EMPIRICALLY MEASURING THE ENERGY EFFICIENCY OF OFF- ROAD BICYCLES

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The objective of this study was to determine if the energy efficiency of dual suspension bicycles could be measured quantitatively under realistic race conditions. A SRM Powermeter was used to collect heart rate, power, and velocity data while a group of skilled cyclists rode laps on an outdoor test course. Six different suspension designs were compared. Results indicated that one dual suspension bicycle was significantly faster than the bicycle with front fork suspension only. The results also indicated that a large variation in the energy efficiency between dual suspension designs exists. Proper selection of equipment could reduce a typical race time by up to 3 minutes.

KEY WORDS: off-road bicycle, mountain, suspension, energy

INTRODUCTION: Quantifying the energy efficiency of off-road bicycle suspension systems is important due to the limited power source in cycling. Suspension systems are beneficial because they dissipate vibrational energy and a lower vibration dosage can reduce the metabolic energy expenditure of the cyclist (Berry et al, 1993). Unfortunately, dampers dissipate energy and the energy dissipated must be compensated by additional input from the cyclist. Estimates of the amount of energy dissipated by the suspension system range from 1-2% of the total power input by the cyclist (Kyle, 1990; Wang and Hull 1996; Good and McPhee, 1999). Additionally, suspension systems add weight to a bicycle, which also requires additional energy when hill climbing and accelerating.

Predicting the energy efficiency of suspension systems is relatively straightforward for uphill riding on a relatively smooth surface (e.g. Wang and Hull, 1997). However, the complex (active) response of the cyclist makes predicting the suspension motion on rough terrain difficult, even for simply coasting downhill (Wang and Hull, 1999). Thus, predicting the overall energy efficiency of a suspension system for actual race conditions has yet to be achieved.

The nearly universal adoption of front fork suspension systems indicates, at least anecdotally, that there must be a net increase in energy efficiency for suspension forks for most riding conditions. However, the net advantage or disadvantage of rear suspension systems is still a topic of much debate among athletes that participate in cross-country (XC) racing events.

Given the current uncertainty towards the use of rear suspension systems, the objective of this project was to devise a method of experimentally quantifying the energy efficiency of an off-road bicycle under realistic race conditions.

METHODS: The basic concept was to measure heart rate, power, and time as a cyclist rode a given course on different bicycles to determine if a measurable difference between bicycles existed.

The course was a 1.6 km circuit course located in Reno, NV at approximately 1500m above sea level. The course was selected as representative of a NORBA cross-country course. The course was a loop that consisted of an initial 0.8 km section of fire-road that had a total of 61 m of elevation gain. The fire-road can be characterized as generally smooth with very few rocks or ruts. A seated cycling position could be maintained for the entire uphill section. The uphill section was neither very steep nor very long due to concerns of rider fatigue. The uphill section was immediately followed by a 0.8 km rocky, single-track descent which contained numerous obstacles, turns, and dips. Both the seated and standing cycling positions and a mixture of coasting and pedaling were used during the downhill portion of the course. Dry, hard packed soil conditions existed for all tests on both the ascent and descent.

Six male experienced cyclists participated in the experiment. All riders were Expert class NORBA racers with at least 5 years of competitive racing experience. Since the course was part of a popular trail, every participant had ridden the course numerous times prior to the experiment. Ages ranged from 30 to 53 (mean = 38.2, std = 7.8). All the cyclists were of similar stature; masses and heights ranged from 66 to 80 kg (mean = 74.5, std = 4.9) and 1.85 to 1.75 m (mean = 1.81, std = 0.04) respectively.

Six different bicycles representing a wide range of suspension designs were acquired for this project. Five of the bicycles were dual suspension and one was front suspension only: Trek VRX-300, Scott G-Zero Team, Specialized S-Works FSRxc, GT I-Drive XCR 1000, Cannondale Raven 900SX, and Specialized S-Works M4 (front suspension only). To avoid endorsing any particular company, the brand/model have been omitted from the results. The various bicycles are simply referred to as bike1 through bike6 ranked by mean uphill times, with bike4 being the front only suspension, which must be identified for comparative purposes. The numbering does not reflect the order listed above.

The differences between bicycles were controlled as much as possible. However due to differences in design and construction materials, each bicycle had a different mass. The same wheels, including tires and gears, were used on each bike for every test. Each bike was outfitted with identical bottom bracket spindles which accepted the instrumented SRM crankset (see below) that was used for all tests. Saddle height was adjusted to fit each rider according to personal preference. Each rider used his own shoes and pedals for all tests. All cyclists wore CPSC approved helmets.

All tests were conducted within a one-week period. Each cyclist participated in two test sessions over the course of the week. Three bicycles were ridden during each of the two test sessions. During each test session, each bicycle was ridden 4 laps (6.4 km). Each lap took approximately 5 minutes to complete. Bikes were tested in a random order, which was different for every test rider. Each cyclist was instructed to ride at a comfortable pace while attempting to ride at the same exertion level for all laps and all bicycles.

Unbeknownst to the cyclists, the first lap on each bike was not used in the data analysis to allow for each rider to adapt to each bicycle. Each rider was interviewed after the last lap on each bike. Relative Perceived Exertion (RPE) was solicited along with opinions concerning overall ride quality, handling, climbing, and comfort. After all six bicycles were ridden each cyclist was asked to rank the bicycles based on cross-country racing needs.

Data acquisition was accomplished with an SRM Powermeter crankset (Schoberer Rad Messtechnik, Fuchsend, Germany). The crankset measures instantaneous power (Watts), speed (km/hr), and cadence (rpm) and accepts input from a standard heart rate monitor (bpm). The SRM also calculates total energy expended (kJ). Data was recorded at 0.5 second intervals and downloaded to a portable computer. Lap times were recorded using a stopwatch and verified by examining the SRM data.

Data analysis was conducted using a two-way Analysis of Variance (ANOVA) with the rider and bicycle as the two factors. Energy (kJ) and time (sec) for the uphill and downhill sections were analyzed as dependent variables. All statistics were performed at α = 0.05 using SigmaStat 2.0 software package (SPSS Inc, Chicago, IL).

RESULTS: Data for one of the six cyclists was discarded a priori based on the presence of wind during the second test session. The average speeds for the remaining 5 cyclists were approximately 18 km/hr uphill and 32 km/hr downhill.

The ANOVA results indicated no difference in energy expended for a given cyclist. This indicated that the cyclists were consistent during the test rides (i.e. no bike was "ridden harder" than any other). Some of the cyclists did, however, ride harder (higher energy expenditures) than others. The results also indicated that the RPE was constant across all bikes within a given subject.

The differences in mean times for the uphill and downhill portions of the course are presented in Tables 1 and 2 respectively. The ANOVA on the uphill times indicated that bikes 5 and 6 were statistically slower uphill than the other 4 bicycles tested, including the front only suspension bike (bike4). The remaining 4 bikes were not statistically different from each other during the uphill portion of the course.

On the downhill section, bike5 was statistically faster than all the other bikes. Furthermore bike1 was statistically faster than both bikes 4 and 6 on the downhill. All other pairwise comparisons were not statistically significant for the downhill portion of the course. While not shown, an ANOVA on total lap times indicated that bike1 is the only dual suspension bicycle that is statistically faster than bike4 (by 5.3 seconds per lap). Bike1 was also faster than bike5 by 9.1 seconds and bike6 by 6.7 seconds per lap.

Statistical differences in the times were also found when comparing cyclists for both the uphill and downhill sections. However, these differences are obviously attributed to rider ability not bicycle performance.

Both the total lap times and the average ranking by the cyclists are presented in Table 3. The subjective rankings agree quite well with the total lap times with bike1 being both the fastest and most popular bike for XC racing.

Table 1 Difference in Mean Hill Climb Times (seconds). * indicates $P < 0.05$

bike	1	2	3	4	5
2	2.40				
3	2.80	0.77			
4	3.47	1.07	0.67		
5	8.33*	5.93*	5.53*	4.87*	
6	7.33*	4.93*	4.53*	3.87*	1.00

Table 2 Difference in Mean Downhill Times (seconds). * indicates $P < 0.05$

bike	1	2	3	4	5
2	0.73				
3	0.63	0.10			
4	1.87*	1.13	1.23		
5	1.67*	2.40*	2.30*	3.53*	
6	1.73*	1.00	1.10	0.13	3.40*

Table 3 Mean Total Lap Times (seconds) and Average Ranking (1=best).

	bike1	bike2	bike3	bike4	bike5	bike6
Total time	305.8	308.93	309.23	311.13	314.87	312.47
Avg. Rank	1.2	3.2	5.6	3.4	4.0	3.6

Figure 1 - Front only suspension bicycle.

Figure 2 - Dual suspension bicycle.

DISCUSSION: The methodology used in this study has several limitations that should be pointed out. Rider fatigue is always an issue for this type of study. However, all the participants were accustomed to cycling for more than the one hour it took to complete each test session. Furthermore, after each test session plots of heart rate versus power were generated and examined as evidence that rider fatigue was not occurring during the course of the tests.

The issue of bicycle weight was not addressed in this study. No effort was made to "level the playing field" by normalizing all the bicycle weights. The difference in component groups caused a significant weight difference between bikes (bike4 was the lightest bike in this test). However, the results showed no correlation between bike weight and lap times.

Finally, the affect of suspension tuning was not considered during the tests performed. The suspension (front and/or rear) was adjusted for the correct preload for each rider based on the self-reported rider weights, but the damping was not adjusted unless requested by the rider after the first lap.

Despite the limitations of the study, the results corroborate the mixed attitudes of athletes towards the use of dual suspension bicycles in cross-country races. Only one dual suspension bicycle (bike1) was found to be faster than the front only suspension bicycle (bike4). Furthermore, a large difference between dual suspension bicycles was discovered. For example bike1 was found to be approximately 3% faster than bike5.

Assuming the 1.6 km course used for these tests represents a typical cross-country racecourse, bike1 affords a time advantage of about 3.3 seconds per km over the bike4 and 5.7 seconds per km over bike5. For a 35 km course, this translates into 1.9 and 3.3 minute advantages due to the bike alone. Time differentials of this magnitude are clearly important in competitive off-road racing.

Additionally, the empirical data collected in this study appears to agree with theoretical predictions. For the uphill section of the course, the mean time for all bikes was approximately 200 seconds. Thus, from Table 1 it can be seen that differences in velocities ranged from approximately 1 - 4%. Using typical values for off-road bicycles (Wang and Hull, 1996), a 1% change in velocity can be equated to a 1% change in total power required, which includes aerodynamic, rolling resistance, and hill climbing power components (Whitt and Wilson, 1983). Similarly, a 4% change in velocity equates to a 4% change in total power. This agrees well with the 1-2% estimated previously (Klye 1990; Wang and Hull, 1996; Good and McPhee, 1999).

CONCLUSIONS: The tests conducted indicate that dual suspension bicycles can be more energy efficient that front only suspension bicycles by as much as 3 seconds per km for typical cross-country races. This represents approximately 1% improvement in both speed and energy efficiency. However, the results also indicate the selection of the suspension design is very critical. Incorrect selection of equipment can degrade performance by as much as 4%.

The results presented herein also reflect the performance of a given bicycle averaged over all riders. Thus, for a particular athlete, it may be best to reproduce the tests described to determine the most energy efficient equipment.

REFERENCES:

Berry, M. J., Woodard, C. M., Dunn, C. J., Edwards, D. G., and Pittman, C. L. (1993). The Effects of a Mountain Bike Suspension System on Metabolic Energy Expenditure. *Cycling Science*, **5**(1):8-14.

Good, C. and McPhee, J., (1999) "Dynamics of Mountain Bicycles with Rear Suspensions: Modelling and Simulation," *Sports Engineering*, **2**:129-143.

Kyle, C. (1990). Chain Friction, Windy Hills and Other Quick Calculations. *Cycling Science*, **2**(1):23-26.

Wang, E. L., and Hull, M. L. (1996). A Model for Determining Rider Induced Energy Losses in Bicycle Suspension Systems. *Vehicle System Dynamics*, **25**(3):223-246.

Wang, E. L., and Hull, M. L. (1997). Optimization of Off-Road Bicycle Rear Suspension Systems. *Vehicle System Dynamics*, **28**(4):291-306.

Wang, E. and Hull, M. (1999). A Dynamic Model of an Off-Road Bicycle and Cyclist. XVIIth International Society of Biomechanics (ISB) Congress, Calgary, AB, August 1999.

Whitt, F. R. and Wilson, D. G. (1982). Bicycling Science 2nd ed., MIT Press, Cambridge, MA.