-measured Mechanical Power (W/kg)							
Subject	Mass (kg)	Baseline 1	Rigid Sit	Compliant Sit	Rigid Stand	Compliant Stand	Baseline 2
1	77.8	2.80	2.79	2.82	2.81	2.82	2.86
2	75.9	2.89	2.86	2.87	2.92	2.91	2.90
3	75.8	2.82	2.88	2.85	2.85	2.84	2.86
4	93.3	2.80	2.81	2.80	2.87	2.86	2.82
5	71.6	2.90	2.87	2.89	2.86	2.86	2.89
6	69.9	2.84	2.81	2.78	2.83	2.83	2.79
7	72.1	2.83	2.84	2.83	2.83	2.84	2.85
8	67.6	2.91	2.95	2.96	2.91	3.02	2.88
9	67.2	2.85	2.83	2.85	2.87	2.86	2.84
10	76.4	2.80	2.72	2.71	2.84	2.86	2.74
11	69.3	2.85	2.83	2.82	2.85	2.86	2.80
12	83.7	2.84	2.77	2.83	2.84	2.82	2.81
Mean	75.05	2.84	2.83	2.83	2.86	2.87	2.84
S.D.	7.48	0.04	0.06	0.06	0.03	0.05	0.05

While riding in the seated position, the metabolic power averaged 13.10±0.5W/kg for the rigid steering tube and 13.21±0.5W/kg (Table 1) for the compliant steering tube. The compliant Future Shock steering tube suspension system required numerically ~0.9% more metabolic power but that difference was not statistically significant ($p=0.15$). The crank-based mechanical power measurements averaged 2.83±0.06W/kg for the rigid steering tube and 2.83±0.06W/kg (Table 2) for the compliant steering tube. Those values numerically differed by less than 0.1% and were not statistically significant ($p=0.81$).

During the standing trials, the metabolic power averaged 14.22±0.7W/kg for the rigid steering tube and 14.17±0.8W/kg (Table 1) for the compliant steering tube. Those values were numerically less than 0.4% different and were again not statistically different ($p=0.45$). The crank-based mechanical power values averaged 2.86±0.03W/kg for the rigid steering tube and

2.87±0.05W/kg for the compliant steering tube (Table 2) and those values were not statistically different ($p=0.40$).

Between the seated and standing positions, there was a sizable difference in metabolic power even though there were no differences in crank-measured mechanical power. When the FS was in the locked-out position, climbing while standing required 8.2±2.6 % (Table 1) more metabolic power than in the seated position ($P<0.0001$).

Using the calibrated GoPro video recordings, we were able to measure the compression of the FS with each pedal stroke (mean compression: 4.5 (sitting), and 9.0 mm (standing)) and calculated the axial forces acting on the FS. From the compression and force values, we calculated that the mechanical work done on the FS steering tube suspension system for each half pedal cycle. Knowing cadence, we could then calculate the rate of work done or mechanical power input to the FS (Equation 6,7). During the FS_{Sit} condition, we calculated an average power input of just 0.64±0.43 W, which increased to 2.53±0.98 W during standing (Table 3). The maximum force applied by the rider to the bicycle's handlebars increased from 13.8±4.6% of body weight while seated to 22.2±4.2 % while standing (Table 4).

On average, the power input to the FS while sitting was less than 0.4% of the overall mechanical power produced. When standing, the power input to the FS was still only 1.2% of the overall mechanical power required for cycling.

Discussion

Our primary objective was to quantify the effects of a front suspension system on the energetics and mechanics of uphill road bicycling on a smooth surface. We tested the null hypothesis that the FS steering tube suspension system would not significantly increase either metabolic or mechanical power output. Under any of the conditions tested, the FS suspension system did not require more metabolic or mechanical power. Thus, we retain our null hypothesis.

Our results are consistent with previous research on bicycle suspension systems. For example, recall that Berry et al. (1993) found no difference in metabolic power differences between riding dual-suspension vs. rigid framed mountain bikes at 6.5 MPH up a 4% inclined smooth treadmill. Similarly, Nielens et al. (2000) found no differences in metabolic cost for riding mountain bikes with front and dual-suspension systems. Although there are other bicycle suspension studies (Wang & Hull, 1996; MacRae et al., 1999; Titlestad et al., 2007), our results are not easily comparable because those studies did not compare a rigid condition to a suspension condition, but rather front suspension to dual-suspension.

In addition to measuring the metabolic power of the riders and their mechanical power output at the cranks, we estimated the mechanical work and power input to the suspension system. We were unable to determine if the work done on the spring by the rider was simply lost upon recoil or if mechanical energy was effectively returned to re-lift the weight of the rider's upper body. However, we know that at worst, if all of the power was simply dissipated, it was a very small amount (0.64W sitting, 2.53W standing) especially compared to the ~200W of overall mechanical power (Table 2.). At best, if all of the mechanical energy stored in the FS was effectively returned back to the rider, the net result would be zero. Lastly, we consider the calculated mechanical power on the treadmill to be the gold standard to which we related the data from the Quarq® crank-based powermeter. The calculated mechanical power and the crank-measured power during Baseline 1 trial differed by less than 1%. That is well within the expected accuracy of commercial power meters, verifying the trueness of our calculation method and measurements.

Although it was not our primary focus, we found an unequivocal ~9% greater metabolic cost for riding uphill while standing vs. sitting. Previous research on this topic however has reached mixed conclusions. Tanaka et al. (1996) compared sitting versus standing positions during motorized treadmill road bike riding up a 4% (2.3º) grade and found oxygen uptake increased 5.3% when standing. Inexplicably, when the grade was increased to 10% (5.7º), they found no difference in oxygen uptake. Ryschon and Stray-Gundersen (1999) found an 11.3% increase in oxygen uptake for standing when compared to sitting while riding up at 4% (2.3º) incline, again on a motorized treadmill. In contrast, Millet et al. (2002) studied subjects cycling outdoors up a hill (5.3% (3.0º) incline) and reported only negligible (non-significant) differences between seated and standing positions. That finding is difficult to explain since we would expect the standing position to be even more expensive outdoors when air resistance does play a role. Further research is needed to gain a better understanding of the differences in oxygen uptake between sitting and standing both on a treadmill and outdoors.

One possible limitation of our study is our use of a motorized treadmill. Unlike during outdoor cycling, when riding on a treadmill, there are no substantial aerodynamic forces. However, using a treadmill allows for tight experimental control, high reproducibility and consistency because random environmental factors (i.e. wind) are eliminated. Further, compared to other indoor bicycle testing options (ergometers and stationary trainers), the treadmill allows for the use of an actual bicycle and balance, mental focus and riding style are quite realistic.

Future studies should investigate the benefits and/or drawbacks to the use of the steering tube FS suspension system while riding on rough terrain. It is possible that on rougher terrain, a suspension system can save the rider metabolic energy by reducing shock and vibrations to the rider's body and thus muscle actions and co-contractions as well as fatigue.

In conclusion, bicycle riders input minimal mechanical work into an undamped steering tube suspension system and as a result, the FS suspension system tested incurred no significant metabolic or mechanical power penalties.

Chapter II.

The effects of mountain bike suspension on the energetics and mechanics of smooth uphill riding during sitting and standing

Introduction

Almost immediately after the invention of the first bicycle in the 1800s, manufacturers developed rudimentary suspension systems to protect the rider from the irregularities of early road surfaces (Wilson, 2004). Suspension elements were incorporated into the frame (Kellogg, 1883), handlebars (Copeland, 1889) and saddle (Serrell, 1896 & Little, 1897) in order to enhance rider comfort. But, as road surfaces improved, suspension systems for road bicycles became obsolete and were abandoned. However, after the invention of mountain bikes in the 1970s, bicycle suspension systems re-emerged and have evolved over the ensuing decades. Modern suspension systems for mountain bikes are highly compliant and thus the suspension elements undergo greater displacements (known colloquially as "travel"). Modern-day mountain bikes are categorized as: rigid (no suspension), front wheel suspension only (aka "hardtail"), and dual-suspension (both front and rear wheels with suspension systems). The evolution of suspension systems has enabled riders to ride on rougher trails with increased comfort and speed.

However, many in the mountain bike community (riders, journalists, manufacturers) perceive/believe that mountain bike suspension systems increase the mechanical and hence metabolic power demands. A 2004 review by Nielens & Lejeune states "The fact that suspensions may also dissipate the cyclist-generated power remains a major concern for bike manufacturers and competitors". Indeed, manufacturers have developed many different sophisticated linkage systems to minimize the compression of the suspension elements due to rider induced forces applied to the pedals. Further, manufacturers have developed manual and automatic devices that disengage ("lock-out") the suspension systems. These devices allow the rider to transform the suspension from a compliant mode to a more rigid mode for riding over surfaces that do not warrant suspension (i.e. smooth surfaces).

In contrast to rider perceptions and manufacturer concerns, scientific research has consistently found that mountain bike suspension systems do not incur any mechanical or physiological penalty even on smooth surfaces. Berry et al. (1993) was the first to investigate the effects of mountain bike suspension on metabolic energy cost. They compared the metabolic cost of riding a dual-suspension mountain bike vs. a fully rigid mountain bike with no suspension. Their laboratory testing involved riding at 6.5 MPH (10.5 km/hr, 2.91 m/sec) on a motorized treadmill with a smooth surface inclined to 4% (2.3°). They reported no difference in oxygen uptake, rate of perceived exertion or heart rate. Surprisingly, although the suspension was free to travel during the suspension trials, the investigators visually observed no pedal force induced compression of the suspension elements. It may be that the suspension system that they tested was simply too stiff. With no compression of the suspension elements, we can only surmise that no mechanical work was done on the suspension.

Subsequently, MacRae et al., (1999) tested mountain bikes on a paved road. The paved road was 1.61km long with 183-m of elevation gain (averaging 11.4% or 6.5°). Testing both a mountain bike with a front wheel suspension only and a dual-suspension mountain bike, they found no difference in course completion time heart rate, or oxygen uptake between bicycles. However, they reported an inexplicable 25.8% lower mechanical power output measured at the cranks for the front suspension mountain bike compared to the dual-suspension mountain bike.

Moreover, the testing was done in the style of a time trial, which had subjects completing the course at ~84% of their $\dot{V}O_{2MAX}$ rather than at steady-state.

Nielens and Lejeune (2001) quantified the metabolic cost due to mountain bike suspension using a stationary device that applied resistance to the rear wheel via a roller. At a mechanical power outputs between 50-250W, they found no difference in oxygen uptake between three different bicycles: a dual-suspension bike, a front suspension bike and a rigid bike. However, it is not clear if the Nielens and Lejeune simulator is a valid representation of real mountain biking on a smooth surface. Regardless, among the three studies, the data are overall quite consistent in finding no effect of mountain bike suspension systems on the energetic cost of cycling.

Despite their consistency, the previous studies described above have serious limitations. Further, they only considered riding in a sitting position and the older suspensions systems were much stiffer than today's bikes and thus had limited suspension travel. During true outdoor riding, mountain bikers often stand when climbing up steep hills or when they are trying to generate high mechanical power outputs such as during accelerations or sprints. When standing during climbing, the pedaling forces are likely larger and engage the suspension elements to a greater degree than during sitting. Further, modern bike suspension systems are substantially more compliant than their forebears.

Thus, we set out to study both the metabolic power requirements and mechanical power outputs of riders on bikes with modern suspension systems. We tested the null hypothesis that suspension systems would not significantly affect either the metabolic or mechanical power required to ride in seated or standing positions on a smooth treadmill at a fixed velocity and incline.

Methods

Subjects

We tested 9 male and 4 female subjects (Age: 26 ± 3.06 yrs, body mass: 69.02 ± 9.15 kg, mean ± SD). All subjects reported riding a mountain bike for at least one year prior to the start of the study and had no current musculoskeletal injuries. Participants provided written consent as per the University of Colorado Boulder Institutional Review Board.

Mountain Bike Configuration

The bicycles tested were 2018 Epic® models with both front and rear Brain® suspension systems (Specialized Bicycle Components Inc., Morgan Hill, CA, USA). The suspension systems each comprise a Horst linkage design with a shock absorber consisting of a pressurized air spring with oil-based damping. Maximum front and rear wheel travel is 100mm. These suspension systems are designed to automatically engage and disengage in response to the riding surface conditions. On a rough surface, the suspension compression damping is minimized and when the surface is smooth, the damping is automatically increased. Shock absorber air pressure was set to manufacturer recommendations. Depending on their leg length, subjects rode either a large (10.93 kg total bike mass) or small (11.36 kg) size frame.

Subjects rode at a velocity of 2.78 meters/second (= 10.0 km/hr, 6.21 MPH) on a custom-built, wide and long motorized treadmill (length 3.2m, width 0.9m) inclined to 4.1° or ~7%. Tire pressure was set to 28 PSI. We equipped the bike with a Quarq® (Spearfish, SD, USA) crank-based mechanical power meter. The riders were not allowed to view the power output display. Both bikes were equipped with SRAM® component groups (Chicago, IL, USA) fitted with a single 32 tooth chainring. The large size bike had a 10-50 tooth rear cassette rear cassette, which gave the rider options of 10, 12, 14, 16, 18, 21, 24, 28, 32, 36, 42, 50. The small sized bicycle had a 10-42 tooth rear cassette rear cassette, giving the rider options of 10, 12, 14, 16, 18, 21, 24, 28, 32, 36, 42. We calculated the riders' cadences using Equation 1:

$$\text{Cadence (RPM)} = \text{Speed (m/s)} \div (\text{distance per revolution}) \cdot 60 \qquad \text{(Equation 1)}$$

where distance per revolution = (wheel circumference • gear ratio). Wheel circumference with tire = 2.31m.

We calculated each factor that contributes to the total mechanical power output required to ride at the specified conditions. First, we measured the coefficient of rolling resistance (C_{RR}) for the test bicycles with a rider on the treadmill at the 4.1° incline (Figure 1). To do so, we attached a cord to the head-tube of the bicycle frame. The cord ran parallel to the treadmill deck and passed over a low-friction pulley mounted in front of the treadmill. We hung weights at the end of the cord and turned on the treadmill to 3.35 m/sec. We manipulated the amount of the hanging weight (F_{PULL}) until the freewheeling rider was in equilibrium, neither drifting forwards nor backwards. The force perpendicular (normal) to the treadmill surface (F_N) equals (M+m), where M equals the rider mass and m equals the bicycle mass multiplied by gravitational acceleration, g, 9.81 m/s^2 and the cosine of the inclination angle (Equation 2).

$$F_N=(M+m)\, g \cos(4.1°) \qquad \text{(Equation 2)}$$

C_{RR} is equal to the ratio of those two forces.

$$C_{RR} = F_{Pull} / F_N. \qquad \text{(Equation 3)}$$

With the C_{RR} determined, we calculated the rolling resistance force and knowing the velocity, we calculated the power (P) to overcome rolling resistance using Equation 4.

$$P_{RR} = (M + m)\, g \cos(4.1°)\, C_{RR}\, v_{treadmill} \qquad \text{(Equation 4)}$$

We then calculated the vertical power required to ride up the 4.1° incline against gravity using Equation 5.

$$P_{VERT} = (M + m)\ g\ v_{treadmill} \sin(4.1°) \qquad \text{(Equation 5)}$$

Finally, we multiplied the sum of the vertical and rolling resistance powers by 1.02 in order to account for drivetrain losses (Martin et al., 1998) (Equation 6).

$$(P_{VERT} + P_{RR}) \cdot 1.02 \qquad \text{(Equation 6)}$$

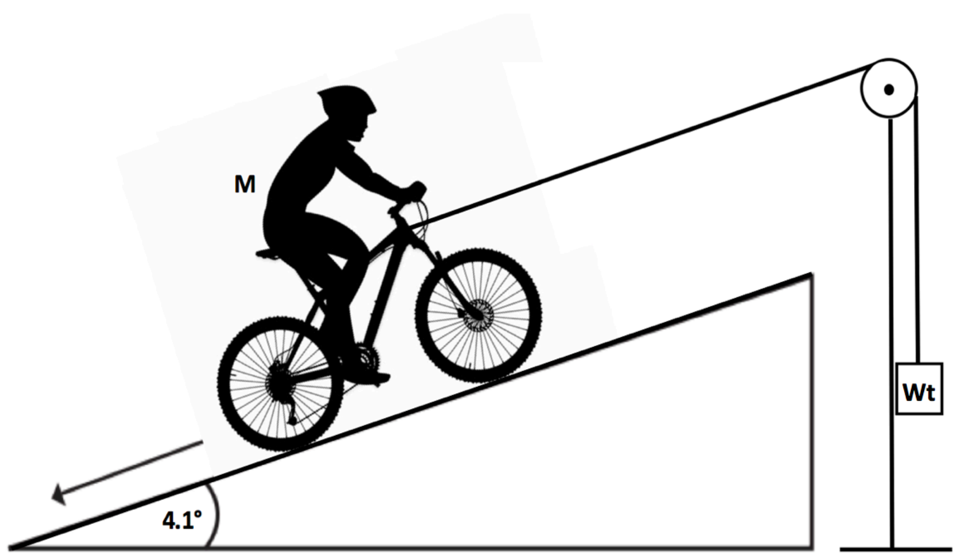

Figure 1: Diagram depicting how we measured C_{RR} on the treadmill

Experimental Protocol

Each subject reported to the lab for one session, lasting up to two and a half hours. They first practiced cycling on the uphill treadmill for two 5-minute periods and a third 5-minute period of riding while wearing an expired gas analysis mouthpiece and noseclip. The participants practiced riding in both the sitting and standing positions. Following the treadmill practice, subjects were given the opportunity to recover and rest for 5 minutes before actual testing began. Next, subjects completed six, 5-minute experimental trials separated by 5-minute rest periods between trials. The first and last trials were baseline trials in the seated position with the suspension in both the front and rear set to the "Firm/Brain on". On a smooth surface, when the Brain is in the "on" position, the suspension is most rigid and during the "off" position, it is most compliant. The two baseline trials ("Baseline 1" and "Baseline 2") allowed us to evaluate if any parameters drifted due to fatigue, or learning etc. Of the four middle trials, two consisted of riding with the suspension in the "Soft/Brain off" setting (one seated and one standing) and two trials were with the suspension set to the "Firm/Brain on" position (one seated and one standing). We randomized and counterbalanced the order of the trials. During the trials, riders were allowed to freely choose their gear ratio for both sitting and standing trials. The gear ratio they chose for the first sitting trial had to be used for the other sitting trial and likewise for the standing trials.

During the six experimental trials, we collected each participant's expired gases and calculated the STPD rates of oxygen uptake ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) using an open-circuit expired gas analysis system (TrueOne 2400; ParvoMedics, Sandy, UT). Before each experiment, we calibrated the gas analyzers and pneumotach using reference gases, and a calibrated 3-L syringe, respectively. We averaged $\dot{V}O_2$, $\dot{V}CO_2$, and respiratory exchange ratio (RER) for the last 2 minutes of each trial. We planned to exclude any participants whose RER values exceeded 1.0, but all values remained below 1.0. From the $\dot{V}O_2$ and $\dot{V}CO_2$ measurements, we calculated metabolic power in watts (W) (Brockway, 1987).

We equipped the bikes with a small lightweight video camera (GoPro®, San Mateo, CA, USA), mounted to a water bottle mount on the bicycle's frame. We then focused the camera on the rear shock absorber. We marked two small dots on the shock absorber; one on the piston shaft (which moves during compression and rebound) and a second dot on the body of the shock absorber (the part that does not move). By measuring the change in distance between the two dots with the use of Kinovea motion analysis Software (www.kinovea.org), we could quantify the displacement of the shock absorber throughout each trial. We only measured suspension displacement for the rear shock absorber.

Results

Before we tested for differences between the Soft and Firm conditions, we evaluated the repeatability of our metabolic power measurements. We excluded one subject because his metabolic power increased from Baseline 1 to Baseline 2 by more than 3.0% likely due to fatigue. For the 12 remaining subjects, we found no significant difference in metabolic power between the Baseline 1 (11.49±0.58 W/kg) and Baseline 2 (11.47±0.49 W/kg) trials (P=0.63) (Table 1).

For the middle four experimental trials, the metabolic power averaged 11.44±0.49W/kg for the Soft Sit condition and 11.38±0.48W/kg for the Firm Sit condition (Table 1). That numerical 0.54% difference was not statistically significant (p=0.21). Further, during the standing condition, the metabolic power averaged 12.63±0.90W/kg for Soft Stand and 12.46±0.62W/kg for Firm Stand (Table 1). However, that numerical difference (1.4%) was again not statistically significant (p=0.24).

Riding in the Firm Standing suspension setting required 9.54% more metabolic power than the Firm Sitting condition (p<0.01) (Table 1). This is consistent with our earlier observation on road bikes in which standing increased metabolic cost by ~9%, above sitting. (Straw et al. Chapter 1).

Table 1: Body mass, mechanical and metabolic power (W/kg body mass) data for each subject across all conditions. Soft is with the Brain® in the off position and Firm is with the Brain® in the on position. During the trials for subject F1 there was no cadence sensor on the bicycle

Metabolic Power Across All Conditions (W/kg)										
Subject	Rider Mass (kg)	Calculated Mechanical Power	Sit RPM	Stand RPM	Base 1	Soft Sit	Firm Sit	Soft Stand	Firm Stand	Base 2
F1	54.5	2.57	N/A	N/A	11.81	11.74	11.75	12.36	12.31	11.71
F2	56.3	2.56	63.8	41.0	12.54	12.31	12.19	12.90	12.46	12.33
F3	62.1	2.52	63.8	50.1	11.76	11.31	11.55	12.43	13.10	11.59
F4	61.0	2.52	63.8	43.3	10.42	10.36	10.41	10.87	11.49	10.38
M1	69.1	2.49	72.9	47.8	11.84	11.79	11.86	12.49	12.42	11.68
M2	76.4	2.45	63.8	54.7	10.84	10.90	10.87	12.57	12.27	11.12
M3	78.5	2.45	63.8	47.8	11.59	11.32	11.34	12.24	12.36	11.61
M4	70.7	2.48	72.9	54.7	10.90	11.39	11.05	12.40	11.97	10.99
M5	69.5	2.48	82.0	63.8	11.42	11.55	11.28	12.87	12.55	11.31
M6	82.3	2.43	72.9	54.7	11.90	11.87	11.73	13.61	12.77	11.88
M7	68.5	2.49	72.9	63.8	11.72	11.54	11.47	14.65	13.90	11.66
M8	79.6	2.44	63.8	47.8	11.16	11.23	11.08	12.13	11.89	11.38
Mean	69.0	2.49	68.8	51.8	11.49	11.44	11.38	12.63	12.46	11.47
S.D.	9.2	0.05	6.3	7.4	0.58	0.49	0.48	0.90	0.62	0.49
Female	58.5	2.54	63.8	44.8	11.63	11.43	11.47	12.14	12.34	11.50
Male	74.3	2.46	70.6	54.4	11.42	11.45	11.33	12.87	12.52	11.45

Regarding the mechanical power requirements, recordings from the Quarq® crank-based power meter did not differ between the Soft Sit or the Firm Sit conditions. (175.1±13.7W and 175.3±13.9W, respectively p=0.71) (Table 2). Nor did the power outputs differ in the standing position between Soft and Firm settings (177.3±14.4W and 177.2±14.5W, respectively) (Table 2). It should be noted that the mean Quarq® crank-based power meter values averaged for the baseline trials were within 2.3% of the calculated power. That small mean difference was just barely not statistically significant (p = 0.0504). It is possible that some of the 2.3% difference between the calculated to crank-measured values represents the additional power done on the suspension system and subsequently dissipated.

Table 2: Body mass, calculated and recorded mechanical power (W) data for each subject across all conditions. Soft is with the Brain® in the off position and Firm is with the Brain® in the on position. During the trials for subject F1 there was no power meter on the bicycle.

Calculated Mechanical Power vs. Recorded Mechanical Power (W)									
Subject	Rider Mass (kg)	Calculated Mechanical Power	Calculated (W/kg)	Base 1	Soft Sit	Firm Sit	Soft Stand	Firm Stand	Base 2
F1	54.5	140.6	2.59	N/A	N/A	N/A	N/A	N/A	N/A
F2	56.3	145.0	2.57	151.5	151.2	151.6	150.4	150.8	151.9
F3	62.1	156.4	2.52	163.9	163.9	163.4	164.6	164.8	165.7
F4	61.0	153.8	2.52	161.7	159.6	160.4	161.6	161.4	159.7
M1	69.1	171.9	2.49	175.7	169.3	172.3	175.9	173.5	169.9
M2	76.4	187.1	2.45	189.8	190.6	192.1	192.5	194.0	191.2
M3	78.5	192.0	2.45	187.5	185.4	185.6	190.0	191.1	N/A
M4	70.7	175.5	2.48	169.9	175.8	170.1	175.5	176.4	169.3
M5	69.5	172.6	2.49	173.9	173.6	174.3	176.5	177.5	172.8
M6	82.3	200.3	2.43	205.0	183.1	184.0	188.0	186.6	184.1
M7	68.5	170.7	2.49	176.1	175.9	176.5	177.2	175.0	175.1
M8	79.6	194.5	2.44	197.7	197.4	198.2	197.8	197.7	197.8
Mean	69.0	171.7	2.49	177.5	175.1	175.3	177.3	177.2	173.8
S.D.	9.2	19.6	0.05	16.1	13.7	13.9	14.4	14.5	14.0
Female	58.5	148.9	2.55	159.1	158.3	158.5	158.9	159.0	159.1
Male	74.3	183.1	2.47	184.5	181.4	181.6	184.2	184.0	180.0

All riders preferred to use a higher gear ratio (smaller cog) while standing ($p < 0.001$) (Table 1) and given a fixed velocity, that translated to a slower cadence (51.8±7.4RPM) while riding in the standing position, compared to sitting (68.8±6.3RPM).

Finally, using the data collected from the GoPro® video camera mounted to the frame, we determined that displacements of the rear shock absorber were greater during the Soft conditions for both sitting and standing positions. During sitting, the average shock absorber displacements were 3.12±1.22mm for the Soft condition vs. 0.94±0.33mm for the Firm condition

($p<0.001$). During the standing conditions, average displacement for the Soft condition was much greater than for the Firm condition (11.24±2.87mm vs. 4.37±1.65mm, $p<0.001$). Note that due to the rear suspension mechanical linkage, vertical travel of the rear wheel = 2.0 • shock absorber travel.

Discussion

Our primary objective was to quantify the effects of mountain bike suspension systems on the energetics and mechanics of uphill mountain bicycling on a smooth surface in both the sitting and standing positions. We tested the null hypothesis that the suspension systems would not significantly affect either the metabolic or mechanical power required to ride in either seated or standing positions at a given speed and incline. Under the conditions tested, the suspension system did not require more metabolic or mechanical power. Thus, we retain our null hypothesis.

Our findings replicate those of Berry et al., (1993). This is not surprising since our methods were nearly identical, apart from a few key differences. Berry et al. used a much shorter treadmill inclined to only 2.3° vs. our 4.1°. However, the biggest difference between Berry et al and the present study is the properties of the suspension systems. The Berry et al. study was conducted on one of the very first commercial mountain bike suspension systems. The front wheel suspension forks used in our study were much more compliant than the 1993-era forks.

Superficially, our findings appear similar to those of MacRae et al., (1999) but the two studies are fundamentally different. MacRae et al. had their subjects complete the outdoor course as fast as possible (i.e. simulated time trial race conditions). During the testing, their subjects performed at ~84% $\dot{V}O_{2MAX}$ and they had blood lactate concentration values of ~8mmol. Thus, they were exercising well above their lactate thresholds and the oxygen consumption values were not steady-state. Thus, it is not possible to firmly conclude anything about the effects of suspension systems on the energetic cost of cycling. However, we do recognize that the most important finding of MacRae et al. was that of equal performance with/without a suspension system which does suggest equal submaximal efficiency.

However, the mechanical power data in MacRae et al. are difficult to accept at face value. They report a 25.8% greater power output while riding the dual-suspension mountain bike vs. the “hard-tail” bike on asphalt and attribute that difference to the rear suspension. However, because MacRae et al. found no differences in oxygen consumption or time to course completion, they suggested the power put into the rear suspension somehow was re-directed to the forward propulsion of the rider. We are skeptical of that interpretation and suggest that there was a calibration difference between the two separate crank-based power meter units. While our results are consistent with Nielens and Lejeune (2001), it is not well established that their stationary bicycle rig accurately simulates treadmill or overground bicycling.

Although not hypothesized, the ~9% greater metabolic cost of standing vs. sitting is interesting. That difference is consistent with our previous finding also of ~9% greater metabolic cost for uphill road bike riding in a standing vs. sitting position (Chapter 1). These results, are consistent with most other studies of sitting vs. standing in road bicycles, although varying in magnitude (Tanaka et al. ,1996; Ryschon & Stray-Gundersen, 1999). However, Millet et al., (2002) reported no difference between the two riding positions. It is unclear why they found no difference, especially considering that they studied outdoor riding during which aerodynamic resistance would be greater in the standing position.

One possible limitation of our study is our use of a motorized treadmill. Unlike during outdoor cycling, when riding on a treadmill, the rider is not affected by aerodynamic forces and thus using a treadmill is not an entirely realistic simulation of outdoor riding. However, using a treadmill provides excellent reproducibility and consistency by eliminating confounding variables such as random environmental factors (i.e. wind). Unlike an ergometer, treadmills allow for the use of actual bicycles and thus afford a realistic simulation of balance, mental focus and riding style. Another limitation of our study is that we did not quantify the compression of the front wheel suspension forks.

Future studies should investigate the possible benefits and/or drawbacks of more modern suspension systems such as the one tested here on rough surfaces. It is possible that on rougher terrain, a suspension system can save the rider metabolic energy by reducing shock and vibrations to the rider's body. In fact, previous research has shown significant differences in metabolic cost between rigid and compliant bicycles when riding on bumpy surfaces (Berry et al., 1993, Titlestad et al., 2007). Lastly, it may be beneficial for future studies to quantify the mechanical power losses in the suspension elements.

In conclusion, the Brain® mountain bike suspension system did not incur any significant metabolic or mechanical power penalties in either sitting or standing positions.

Thesis Discussion

In this M.S. thesis, I have presented two scientific experiments on bicycle suspension. The first study pertained to a road bike with novel front suspension and the second investigated a mountain bike with both front and rear large travel suspension systems. In both cases, I found that suspension does not affect the energetics and mechanics of smooth, uphill bicycling.

In both experiments, I compared riding in both sitting and standing positions. In both cases, I expected that the suspension would be displaced more during standing and thus exact a greater penalty than in the sitting position. To my surprise this was not the case. In both studies, there was no difference in either energetics or mechanics in either sitting or standing positions. Further, for both road and mountain biking, I found that standing incurs a ~9% greater energetic cost compared to sitting.

During my M.S. thesis research, I refined the use of a treadmill as a useful tool for studying cycling in the laboratory. Although treadmill riding involves zero air resistance acting on the rider, the treadmill provides excellent repeatability and experimental control. Moreover, treadmills allow the study of actual bicycles, not just laboratory ergometers. In many research studies, stationary ergometers are used as a proxy for a real bicycle. But such ergometers do not simulate many important factors in cycling such as balance, steering and most relevant here, suspension systems. With the treadmill, we can simulate almost real-world riding scenarios on actual bicycles.

Future studies on bicycle suspension in general should focus more on rough surfaces. In this thesis, I have showed that on smooth surfaces suspension systems do not negatively affect the energetics or biomechanics of cycling. However, future studies should pursue if on rough riding surfaces suspension systems have any energetic or biomechanical benefits. Such experiments may help improve bicycle suspension designs and even further the sport of cycling.

In conclusion, in both road and mountain bicycles, suspension elements, whether small or large, have no effect on the energetics or mechanics of bicycle riding on smooth surfaces in either a seated or standing positions.

References

Berry, M. J., Woodard, C. M., Dunn, C. J., Edwards, D. G., & Pittman, C. L. (1993). The effects of a mountain bike suspension system on metabolic energy expenditure. *Cycling Science*, *3*, 8-14.

Brockway, J.M. (1987). Derivation of formulae used to calculate energy expenditure in man. Human Nutrition Clinical Nutrition, 41, 463-471.

Copeland, J.S. (1889). *U.S. patent No 367,368*. Washington DC: U.S. Patent and Trademark Office

Hadland, T., & Lessing, H-E. (2014). Bicycle design: An illustrated history. Cambridge, MA: MIT Press.

Kellogg, H. (1883). *U.S. patent No 283,612*. Washington DC: U.S. Patent and Trademark Office

Little, C.H. (1897). *U.S. patent No 584,944*. Washington DC: U.S. Patent and Trademark Office

MacRae, H. H., Hise, K. J., & Allen, P. J. (2000). Effects of front and dual suspension mountain bike systems on uphill cycling performance. *Medicine and science in sports and exercise*, *32*(7), 1276-1280.

Martin, J. C., Milliken, D. L., Cobb, J. E., McFadden, K. L., & Coggan, A. R. (1998). Validation of a mathematical model for road cycling power. *Journal of applied biomechanics*, *14*(3), 276-291.

Millet, G. P., Tronche, C., Fuster, N., & Candau, R. (2002). Level ground and uphill cycling efficiency in seated and standing positions. *Medicine & Science in Sports & Exercise*, *34*(10), 1645-1652.

Minetti, A. E., Pinkerton, J., & Zamparo, P. (2001). From bipedalism to bicyclism: evolution in energetics and biomechanics of historic bicycles. *Proceedings of the Royal Society of London B: Biological Sciences*, *268*(1474), 1351-1360.

Nielens, H., & Lejeune, T. M. (2001). Energy cost of riding bicycles with shock absorption systems on a flat surface. *International journal of sports medicine*, *22*(06), 400-404.

Reid, C. (2011). 19th century cyclists paved the way for modern motorists' roads**.** The Guardian.

Ryschon, T. W., & Stray-Gundersen, J. A. M. E. S. (1991). The effect of body position on the energy cost of cycling. *Medicine and science in sports and exercise*, *23*(8), 949-953.

Serrell, H. (1896). *U.S. patent No 562,203*. Washington DC: U.S. Patent and Trademark Office

Tanaka, H., Bassett Jr, D. R., Best, S. K., & Baker Jr, K. R. (1996). Seated versus standing cycling in competitive road cyclists: uphill climbing and maximal oxygen uptake. *Canadian journal of applied physiology*, *21*(2), 149-154.

Titlestad, J., Fairlie-Clarke, T., Whittaker, A., Davie, M., Watt, I., & Grant, S. (2006). Effect of suspension systems on the physiological and psychological responses to sub-maximal biking on simulated smooth hand bumpy tracks. *Journal of sports sciences*, *24*(2), 125-135.

Wang, E. L., & Hull, M. L. (1996). A model for determining rider induced energy losses in bicycle suspension systems. *Vehicle System Dynamics*, *25*(3), 223-246.

Wilson, D. A. (2004). Bicycling Science: Third Edition. Cambridge, MA: MIT Press.