AN ABSTRACT OF THE DISSERTATION OF

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The aim of the present project was to quantify and compare differences in impact performance and damping effectiveness among various off-road bicycle suspension systems. Two experiments were conducted to compare suspensions. Fork impact performance was tested by measuring peak antero-posterior braking forces and impulses during impact with bumps of 6- and 10-cm height for five mountain bike suspension systems. These results were compared to a rigid fork condition. Comparisons among suspension systems showed small but significant differences in performance. While only marginal differences in peak force were found for the suspension conditions, more substantial differences in braking impulse were observed. Air-Oil design forks had the lowest braking impulse for the range of speeds and impact characteristics of this experiment. In another setting, an analysis of acceleration signals over a range of frequencies on two surface conditions (gravel and trail) was conducted to assess the damping effectiveness of the five suspension systems. The mountain bike was equipped with accelerometers mounted at the axle and frame. A spectral analysis of the signal was performed for each signal to provide a measure of fork effectiveness. Results showed that accelerations ranged from –33 to +40 g at the axle and from –13 to +13 g at the frame, while spectral analyses of the acceleration signals revealed two distinct frequency regions from 0 to 100 Hz and from 300 to 400 Hz. The various suspension systems were all effective in attenuating vibration over the first region. Vibration amplitudes at the frame were considerably less than at the axle for the suspension conditions while similar axle-frame vibrations were observed with the rigid fork. Lower frequency vibration amplitudes were typically greater on the trail than on gravel. In the frequency region between 300-400 Hz, the signal was attenuated at the frame for all conditions including the rigid fork. The quantification and comparison process of the various suspension forks using impulse provided an objective marker for performance, and allowed differentiation between various suspension conditions. Moreover, the effectiveness analysis through the use of accelerometers provided insight into the range of frequencies dampened by a suspension. The lower frequency range dampening suggested that effectiveness of a suspension fork can be quantified even though the experiment did not conclusively differentiate between the forks.

Kinetic and Vibration Analysis of Off-Road Bicycle Suspension Systems

By

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Morris Levy, Author

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I do not think I have the eloquence or the literary talent to properly express my gratitude to so many who have helped in this endeavor...However, I will do my best to convey my heartfelt thanks to all.

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For all of you and those that I did not name here, I leave you with this phrase from the book "The Little Prince" by Antoine de Saint-Exupéry:
"On ne voit bien qu'avec le coeur. L'essentiel est invisible pour les yeux". It roughly translates like this: "You only see clearly with your heart. The essential is invisible to the eyes"... I see you all with my heart...

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KINETIC AND VIBRATION ANALYSIS OF OFF-ROAD BICYCLE SUSPENSION SYSTEMS

CHAPTER 1

INTRODUCTION

In the beginning, there were two wheels and a seat! The inventor of the ancestor of the bicycle as we know it today was a German baron/inventor from Karlsruhe, Karl Friedrich Drais von Sauerbronn (Dodge, 1996). While Drais was responsible for such inventions as the meat grinder, the binary system and a typewriter, the Draisienne, as it became known, was his claim to fame. This rudimentary device was first introduced to the public in 1817 and had been designed as a running machine (Laufmaschine). It allowed the user to balance himself on the seat placed between two wheels and use his legs to power the machine. The Draisienne was a step forward from previous "hobby-horses" as steering and braking systems were included (Whitt and Wilson, 1982).

Draisiennes and other similar machines did not convince the scientific community of the time that it could be an efficient mode of human-powered transportation. In 1832, the editor of *The Mechanic's Magazine* dismissed the velocipede as a viable mode of human-powered transport which could not be improved by the inclusion of cranks or wheels. The article even concluded with a statement that inventions in two-wheels transportation had been in decline because "there was nothing to be gained by them" (Dodge, 1996).

The big step in the development of the bicycle was to find a more efficient way to channel the human-generated force and convert it into motion. This came with the introduction of the pedal and cranks. It is still the subject of debate as to who first thought of adding pedals to the velocipede, but it became widely used in the 1860's. Pedals were directly attached to the front wheel axle by a crank. To get more distance from a pedal revolution, wheels with a larger diameter were designed which eventually produced the classic high-wheel bicycle. To avoid larger front wheel collapse, James Starley introduced tangent-tension spoking which is used on most bicycles today (Whitt and Wilson, 1982).

It had been recognized that the high-wheel bicycle was lacking features that would make the bicycle safe to ride for everyone. To climb on a high-wheeler required agility, and forward falls were common. Experimentation with handlebars were made, but it was the introduction of the chain and direct steering which made the bicycle safer. The inclusion of these technological improvements occurred in the 1880's, and it is highly probable that these inventions were made simultaneously by different bicycle makers (Dodge, 1996).

The "Safety" bicycle, as the name implied, was concerned with making the ride safer and more comfortable for the user. Features such as a suspended seat post were included, which can be considered as the first suspension feature ever put on a bicycle. The other suspension feature to be included came with the introduction of the pneumatic tire.

John Boyd Dunlop, a veterinarian from Belfast, developed the first pneumatic tire for his son's tricycle in 1887 (Dodge, 1996). However, a patent for such an invention had already been filed in 1845 by Robert William Thomson to accommodate horse-drawn vehicles but was of little interest at the time (Campbell, 1981). The industry was somewhat fearful of following in the footsteps of the newly created Dunlop Pneumatic Tire Company because of issues related to retooling the current machinery available but it quickly followed suit in part due to the success of W. Hume. He was the first to race a bicycle equipped with pneumatic tires winning four out of four races in Belfast, which was enough to convince the public and the industry of the worthiness of the tire (Whitt and Wilson. 1982). Within four years, the pneumatic tire had become the norm on all bicycles, providing better comfort for the rider, and increases in speed while not compromising rider safety.

From the late 1880's to the 1970's, many inventions allowed the bicycle to become a safer and more convenient mode of transportation. The human desire for competition was also fulfilled by the creation of races which further encouraged inventors to improve the speeds and effectiveness of the rider. Experimentation with materials improved the weight of the bicycle, and gearing systems were introduced. All these early innovations focused on improving riding on smooth roads.

A new way to build bicycles would have to take place with the development of mountain biking in the early 1970's. These off-road riders were attracted by the thrill of riding down fire roads or single-track trails. It all started in the wilderness area around Mount Tamalpais in Marin County, California. The bicycles used were "cruisers" with balloon tires and only one speed. Gary Fisher was the first one to experiment with equipment and frames to make his machine more suited for the rough trail. He used a Schwinn Excelsior frame because it provided better pedal-to-ground clearance and used drum bakes with motorcycle brake levers. Soon after, derailleurs were incorporated so that the riders could ride up the mountain as well rather than hitch a ride to the top in the back of some truck or tractor (Dodge, 1996). In 1979, Gary Fisher and Charlie Kelly founded a company called MountainBikes which would become the generic name of this type of bicycle. Additions were made to the original mountain bike including gearing, and more recently, suspension forks (an idea borrowed from motorcycle design).

This rapid development of mountain biking in the past ten years with its culmination as an Olympic sport in 1996 has also prompted a number of innovations in bicycle design. The inclusion of suspension forks as a standard component is now very common even on low-end mountain bikes. Because mountain bike riding is performed over rough terrain, the improvement provides the rider a more comfortable ride at intermediate and high speeds. A wide variety of suspension forks are available in today's market, all of which have been tested by expert riders whose critique of the damping system is highly qualitative and subjective to their own perception.

Because of the popularity of cycling, the biomechanics of this activity and equipment characteristics related to better cycling performance have been investigated with a large degree of success (Burke, 1986; Whitt and Wilson, 1982). As Gregor, Broken, and Ryan (1991) summarized, experimental testing has been performed on a number of equipment characteristics from optimal seat height and crank length to chainring and handlebar configuration. These investigations led to better equipment design and athlete performances.

However, off-road cycling has seldom been included in these investigations. Of particular interest are suspension forks, which were developed to provide the rider with more comfortable riding conditions over rough terrain. While Seifert, Luetkemeier, Spencer, Miller, and Burke (1994) have shown that the use of suspension forks resulted in less muscular trauma on a flat course, the interaction of such forks with bumps of various heights and at different velocities has not been investigated. Frequently, a racer will follow the straightest line down a hill and will rely on the suspension fork to absorb the shock of collision with obstacles that may be in the way. Orendurff and colleagues (1994, 1996) have suggested that specific suspension fork settings may be best suited for particular conditions of bump size and bike speed (based on measurements using an accelerometer-instrumented bike). However, a single fork setting may not be appropriate for every combination of speed and bump size.

The aim of the present project was to quantify and compare differences in impact performance and damping effectiveness among various suspension systems. Fork impact performance was evaluated by measuring the braking impulse associated with a bump impact and investigating the relationships that existed between braking impulse and bike speed. To assess the damping effectiveness of a suspension system, an analysis of acceleration signals over a range of frequencies on two surface conditions was conducted. The mountain bike was equipped with accelerometers mounted at the axle and frame. A spectral analysis of the signal was performed for each signal to provide a measure of fork effectiveness.

The quantification and comparison process of the various suspension forks using impulse provided an objective marker for performance, and allowed differentiation among various suspension conditions. Moreover, the damping effectiveness analysis through the use of accelerometers provided insight into the range of frequencies dampened by a suspension.

CHAPTER 2

EFFECTS OF FRONT SUSPENSION ON MOUNTAIN BIKE IMPACT PERFORMANCE

Morris Levy and Gerald A. Smith

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ABSTRACT

Five mountain bike suspension systems were tested to assess peak antero-posterior braking forces and impulses during impact with bumps of 6- and 10-cm height. The results were compared to a rigid fork condition. As anticipated, peak force and impulse for rigid forks were significantly greater than observed with any suspension system. Comparisons between suspension systems showed small but significant differences in performance. While only marginal differences in peak force were found for the suspension conditions, more substantial differences in braking impulse were observed. Air-Oil design forks had lowest braking impulse for the speeds and impact characteristics of this study.

INTRODUCTION

The rapid development of mountain biking in this decade and its inclusion as an Olympic sport in 1996 has stimulated considerable innovation in bicycle design. While suspension systems are not typically incorporated on road bicycles, the rough terrain encountered in off-road cycling has made such systems a common component of both high performance competition bikes as well as low-end consumer equipment.

With the increasing popularity of cycling, the biomechanics of this activity and equipment characteristics related to better cycling performance have been investigated with a large degree of success (Burke, 1986; Whitt and Wilson, 1982). As Gregor, Broker, and Ryan (1991) summarized, experimental testing has been performed on a number of equipment characteristics from optimal seat height and crank length to chainring and handlebar configuration. These investigations led to better equipment design and athlete performances.

Initially modeled after motorcycle suspension forks, a variety of mountain bike suspension systems are now available. These include relatively simple elastomer "bumpers", air-oil telescopic shock absorbers, linkage designs with a flexible connection of fork to frame, and various full frame suspensions. The issue for the potential owner of a suspension fork is often related to which type of fork and damping system should be chosen. Olsen (1993) briefly summarized the differences between damping systems and how the energy loss is controlled. In particular, it was suggested that friction, hysteresis and hydraulic damping were the most common types of systems used in front suspension forks. Moreover, linkage design forks having pivot joints instead of sliding joints were identified as an excellent option since the wheel would travel in an arc rather than in a straight line (Olsen, 1993).

While considerable subjective experience with bike suspension systems supports the advantages of their use, relatively little mechanical testing of the various systems is publicly available. Seifert, Luetkemeier, Spencer, Miller, and Burke (1994) have described the physiological advantage of using suspension forks by showing a decrease in muscular trauma on a flat course, but did not assess potential differences in forks. A subsequent study by Seifert and colleagues (1997) compared the effects of various suspension systems (rigid, air/oil damped, and full suspensions) on energy expenditure, physical exertion and time trial performance during mountain biking. While no differences were found between the forks for the metabolic data (absolute and relative VO_2, mean and peak heart rate), time trial performance was significantly improved when using a front suspension system rather than a rigid or full suspension system. Seifert et al. (1997) speculated that these differences might be due to the absorption of shock with minimal loss of energy as compared to the rigid and fully suspended conditions.

Orendurff and colleagues (1994, 1996) have suggested that specific suspension fork settings may be best suited for particular conditions of bump size and bike speed (based on measurements using an accelerometer-instrumented bike). They found that medium stiffness settings performed slightly better than either soft or firm fork configurations at about 5 m/s. However, a single fork setting may not be appropriate for every combination of speed and bump size.

A recent study by Gillespie, Groesz, Avedisian, and Rutt (1998) examined the maximum vertical displacement of the wrist and the bike's hub when riding over a series of bumps with different suspension forks. They found significant speed reductions during bicycle impacts with a series of bumps but did not distinguish performance differences for various suspensions. No significant statistical difference was found between the forks in terms of vertical displacement even though the vertical displacement of the wrist and hub was systematically lower for the suspension fork conditions as compared to the rigid fork. With only four subjects involved in this study, statistical power was a concern in the findings.

Most recently, Pritlove and colleagues (1998) used a bump mounted on a force plate to measure vertical and horizontal forces during an impact of bike with bump. Suspension forks reduced the peak forces in both directions. Using a similar methodology, this project assessed performance through measurement of horizontal force and impulse with various conditions of mountain bike suspension.

The aim of the present project was to assess performance differences between various suspension systems. This was accomplished by quantifying the relationships that exist between peak antero-posterior (AP) forces and bike speed, as well as braking impulse and bike speed during impact. Additionally, suspension performance was assessed over two bump heights.

PROCEDURES

Suspension Conditions

The suspension conditions in this study are described by the combination of a particular fork with a frame. Five suspension conditions were tested to reflect the most common options that were available on the market. A standard rigid fork/rigid frame system (R-R) was compared against three suspensions systems: air-oil (A-R), elastomer (E-R), and linkage (L-R) design forks. A single rigid frame was used with these fork conditions and was composed of rigid links with no moving parts. The air-oil and linkage design forks were further tested with a rear-suspended frame (designated A-S and L-S, respectively). In the suspended frame, a rear suspension system was integrated with the frame which provided some impact dampening to the back wheel. Both frames were of similar size (46 centimeters distance between the bottom bracket and the top of the vertical tube).

Elastomer and air-oil suspension forks have a telescopic design which means that the damping system is set up as tubes sliding in relation to each other (Figure 2.1). The Linkage design fork is structured with pin joints allowing for some horizontal displacement (Figure 2.2). This design should theoretically allow for better damping of horizontal impacts.

The suspended frame was composed of a dual dampening system (air-spring) located under the seat post, connecting the horizontal bar of the frame to the back wheel. Additional hinges were located close to the back wheel axis and above the pedal axis to complete the suspension setup.

Since most forks came with variable stiffness settings, it was important to keep them constant throughout the experiment. Fork stiffness settings were set according to the manufacturer's recommendations based on rider characteristics. (Frame and fork specifications are described in Appendix E.)

Single Subject

One subject performed repeated trials to minimize the variability due to riding styles. The 40-year old male subject was a proficient off-road cyclist and had approximately 8 years of racing experience. The subject was chosen so that his morphology fit the size of the frames provided. His height and weight were 1.8 meters and 80.4 kilograms respectively.

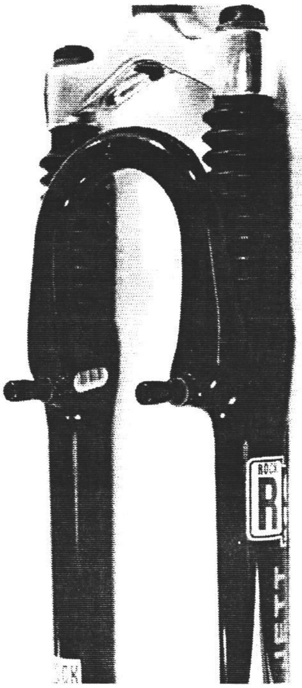

Figure 2.1. Telescopic fork illustration

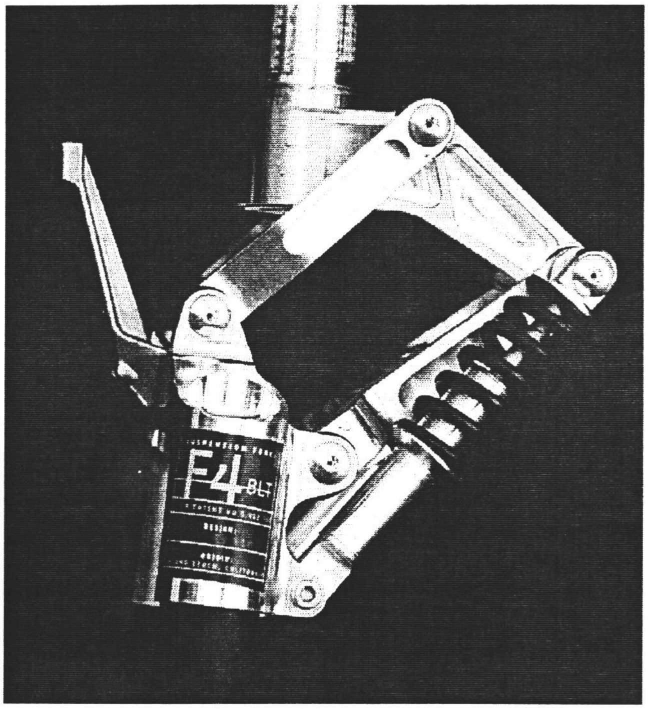

Figure 2.2. Linkage design fork illustration.

Experimental Conditions

Each suspension condition was tested across bumps of 6- and 10-cm height at speeds ranging from approximately 5 to 8 meters per second. Bump heights were chosen to reflect a typical obstacle encountered during cross-country mountain biking. Each rounded timber bump was secured with brackets onto a Kistler force plate to provide an immovable obstacle to the rider (Figure 2.3).

The riding speeds ranged from approximately 5 to 8 m/s. Speed of impact was evaluated using a photoelectric timer. Two infrared photoelectric cells were placed 2 meters apart directly before the bump. The timer activated as the rider broke the first beam of light and stopped after breaking the second beam. Knowing time and distance, average speed prior to impact was derived.

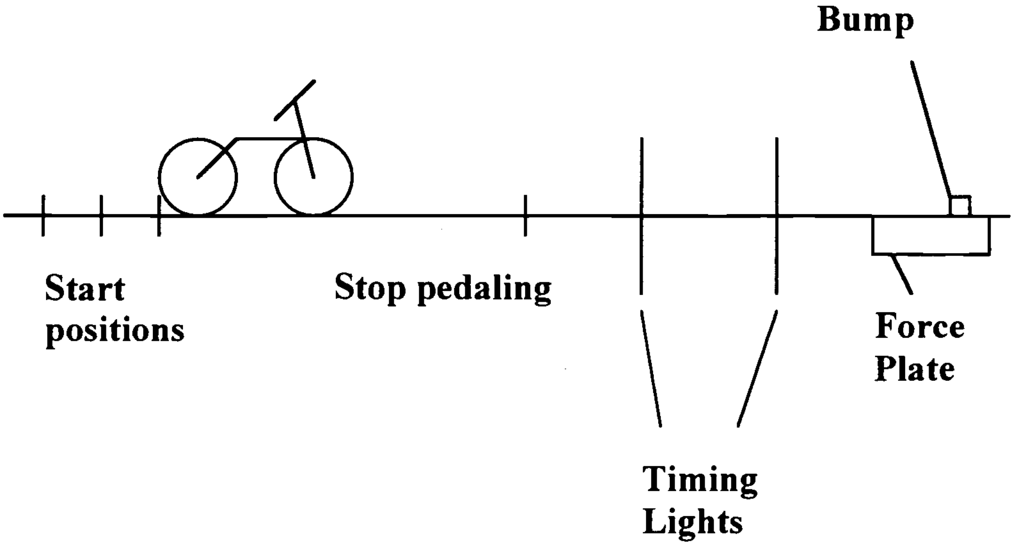

Figure 2.3. Experimental setup.

Testing Procedures

The subject's and bicycle weights were recorded before the start of each testing condition. The tire pressure was initially set at 45 pounds per squared inch (psi), determined to suit the subject's comfort. Tire pressure was monitored after every 30 trials and adjusted to the initial level if necessary. Spoke tension was verified prior to testing, after 150 trials, and finally at the end of the tests to control for possible wheel deformation. The rider initially accelerated on a long in-run and then coasted through the last several meters and the bump impact. He was instructed to ride passively over the bump slightly elevated out of the saddle. Thirty trials per condition were performed at speeds ranging between 5 and 8 m/s.

The sequence of suspension conditions was randomized, as were speeds within a condition of suspension and bump. However, bump heights were randomized only within each suspension condition. Data collection of antero-posterior reaction forces was triggered by the initial contact of the front wheel with the front of the force plate. The reaction forces were recorded at 1000 Hz for a period of 0.5 seconds. The force data were smoothed using a second-order Butterworth filter with a cutoff frequency of 180 Hz.

Data Analysis

Being directly proportional to change of velocity, impulse was used as an indicator of fork performance. Forks that minimize braking impulse would likely decrement bike speed the least and were thus the best performing. Braking impulse was calculated by numerically integrating the force-time data from the time of initial contact with the bump until the forces went to zero, indicating the front wheel had cleared the bump. Peak braking force during the impact was also recorded.

A regression analysis was used to graphically describe the relationship between velocity prior to impact and peak AP forces as well as braking impulse for each suspension condition. An analysis of covariance (ANCOVA) was used to compare the various forks using speed as a covariate ($\alpha = 0.05$). Post hoc comparisons using the Bonferroni method were also computed to further identify differences between suspension conditions. This analysis was repeated separately for both bump heights. Statistical assumptions related to the ANCOVA were verified and met using SPSS statistical software.

RESULTS

6-cm Bump Height

Forces. Typical force–time curves for two suspension conditions are shown in Figure 2.4. The initial impact point occurred at the moment where the tire first contacted the obstacle and ended when the front tire became airborne after rolling over the bump. This resulted in reaction forces which were mainly opposing the forward motion but included a small propulsive force shortly before tire takeoff. The curves were integrated from the initial contact to the point where the curve reached zero after the negative phase.

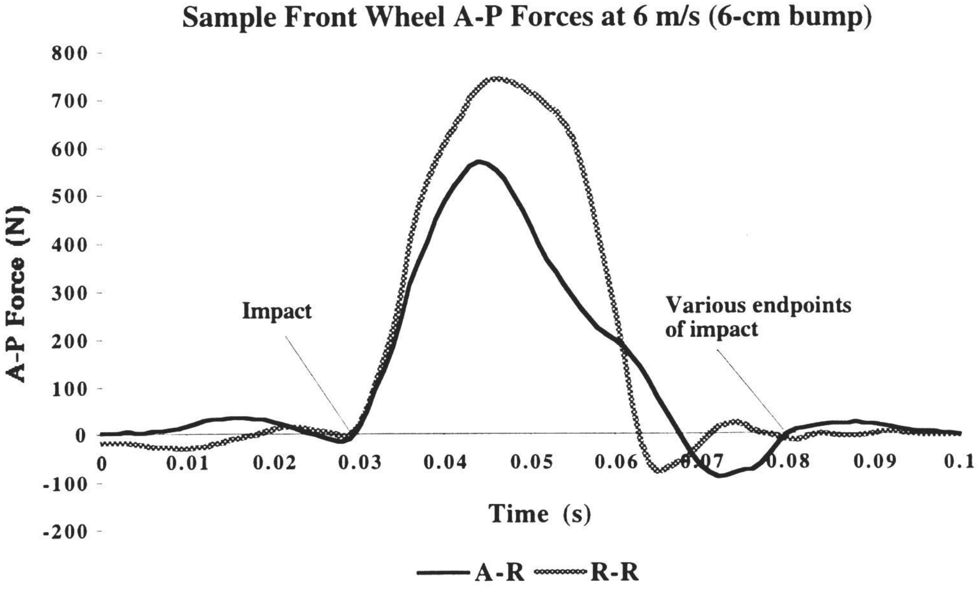

Figure 2.4. Typical force-time curves for the rigid and air-oil suspension conditions with 6-cm bump.

Figure 2.5 illustrates the relationship of riding speed to peak braking force. Clear relations of force to speed existed for each fork condition with correlations ranging from about 0.84 to 0.96 (Table 2.1). As expected, peak forces increased with speed.

ANCOVA was used to compare the forks using speed as a covariate. As expected, significant differences were observed between suspension forks ($p < 0.01$) with the simplest designed suspension (E-R) providing the greatest peak force attenuation (Table 2.2 and Appendix F). Generally, suspension forks attenuated the braking forces by 20-25% compared to the rigid fork.

Post hoc pairwise comparisons revealed expected significant differences between the rigid fork and all other suspension conditions ($p < 0.01$). The tests also showed significant differences between the elastomer (E-R) suspension and both full suspension conditions with $p < 0.05$ (A-S and L-S). However, all other comparisons were not significant (Table 2.3).

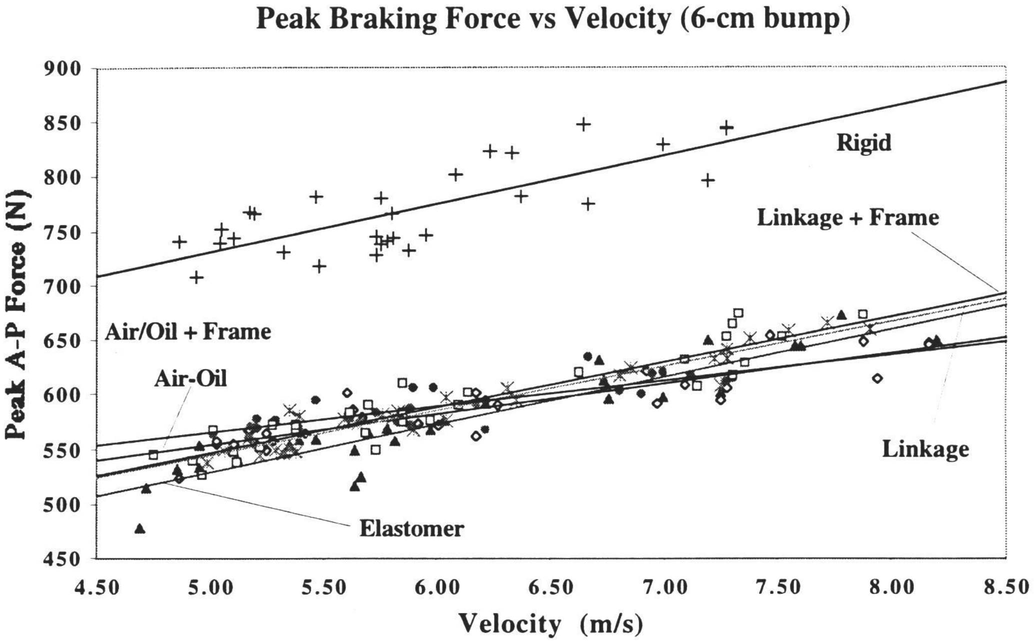

Figure 2.5. Relationship of velocity to peak braking force with 6-cm bump. For all forks, peak braking force increased with velocity ($p < 0.01$).

Table 2.1. Correlations of speed with dependent variables for various suspension conditions with 6-cm bump.

	A-R	E-R	L-R	A-S	L-S	R-R
Force-Velocity Correlation	0.90	0.92	0.96	0.84	0.93	0.78
Impulse-Velocity Correlation	-0.81	-0.72	-0.82	-0.57	-0.83	-0.83

All correlations are significant at the 0.01 level

Table 2.2. Impact force descriptive statistics for various suspension conditions with 6-cm bump.

Group	N	Mean ± SD (Newtons)	Range (Newtons)
Air-Oil	30	587.7 ± 32.9	523.3 to 654.6
Elastomer	30	575.8 ± 46.9	478.4 to 673.2
Linkage	30	593.0 ± 38.7	538.3 to 666.3
Air-Oil + Frame	30	591.0 ± 21.2	560.9 to 635.0
Linkage + Frame	30	592.6 ± 42.3	526.3 to 673.7
Rigid	29	770.4 ± 40.4	708.5 to 847.6

Table 2.3. Post-hoc p-values (Bonferroni) for maximal braking force with 6-cm bump.

	A-R	E-R	L-R	A-S	L-S	R-R
A-R	----					
E-R	0.98	----				
L-R	0.99	0.16	----			
A-S	0.87	0.05	1.00	----		
L-S	0.79	0.03	1.00	1.00	----	
R-R	<0.01	<0.01	<0.01	<0.01	<0.01	----

Impulse. As with braking forces, impulse and speed were significantly correlated for all suspension conditions. The correlations varied between –0.57 and –0.87 (Table 2.1). Figure 2.6 showed the negative relationship between impulse and speed, meaning that speed changes due to bump impact decreased as speed increased. The ANCOVA showed significant differences between the suspension conditions. Suspension forks decreased the magnitude of the impulse by 29-36% compared to the rigid condition (Table 2.4 and Appendix F).

Based on impulse of the impact forces, significant differences among conditions were observed. As expected, all suspended fork conditions involved less braking impulse than the rigid fork condition. The air-oil fork with suspended frame outperformed all other conditions; on the rigid frame the air-oil fork had significantly lower impulse than the linkage fork on either frame. The L-S and E-R, L-S and L-R impulses were not different from each other, along with the A–R and

E-R comparison (Table 2.5). It should be noted that the differences observed in these comparisons involved impulse magnitudes that differed by less than 10%. This is likely important for race performance but probably would be undetectable in recreational riding.

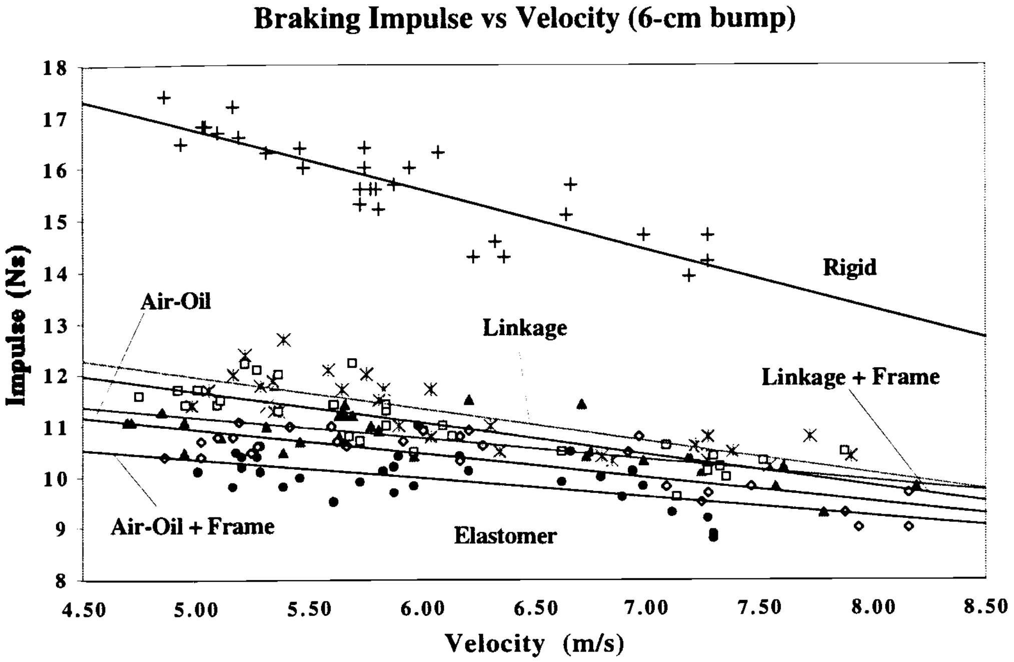

Figure 2.6. Relationship of velocity to braking impulse with 6-cm bump. For all forks, braking impulse decreased with velocity ($p < 0.01$).

Table 2.4. Impulse descriptive statistics for various suspension conditions with 6-cm bump.

Group	N	Mean ± SD (Ns)	Range (Ns)
Air-Oil	30	10.4 ± 0.61	9.0 to 11.1
Elastomer	30	10.8 ± 0.60	9.3 to 11.8
Linkage	30	11.2 ± 0.70	10.2 to 12.7
Air-Oil + Frame	30	10.0 ± 0.49	8.8 to 11.0
Linkage + Frame	30	11.0 ± 0.70	9.6 to 12.2
Rigid	29	15.7 ± 0.95	13.9 to 17.4

Table 2.5. Post-hoc p-values (Bonferroni) for braking impulse with 6-cm bump.

	A-R	E-R	L-R	A-S	L-S	R-R
A-R	----					
E-R	0.24	----				
L-R	<0.01	<0.01	----			
A-S	<0.01	<0.01	<0.01	----		
L-S	<0.01	0.31	0.53	<0.01	----	
R-R	<0.01	<0.01	<0.01	<0.01	<0.01	----

10-cm Bump Height

Forces. Typical force-time curves were similar to those observed with the 6-cm bump (Figure 2.7 and Appendix F). Correlations between force and speed ranged from 0.80 to 0.97 (Table 2.6) and these relationships are illustrated in Figure 2.8. As expected, peak forces were larger with this bump and increased with speed.

Comparisons of the forks using ANCOVA (with speed as covariate) revealed significant peak force attenuation ($p < 0.01$) with all suspension forks compared to the rigid fork (Table 2.7). Peak braking forces of suspension forks were diminished by 45-47% compared to the rigid fork with the Air-Oil condition providing the largest peak force attenuation. However, all suspension fork mean force values were within 40 Newtons of each other. As expected, post hoc comparisons between the rigid condition and all other suspension conditions were significant. All other comparisons were not significant (Table 2.8).

Impulse. Similarly to the braking forces, relationships between impulse and speed were observed for most conditions. Correlations varied between 0.22 and –0.92 (Table 2.6). Both the A-R and A-S conditions had positive correlations (+0.22 and +0.44, respectively). While this result was not expected, it was interesting to observe that both conditions including the Air-Oil fork had similar speed-impulse relationships. However, only the A-S correlation was found significant at the 0.01 level. All other relationships between impulse and speed were negative as illustrated in Figure 2.9.

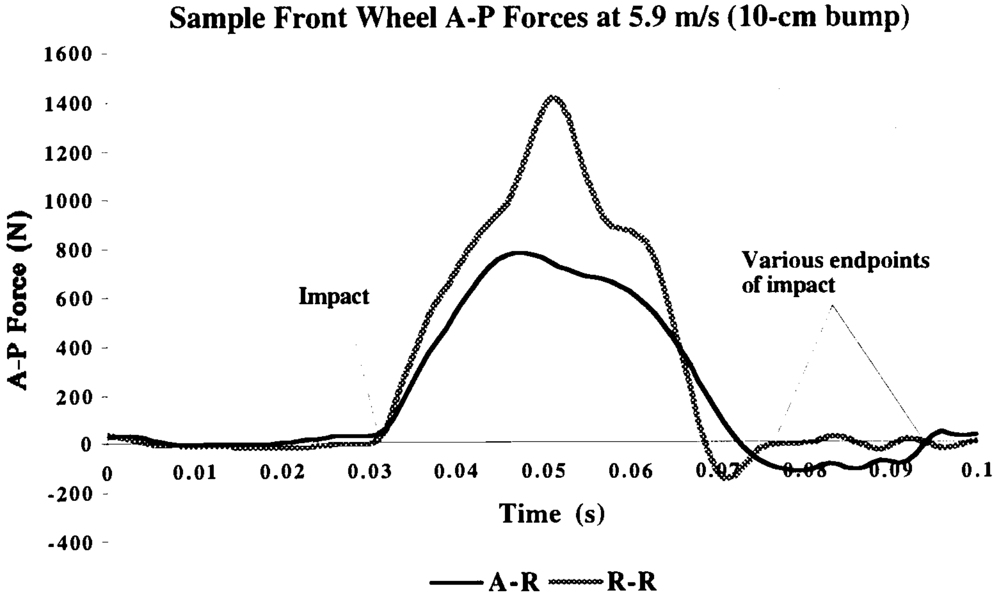

Figure 2.7. Typical force-time curves for the rigid and air-oil suspension conditions with 10-cm bump.

Table 2.6. Correlations of speed with dependent variables for various suspension conditions with 10-cm bump.

	A-R	E-R	L-R	A-S	L-S	R-R
Force-Velocity Correlation	0.94*	0.92*	0.93*	0.96*	0.97*	0.80*
Impulse-Velocity Correlation	0.22	-0.78*	-0.92*	0.44*	-0.52*	-0.51*

(*) Correlations significant at the 0.01 level

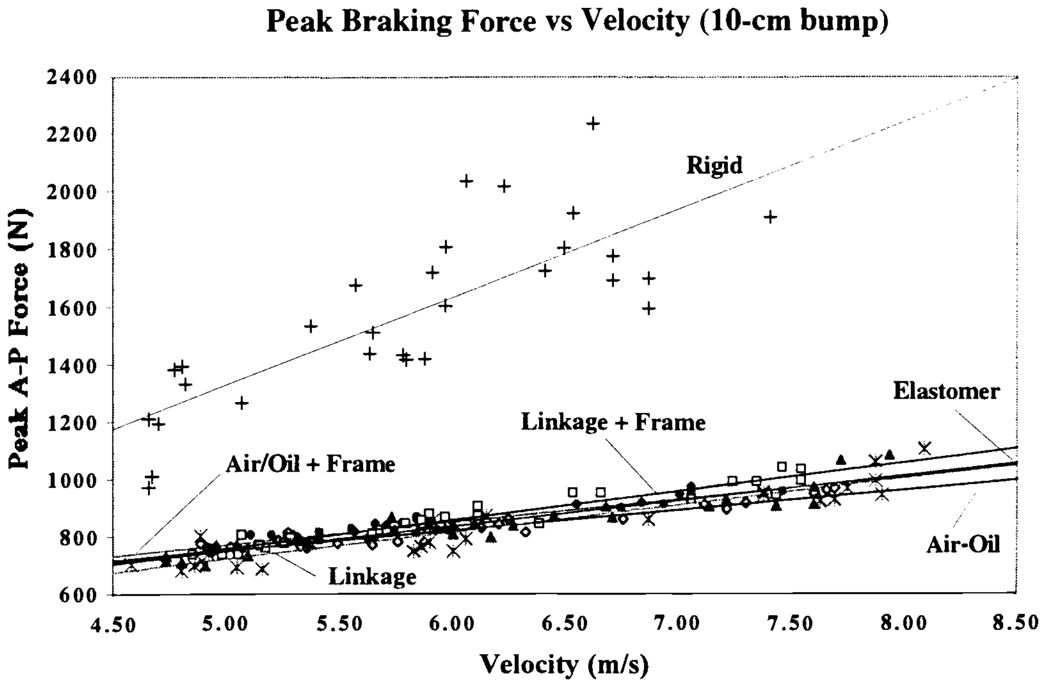

Figure 2.8. Relationship of velocity to peak braking force with 10-cm bump. For all forks, peak braking force increased with velocity ($p < 0.01$).

Table 2.7. Impact force descriptive statistics for various suspension conditions with 10-cm bump.

Group	N	Mean ± SD (Newtons)	Range (Newtons)
Air-Oil	29	834.5 ± 65.9	758.9 to 966.6
Elastomer	30	837.4 ± 92.2	698.7 to 1081.7
Linkage	29	837.6 ± 115.7	683.2 to 1107.9
Air-Oil + Frame	30	850.5 ± 65.3	746.0 to 974.8
Linkage + Frame	30	868.8 ± 92.6	739.2 to 1037.4
Rigid	30	1573.9 ± 300.2	973.4 to 2240.6

Table 2.8. Post-hoc p-values (Bonferroni) for maximal braking force with 10-cm bump.

	A-R	E-R	L-R	A-S	L-S	R-R
A-R	----					
E-R	1.00	----				
L-R	1.00	1.00	----			
A-S	1.00	1.00	0.88	----		
L-S	1.00	1.00	0.78	1.00	----	
R-R	<0.01	<0.01	<0.01	<0.01	<0.01	----

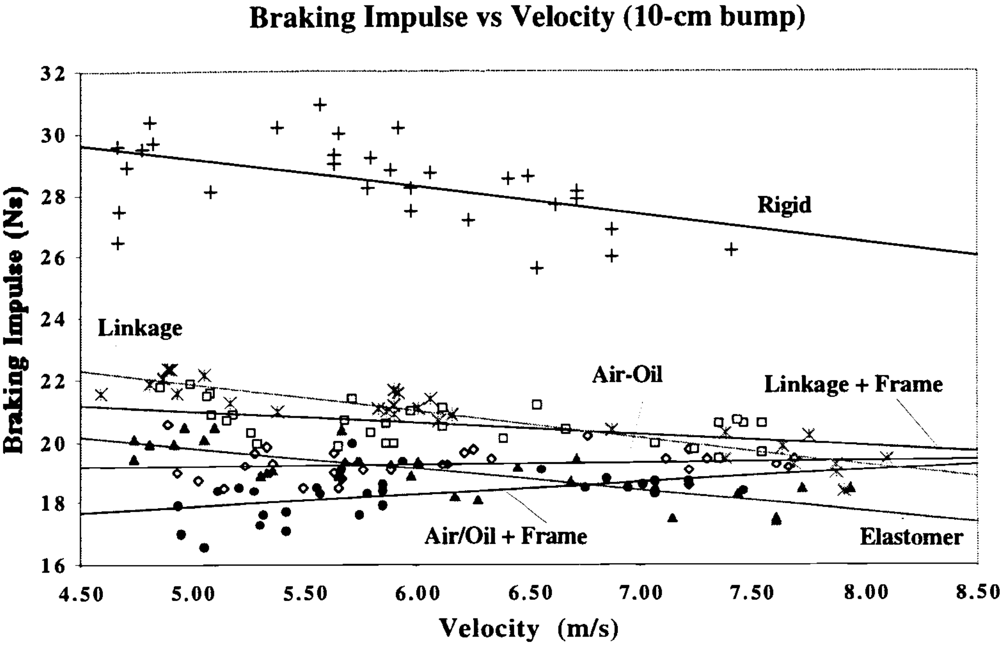

Figure 2.9. Relationship of velocity to braking impulse with 10-cm bump.

The ANCOVA showed significant differences between suspension conditions. The magnitude of the impulse was decreased by 27-36% with suspension forks as compared to the rigid condition (Table 2.9 and Appendix F). Significant differences in performance were observed between most conditions. Only the A-R and E-R, and L-R and L-S comparisons showed no significant differences. As with the 6-cm bump, the air-oil fork with suspended frame outperformed all other conditions, with both linkage conditions having significantly higher impulses than all other suspension conditions (Table 2.10). However, the impulse magnitudes differed by less than 10%, and in competitive conditions, the rider might use an alternate strategy in order to clear a bump of this height.

The positive correlations observed with both air-oil conditions suggest that fork performance may vary as a function of speed. For instance, the A-R and E-R conditions yield similar impulse values between 4.5 and 6 m/s. However, the A-R impulse values become higher at speeds higher than 6.5 m/s.

DISCUSSION

This study was conducted to assess the differences in mountain bike suspension fork performance. Peak anterior-posterior braking force and braking impulse were the performance markers selected to assess potential differences among suspension forks. The experimental setup was similar to that of Pritlove et al. (1998), which

Table 2.9. Impulse descriptive statistics for various suspension conditions with 10-cm bump.

Group	N	Mean ± SD (Ns)	Range (Ns)
Air-Oil	29	19.3 ± 0.5	18.5 to 20.6
Elastomer	30	19.1 ± 0.9	17.4 to 20.5
Linkage	29	20.8 ± 1.1	18.4 to 22.4
Air-Oil + Frame	30	18.3 ± 0.7	16.6 to 20.0
Linkage + Frame	30	20.6 ± 0.6	19.5 to 21.9
Rigid	30	28.4 ± 1.4	25.6 to 30.9

Table 2.10. Post-hoc p-values (Bonferroni) for braking impulse with 10-cm bump.

	A-R	E-R	L-R	A-S	L-S	R-R
A-R	----					
E-R	0.99	----				
L-R	<0.01	<0.01	----			
A-S	<0.01	<0.01	<0.01	----		
L-S	<0.01	<0.01	0.96	<0.01	----	
R-R	<0.01	<0.01	<0.01	<0.01	<0.01	----

used a bump secured to a force plate to evaluate vertical and AP ground reaction forces. This study assessed the differences among five suspension conditions, and used a rigid fork as the control condition. The experiment was repeated for two bump heights.

The various force curves showed a small negative component at the end of the impact that was the result of the wheel pushing in the opposite direction at the end of impact. Indeed, video data showed that the wheel does not immediately become airborne, but rather rolls over the bump before getting airborne. This explained the negative component seen in the force curves (Figure 2.4 and 2.7).

As expected, the rigid fork produced significantly larger peak forces and impulse than all other conditions with both bump heights. Post hoc tests revealed further differences between the suspension conditions for both force and impulse. With the 6-cm bump, most pairwise comparisons for impulse were significant while comparisons of peak braking forces revealed few significant differences--only the elastomer fork had reduced peak force compared to the full suspension conditions. Comparisons of peak forces for the 10-cm bump condition showed no difference between the suspension forks. However, as it was the case with the 6-cm bump, most comparisons of impulse were statistically significant. Impulse rather than peak braking force was better at discriminating between forks and it is probably the more important characteristic with respect to performance.

Suspension conditions using the air-oil fork (A-R and A-S) performed well for both peak force and impulse in both bumps conditions. With the 6-cm bump, the A-R condition provided the second best peak force attenuation, while A-S was third. In terms of impulse, A-S and A-R ranked first and second respectively. Excluding the rigid condition, the linkage design conditions (L-R and L-S) surprisingly had the highest values for both peak forces and impulse, though the elastomer-linkage comparison alone was significant. Similar rankings were observed with the 10-cm bump. The A-R condition had the highest peak force attenuation and the third lowest impulse, while the A-S ranked fourth and first respectively. From these results, it would seem that a suspension fork involving a double dampening system (for impact and rebound) such as the air-oil condition would maximize the performance of the rider during a race. However, this would have to be confirmed by testing various damping systems in race conditions. With both bump heights, this fork allowed good impact attenuation and generated small impulse values which in turn decreased velocity the least. Even though the linkage design fork, through its design, would seem to provide attenuation in the horizontal direction, the results did not confirm this characteristic.

The 10-cm impulse values for both air-oil conditions tend to increase with speed instead of decreasing as observed with all other conditions (Figure 2.9). While the correlation coefficients between impulse and speed were not found significant for these two conditions, it does suggest that fork performance may change with speed and that particular conditions of speed are best suited for a specific fork. At lower speeds (between 4.5 and 6 m/s), the A-R and E-R conditions seem to yield similar impulses while the elastomer fork is found to have lower impulse values at higher speed (above 6.5 m/s). While it is important to note that a rider is unlikely to ride passively over 10-cm bump, it is possible that similar results could be observed with a lower height bump at higher speeds. The forks would have to be tested at speeds higher than 8 m/s but within the limits observed in competition, most likely around 11 or 12 m/s.

Pritlove et al. (1998) used a similar size bump (6 cm), which allowed a comparison of results. Similar AP braking force percentage attenuations between rigid and suspension conditions were observed. However, velocity and impulse characteristics were not included in their report.

Fork stiffness settings were not tested in this project, as each was set at mid-range. Adjustments to each of the suspensions could conceivably improve performance as Orendurff et al. (1996) have previously implied in a study comparing accelerations at the axle and frame. Thus, while statistical differences in impulse existed between the five suspension conditions, conclusions about performance should be limited to specific stiffness settings. Moreover, different bump configurations and height should be tested to assess their influence on fork performance.

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CHAPTER 3

EFFECTIVENESS OF FRONT SUSPENSION VIBRATION DAMPING IN OFF-ROAD CYCLING

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ABSTRACT

Five mountain bike suspension systems and a rigid fork were tested on gravel and trail conditions to assess accelerations at the axle and frame. Accelerations ranged from –33 to +40 g at the axle and from –13 to +13 g at the frame. Spectral analyses of the acceleration signals revealed two distinct frequency regions from 0 to 100 Hz and from 300 to 400 Hz. The various suspension systems were all effective in attenuating vibration over the first region. Vibration amplitudes at the frame were considerably less than at the axle for the suspension conditions while similar axle-frame vibrations were observed with the rigid fork. Low frequency vibration amplitudes were typically greater on the trail than on gravel. In the frequency region between 300-400 Hz, the signal was attenuated at the frame for all conditions including the rigid fork. On both trail and gravel surface, the linkage design fork allowed greater vibration of the wheel than did other suspension forks, but had similar accelerations at the frame.

INTRODUCTION

Mountain biking's popularity as a sport has developed rapidly over the past fifteen years, and culminated with its inclusion as an Olympic sport in 1996. This rapid development of the sport has stimulated considerable innovation in bicycle design. While suspension systems are not typically incorporated on road bicycles, the rough terrain encountered in off-road cycling has made such systems a common component of both high performance competition bikes as well as low-end consumer equipment.

Equipment characteristics related to better cycling performance have been investigated with a large degree of success (Burke, 1986; Whitt and Wilson, 1982), and as Gregor, Broker, and Ryan (1991) summarized, experimental testing has been performed on bicycle equipment from optimal seat height and crank length to chainring and handlebar configuration. These investigations have led to better equipment design and athlete performance.

A variety of suspension forks are now available to the consumer and include relatively simple elastomer "bumpers", air-oil telescopic shock absorbers, linkage designs with a flexible connection of fork to frame, and various full frame suspensions. The appropriate choice in suspension fork is often left to the consumer and based on subjective statements, with little mechanical testing results available.

Due to its configuration, a suspension fork is constructed so that it vibrates at low frequencies, based on the uneveness of the terrain. In the 1960's, human performance in a vibration environment received increased attention because of the interest by the military in high-speed flight at low altitude where the pilot is submitted to significant turbulences (Grether, 1971). However, the earliest studies on vibration were concerned with its effects on human performance caused by heavy machinery such as trucks, earth-moving vehicles and farm equipment (Hornick, 1962). In a review of the effects of vibrations on human performance, Grether (1971) explained that frequencies between 10 and 25 Hz would cause reductions in visual acuity that were proportional to the amplitude of the vibration. Moreover, manual tasks such as marker tracking, and other tasks requiring fine muscular control were also affected by vibrations. However, most of the tasks analyzed did not necessarily correspond to real-life actions and the difference between the effects of cyclical versus random vibration stimuli was not addressed.

Nakamura and Haverkamp (1991) showed that vibrations do not seem to affect fine manual control as long as the amplitudes of these vibrations remained below 8 m/s^2. Other studies have focused on discomfort associated with whole-body vibrations. It was found that workers exposed to vibration amplitudes of less than 7.5 m/s^2 had more mobility in the wrists, elbows and shoulders than those exposed to vibrations greater than 7.5 m/s^2 (Mistrot, Donati, and Galmiche, 1990; Bovenzi, Zadini, Franzinelli, and Borgogni, 1991). While these disorders seem to be caused by high vibration exposure, it is important to note that exposure was cumulative over periods of time averaging 4 hours daily. It is highly unlikely that mountain bike riders would be submitted to such vibration amplitudes. As Moraal (1984) suggested, personality, motivation and attitudes can be internal factors involved in shaping the performance. With this idea, it is possible that vibrations which could potentially result in stresses and injury in a work environment may be tolerated as part of an enjoyable physical activity.

Few studies have investigated vibrations in the performance of a physical activity. Hatze (1992) quantified the effectiveness of cushion grip bands in tennis rackets to dissipate vibrations. The vibrations due to tennis ball impacts were shown to be significantly decreased with the use of grip bands. However, the largest reduction in vibration transfer was found to be 8.85 percent which may not, as the author suggests, be biologically relevant.

While Hatze (1992) used an artificial arm instrumented with grip pressure sensors to estimate vibration transfer, Hennig, Rosenbaum, and Milani (1992) relied on measurements collected on human subjects. Accelerometers were placed on the wrist and elbow of the subjects and characteristics of the arm vibrations were assessed with 23 different tennis racket constructions. Even though it was found that higher resonance frequency of the racket tends to reduce arm vibration characteristics, other factors were also found to reduce accelerations at the wrist and elbow. These variables included playing experience and location of ball impact on the racket. Although the study relied on human subjects to assess vibration on the human body, no conclusion could be derived concerning the potential biological consequences of impact vibrations on the arm.

If a particular terrain can be modeled as a signal with a certain frequency content, a suspension system could be modeled as a smoothing filter for that signal. The effectiveness of the suspension system would be described by its ability to attenuate a wide range of input frequencies. The purpose of this investigation was to describe the damping effectiveness patterns associated with various suspension forks over different surface conditions. Using a setup similar to that of Orendurff et al. (1996), accelerations were collected along the fork axis at the axle and the frame and a spectral analysis performed to determine the range of frequencies associated with riding on gravel or trail conditions.

PROCEDURES

Suspension Conditions

The suspension conditions in this study are described by the combination of a particular fork with a frame. Five suspension conditions were tested to reflect the most common options that were available on the market. A standard rigid fork/rigid frame system (R-R) was compared against three suspensions systems: air-oil (A-R), elastomer (E-R), and linkage (L-R) design forks. A single rigid frame was used with these fork conditions and was composed of rigid links with no moving parts. The air-oil and linkage design forks were further tested with a rear-suspended frame (designated A-S and L-S, respectively). In the suspended frame, a rear suspension system was integrated with the frame which provided some impact dampening to the back wheel. Both frames were of similar size (46 centimeters distance between the bottom bracket and the top of the vertical tube).

Elastomer and air-oil suspension forks have a telescopic design which means that the damping system is set up as tubes sliding in relation to each other (Figure 3.1). The linkage design fork is structured with pin joints allowing for some horizontal displacement (Figure 3.2). This design should theoretically allow for better damping of horizontal impacts.

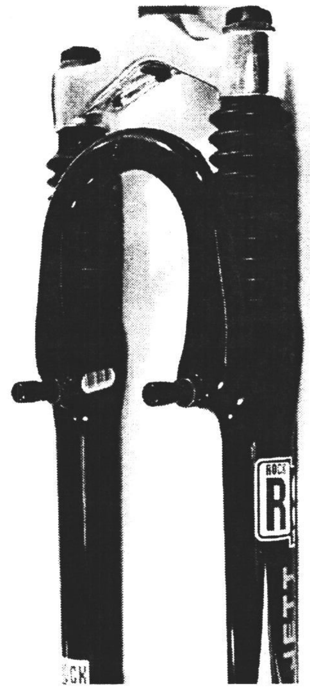


Figure 3.1. Telescopic fork illustration

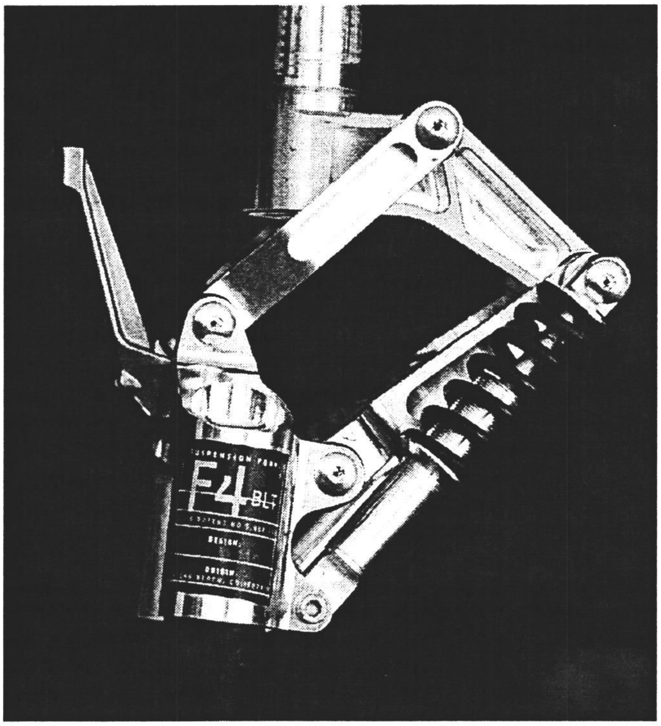


Figure 3.2. Linkage design fork illustration.

The suspended frame was composed of a dual dampening system (air-spring) located under the seat post, connecting the horizontal bar of the frame to the back wheel. Additional hinges were located close to the back wheel axis and above the pedal axis to complete the suspension setup.

Since most forks came with variable stiffness settings, it was important to keep them constant throughout the experiment. Fork stiffness settings were set according to the manufacturer's recommendations based on rider characteristics (Frame and fork specifications are described in Appendix E).

Single Subject

One subject performed repeated trials to minimize the variability due to riding styles. The 40-year old male subject was a proficient off-road cyclist and had approximately 8 years of racing experience. The subject was chosen so that his morphology fit the size of the frames provided. His height and weight were 1.8 meters and 80.4 kilograms respectively.

Bike Instrumentation

The instrumentation of the bike was similar to that of Orendurff et al. (1996). Two uniaxial accelerometers (PCB UB353B31) were screwed onto aluminum plates which were secured at the axle and the frame (Figure 3.3 and 3.4). An aluminum plate was used to fit the accelerometer axes parallel to that of the forks.

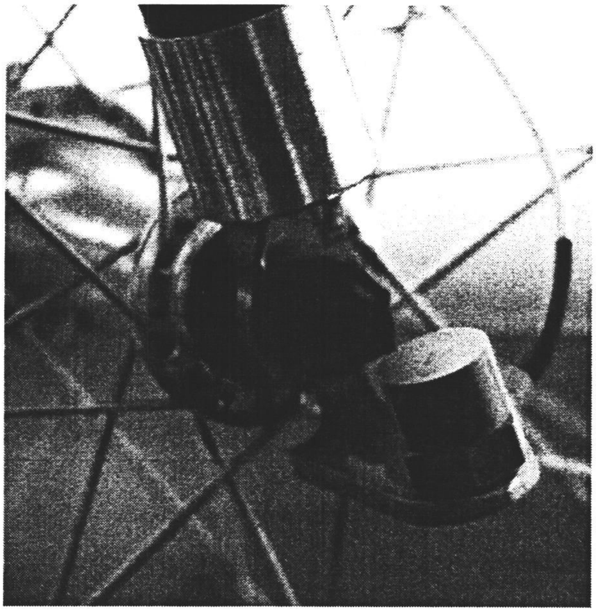


Figure 3.3. Axle accelerometer setup.

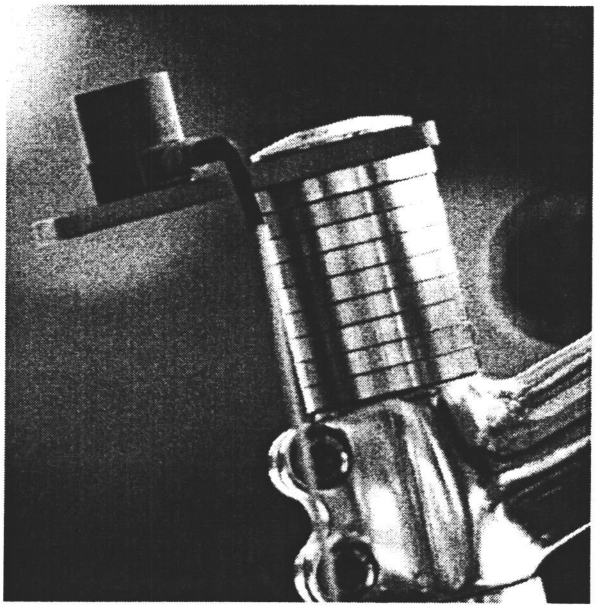


Figure 3.4. Frame accelerometer setup.

The axle and frame accelerometer sensitivities were 37.9 and 42.7 mV/g, respectively. Coaxial cables were used to transmit the accelerometer outputs to a microcomputer via an analog-to-digital (A/D) conversion board (Keithley-Metrabyte DAS-16). Accelerometer data were sampled at a frequency of 1000 Hz. To avoid altering the content of the acceleration signals, no filtering procedures were used during the acceleration data collection.

Experimental conditions

Each suspension condition was tested on two types of terrain conditions. The "trail" condition consisted of a leveled stretch of hard-packed dirt. This condition was similar to that encountered in single-track riding. The "gravel" condition was made up of coarse gravel similar to that found along railroad tracks. The subject rode along these tracks at speeds ranging from approximately 6.5 to 7 meters per second.

The riding speeds were evaluated using a photoelectric timer. Two infrared photoelectric cells were placed 2.76 meters directly before the data collection stretch. The timer activated as the rider broke the first beam of light and stopped after breaking the second beam. Knowing time and distance, average speed was derived. An obstacle was placed toward the end of the run to provide an obvious marker peak in the data.

Testing Procedures

The subject's and bicycle weights were recorded before the start of each testing condition. The tire pressure was initially set at 45 pounds per squared inch (psi), determined to suit the subject's comfort. Tire pressure was monitored between every suspension condition and adjusted to the initial level if necessary. Spoke tension was verified prior to testing, and at the end of the tests to control for possible wheel deformation. The rider initially accelerated on a long in-run and then coasted after passing by a marker placed prior to the photoelectric timer. He was instructed to ride passively over the trail or gravel slightly elevated out of the saddle. The sequence of suspension conditions was randomized for each surface condition. Data collection was triggered manually when the rider passed by a marker set before the timer. The photoelectric timer was placed in the middle of the data collection interval. Acceleration data were collected for 4 seconds at 1000 Hz. The distance covered during that period was approximately 18 meters. The end of the ride was marked with a 10-cm bump which allowed for post-synchronization. The first four trials where speed was between 6.5 and 7 m/s were used for analysis.

Data Analysis

From the 4-second data collection, a one-second sequence was taken using the post-synchronizing peak point as a starting point and taking 1000 data points prior to that point (which allowed the calculation of Fourier coefficients from 0 to 500 Hz at intervals of 1 Hz). Subsequently, a spectral analysis of the accelerometer signals from the axle and frame was performed for each suspension condition and for every trial. The Fourier coefficients were calculated for each trial and the mean amplitude calculated for each harmonic. The difference in signal amplitude between the axle and the frame represented the damping effectiveness at each harmonic level.

RESULTS

Acceleration signals were collected on two surfaces labeled as gravel and trail. As expected, signal characteristics were different on the two surface conditions. The gravel condition produced high frequency accelerations which can be observed on Figure 3.5. In contrast, trail signals produced vibrations that were of lower frequency (Figure 3.6) even though the overall acceleration amplitude ranges were similar (Table 3.1). Moreover, both signals also contained high frequency vibrations.

The spectral analysis graphs averaged over 4 trials (Figures 3.7 to 3.12) revealed patterns associated with both the type of surface and the suspension condition.

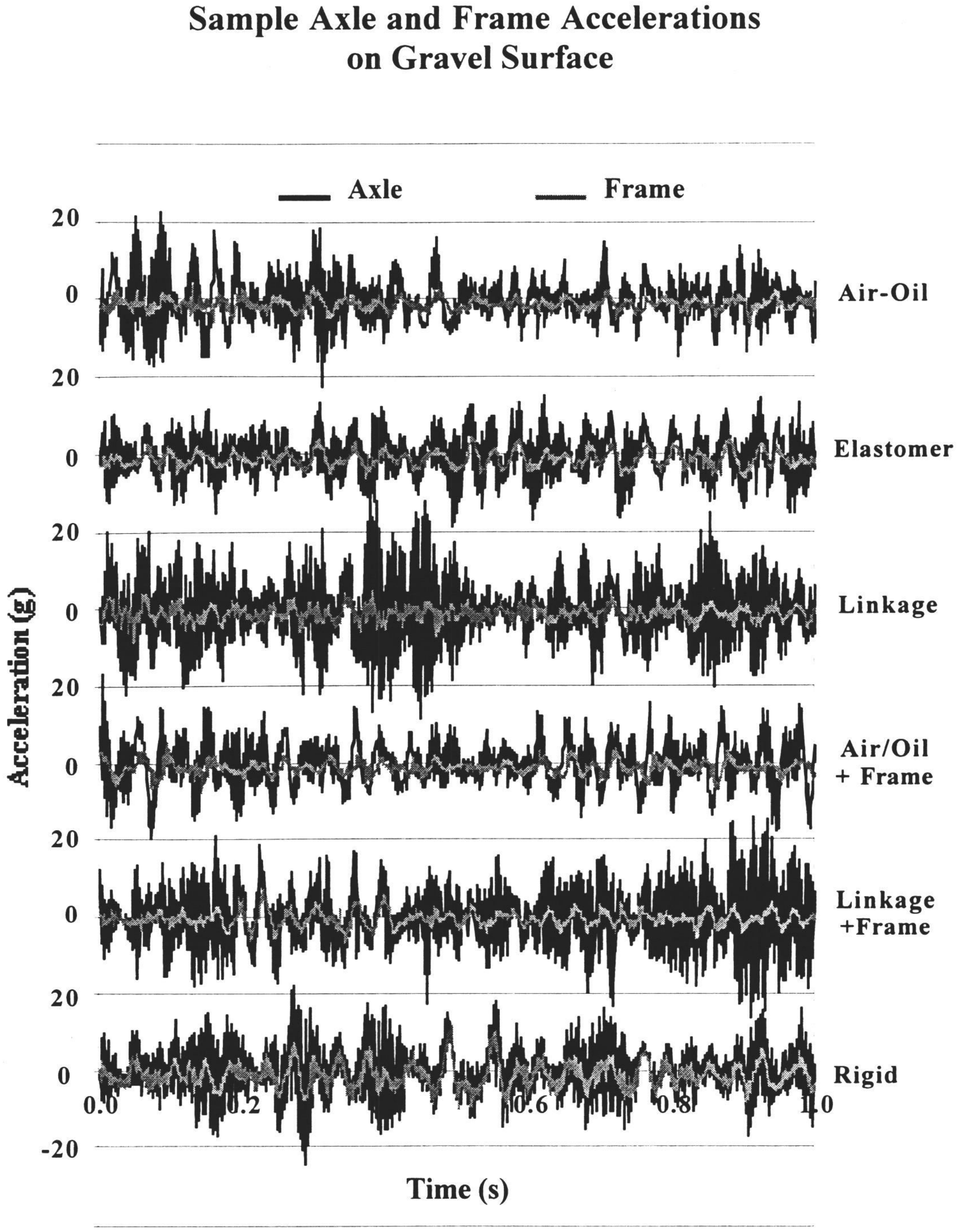


Figure 3.5. Sample acceleration signals on gravel surface.

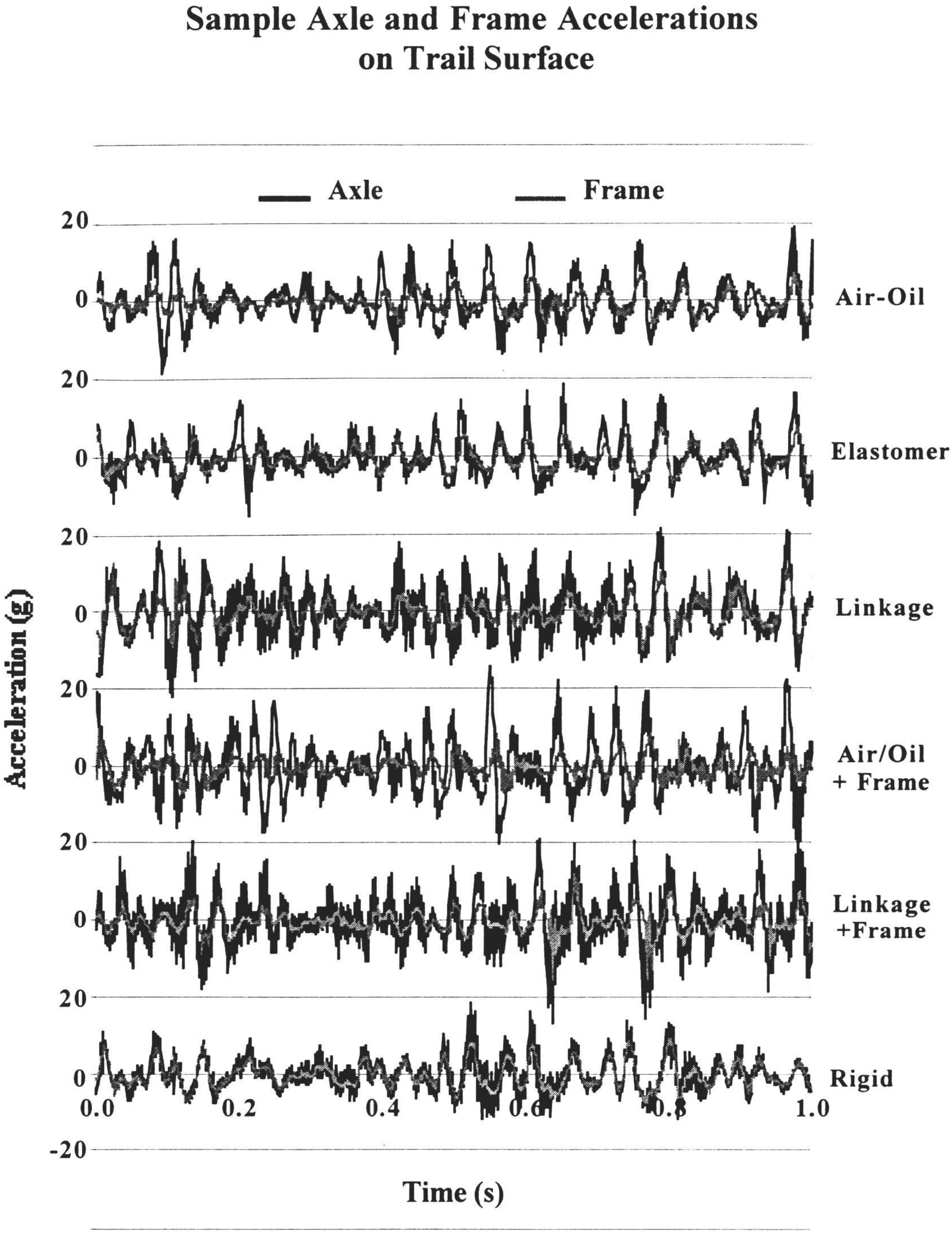


Figure 3.6. Sample acceleration signals on trail surface.

Two distinct regions of high amplitude were observed for the axle acceleration signal. The first region was situated below 100 Hz, while the second region was between 300 and 400 Hz. The frame acceleration signals, including the rigid condition, showed similar patterns in the lower frequency region but not in the 300-400 Hz region.

Vibration amplitudes at the frame were considerably less than at the axle for the suspension conditions in the 0 to 100 Hz range, while similar axle-frame vibrations were observed with the rigid fork. Lower frequency vibration amplitudes were typically greater on the trail than on gravel on this test.

The high frequency region between 300-400 Hz was attenuated at the frame for all conditions including the rigid fork. On both trail and gravel surface, the linkage design fork allowed greater vibration of the wheel than did other suspension forks.

Table 3.1. Acceleration ranges at axle and frame (in g)

	GRAVEL		TRAIL	
	Axle	Frame	Axle	Frame
A-R	-21.1 to 23.5	-7.5 to 5.5	-16.1 to 19.1	-5.7 to 6.5
E-R	-19.0 to 23.4	-7.4 to 5.3	-14.6 to 19.7	-9.9 to 13.0
L-R	-23.9 to 27.8	-7.6 to 4.8	-22.6 to 27.0	-12.1 to 11.4
A-S	-19.1 to 23.0	-7.1 to 5.1	-21.4 to 29.1	-12.1 to 10.1
L-S	-33.0 to 39.8	-6.9 to 7.5	-23.4 to 27.2	-13.2 to 13.0
R-R	-23.3 to 29.2	-9.1 to 17.0	-14.9 to 19.2	-8.8 to 12.4

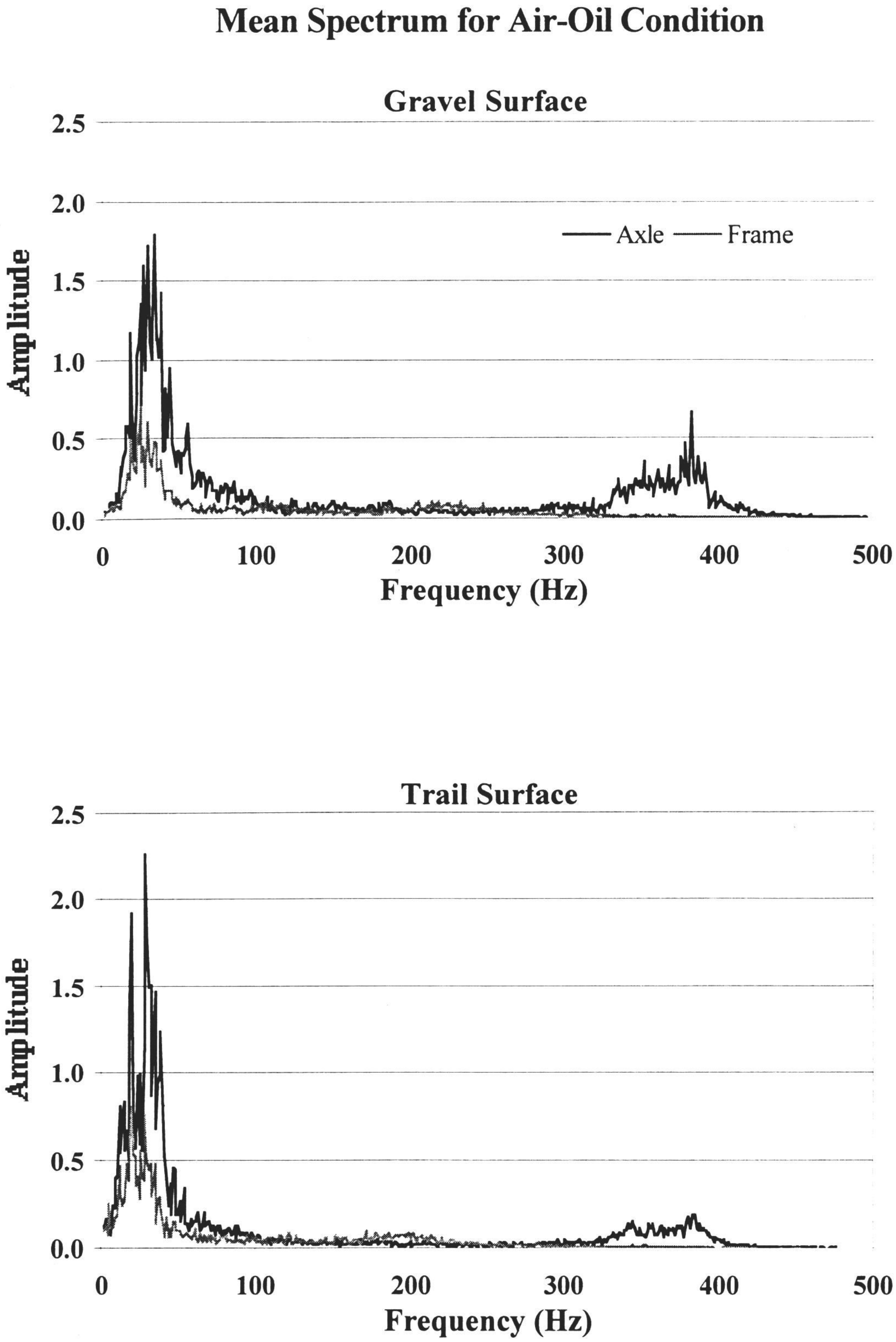


Figure 3.7. Spectral analyses for the air-oil suspension condition.

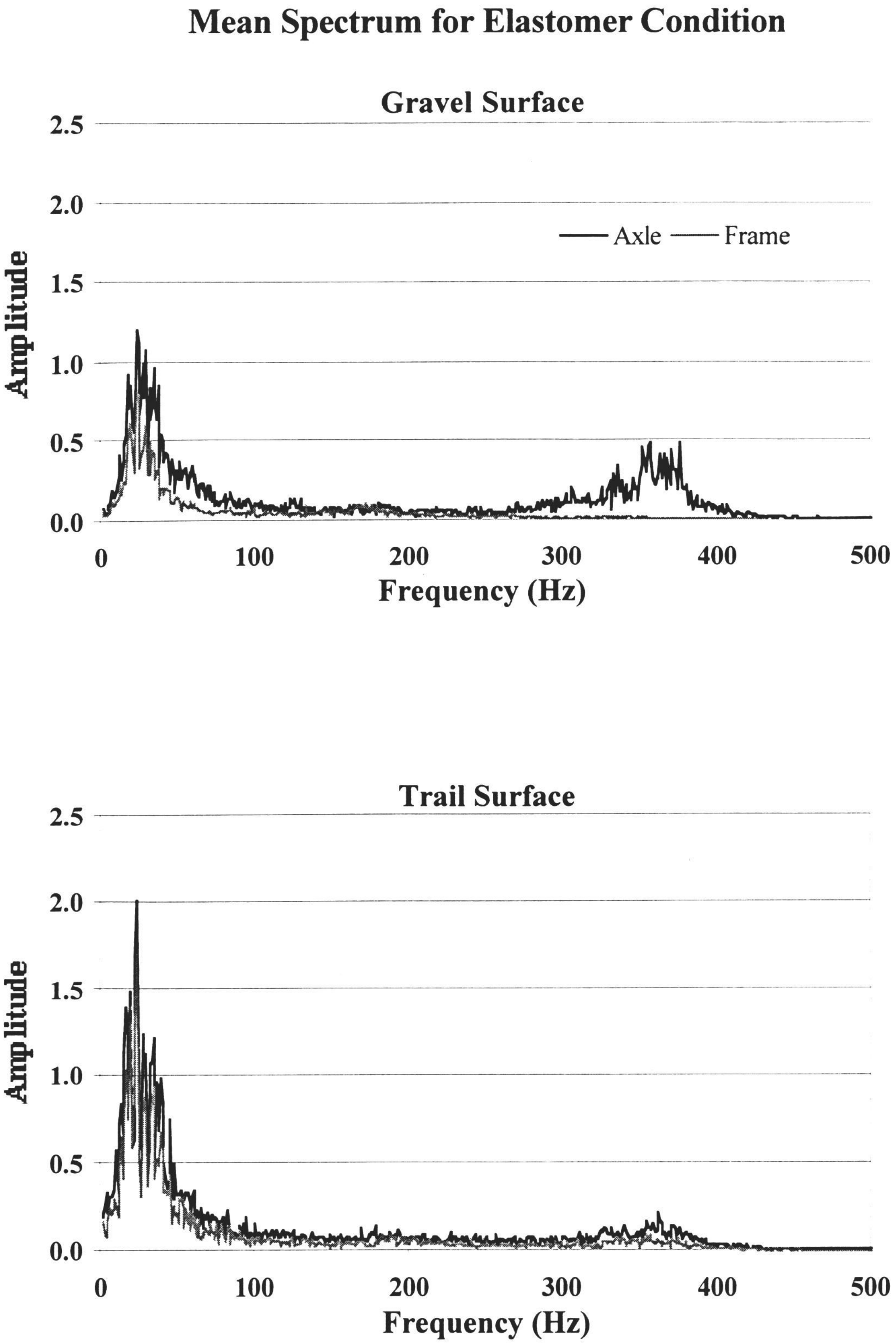


Figure 3.8. Spectral analyses for the elastomer suspension condition.

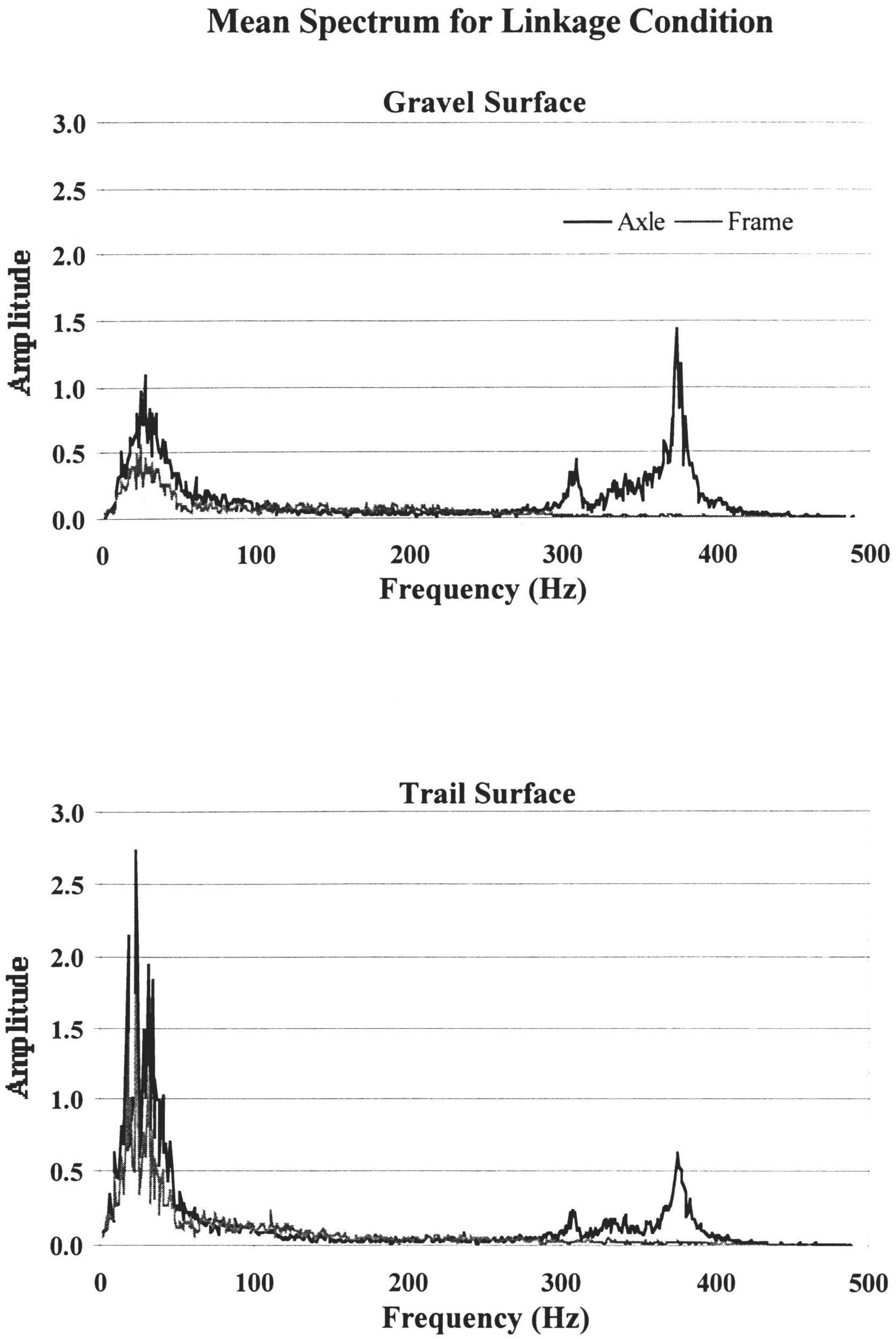


Figure 3.9. Spectral analyses for the linkage design suspension condition.

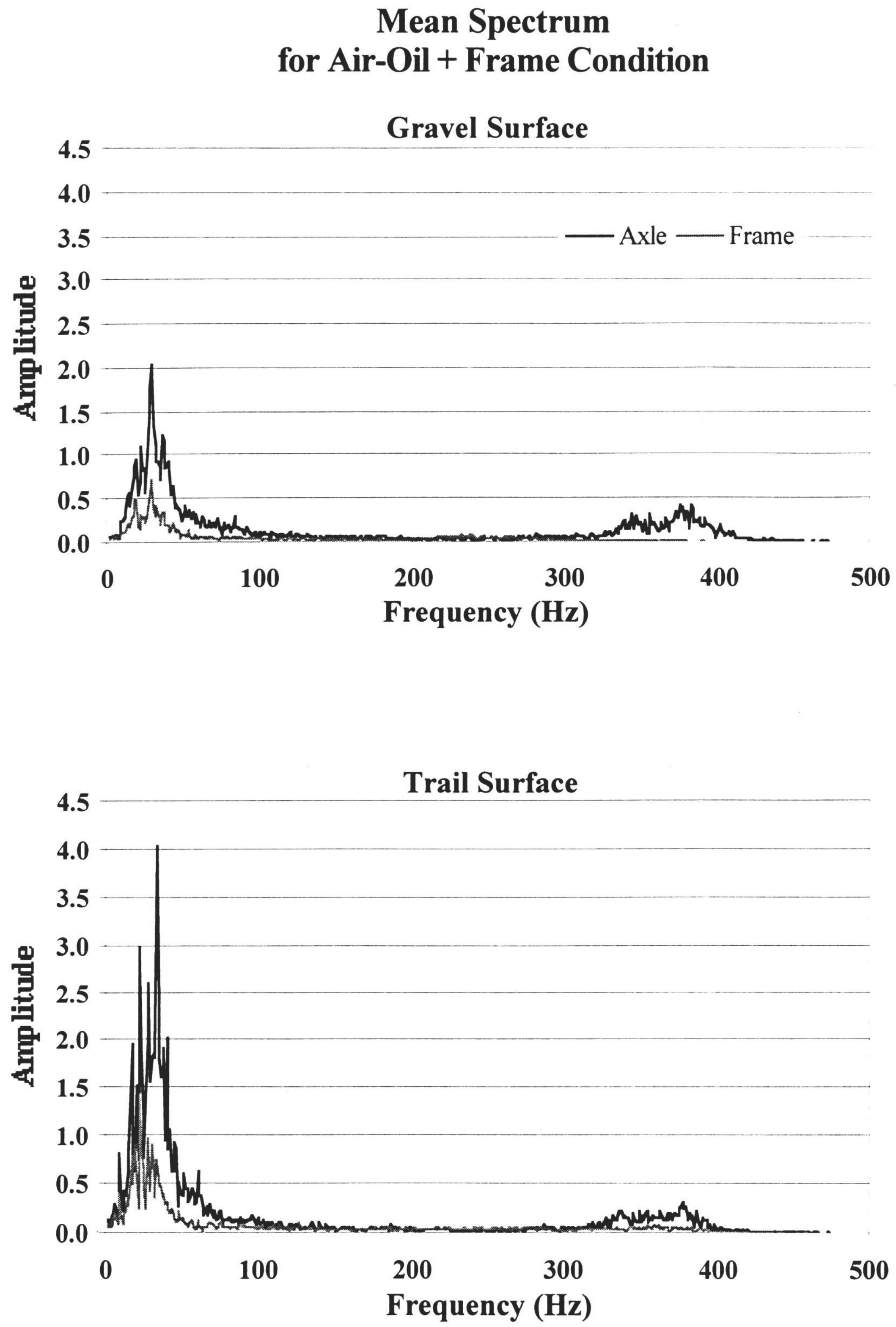
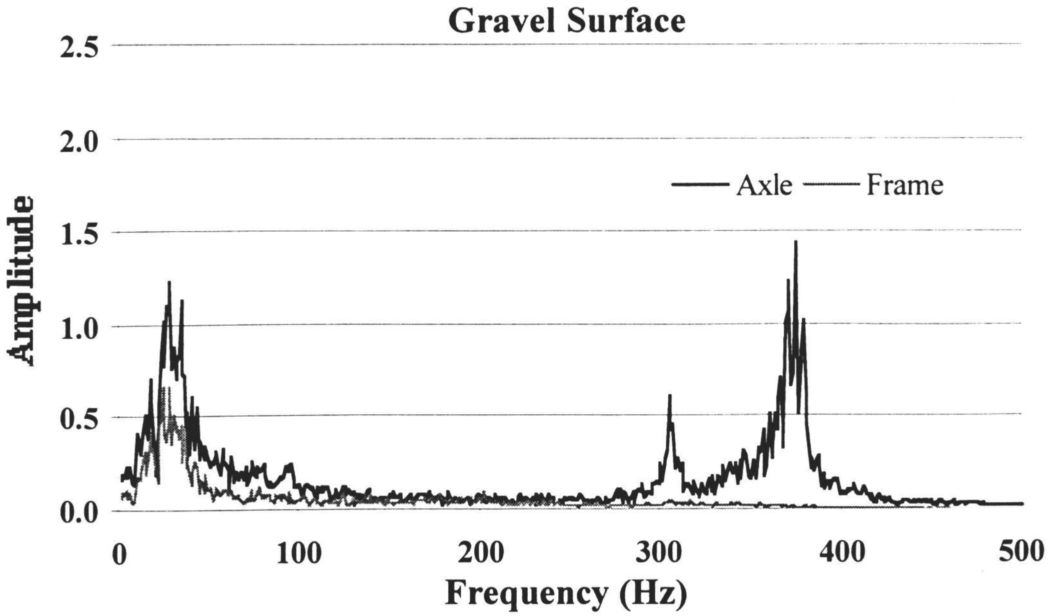


Figure 3.10. Spectral analyses for the air-oil + frame suspension condition.

Mean Spectrum
for Linkage + Frame Condition



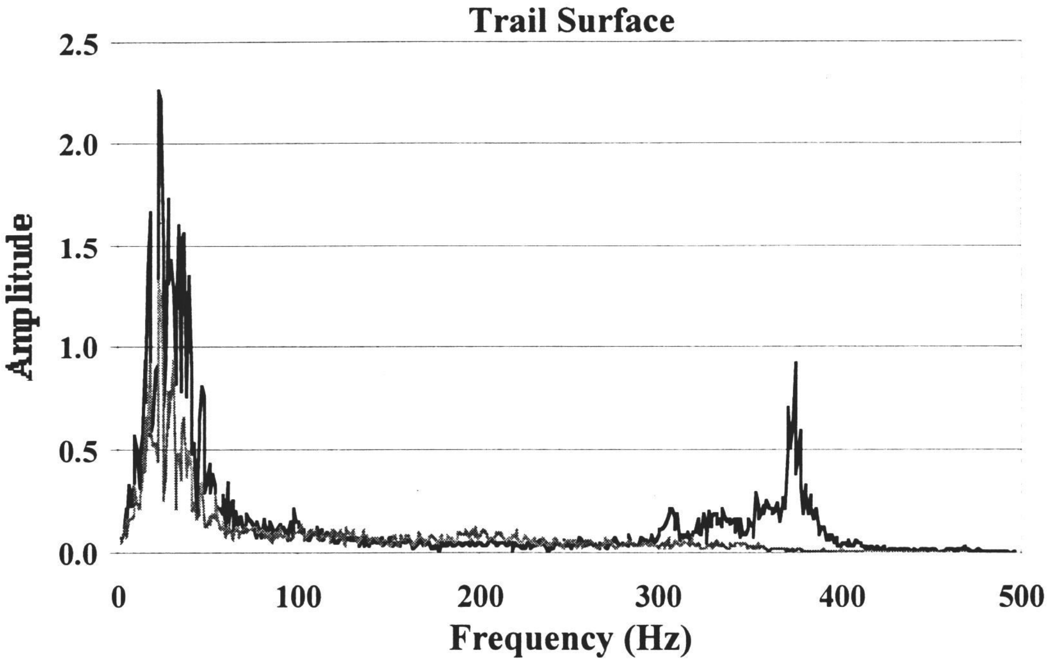


Figure 3.11. Spectral analyses for the linkage + frame suspension condition.

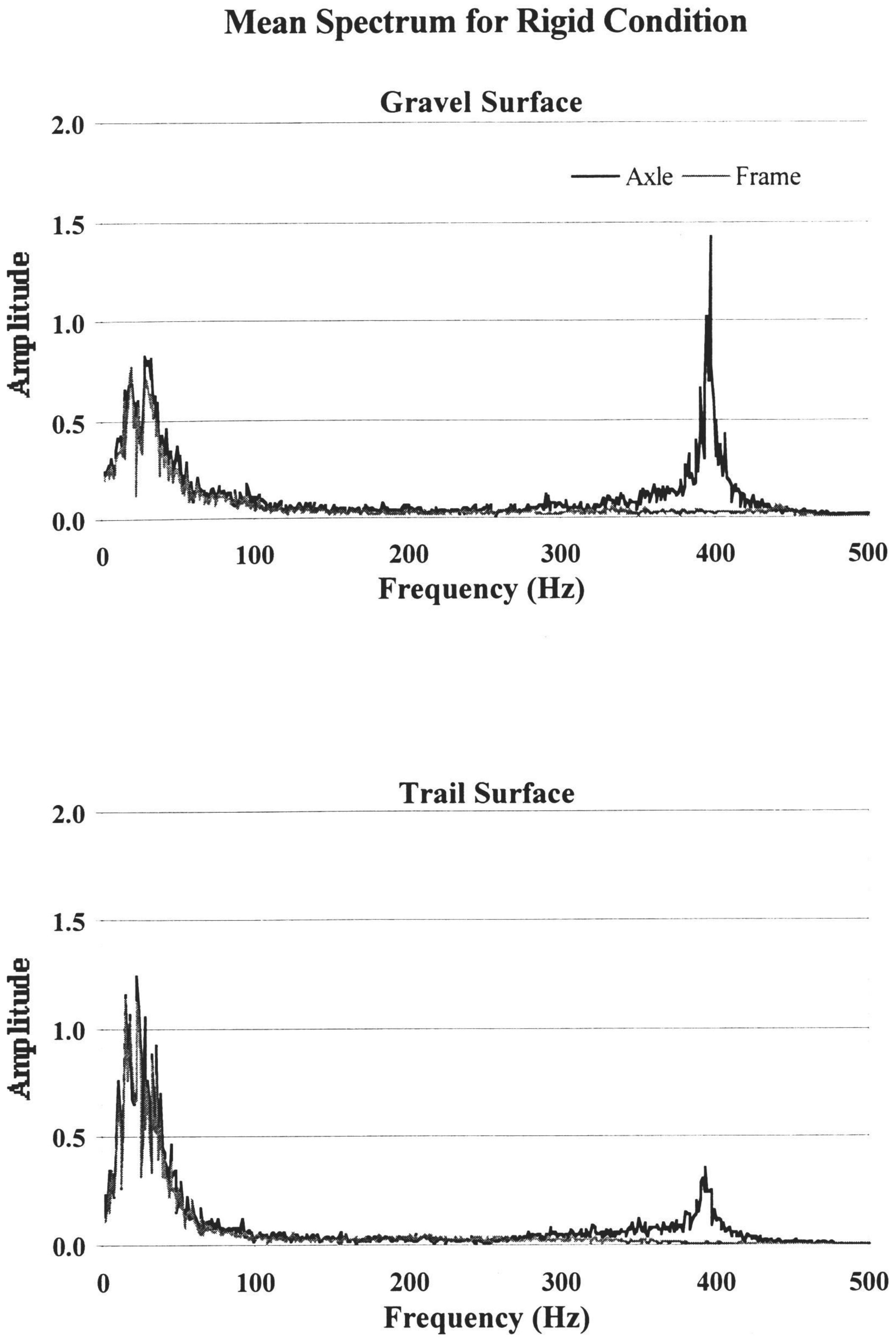


Figure 3.12. Spectral analyses for the rigid suspension condition.

DISCUSSION

This investigation looked at the two surface conditions as a signal, and used the suspension systems as filters. While the quantitative results are limited to the acceleration data in Table 3.1, and the spectral analysis graphs (Figures 3.5 to 3.10), clear relationships were observed. The acceleration magnitude ranges at the axle were higher on gravel than on the trail. However, the opposite relationship was observed at the frame. The acceleration ranges at the frame were lower on gravel for most conditions. Only the air-oil and rigid fork had frame signal ranges greater on gravel than on trail. Moreover, the linkage design fork with suspended frame (L-R) allowed greater vibration at the wheel than all other forks on both gravel and trail surfaces. Still, the dampening observed at the frame for the L-S condition was similar to that of all the other suspension forks.

The spectral graphs showed that the amplitude of the signal at the frame is decreased in all suspension conditions in the 0 to 100 Hz range. Only the rigid condition does not follow this pattern. Therefore, all suspension conditions seem to effectively dampen the vibrations at the frame. However, it is difficult to differentiate the effectiveness of the forks within that range. It might be important that data collection be performed at a higher rate over one second. In this manner, more harmonic values could be derived and differentiation between forks more visible.

The second area with peak amplitudes at the axle was located between 300 and 400 Hz. All fork conditions revealed the same peak patterns. However, the amplitude of the frame spectrum was minimal and it can be concluded that the forks dampen the limited signal of the axle within that range. This pattern was observed for all suspension conditions including the rigid fork. This observation would suggest that another form of dampening must be involved in the high frequency range. It should be noted that the rider most likely contribute to a signal input at the frame and axle. Wang and Hull (1997) have previously modeled an off-road cyclist using the arms and legs as damping elements. They also included the rider's visceral mass natural frequency as an input signal. The results found here suggest that the rider input needs consideration to assess and explain the effectiveness of suspension forks.

The lower frequency range dampening suggests that the effectiveness of a suspension fork can be quantified. However, the spectral graphs produced jagged amplitudes which may be due to the limited number of trials used in the analysis. Indeed, it is quite unlikely that a fork would have such dramatic amplitude changes from one harmonic to the next, and it would contradict the use of a suspension system. With more trials, the average amplitudes would likely follow a smoother curve which would improve the description of fork effectiveness.

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CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

The present project assessed the performance and effectiveness of various suspension forks in off-road cycling. To supplement the subjective and qualitative testing by expert riders, a quantification process of specific variables was applied to provide additional objective information in rating the performance of different suspension forks.

The evaluation of fork performance was done by measuring antero-posterior peak braking force and impulse associated with bump impact. The relationships between these variables and velocity suggest that impulse was better at discriminating between forks and was a more important characteristic than A-P peak braking force with respect to performance.

Based on these results and the structure of the experiment, suggestions for future research can be made:

1. Evaluate the influence of various stiffness settings on performance.
2. Determine the differences in impulse due to various bump configurations.

3. Perform similar tests over a larger range of speeds to determine the possible speed where a fork might change its performance characteristics.
4. Use similar testing procedures to evaluate rear suspension performance.
5. Integrate the braking impulse due to back wheel impact and include it with the front wheel results.

To gain an overall picture of the mountain bike performance as it rides over an obstacle, it will be necessary to integrate both the front and rear wheel impacts. This potentially could lead to better configurations of mountain bikes by combining front and rear suspensions that would complement each other.

To assess the damping effectiveness of a suspension system, an analysis of acceleration signals was conducted for two surface conditions. The trail surface represented a condition likely to be encountered by off-road cyclists during single-track riding, while the gravel condition allowed testing of the fork at a high vibration rate. Comparisons of the axle and frame acceleration signals in spectral analyses were used to assess effectiveness of the suspension forks. While the differences between axle and frame signals were obvious on the spectral graphs as most of the acceleration signals were contained in a frequency range from 0 to 100 Hz, the results were inconclusive in ranking the forks. Because all suspension forks showed a similar dampening effect at the frame over the frequency range from 0 to 100 Hz, and the amplitudes cannot be directly compared to each other, it was difficult to assess which fork would be more effective over a particular terrain. Moreover, the jagged amplitudes observed in the spectral graphs (Figure 3.7 to 3.12) suggest that more trials are necessary to get a smoother mean spectrum.

The effectiveness of a fork, or how well a fork can handle the vibrations due to different types of terrain is an important factor in the choice of a suspension system. Improvements to the current design should include:

1. More trials per fork, which will allow derivation of a smoother mean spectrum curve for a given surface condition.
2. With a smoother curve, other analysis tools could be used, such as transfer functions, which assess the attenuation or amplification effect due to a specific input signal.
3. Isolate the tire as a possible suspension system.
4. Consider the influence of the frame vibration on the rider.

The quantification of vibration levels transmitted through the forks by the terrain surface is necessary to address future research into the understanding of vibration effects on human performance. Some suggestions would include:

1. Evaluate the transfer of vibrations from the handlebars to the wrists and subsequently elbows and shoulders.
2. Quantify the average forces at the wrists and elbows due to riding on various surface conditions.

3. Compare the magnitude of the forces with that of other activities involving a high level of vibrations.
4. Integrate the kinetics and kinematics to assess safer body positions on the bike while riding over various surfaces.

The research presented here provided an insight in the performance and effectiveness of mountain bike suspension forks. These initial results need to be supplemented with additional research endeavors (some of which having been suggested above) that will address the effects of the mechanical behavior of suspension forks on the human body.

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APPENDICES

APPENDIX A

REVIEW OF LITERATURE

The purpose of this chapter was to present the reader with information pertaining to different aspects of mountain biking. Since studies specifically related to mountain biking are scarce, this literature review summarizes research implemented in other areas whose body of knowledge could be applied to the present project. For instance, vibrations studies can give the reader background information about the effect of repeated impacts on various structures including the human body.

This review focus on investigations dealing with injuries related to mountain biking, cycling performance, vibrations, and off-road cycling models.

Mountain Biking Injuries

Shea, Shumsky and Shea (1991) have reported a case of DeQuervain's disease (tenosynovitis of the first dorsal compartment of the wrist) that was caused by mountain bike overuse. In particular, the patient involved suffered the injury because of the strain of long rides on the hands and wrists. The demands of mountain biking require continuous gripping, shifting, braking and steering. Ergonomic shifters as well as shock absorbing devices would reduce the incidence of such a disease even though not tested. Munnings (1991) also mentioned the large incidence of wrist injury while cycling and attributed the cause of injury to improper choices in the bicycle size and position of the hands on the handlebar. Most injuries occur because the hands have to support too much of their body weight on their hands which ultimately impinge the nerve. Minimizing activities which can irritate the nerves of the hand and wrist was proposed as a solution, even though no mention of vibration issues while mountain biking was made.

While most injuries related to road cycling seem to be related to overuse or misuse of equipment, recent data concerning mountain biking would show that acute injuries appear to be more current. A study conducted at a race site in California showed that the overall injury rate at the event was 0.40% (16 out of 4027). An injury was defined as an episode of acute trauma during the competition which necessitated medical attention and did not allow the rider to finish the race. Abrasions and contusions were the most common type of injury reported, and injury events mainly occurred while riding downhill and turning (Kronisch, Chow, Simon, and Wong, 1996). While the incidence of injury was quite low, it is important to note that surveys have shown a greater proportion of riders getting injured while training. In particular, Kronisch and Rubin (1994) found that 20.4% of the riders surveyed suffered a mountain bike injury that required medical attention and prevented them from cycling for at least one day. While these surveys used a loose criterion for participation in the survey, it is interesting to note that most injuries occurred by loss of control of the bike, generally at high speeds. However, while equipment failure has been mentioned as a possible cause of injury, the surveys have failed to report in greater details which piece of equipment was involved in the accident.

Cycling Performance

The physiological profile of mountain bikers has been compared to that of road cyclists at the elite level. Wilber and colleagues (1997) have shown that there is little difference in body composition, maximum heart rate, lactate concentrations at threshold, and volume of oxygen consumption between athletes representing the United States Cycling Federation (USCF) National Road Team and those representing the National Off-Road Bicycle Association (NORBA) National Cross-Country Team. Significant differences were observed for both men and women in power output, which should have been expected considering the nature of both activities. Off-road cyclists will be more likely to use small gear to handle the quick changes up and down that the course will offer. Since mountain bikers tend to do a lot of training on the road to improve their aerobic capacity, similar results in these physiological markers should be expected.

Endurance tests have been performed on road cyclists to determine physiological and biomechanical factors associated with performance. While the better athletes were found to generate higher torque per downstroke, it was also found that the same athletes had as a group a larger percentage of type I muscle fibers (Coyle et al., 1991). Seifert, Luetkemeier, Spencer, Miller, and Burke (1997) have tested the effects of mountain bike suspension systems on energy expenditure, physical exertion and time trial performance during mountain biking. Various suspension forks were compared including rigid, front suspensions (air/oil damped), and front and rear suspensions. While no differences were found between the forks for the metabolic data (absolute and relative VO_2, mean and peak heart rate), time trial performance was significantly different when using a front suspension system than with a rigid or full suspension system. It was speculated that these differences might be due to the absorption of shock with minimal loss of energy as compared to the rigid and front and rear suspension.

Other studies reported comparisons between genders, and levels of experience as a cyclist for various metabolic variables including oxygen consumption, heart rate, Creatine kinase concentrations, and blood lactate (van Baak and Binkhorst, 1981; Swain, Coast, Clifford, Milliken, and Stray-Gundersen, 1987; Coyle, Coggan, Hopper, and Walters, 1988).

Methods for estimating maximal cycling power and optimal or preferred cycling cadences have been developed. Martin, Wagner, and Coyle (1997) have ascertained methods to measure power in short exercise bouts which is beneficial in the investigations dealing with maximal neuromuscular function. However, power output seems to have little effect on preferred cycling cadence as experienced and less experienced riders both chose cadences significantly different than what had been estimated to be their most economical cadence (Marsh and Martin, 1997).

As expressed earlier, mountain bikers do a lot of road riding as part of their training regimen. Kinematic differences seem to exist between road and mountain cycling. Squadrone, Rodano, Gallozzi, and Faina (1998) have found that hip and ankle range of motion were respectively higher or lower when mountain biking. The hip range of motion when mountain biking was 43 degrees versus 34 degrees on the road, and the ankle motion ranged between 19 degrees on a mountain bike versus 25 degrees on a road bike. While these differences have been acknowledged by the authors, no speculation was made as to the cause of these differences. It could be argued that the geometry of the two bicycles, as well as the position of the rider on the bicycle might provide an explanation for these differences.

Suspension Fork Comparisons

In the bicycling community, it is generally accepted that suspension forks provide a more conformable ride. The issue for the potential owner of a suspension fork is often related to the type of fork and damping system associated with it should be chosen. Olsen (1993) briefly summarized the differences between damping systems and how the energy loss is controlled. In particular, it was suggested that friction, hysteresis and hydraulic damping were the most common types of systems used in front suspension forks. Moreover, linkage design forks having pivot joints instead of sliding joints were identified as an excellent option since the wheel would travel in an arc rather than in a straight line (Olsen, 1993).

Unfortunately, there are few data to substantiate the effectiveness or performance of a fork except for the travel length and possibly the return rate. A recent study by Gillespie, Groesz, Avedisian, and Rutt (1998) examined the maximum vertical displacement of the wrist and the bike's hub when riding over a series of bumps with different suspension forks. No significant statistical difference was found between the forks in terms of vertical displacement even though the vertical displacement of the wrist and hub was systematically lower for the suspension fork conditions as compared to the rigid fork. With only four subjects involved in this study, statistical power must be a concern in the findings.

Vibrations

Vibration can be considered as a form of oscillatory motion which can be produced in a cyclical or random manner. The earliest studies which dealt with vibrations and its effects on human performance sprung from the interests developed in space travel and the questions related to the ability of a human being to perform simple tasks in a turbulent environment. In a review of the effects of vibrations on human performance, Grether (1971) explained that frequencies between 10 and 25 Hz will cause decrement in visual acuity proportional to the amplitude of the vibration. Moreover, manual tasks such as marker tracking and other tasks requiring fine muscular control were also affected by vibrations. Most of the studies reviewed only looked at very specific tasks which do not necessarily correspond to real-life actions. Also, the differences between the effects of cyclical versus random vibration stimuli was not addressed.

Nakamura and Haverkamp (1991) have investigated the effects of vertical whole-body shock-type vibration on fine manual control. This study used a simulator of earth-moving machinery and had subjects trying to maintain a cursor between two parallel lines while being subjected to shock of various amplitudes and duration. It was found that the drivers had similar errors whether the shocks were symmetric or asymmetric as long as the shocks had amplitudes below 8 m/s^2. Fine manual control does not seem to be affected by vibrations as long as the amplitudes of these vibrations remain within a certain range. Other studies such as those by Mistrot, Donati, and Galmiche (1990) have focused on discomfort associated with whole-body vibrations. The study focused on the assessment of musculoskeletal disorders between chain saw operators and maintenance workers. The battery of tests involving data collection of anthropometric variables, a physical examination, and range of motion measurements of the head, shoulder, and arms were performed on both groups. The level of vibration exposure for chain saw operators was assessed by instrumenting two chain saws used by the workers. It was found that the workers exposed to vibration amplitudes of less than 7.5 m/s^2 had more mobility in the wrists, elbows and shoulders than those exposed to vibrations greater than 7.5 m/s^2 (Bovenzi, Zadini, Franzinelli, and Borgogni, 1991). While these disorders seem to be caused by high vibration exposure, it is important to note that exposure is repetitive over long periods of time (a minimum of 4 hours daily). It is highly unlikely that mountain bike riders would be submitted to such vibration amplitudes. As Moraal (1984) suggested, personality, motivation and attitudes can be internal factors involved in shaping the performance. With this idea, it could be possible that vibrations which could potentially result in stresses and injury in a work environment may be tolerated in as part a fun physical activity.

Few studies have investigated vibrations in the performance of a physical activity. Hatze (1992) quantified the effectiveness of cushion grip bands in tennis rackets to dissipate vibrations. The vibrations due to tennis ball impacts were shown to be significantly decreased with the use of grip bands. However, the largest reduction in vibration transfer was found to be 8.85 percent which may not, as the author suggests, be biologically relevant.

While Hatze (1992) used an artificial arm instrumented with grip pressure sensors to estimate vibration transfer, Hennig, Rosenbaum, and Milani (1992) relied on measurements collected on human subjects. Accelerometers were placed on the wrist and elbow of the various subjects and characteristics of the arm vibrations were assessed with 23 different tennis racket constructions. Even though it was found that higher resonance frequency of the racket tends to reduce arm vibration characteristics, other factors were also found to reduce accelerations at the wrist and elbow. These variables included playing experience and location of ball impact on the racket. This study had the advantage to rely on human subjects to assess vibration on the human body, but no conclusion could be derived concerning the potential biological consequences of impact vibrations on the arm.

Modeling and Performance in Mountain Biking

Modeling the athlete's or equipment performance has been investigated with various degrees of success in the sport of cycling. In general, the model relies on a single subject's performance to try to repredict that performance from the model. Swain (1997) developed a model to optimize performance by varying power output on hills and in windy situations. The model used mean VO2, changes in VO2 and grade of the hill as independent variables and a separate model with wind speed included in the model. It was found that modest increases in power in the uphill and head-wind segments coupled with slight decreases in the downhill and tailwind segments would significantly improve overall time trial performance (Swain, 1997).

Models of rear suspensions systems have been designed and tested as a mean of quantifying power dissipation while riding uphill. Wang and Hull (1994) developed a model with six degrees of freedom utilizing a rear suspension system with a high pivot point location often used on current dual suspension mountain bikes. The model was not entirely convincing as a phase shift of 29 degrees existed between the experimental and simulation data. Moreover, only one rider was used to test the validity of the model. The findings showed that a power dissipation of 1.3% could be expected with a rear suspension mountain bike. Modeling can provide quick measures and allow for quick adjustments to check how a system would behave, but experimental data are most important to test the accuracy of the model.

A dynamic system model of an off-road cyclist was designed by Wang and Hull (1997) using the arms and legs as damping elements. Moreover, the visceral mass of the upper body was considered and its natural frequency included in the model. To determine frequency response functions, seven subjects were tested in three positions: seated, standing and downhill. The resulting model did not include a typical front suspension system as one of the damping element as the study was mainly concerned with the modeling of the rider in a mountain bike riding position.

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APPENDIX B

INFORMED-CONSENT FORM

Morris Levy, who is a graduate student with the department of Exercise and Sport Science has requested my participation in a study at Oregon State University. The title of this research is "A Comparative Analysis of Off-Road Bicycle Suspension Systems".

I have been informed that the purpose of this research is to test the performance of various suspension systems in mountain biking when riding over bumps. The tests will involve riding mountain bikes equipped with different suspension forks over bumps of various sizes and at increasing speeds. The maximum bump height that will be used is 8 centimeters, which is equivalent to 3.2 inches, and the maximum speed considered will be 7 meters per second which is equivalent to 15.7 miles per hour. Because this project focuses on the testing of suspension systems, I am scheduled to be the only subject participating in this study. I understand that my participation will require a minimum of 30 hours of testing.

I understand that there are foreseeable risks or discomforts if I agree to participate in the study. The possible risks include falling while riding over the bump, losing control of the mountain bike while approaching the bump. These risks could result in bodily injury such as bruises, skin burns and contusions. Other discomforts might include soreness to the arms and shoulders from repeated impacts with the bumps.

I have been informed that the procedures in case of injury are as follows: to be administered first aid, and/or be transported to the nearest hospital if necessary. I am also aware of the fact that I will be responsible for the payment of professional care and facilities that will be provided in case of injury or illness and that the University will not provide compensation for these costs.

I understand that the results of this research study may be published but my name will remain confidential and will not be released or revealed to any other person than those involved in the testing.

Questions about the research, my rights, or research-related injuries should be directed to Morris Levy at (541)737-5933.

I have read the above information. The nature, demands, risks, and benefits of this project have been explained to me. I knowingly assume the risks involved, and understand that I may withdraw my consent and discontinue participation at any time without penalty or loss of benefit to myself. In signing this consent form, I am not waiving any legal claims, rights, or remedies. A copy of this consent form will be given to me.

Subject's signature_________________________ Date_________

I certify that I have explained to the above individual the nature and purpose, the potential benefits, and possible risks associate with participation in this research study, have answered any questions that have been raised, and have witnessed the above signature

I have provided the participant a copy of this signed consent document.

Signature of investigator___________________ Date_________

APPENDIX C

Force and Impulse Data for 6-cm Bump

AR			ER		
Velocity (m/s)	Force (N)	Impulse (Ns)	Velocity (m/s)	Force (N)	Impulse (Ns)
5.03	554.9	10.4	4.85	532.4	11.3
5.17	567.6	10.8	5.12	542.3	10.8
5.25	565.6	10.5	5.35	553.4	11.8
5.03	558.2	10.7	5.39	559.5	10.5
5.42	565.4	11.0	4.95	533.6	11.1
5.25	548.7	10.5	5.46	559.0	10.7
5.19	556.5	11.1	4.69	478.4	11.1
4.87	523.3	10.4	4.72	514.9	11.1
5.28	558.0	10.6	4.95	553.5	10.5
5.10	555.0	10.8	5.32	546.8	11.0
6.17	602.0	10.8	5.63	517.3	10.8
5.67	579.5	10.6	5.78	569.5	11.0
6.17	561.7	10.3	6.02	575.9	10.9
6.27	589.9	10.6	5.63	548.9	11.2
5.60	601.2	11.0	5.97	568.0	10.4
5.60	579.8	11.0	6.21	591.9	11.5
5.63	586.4	10.7	5.67	525.4	11.4
6.21	594.7	10.9	5.81	558.3	10.9
6.01	572.5	10.9	5.67	578.5	11.2
5.92	574.2	10.7	5.70	565.3	11.2
7.27	606.8	9.7	6.76	595.8	10.5
7.94	614.1	9.0	7.60	644.4	10.2
7.09	609.3	9.8	7.58	644.4	9.8
7.25	594.9	9.5	8.20	650.4	9.8
8.16	646.8	9.7	6.99	597.0	10.3
8.16	645.6	9.0	6.71	631.4	11.4
6.92	621.8	10.5	6.73	612.9	10.4
7.46	654.6	9.8	7.25	602.6	10.1
7.87	648.8	9.3	7.19	650.3	10.4
6.97	592.2	10.8	7.78	673.2	9.3

Force and Impulse Data for 6-cm Bump (cont'd)

LR			RR		
Velocity (m/s)	**Force (N)**	**Impulse (Ns)**	**Velocity (m/s)**	**Force (N)**	**Impulse (Ns)**
5.17	560.7	12.0	5.32	730.4	16.3
5.32	546.4	11.4	5.48	717.8	16.0
5.38	547.5	11.3	5.05	753.0	16.8
5.39	580.4	12.7	5.04	739.9	16.8
5.29	549.7	11.8	5.46	782.5	16.4
5.65	573.4	11.7	4.87	740.3	17.4
5.22	545.0	12.4	5.17	767.4	17.2
5.06	549.8	11.7	5.19	767.0	16.6
5.35	551.4	11.9	5.10	744.1	16.7
4.99	538.3	11.4	4.94	708.5	16.5
5.59	577.4	12.1	6.08	801.8	16.3
5.83	585.4	11.7	5.80	766.1	15.6
5.76	581.8	12.0	5.73	728.9	15.3
6.04	597.0	11.7	5.75	781.0	16.4
6.04	576.1	10.8	5.75	738.5	16.0
6.35	594.8	10.5	5.88	733.0	15.7
5.90	567.4	11.0	5.81	744.1	15.2
6.31	606.1	11.0	5.73	744.8	15.6
5.35	586.5	11.3	5.95	746.2	16.0
5.81	579.4	11.5	5.78	741.5	15.6
7.72	666.3	10.8	-	-	-
6.85	624.3	10.3	6.37	782.6	14.3
7.38	652.0	10.5	6.33	822.6	14.6
7.22	632.5	10.6	7.19	796.4	13.9
7.25	608.8	10.4	6.64	847.6	15.1
7.91	660.8	10.4	6.99	828.6	14.7
7.27	641.3	10.8	7.27	844.5	14.7
7.27	633.6	10.3	6.23	824.0	14.3
7.55	658.0	10.2	7.27	842.7	14.2
6.80	616.9	10.4	6.67	774.6	15.7

Force and Impulse Data for 6-cm Bump (cont'd)

AS			LS		
Velocity (m/s)	**Force (N)**	**Impulse (Ns)**	**Velocity (m/s)**	**Force (N)**	**Impulse (Ns)**
5.21	578.0	10.2	5.01	567.9	11.7
5.21	568.7	10.4	5.38	568.2	12.0
5.29	575.8	10.1	5.38	572.0	11.3
5.39	569.6	9.8	4.96	526.3	11.4
5.01	562.9	10.1	5.28	571.9	12.1
5.28	574.3	10.4	5.10	547.4	11.4
5.46	594.7	10.0	5.12	538.4	11.5
5.17	560.9	9.8	4.75	545.7	11.6
5.29	575.3	10.6	5.22	552.2	12.2
5.18	570.1	10.5	4.93	539	11.7
5.62	577.7	9.5	5.85	584.0	11.3
6.17	591.4	10.4	5.85	574.4	11.4
5.97	575.2	9.8	6.13	601.8	10.8
5.73	584.1	9.9	5.68	565.3	10.8
5.99	606.3	11.0	5.73	549.0	10.7
6.21	567.5	10.1	5.62	583.1	11.4
5.83	574.7	10.1	5.85	611.0	11.0
5.88	572.6	9.7	5.70	590.0	12.2
5.90	606.2	10.4	5.97	576.7	10.5
5.88	587.9	10.2	6.10	590.3	11.0
6.80	603.3	10.0	7.30	663.9	10.4
7.30	615.7	8.9	7.33	673.7	10.2
6.90	601.0	9.6	7.30	616.9	10.4
6.94	619.0	10.1	7.27	653.0	10.1
6.67	635.0	10.5	7.09	632.4	10.6
7.27	611.4	9.2	6.62	620.9	10.5
6.99	619.8	9.8	7.35	629.3	10.0
7.12	618.2	9.3	7.87	672.2	10.5
7.30	615.3	8.8	7.52	653.2	10.3
6.62	618.5	9.9	7.14	607.3	9.6

Force and Impulse Data for 10-cm Bump

AR			ER		
Velocity (m/s)	Force (N)	Impulse (Ns)	Velocity (m/s)	Force (N)	Impulse (Ns)
5.33	766.1	19.9	5.36	771.7	19.1
5.14	772.7	18.5	4.74	718.6	19.5
5.21	-	-	5.05	773.3	20.1
4.93	758.9	19.0	5.31	803.9	18.9
5.28	815.4	19.7	4.96	774.3	20.5
5.24	787.7	19.2	4.91	698.7	20.0
5.03	764.5	18.7	5.33	786.4	19.0
4.89	777.9	20.6	4.81	711.1	20.0
5.36	762.5	19.4	4.74	733.4	20.1
5.49	775.7	18.5	5.10	731.0	20.5
6.25	859.7	19.8	5.88	861.7	19.3
5.67	814.2	18.8	6.17	797.3	18.2
6.13	834.2	19.3	5.73	868.5	19.4
5.63	790.5	19.7	6.01	842.1	19.4
5.88	781.2	19.1	5.65	803.5	18.9
6.12	855.0	19.3	5.97	826.4	18.9
6.21	841.9	19.7	5.68	820.6	19.4
5.65	772.4	18.5	6.01	809.5	19.3
5.63	800.6	19.0	5.67	834.8	20.4
5.76	782.1	19.1	5.75	821.7	19.4
7.69	966.6	19.5	7.43	905.5	18.3
7.12	909.7	19.5	7.60	973.1	17.5
7.22	909.2	19.8	6.27	838.2	18.1
7.66	961.4	19.2	7.94	1081.7	18.5
7.22	909.8	19.1	6.69	906.4	18.7
7.60	947.4	19.3	6.45	874.7	19.2
6.33	815.4	19.5	6.71	866.3	19.5
7.22	895.4	18.6	7.14	905.5	17.5
6.76	858.9	20.2	7.72	1068.1	18.5
7.30	913.9	19.5	7.60	913.2	17.4

Force and Impulse Data for 10-cm Bump (cont'd)

LR			RR		
Velocity (m/s)	**Force (N)**	**Impulse (Ns)**	**Velocity (m/s)**	**Force (N)**	**Impulse (Ns)**
4.93	738.3	21.6	4.71	1195.0	28.9
4.81	683.2	21.9	4.81	1395.3	30.4
5.17	691.6	21.3	5.08	1265.1	28.1
4.85			4.77	1385.3	29.5
5.05	692.8	22.2	4.66	973.4	26.5
4.89	806.3	22.4	4.67	1013.6	27.5
5.38	778.1	21.0	5.57	1678.2	30.9
4.87	698.2	22.1	4.66	1208.5	29.6
4.59	705.5	21.6	5.38	1532.1	30.2
4.90	714.4	22.4	4.82	1334.1	29.7
5.92	855.9	21.6	5.97	1607.0	28.2
5.90	781.0	21.2	5.78	1434.3	28.2
6.15	871.0	20.9	5.92	1721.7	30.2
5.87	769.1	21.0	5.65	1511.3	30.0
6.06	794.9	21.4	5.97	1808.5	27.5
6.01	752.1	21.1	5.63	1439.0	29.0
5.90	841.0	20.9	6.06	2037.1	28.7
6.10	841.8	20.7	5.80	1419.0	29.2
5.90	842.6	21.7	5.63	1437.2	29.3
5.83	747.5	21.1	5.88	1425.0	28.8
7.87	992.7	19.0	7.41	1911.8	26.2
7.38	956.1	20.3	6.49	1808.3	28.6
6.87	862.4	20.4	6.71	1692.9	28.1
7.63	923.1	19.9	6.71	1777.1	27.9
7.38	944.0	19.5	6.87	1592.5	26.0
8.10	1107.9	19.5	6.62	2240.6	27.7
7.87	1059.7	19.3	6.87	1700.3	26.9
7.69	927.9	19.3	6.54	1925.8	25.6
7.91	943.9	18.4	6.23	2018.7	27.2
7.75	966.5	20.2	6.41	1726.8	28.5

Force and Impulse Data for 10-cm Bump (cont'd)

AS			LS		
Velocity (m/s)	**Force (N)**	**Impulse (Ns)**	**Velocity (m/s)**	**Force (N)**	**Impulse (Ns)**
5.21	804.1	18.5	5.18	762.2	20.9
5.42	789.3	17.1	5.15	772.6	20.7
5.42	819.0	17.7	5.08	803.2	21.6
4.95	746.0	17.0	5.06	739.4	21.5
4.94	762.9	17.9	4.85	741.3	21.8
5.28	800.1	18.4	5.26	779.2	20.3
5.12	803.4	18.4	5.65	810.8	19.9
5.05	748.0	16.6	5.09	760.5	20.9
5.31	786.6	17.3	5.29	796.9	20.0
5.32	798.1	17.6	4.99	739.2	21.9
5.85	808.5	18.6	5.90	876.2	20.0
5.71	837.0	20.0	5.87	844.5	20.0
5.56	828.2	18.5	6.39	841.7	20.1
5.75	818.6	17.6	6.12	872.4	21.1
5.57	814.7	18.3	5.80	841.7	20.3
5.93	821.2	19.4	5.97	868.6	21.0
5.67	845.3	19.1	5.87	857.4	20.6
5.78	846.9	18.3	5.68	822.9	20.7
5.85	860.5	17.9	6.12	907.0	20.5
5.85	864.9	18.4	5.71	818.2	21.4
6.56	908.6	19.1	7.55	994.3	20.6
6.85	914.9	18.8	7.35	991.2	19.5
7.22	922.8	18.7	7.46	1037.4	20.6
7.46	953.0	18.4	6.67	951.6	20.4
7.02	946.7	18.6	7.43	945.4	20.7
7.07	974.8	18.4	7.35	988.1	20.6
6.76	897.5	18.5	6.54	948.3	21.2
7.07	933.6	18.7	7.07	929.7	20.0
6.94	911.4	18.5	7.25	987.9	19.8
7.07	947.4	18.3	7.55	1033.1	19.7

APPENDIX D

Mean Amplitude Data for Air-Oil Condition
Gravel Surface

Frequency	Axle	Frame	Frequency	Axle	Frame	Frequency	Axle	Frame
1	0.054	0.023	**35**	1.178	0.313	**69**	0.265	0.081
2	0.045	0.040	**36**	1.028	0.329	**70**	0.224	0.046
3	0.060	0.050	**37**	1.168	0.329	**71**	0.185	0.061
4	0.059	0.054	**38**	1.429	0.376	**72**	0.189	0.096
5	0.093	0.065	**39**	0.430	0.222	**73**	0.177	0.047
6	0.110	0.085	**40**	0.452	0.133	**74**	0.139	0.039
7	0.094	0.060	**41**	0.826	0.185	**75**	0.119	0.061
8	0.111	0.105	**42**	0.525	0.186	**76**	0.211	0.076
9	0.170	0.091	**43**	0.960	0.181	**77**	0.180	0.045
10	0.118	0.085	**44**	0.599	0.187	**78**	0.174	0.057
11	0.335	0.075	**45**	0.493	0.135	**79**	0.230	0.059
12	0.280	0.112	**46**	0.425	0.102	**80**	0.217	0.081
13	0.392	0.172	**47**	0.336	0.136	**81**	0.092	0.076
14	0.442	0.187	**48**	0.421	0.079	**82**	0.193	0.076
15	0.587	0.177	**49**	0.441	0.124	**83**	0.164	0.071
16	0.587	0.294	**50**	0.300	0.068	**84**	0.176	0.066
17	0.521	0.253	**51**	0.415	0.078	**85**	0.238	0.086
18	1.174	0.512	**52**	0.408	0.095	**86**	0.118	0.067
19	0.643	0.389	**53**	0.455	0.116	**87**	0.136	0.048
20	0.378	0.324	**54**	0.508	0.093	**88**	0.138	0.069
21	0.731	0.297	**55**	0.610	0.126	**89**	0.105	0.053
22	1.028	0.550	**56**	0.350	0.095	**90**	0.182	0.058
23	1.116	0.475	**57**	0.283	0.078	**91**	0.112	0.025
24	1.363	0.721	**58**	0.193	0.057	**92**	0.146	0.039
25	0.597	0.371	**59**	0.213	0.071	**93**	0.128	0.052
26	1.607	0.462	**60**	0.238	0.057	**94**	0.125	0.043
27	0.937	0.207	**61**	0.277	0.059	**95**	0.176	0.052
28	1.073	0.286	**62**	0.311	0.037	**96**	0.152	0.078
29	1.722	0.614	**63**	0.216	0.082	**97**	0.077	0.049
30	1.126	0.380	**64**	0.288	0.099	**98**	0.136	0.064
31	1.008	0.336	**65**	0.295	0.042	**99**	0.099	0.054
32	1.198	0.346	**66**	0.235	0.063	**100**	0.094	0.056
33	1.803	0.495	**67**	0.145	0.041			
34	1.141	0.481	**68**	0.226	0.065			

Frequency expressed in Hz; Axle and Frame expressed in g.

Mean Amplitude Data for Air-Oil Condition
Trail Surface

Frequency	Axle	Frame	Frequency	Axle	Frame	Frequency	Axle	Frame
1	0.124	0.096	**35**	0.684	0.136	**69**	0.155	0.073
2	0.104	0.107	**36**	0.948	0.268	**70**	0.098	0.035
3	0.171	0.131	**37**	0.992	0.289	**71**	0.131	0.080
4	0.164	0.079	**38**	1.241	0.254	**72**	0.125	0.055
5	0.217	0.258	**39**	0.928	0.163	**73**	0.082	0.060
6	0.082	0.115	**40**	0.522	0.091	**74**	0.097	0.029
7	0.241	0.117	**41**	0.533	0.068	**75**	0.131	0.041
8	0.224	0.161	**42**	0.392	0.182	**76**	0.093	0.048
9	0.393	0.162	**43**	0.239	0.064	**77**	0.122	0.058
10	0.412	0.190	**44**	0.363	0.108	**78**	0.067	0.058
11	0.816	0.464	**45**	0.195	0.063	**79**	0.098	0.061
12	0.549	0.311	**46**	0.453	0.151	**80**	0.049	0.071
13	0.733	0.240	**47**	0.444	0.157	**81**	0.096	0.044
14	0.833	0.277	**48**	0.188	0.099	**82**	0.114	0.050
15	0.555	0.262	**49**	0.186	0.101	**83**	0.094	0.051
16	0.677	0.485	**50**	0.265	0.096	**84**	0.079	0.036
17	0.512	0.379	**51**	0.158	0.090	**85**	0.089	0.039
18	1.308	0.538	**52**	0.232	0.068	**86**	0.126	0.046
19	1.924	0.815	**53**	0.340	0.077	**87**	0.034	0.036
20	0.757	0.535	**54**	0.137	0.078	**88**	0.121	0.050
21	0.629	0.526	**55**	0.143	0.090	**89**	0.082	0.036
22	0.574	0.356	**56**	0.103	0.061	**90**	0.081	0.048
23	0.984	0.411	**57**	0.160	0.060	**91**	0.088	0.041
24	0.595	0.284	**58**	0.127	0.051	**92**	0.070	0.027
25	1.008	0.561	**59**	0.155	0.079	**93**	0.089	0.075
26	0.563	0.406	**60**	0.153	0.114	**94**	0.082	0.058
27	1.130	0.383	**61**	0.168	0.058	**95**	0.054	0.034
28	2.269	0.759	**62**	0.198	0.034	**96**	0.084	0.044
29	1.778	0.502	**63**	0.091	0.089	**97**	0.093	0.060
30	1.496	0.442	**64**	0.097	0.088	**98**	0.065	0.061
31	1.516	0.481	**65**	0.124	0.036	**99**	0.047	0.034
32	0.870	0.294	**66**	0.205	0.076	**100**	0.045	0.063
33	1.164	0.370	**67**	0.125	0.070			
34	1.467	0.483	**68**	0.133	0.033			

Frequency expressed in Hz; Axle and Frame expressed in g.

Mean Amplitude Data for Elastomer Condition
Gravel Surface

Frequency	Axle	Frame	Frequency	Axle	Frame	Frequency	Axle	Frame
1	0.086	0.064	**35**	0.759	0.268	**69**	0.224	0.053
2	0.079	0.045	**36**	0.644	0.306	**70**	0.133	0.068
3	0.044	0.044	**37**	0.860	0.339	**71**	0.232	0.052
4	0.060	0.045	**38**	0.355	0.135	**72**	0.130	0.047
5	0.093	0.067	**39**	0.551	0.212	**73**	0.178	0.054
6	0.109	0.056	**40**	0.507	0.217	**74**	0.094	0.054
7	0.192	0.123	**41**	0.373	0.171	**75**	0.133	0.060
8	0.154	0.095	**42**	0.434	0.215	**76**	0.104	0.059
9	0.156	0.092	**43**	0.423	0.193	**77**	0.098	0.056
10	0.200	0.120	**44**	0.295	0.191	**78**	0.123	0.068
11	0.284	0.159	**45**	0.232	0.129	**79**	0.132	0.069
12	0.421	0.234	**46**	0.393	0.118	**80**	0.171	0.057
13	0.261	0.163	**47**	0.299	0.113	**81**	0.084	0.053
14	0.373	0.247	**48**	0.177	0.124	**82**	0.145	0.068
15	0.472	0.237	**49**	0.321	0.154	**83**	0.146	0.068
16	0.527	0.232	**50**	0.265	0.139	**84**	0.176	0.082
17	0.925	0.554	**51**	0.374	0.138	**85**	0.136	0.050
18	0.715	0.523	**52**	0.272	0.077	**86**	0.105	0.043
19	0.851	0.625	**53**	0.328	0.129	**87**	0.121	0.046
20	0.632	0.450	**54**	0.314	0.109	**88**	0.089	0.060
21	0.557	0.315	**55**	0.339	0.094	**89**	0.137	0.037
22	0.604	0.477	**56**	0.208	0.082	**90**	0.093	0.051
23	1.202	0.813	**57**	0.309	0.099	**91**	0.078	0.040
24	1.128	0.801	**58**	0.278	0.123	**92**	0.123	0.061
25	0.659	0.339	**59**	0.358	0.089	**93**	0.099	0.050
26	0.821	0.417	**60**	0.252	0.115	**94**	0.129	0.033
27	1.003	0.465	**61**	0.288	0.090	**95**	0.144	0.069
28	0.784	0.479	**62**	0.183	0.083	**96**	0.106	0.049
29	1.086	0.605	**63**	0.159	0.068	**97**	0.113	0.057
30	0.451	0.302	**64**	0.225	0.073	**98**	0.071	0.058
31	0.841	0.503	**65**	0.233	0.065	**99**	0.095	0.078
32	0.643	0.297	**66**	0.200	0.067	**100**	0.118	0.035
33	0.736	0.453	**67**	0.234	0.055			
34	0.971	0.427	**68**	0.142	0.063			

Frequency expressed in Hz; Axle and Frame expressed in g.

Mean Amplitude Data for Elastomer Condition
Trail Surface

Frequency	Axle	Frame	Frequency	Axle	Frame	Frequency	Axle	Frame
1	0.189	0.151	**35**	0.468	0.409	**69**	0.217	0.097
2	0.208	0.163	**36**	0.962	0.516	**70**	0.137	0.087
3	0.248	0.084	**37**	0.908	0.523	**71**	0.151	0.150
4	0.333	0.071	**38**	0.681	0.485	**72**	0.209	0.100
5	0.211	0.167	**39**	0.989	0.679	**73**	0.182	0.103
6	0.310	0.243	**40**	0.847	0.588	**74**	0.187	0.066
7	0.301	0.208	**41**	0.505	0.332	**75**	0.183	0.153
8	0.341	0.236	**42**	0.416	0.339	**76**	0.113	0.044
9	0.343	0.295	**43**	0.354	0.314	**77**	0.164	0.059
10	0.571	0.253	**44**	0.398	0.350	**78**	0.147	0.149
11	0.330	0.186	**45**	0.754	0.434	**79**	0.191	0.101
12	0.716	0.443	**46**	0.332	0.158	**80**	0.103	0.070
13	0.837	0.650	**47**	0.292	0.259	**81**	0.143	0.054
14	0.678	0.409	**48**	0.501	0.207	**82**	0.224	0.126
15	1.103	0.619	**49**	0.313	0.219	**83**	0.118	0.145
16	1.401	1.037	**50**	0.322	0.154	**84**	0.111	0.038
17	1.259	0.900	**51**	0.323	0.293	**85**	0.106	0.111
18	0.804	0.743	**52**	0.337	0.285	**86**	0.083	0.063
19	1.483	1.401	**53**	0.250	0.301	**87**	0.103	0.078
20	0.596	0.584	**54**	0.282	0.133	**88**	0.095	0.077
21	0.631	0.828	**55**	0.330	0.242	**89**	0.087	0.061
22	1.661	1.313	**56**	0.332	0.148	**90**	0.141	0.112
23	2.017	1.714	**57**	0.274	0.225	**91**	0.079	0.061
24	1.022	0.838	**58**	0.190	0.119	**92**	0.148	0.073
25	0.657	0.550	**59**	0.299	0.216	**93**	0.094	0.039
26	0.585	0.301	**60**	0.339	0.122	**94**	0.185	0.034
27	1.248	0.871	**61**	0.166	0.193	**95**	0.057	0.058
28	1.079	0.851	**62**	0.228	0.082	**96**	0.066	0.021
29	1.135	0.848	**63**	0.189	0.174	**97**	0.106	0.059
30	0.510	0.364	**64**	0.129	0.078	**98**	0.089	0.071
31	0.867	0.566	**65**	0.236	0.065	**99**	0.079	0.044
32	1.066	0.776	**66**	0.132	0.098	**100**	0.157	0.043
33	1.078	0.844	**67**	0.207	0.075			
34	1.213	0.937	**68**	0.174	0.132			

Frequency expressed in Hz; Axle and Frame expressed in g.

Mean Amplitude Data for Linkage Condition
Gravel Surface

Frequency	Axle	Frame	Frequency	Axle	Frame	Frequency	Axle	Frame
1	0.054	0.038	**35**	0.635	0.377	**69**	0.191	0.111
2	0.023	0.033	**36**	0.531	0.380	**70**	0.116	0.128
3	0.044	0.067	**37**	0.502	0.258	**71**	0.146	0.086
4	0.076	0.077	**38**	0.464	0.261	**72**	0.192	0.084
5	0.081	0.079	**39**	0.607	0.262	**73**	0.114	0.108
6	0.091	0.068	**40**	0.442	0.178	**74**	0.175	0.103
7	0.095	0.052	**41**	0.582	0.271	**75**	0.125	0.049
8	0.132	0.093	**42**	0.442	0.249	**76**	0.107	0.053
9	0.208	0.156	**43**	0.448	0.274	**77**	0.121	0.066
10	0.313	0.203	**44**	0.363	0.171	**78**	0.188	0.096
11	0.339	0.209	**45**	0.322	0.149	**79**	0.178	0.082
12	0.525	0.299	**46**	0.353	0.212	**80**	0.100	0.048
13	0.339	0.245	**47**	0.359	0.181	**81**	0.092	0.061
14	0.417	0.236	**48**	0.244	0.086	**82**	0.118	0.074
15	0.317	0.213	**49**	0.348	0.118	**83**	0.118	0.080
16	0.456	0.276	**50**	0.246	0.126	**84**	0.111	0.065
17	0.512	0.382	**51**	0.215	0.060	**85**	0.147	0.082
18	0.622	0.314	**52**	0.211	0.109	**86**	0.148	0.093
19	0.565	0.413	**53**	0.190	0.081	**87**	0.076	0.108
20	0.624	0.410	**54**	0.278	0.093	**88**	0.150	0.112
21	0.663	0.241	**55**	0.172	0.074	**89**	0.139	0.107
22	0.803	0.512	**56**	0.202	0.069	**90**	0.070	0.096
23	0.553	0.333	**57**	0.146	0.058	**91**	0.160	0.092
24	0.974	0.568	**58**	0.122	0.096	**92**	0.142	0.106
25	0.791	0.416	**59**	0.182	0.104	**93**	0.127	0.072
26	0.719	0.248	**60**	0.319	0.128	**94**	0.138	0.067
27	1.090	0.420	**61**	0.150	0.081	**95**	0.129	0.068
28	0.827	0.476	**62**	0.185	0.108	**96**	0.126	0.044
29	0.592	0.361	**63**	0.173	0.137	**97**	0.078	0.060
30	0.848	0.408	**64**	0.164	0.074	**98**	0.064	0.071
31	0.481	0.295	**65**	0.114	0.060	**99**	0.074	0.070
32	0.810	0.436	**66**	0.211	0.110	**100**	0.118	0.061
33	0.661	0.282	**67**	0.109	0.094			
34	0.802	0.386	**68**	0.224	0.074			

Frequency expressed in Hz; Axle and Frame expressed in g.

Mean Amplitude Data for Linkage Condition
Trail Surface

Frequency	Axle	Frame	Frequency	Axle	Frame	Frequency	Axle	Frame
1	0.097	0.082	**35**	1.145	0.591	**69**	0.166	0.161
2	0.089	0.065	**36**	0.998	0.517	**70**	0.179	0.163
3	0.101	0.127	**37**	0.998	0.441	**71**	0.098	0.152
4	0.205	0.217	**38**	0.542	0.220	**72**	0.112	0.118
5	0.104	0.113	**39**	0.931	0.449	**73**	0.177	0.155
6	0.357	0.219	**40**	1.040	0.519	**74**	0.134	0.223
7	0.210	0.182	**41**	0.635	0.276	**75**	0.119	0.187
8	0.165	0.177	**42**	0.705	0.273	**76**	0.076	0.160
9	0.647	0.486	**43**	0.434	0.274	**77**	0.161	0.134
10	0.477	0.271	**44**	0.718	0.381	**78**	0.170	0.137
11	0.456	0.289	**45**	0.716	0.373	**79**	0.143	0.192
12	0.520	0.325	**46**	0.540	0.257	**80**	0.143	0.142
13	0.818	0.616	**47**	0.267	0.255	**81**	0.130	0.096
14	0.697	0.413	**48**	0.229	0.185	**82**	0.108	0.153
15	0.780	0.347	**49**	0.278	0.129	**83**	0.135	0.186
16	1.392	0.706	**50**	0.244	0.117	**84**	0.102	0.126
17	2.145	1.457	**51**	0.371	0.162	**85**	0.143	0.094
18	0.670	0.660	**52**	0.300	0.130	**86**	0.096	0.168
19	0.735	1.027	**53**	0.162	0.109	**87**	0.177	0.092
20	1.023	0.549	**54**	0.287	0.167	**88**	0.135	0.128
21	0.975	0.497	**55**	0.236	0.159	**89**	0.098	0.114
22	2.741	1.729	**56**	0.223	0.169	**90**	0.093	0.156
23	2.093	1.119	**57**	0.203	0.128	**91**	0.138	0.134
24	1.006	0.513	**58**	0.221	0.205	**92**	0.127	0.127
25	0.612	0.346	**59**	0.195	0.150	**93**	0.115	0.131
26	0.814	0.490	**60**	0.261	0.066	**94**	0.125	0.120
27	1.486	0.730	**61**	0.180	0.129	**95**	0.124	0.161
28	1.379	0.772	**62**	0.218	0.095	**96**	0.157	0.117
29	1.016	0.602	**63**	0.151	0.111	**97**	0.097	0.113
30	1.946	1.181	**64**	0.173	0.153	**98**	0.131	0.154
31	0.998	0.617	**65**	0.161	0.179	**99**	0.108	0.099
32	0.802	0.291	**66**	0.145	0.212	**100**	0.104	0.106
33	1.843	0.793	**67**	0.153	0.241			
34	0.750	0.327	**68**	0.134	0.174			

Frequency expressed in Hz; Axle and Frame expressed in g.

Mean Amplitude Data for Air-Oil + Frame Condition
Gravel Surface

Frequency	Axle	Frame	Frequency	Axle	Frame	Frequency	Axle	Frame
1	0.063	0.046	**35**	0.726	0.191	**69**	0.215	0.043
2	0.071	0.049	**36**	1.243	0.355	**70**	0.187	0.053
3	0.075	0.065	**37**	1.172	0.363	**71**	0.206	0.040
4	0.097	0.099	**38**	0.872	0.211	**72**	0.290	0.047
5	0.107	0.061	**39**	0.893	0.202	**73**	0.149	0.036
6	0.103	0.071	**40**	0.936	0.193	**74**	0.168	0.060
7	0.079	0.051	**41**	0.853	0.139	**75**	0.093	0.066
8	0.108	0.051	**42**	0.566	0.156	**76**	0.218	0.049
9	0.258	0.113	**43**	0.654	0.218	**77**	0.149	0.051
10	0.243	0.133	**44**	0.409	0.161	**78**	0.176	0.072
11	0.300	0.121	**45**	0.464	0.116	**79**	0.205	0.048
12	0.353	0.136	**46**	0.409	0.143	**80**	0.132	0.058
13	0.535	0.205	**47**	0.389	0.136	**81**	0.147	0.056
14	0.585	0.239	**48**	0.382	0.062	**82**	0.185	0.077
15	0.442	0.176	**49**	0.242	0.111	**83**	0.306	0.058
16	0.605	0.284	**50**	0.345	0.097	**84**	0.172	0.066
17	0.746	0.329	**51**	0.436	0.097	**85**	0.177	0.060
18	0.860	0.477	**52**	0.298	0.086	**86**	0.163	0.069
19	0.949	0.493	**53**	0.325	0.141	**87**	0.140	0.074
20	0.563	0.196	**54**	0.371	0.103	**88**	0.142	0.050
21	0.702	0.164	**55**	0.283	0.062	**89**	0.110	0.045
22	1.103	0.338	**56**	0.346	0.043	**90**	0.139	0.044
23	0.832	0.286	**57**	0.227	0.094	**91**	0.171	0.062
24	0.871	0.312	**58**	0.323	0.079	**92**	0.121	0.055
25	0.571	0.237	**59**	0.222	0.062	**93**	0.095	0.067
26	0.966	0.313	**60**	0.227	0.077	**94**	0.077	0.044
27	1.450	0.510	**61**	0.166	0.088	**95**	0.105	0.059
28	1.749	0.477	**62**	0.298	0.078	**96**	0.117	0.044
29	2.049	0.729	**63**	0.243	0.049	**97**	0.075	0.054
30	1.341	0.404	**64**	0.206	0.072	**98**	0.066	0.039
31	1.126	0.296	**65**	0.180	0.060	**99**	0.126	0.041
32	0.947	0.439	**66**	0.200	0.057	**100**	0.080	0.048
33	0.923	0.348	**67**	0.251	0.070			
34	0.891	0.273	**68**	0.170	0.064			

Frequency expressed in Hz; Axle and Frame expressed in g.

Mean Amplitude Data for Air-Oil + Frame Condition
Trail Surface

Frequency	Axle	Frame	Frequency	Axle	Frame	Frequency	Axle	Frame
1	0.102	0.081	**35**	1.822	0.504	**69**	0.203	0.101
2	0.128	0.064	**36**	1.628	0.477	**70**	0.164	0.091
3	0.092	0.059	**37**	1.707	0.359	**71**	0.231	0.088
4	0.174	0.169	**38**	1.922	0.414	**72**	0.136	0.046
5	0.106	0.072	**39**	0.955	0.286	**73**	0.157	0.074
6	0.308	0.195	**40**	2.022	0.323	**74**	0.203	0.083
7	0.236	0.142	**41**	0.864	0.245	**75**	0.225	0.103
8	0.166	0.099	**42**	1.078	0.196	**76**	0.099	0.071
9	0.812	0.416	**43**	0.642	0.259	**77**	0.134	0.073
10	0.355	0.177	**44**	0.634	0.187	**78**	0.138	0.064
11	0.224	0.083	**45**	0.943	0.150	**79**	0.140	0.073
12	0.433	0.174	**46**	0.859	0.103	**80**	0.153	0.073
13	0.386	0.235	**47**	0.281	0.134	**81**	0.155	0.055
14	0.620	0.384	**48**	0.535	0.221	**82**	0.121	0.066
15	0.793	0.280	**49**	0.411	0.142	**83**	0.135	0.075
16	1.356	0.483	**50**	0.393	0.160	**84**	0.117	0.077
17	1.968	0.791	**51**	0.609	0.134	**85**	0.148	0.080
18	0.780	0.506	**52**	0.448	0.087	**86**	0.128	0.040
19	0.645	0.922	**53**	0.463	0.094	**87**	0.096	0.058
20	1.541	0.539	**54**	0.319	0.075	**88**	0.157	0.094
21	0.746	0.262	**55**	0.375	0.109	**89**	0.064	0.063
22	2.983	1.446	**56**	0.464	0.130	**90**	0.145	0.090
23	1.852	0.866	**57**	0.387	0.047	**91**	0.115	0.076
24	1.234	0.675	**58**	0.298	0.072	**92**	0.129	0.067
25	0.769	0.484	**59**	0.327	0.045	**93**	0.135	0.063
26	1.402	0.255	**60**	0.638	0.127	**94**	0.134	0.058
27	2.031	0.928	**61**	0.390	0.065	**95**	0.180	0.070
28	2.602	0.982	**62**	0.379	0.058	**96**	0.128	0.079
29	1.573	0.432	**63**	0.276	0.032	**97**	0.135	0.064
30	1.832	0.924	**64**	0.181	0.070	**98**	0.084	0.047
31	1.862	0.600	**65**	0.224	0.065	**99**	0.152	0.061
32	1.824	0.354	**66**	0.272	0.067	**100**	0.124	0.053
33	4.049	0.761	**67**	0.192	0.091			
34	2.549	0.594	**68**	0.303	0.122			

Frequency expressed in Hz; Axle and Frame expressed in g.

Mean Amplitude Data for Linkage + Frame Condition
Gravel Surface

Frequency	Axle	Frame	Frequency	Axle	Frame	Frequency	Axle	Frame
1	0.174	0.065	**35**	0.744	0.260	**69**	0.165	0.040
2	0.198	0.095	**36**	0.730	0.455	**70**	0.241	0.054
3	0.186	0.078	**37**	0.254	0.241	**71**	0.141	0.075
4	0.236	0.111	**38**	0.533	0.261	**72**	0.170	0.058
5	0.187	0.071	**39**	0.312	0.198	**73**	0.224	0.112
6	0.244	0.095	**40**	0.622	0.146	**74**	0.261	0.054
7	0.155	0.046	**41**	0.542	0.214	**75**	0.192	0.062
8	0.144	0.053	**42**	0.332	0.271	**76**	0.181	0.095
9	0.199	0.073	**43**	0.557	0.245	**77**	0.235	0.078
10	0.423	0.179	**44**	0.285	0.094	**78**	0.208	0.125
11	0.322	0.174	**45**	0.386	0.171	**79**	0.229	0.065
12	0.310	0.200	**46**	0.336	0.152	**80**	0.248	0.091
13	0.442	0.277	**47**	0.287	0.103	**81**	0.197	0.070
14	0.515	0.321	**48**	0.346	0.193	**82**	0.140	0.088
15	0.462	0.203	**49**	0.299	0.110	**83**	0.125	0.087
16	0.387	0.287	**50**	0.245	0.112	**84**	0.153	0.062
17	0.715	0.428	**51**	0.270	0.124	**85**	0.122	0.060
18	0.604	0.356	**52**	0.256	0.061	**86**	0.141	0.047
19	0.413	0.321	**53**	0.299	0.092	**87**	0.147	0.089
20	0.198	0.223	**54**	0.326	0.123	**88**	0.159	0.075
21	0.446	0.159	**55**	0.235	0.101	**89**	0.178	0.078
22	0.544	0.449	**56**	0.195	0.089	**90**	0.165	0.060
23	0.844	0.506	**57**	0.340	0.106	**91**	0.182	0.088
24	1.019	0.676	**58**	0.272	0.115	**92**	0.235	0.069
25	0.780	0.428	**59**	0.250	0.107	**93**	0.214	0.049
26	1.105	0.384	**60**	0.219	0.090	**94**	0.242	0.096
27	1.074	0.485	**61**	0.081	0.108	**95**	0.255	0.058
28	1.239	0.670	**62**	0.302	0.118	**96**	0.172	0.040
29	0.778	0.368	**63**	0.211	0.070	**97**	0.120	0.045
30	0.882	0.517	**64**	0.159	0.081	**98**	0.128	0.061
31	0.717	0.433	**65**	0.206	0.076	**99**	0.141	0.052
32	0.809	0.463	**66**	0.169	0.085	**100**	0.146	0.057
33	0.847	0.388	**67**	0.188	0.070			
34	1.140	0.465	**68**	0.209	0.053			

Frequency expressed in Hz; Axle and Frame expressed in g.

Mean Amplitude Data for Linkage + Frame Condition
Trail Surface

Frequency	Axle	Frame	Frequency	Axle	Frame	Frequency	Axle	Frame
1	0.076	0.053	**35**	1.520	0.606	**69**	0.105	0.116
2	0.055	0.048	**36**	1.573	0.664	**70**	0.126	0.130
3	0.108	0.105	**37**	0.764	0.406	**71**	0.186	0.103
4	0.220	0.162	**38**	0.777	0.367	**72**	0.159	0.109
5	0.113	0.082	**39**	1.358	0.494	**73**	0.156	0.120
6	0.324	0.169	**40**	0.932	0.410	**74**	0.151	0.115
7	0.229	0.160	**41**	0.484	0.206	**75**	0.127	0.124
8	0.326	0.179	**42**	0.531	0.247	**76**	0.078	0.122
9	0.566	0.334	**43**	0.192	0.170	**77**	0.153	0.099
10	0.508	0.247	**44**	0.552	0.194	**78**	0.113	0.099
11	0.321	0.217	**45**	0.636	0.264	**79**	0.076	0.120
12	0.473	0.267	**46**	0.815	0.343	**80**	0.169	0.107
13	0.570	0.350	**47**	0.756	0.168	**81**	0.157	0.080
14	0.939	0.654	**48**	0.288	0.127	**82**	0.093	0.103
15	0.732	0.392	**49**	0.346	0.132	**83**	0.126	0.062
16	1.383	0.629	**50**	0.429	0.180	**84**	0.148	0.106
17	1.671	0.929	**51**	0.298	0.139	**85**	0.128	0.050
18	0.569	0.606	**52**	0.383	0.186	**86**	0.076	0.104
19	0.639	0.515	**53**	0.336	0.161	**87**	0.090	0.102
20	0.892	0.533	**54**	0.244	0.273	**88**	0.119	0.081
21	0.908	0.448	**55**	0.218	0.170	**89**	0.141	0.126
22	2.272	1.335	**56**	0.212	0.112	**90**	0.124	0.086
23	2.226	1.244	**57**	0.190	0.110	**91**	0.130	0.077
24	1.557	0.830	**58**	0.284	0.156	**92**	0.108	0.091
25	0.687	0.253	**59**	0.108	0.074	**93**	0.062	0.075
26	0.922	0.365	**60**	0.341	0.141	**94**	0.106	0.080
27	1.743	0.781	**61**	0.108	0.099	**95**	0.151	0.059
28	1.322	0.611	**62**	0.227	0.113	**96**	0.079	0.075
29	1.440	0.769	**63**	0.257	0.063	**97**	0.219	0.105
30	1.283	0.945	**64**	0.115	0.082	**98**	0.148	0.096
31	0.822	0.217	**65**	0.203	0.133	**99**	0.154	0.097
32	1.144	0.458	**66**	0.111	0.124	**100**	0.126	0.106
33	1.610	0.479	**67**	0.163	0.082			
34	0.787	0.355	**68**	0.180	0.095			

Frequency expressed in Hz; Axle and Frame expressed in g.

Mean Amplitude Data for Rigid Condition
Gravel Surface

Frequency	Axle	Frame	Frequency	Axle	Frame	Frequency	Axle	Frame
1	0.225	0.198	**35**	0.507	0.429	**69**	0.110	0.074
2	0.248	0.227	**36**	0.598	0.497	**70**	0.129	0.096
3	0.252	0.234	**37**	0.222	0.229	**71**	0.143	0.118
4	0.283	0.258	**38**	0.419	0.315	**72**	0.156	0.118
5	0.223	0.210	**39**	0.425	0.381	**73**	0.127	0.106
6	0.309	0.285	**40**	0.303	0.265	**74**	0.094	0.070
7	0.232	0.213	**41**	0.295	0.292	**75**	0.114	0.105
8	0.279	0.246	**42**	0.459	0.326	**76**	0.170	0.135
9	0.351	0.300	**43**	0.266	0.199	**77**	0.138	0.108
10	0.411	0.338	**44**	0.351	0.312	**78**	0.130	0.109
11	0.405	0.365	**45**	0.340	0.283	**79**	0.149	0.129
12	0.422	0.373	**46**	0.236	0.190	**80**	0.098	0.092
13	0.338	0.330	**47**	0.305	0.254	**81**	0.114	0.101
14	0.663	0.605	**48**	0.290	0.237	**82**	0.131	0.103
15	0.355	0.314	**49**	0.369	0.256	**83**	0.131	0.104
16	0.607	0.530	**50**	0.246	0.194	**84**	0.120	0.079
17	0.689	0.612	**51**	0.331	0.230	**85**	0.076	0.086
18	0.672	0.714	**52**	0.142	0.129	**86**	0.072	0.083
19	0.749	0.779	**53**	0.226	0.177	**87**	0.147	0.119
20	0.580	0.477	**54**	0.162	0.128	**88**	0.051	0.053
21	0.594	0.530	**55**	0.291	0.242	**89**	0.101	0.075
22	0.165	0.122	**56**	0.105	0.086	**90**	0.133	0.106
23	0.607	0.572	**57**	0.140	0.110	**91**	0.098	0.084
24	0.388	0.416	**58**	0.192	0.153	**92**	0.111	0.114
25	0.472	0.376	**59**	0.085	0.101	**93**	0.091	0.073
26	0.461	0.342	**60**	0.150	0.123	**94**	0.177	0.110
27	0.696	0.642	**61**	0.120	0.124	**95**	0.149	0.077
28	0.827	0.679	**62**	0.214	0.190	**96**	0.098	0.054
29	0.782	0.704	**63**	0.143	0.099	**97**	0.084	0.078
30	0.808	0.638	**64**	0.154	0.133	**98**	0.108	0.079
31	0.715	0.578	**65**	0.147	0.123	**99**	0.050	0.051
32	0.824	0.641	**66**	0.151	0.116	**100**	0.107	0.046
33	0.592	0.514	**67**	0.125	0.082			
34	0.630	0.522	**68**	0.139	0.109			

Frequency expressed in Hz; Axle and Frame expressed in g.

Mean Amplitude Data for Rigid Condition
Trail Surface

Frequency	Axle	Frame	Frequency	Axle	Frame	Frequency	Axle	Frame
1	0.230	0.117	**35**	0.927	0.788	**69**	0.112	0.088
2	0.108	0.110	**36**	0.427	0.398	**70**	0.068	0.077
3	0.190	0.183	**37**	0.662	0.584	**71**	0.119	0.069
4	0.344	0.295	**38**	0.703	0.582	**72**	0.083	0.060
5	0.179	0.154	**39**	0.444	0.310	**73**	0.099	0.062
6	0.327	0.341	**40**	0.423	0.400	**74**	0.076	0.076
7	0.219	0.230	**41**	0.384	0.315	**75**	0.118	0.066
8	0.435	0.379	**42**	0.353	0.303	**76**	0.075	0.071
9	0.482	0.405	**43**	0.268	0.224	**77**	0.047	0.048
10	0.758	0.677	**44**	0.462	0.390	**78**	0.085	0.052
11	0.528	0.510	**45**	0.313	0.251	**79**	0.075	0.066
12	0.268	0.273	**46**	0.337	0.261	**80**	0.063	0.058
13	0.581	0.521	**47**	0.340	0.221	**81**	0.069	0.059
14	1.151	1.141	**48**	0.154	0.163	**82**	0.081	0.063
15	1.159	1.054	**49**	0.205	0.261	**83**	0.064	0.060
16	0.800	0.757	**50**	0.192	0.170	**84**	0.069	0.051
17	1.028	0.968	**51**	0.299	0.240	**85**	0.085	0.060
18	1.064	1.038	**52**	0.176	0.169	**86**	0.081	0.042
19	0.678	0.824	**53**	0.125	0.083	**87**	0.062	0.044
20	0.651	0.661	**54**	0.104	0.110	**88**	0.086	0.054
21	0.699	0.673	**55**	0.219	0.153	**89**	0.064	0.041
22	1.245	1.127	**56**	0.121	0.159	**90**	0.077	0.048
23	1.103	1.065	**57**	0.130	0.134	**91**	0.125	0.047
24	0.888	0.775	**58**	0.216	0.213	**92**	0.038	0.061
25	0.424	0.317	**59**	0.144	0.110	**93**	0.065	0.051
26	0.670	0.465	**60**	0.126	0.107	**94**	0.064	0.045
27	1.051	0.759	**61**	0.119	0.103	**95**	0.067	0.032
28	0.650	0.535	**62**	0.088	0.071	**96**	0.049	0.051
29	0.757	0.733	**63**	0.072	0.051	**97**	0.064	0.034
30	0.636	0.498	**64**	0.175	0.122	**98**	0.021	0.042
31	0.362	0.334	**65**	0.092	0.056	**99**	0.039	0.029
32	0.878	0.850	**66**	0.086	0.078	**100**	0.048	0.054
33	0.641	0.553	**67**	0.114	0.109			
34	0.591	0.514	**68**	0.099	0.069			

Frequency expressed in Hz; Axle and Frame expressed in g.

APPENDIX E

FRAME AND FORK SPECIFICATIONS

FRAMES

The rigid frame was that of a Specialized StumpJumper model (Cro-Mo steel tubing). The weight of the frame including all components except the front fork was 10.2 kg.

The Suspended frame was that of a Specialized FSR Pro model (aluminum tubing). The weight of the frame including all components except the front fork was 11.6 kg.

FORKS

The rigid fork was made of Cro-Mo steel tubing. Its weight was 1.0 kg.

The Elastomer fork was a Rock Shox Jett C model with a weight of 1.6 kg, and a travel length of 48 millileters

The Air-Oil fork was a Marzocchi Bomber Z3 Hydra model with a weight of 1.8kg, and a travel length of 65 millimeters

The linkage design fork was an AMP F4BLT model with a weight of 1.6kg. Travel length was not available.

APPENDIX F

ADJUSTED MEANS AND STANDARD DEVIATIONS

6-cm Bump Height

A-P Impact Force Adjusted Means from ANCOVA

Group	N	Adjusted Mean (Newtons)	SD (Newtons)
Air-Oil	30	584.4	17.1
Elastomer	30	576.7	17.0
Linkage	30	589.2	17.0
Air-Oil + Frame	30	591.6	17.0
Linkage + Frame	30	592.3	17.0
Rigid	29	778.4	17.5

A-P Braking Impulse Adjusted Means from ANCOVA

Group	N	Adjusted Mean (Ns)	SD (Ns)
Air-Oil	30	10.4	0.42
Elastomer	30	10.7	0.41
Linkage	30	11.3	0.42
Air-Oil + Frame	30	10.0	0.41
Linkage + Frame	30	11.0	0.41
Rigid	29	15.5	0.43

10-cm Bump Height

A-P Impact Force Adjusted Means from ANCOVA

Group	N	Adjusted Mean (Newtons)	SD (Newtons)
Air-Oil	29	828.6	80.9
Elastomer	30	840.2	80.1
Linkage	29	820.2	81.6
Air-Oil + Frame	30	855.2	80.8
Linkage + Frame	30	862.4	80.7
Rigid	30	1645.6	84.2

A-P Braking Impulse Adjusted Means from ANCOVA

Group	N	Adjusted Mean (Ns)	SD (Ns)
Air-Oil	29	19.3	0.70
Elastomer	30	19.1	0.70
Linkage	29	20.1	0.71
Air-Oil + Frame	30	18.3	0.70
Linkage + Frame	30	20.6	0.70
Rigid	30	28.2	0.73