AN ABSTRACT OF THE THESIS OF:

Michael Orendurff for the degree of Master of Science in Human Performance presented on October 24, 1996. Title: The Effect of Mountain Bicycle Suspension Fork Stiffness on Impact Acceleration.

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Abstract approved: ______________________________
Gerald A. Smith

Mountain bike suspension forks have been developed to reduce the accelerations transmitted to the rider. However, the effectiveness of suspension forks has not been systematically investigated. It was the goal of this project to quantify the amount of impact acceleration damping afforded by three stiffness settings of suspension forks compared to rigid mountain bike forks.

Seven experienced mountain bike riders gave their informed consent to participate in the study. The subjects coasted down a ramp and impacted a bump at 5.4 m/s located about 2.3 m past the ramp end. Accelerometers were placed on the axle and frame of the bicycle which was fitted with either a rigid fork (FR) or suspension forks set on soft (F1), medium (F3), or firm (F6) stiffness. Bumps were either small (B1), medium (B2) or large (B3). Accelerometer data were telemetered to a computer, sampled at 1000 Hz and smoothed with Butterworth filter with 50 Hz cutoff. Peak acceleration during impact (P1) and landing (P2) as well as the slope of the impact acceleration peak (jerk, J) were extracted from the data and analyzed using a 2 x 3 x 4 repeated measures ANOVA for each of the dependent variables (P1, P2, J),

and with linear contrasts as follow-up tests. A significance level of $p < .01$ was chosen.

All forks were found to produce similar impact acceleration (P1) at the axle and frame on the small bump (B1). On larger bumps (B2 and B3), softer suspension forks (F1 and F3) significantly reduced acceleration transmitted to the rider during bump impact (P1), while maintaining significantly higher axle acceleration than other forks ($p < .001$); Jerk was significantly reduced at the frame compared to the axle for each suspension fork with the larger bumps. Landing impacts (P2) were of similar magnitude for most fork conditions at both the axle and frame. It appears from these data that suspension forks with moderate stiffness may provide the best impact acceleration damping for mountain bikes encountering impacts with characteristics similar to the bumps and velocity used in this study. It is unclear how these results generalize to other conditions encountered while riding.

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THE EFFECT OF MOUNTAIN BICYCLE FORK STIFFNESS ON IMPACT ACCELERATION

By

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A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented October 24, 1996
Commencement June, 1997

Master of Science thesis of Michael Orendurff presented on October 24, 1996

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Michael Orendurff, Author

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THE EFFECT OF MOUNTAIN BICYCLE FORK STIFFNESS ON IMPACT ACCELERATION

CHAPTER 1 INTRODUCTION

It is generally accepted that mountain biking began near San Francisco in 1971. A group of bike riders began to ride down Mt. Tamalpious in Marin county, California, on modified bikes. Adapted from Schwinn *Excelsior* bicycles, the new breed of bike was used to careen down a road dubbed "repack hill," so named because a single run through the dust and rocks would require repacking all the ball bearings on the bike with new grease. Joe Breezer welded the first mountain bike frame, copying the geometry of the Schwinns, and fitting it with a five-speed deraileur, motorcycle brake levers and heavy duty wheels. This new style of bike began the popular shift toward mountain bikes.

Mountain bikes are typically heavier than road bikes; while frame geometry and wheel bases are approaching similar geometries in both designs, mountain bikes are generally built of thicker walled tubing with more secure fastening (welds, glues, or bolts) at tube junctions. The handlebars are straight and perpendicular to the frame with fewer hand positions, generally producing a rider position that is more upright than road bikes. This position causes more drag, and improves rear wheel traction. Given that air drag forces are minimal in mountain biking due to low speeds and traction is paramount, this compromise is acceptable. Shifting and braking controls are located close to the hand grips and do not require removing the hand from the grip to shift as in road bikes. Tires are wider, with larger lugs designed to improve traction on natural surfaces. Shifting is *indexed,* with hard stops set into the shift mechanism that provides error-free gear changing; beveled gearteeth and laterally flexible chains improve shifting under load, meaning riders can shift while pedaling up steep hills. All these innovations are designed to maximize the ability of the bicycle to negotiate natural surfaces.

The appearance of the mountain bike has increased the number and types of forces incurred by cyclists. In addition to air resistance and frictional forces commonly associated with road cycling, mountain cyclists experience vibration and impact forces that appear to impede forward motion, reduce traction, perturb balance and require additional effort to negotiate. Although mountain bikes are designed to negotiate bumps, these impacts nevertheless require additional riding skills not required during road cycling; in this way there is a much greater need for control and balance. Impact attenuation is thought to be a significant contributor to energy expenditure in mountain cycling, although no scientific investigation has determined to what extent.

Because mountain biking does not take place on the smooth surface of a paved road, impacts are incurred by the rider at increased levels compared to road biking. Conventional wisdom suggests that reducing impacts would increase control and therefore speed, and decrease fatigue caused by the rider's body damping vibration. Many methods of vibration control have been tried in cycling history. Cantilever frames and spring seats were used to soften the ride on the aptly named *boneshakers*—British slang for the early bicycle (Stevenson, 1982). The first inflated tire was created for the bicycle by J. Dunlop in 1876 and was soon used on many bikes (Richie, 1975), making millions for this humble veterinarian. The improvement of roads in Europe and America lead the bicycle toward lighter and more aerodynamic designs, and for decades this dominated racing and popular bicycles. Pneumatic tires, improving road conditions and the highly competitive bicycle market all contributed to the disappearance of suspension systems.

Suspension systems began to appear again on the bikes of professional riders on the mountain bike racing circuit in the late 1980's. By reducing impacts transmitted to the bike and rider, speed and control appeared to be improved (Espanoza, 1990). The increased weight of the suspension systems appeared to be easily offset by the improved handling characteristics. The fastest times at races were consistently from riders with bikes fitted with suspension forks (Espanoza, 1990).

After-market (add-on) suspension forks began to appear in 1988, and were effective but simplistic. While many different designs exist, the most dominant are telescopic in design, with sliding tubes fitted one inside the other. Some forks use urethane bumpers within the tubes, deforming with the force of the impact while others use a combination of oil and air reservoirs to attenuate impact shock. The compression characteristics determine the extent of impact reduction when bumps are incurred.

Rock Shox was among the first companies to design and produce suspension forks for bicycles. Their design involved an after-market front fork with an air-oil dampened strut enclosed in the fork blade. This design allowed the compression of the two tubes within each other when a bump was incurred and the reduction of vibrations passed along to the rider. While the product has proved quite popular and many companies are attempting similar designs, the effectiveness of suspension forks is still debated among cyclists.

Performance and Suspension Forks

It is claimed by many riders and fork manufacturers that suspension forks allow the mountain bike rider to reach and maintain greater speeds. The reasoning is that the fork allows the rider to pick a straight line through rough bumps that otherwise would have to be avoided. Steering around bumps results in lateral displacement of the center of mass path and reduced straight-line velocity, not to mention increased decision-making, effort and ultimately fatigue. In addition to decreasing lateral displacement of the bike-rider system, suspension forks are alleged to reduce the vertical displacement of this system. Since forces that would be transmitted to the system are absorbed and dissipated (as heat eventually), the center of mass does not gain as much altitude as with rigid forks when impacts are incurred. These assertions comprise the *straight line theory*.

If suspension forks reduce the transmission of impact force to the rider this should reduce fatigue. Since eccentric contractions are used to stabilize the bike as bumps are incurred, the risk of delayed onset muscle soreness (DOMS) is quite high in mountain biking on rough surfaces. It has been alleged that by attenuating the acceleration transmitted to the rider the eccentric demands of mountain biking would be reduced. If suspension forks reduced the acceleration transmitted to the rider, then fatigue should be reduced. This is the *fatigue theory*.

In addition to these supposed benefits, common wisdom also suggests that when mountain biking with suspension forks the improved contact between the tire and surface results in faster cornering and improved braking. The claim is that since the tire follows the contours of the surface more closely and large airborne periods are reduced, lateral shear forces—produced between the tire and the surface while landing from a bump while turning—are attenuated. Therefore the tire is less likely to slide out in sharp corners and cause the bike and rider to crash. Riders are able to maintain faster speeds through corners with a suspension fork according to this notion.

This rationale also alleges that braking is improved in a similar way: since the tire maintains a more constant pressure against the contact surface, it is less likely that the longitudinal shear forces exceed the coefficient of static friction, which, when exceeded, the rider experiences as skidding. With suspension forks, braking forces may be applied more evenly throughout the braking period and speed may be reduced without skidding. Feeling more confident at being able to slow more quickly and with greater control, mountain bike riders are more likely to achieve and maintain high speeds. These supposed improvements in braking and cornering are labeled the *traction theory.*

These three theories, the straight line theory, fatigue theory and traction theory are complex and multifaceted. Before these more complex assertions can be addressed, more basic assessments of suspension fork function must be completed.

According to these theories, suspension forks allow the rider to pick a straighter line through bumps, with less fatigue, better traction and speed. The specific question to answer is whether suspension forks do in fact reduce impact acceleration transmitted to the rider, and what suspension fork stiffness provides the greatest reduction. The difference between the axle acceleration and the frame acceleration through an impact event (a bump—see explanation below) would determine the amount of attenuation provided by suspension forks. Determining this value for rigid forks would give a baseline of impact acceleration transmission to the rider while mountain biking for comparison purposes. The aim of this study is to evaluate the axle and frame acceleration for rigid forks and three stiffness settings on suspension forks across small, medium and large bumps at constant speed.

When the tire strikes a bump, a pattern of motion and acceleration occurs. This is called an *impact event* (see figure 1). By reviewing a video of bump impact these events are visible: First, the tire begins to compress, followed shortly thereafter by the compression (suspension) or bending (rigid) of the fork. The wheel is deflected upward and a period of flight occurs where the tire is no longer in contact with the surface. The forks begin to extend

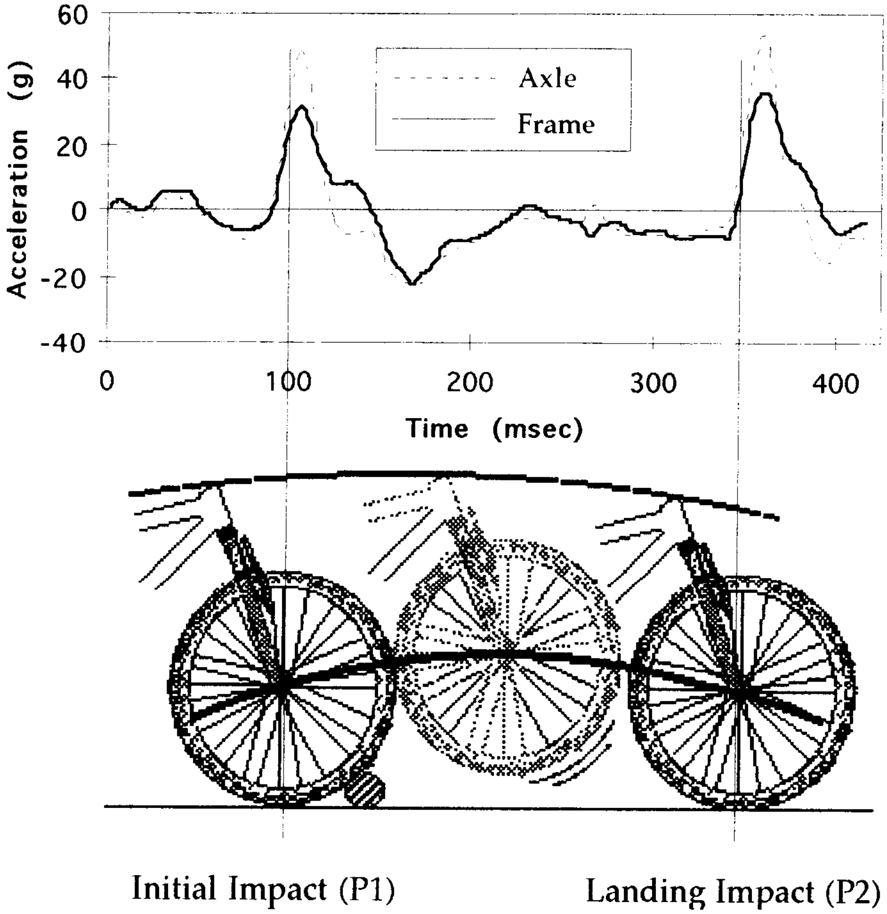

Figure 1. Schematic of impact event with accelerometer output.

(suspension) or bend back (rigid) to the original position either before or after the tire lands on the surface, depending on the size of the bump and the speed at contact. This entire process from bump impact to landing is called an *impact event.* The acceleration output during an impact event shows two distinct peaks, one coinciding with impact (P1) and another peak associated with landing (P2).

If there is a reduction in acceleration transmission for the suspension fork compared to the rigid fork this would indicate that riders would not have to turn to avoid bump impacts, supporting the straight line theory. A decrease in impact acceleration would also require less muscle force from the rider to attenuate the acceleration, supporting the fatigue theory. The support for the assertion that suspension forks permit increased speed is more tenuous, but reduced impact acceleration transmitted to the rider would logically encourage the rider to go faster. The traction theory is best approached by the acceleration allowed at the axle by rigid and suspension forks. It is assumed that greater acceleration of the axle is associated with more rapid displacement of the axle, which would suggest that the tire is able to more closely follow changes in the contour of the surface, resulting in fewer and shorter airborne periods. If axle acceleration is greater with suspension forks then this supports the assertion that contact between the tire and the surface is improved by suspension forks. Greater axle acceleration, and greater rate of acceleration (jerk), for the suspension forks would support the traction theory.

In summary, the goal of this project is to determine the acceleration values at the axle and frame for rigid forks and three suspension forks of varying stiffness. Since mountain biking involves different types of surfaces, these values will be compared across three bump types.

Statement of the Problem

Suspension forks may provide significant performance related enhancements compared to rigid forks by means of reducing impact shocks, transmission of vibration, and increased axle acceleration, but none of these capabilities of suspension forks have been systematically quantified.

Research and Statistical Hypotheses

Under all bump types and fork conditions, the values (first peak acceleration, (P_1); second peak acceleration, (P_2); and jerk, (J)) at the axle are expected to be greater than these variables at the frame.

H_0: $A_{axle} = A_{frame}$ H_a: $A_{axle} > A_{frame}$

For all accelerometer placements and bump types the values are expected to increase as fork stiffness increases.

H_0: $A_{F1} = A_{F3} = A_{F6} = A_{FR}$ H_a: $A_{F1} < A_{F3} < A_{F6} < A_{FR}$

For all accelerometer placements and fork conditions the values are expected to increase as bump size increases.

H_0: $A_{B1} = A_{B2} = A_{B3}$ H_a: $A_{B1} < A_{B2} < A_{B3}$

Definitions

P1: The acceleration, in g's, of the highest value of the acceleration curve at the first impact.

P2: The acceleration, in g's, of the highest value of the acceleration curve at the second (landing) impact.

J: The slope of the acceleration curve between 20% and 80% of the first peak value.

B1: A rod 4 cm in diameter.

B2: A 40 cm ramp up to a 15 cm drop-off.

B3: A 12 cm diameter rounded timber.

CHAPTER 2 REVIEW OF LITERATURE

The upper body is conspicuously absent from cycling research. Biomechanical models used in nearly all cycling related research include only the lower body and do not show the trunk or arms. Impact damping and vibration control are topics that have not concerned the cycling related scientific community, whose work focuses on aerodynamics, pedaling biomechanics, and exercise physiology. Because most studies were concerned with road cycling, only the issues pertinent to this area have been addressed.

This review will cover first the exercise physiology research, then the biomechanical studies, followed by vibration assessment research and concluding with the literature relating to vibration-associated cycling injuries.

McCole, Claney, Conte, Anderson and Hagberg (1990) have investigated energy expenditure during cycling in field settings, using Douglas bags to collect expired air using a pace vehicle. This work has led to the development of an equation to estimate VO_2 during cycling based on rider speed, wind speed, and rider weight. By utilizing the equation and analyzing wind speed in various settings, information was derived concerning energy cost reductions during drafting (following another cyclist closely), as well as riding with various combinations of aerodynamic wheel sets and aerodynamic bike frames. These data show an 18% saving in energy cost when drafting another cyclist, as is common in road races (McCole, 1990). While this study implied inclusion of the upper body as a drag surface, no specific mention of the trunk, arms, or head was included.

Other research into energy costs and exercise physiology of cycling includes Medbø and Tabata's (1989) work on relative contribution of aerobic and anaerobic energy release during short term exhaustive cycling. Although work levels in mountain biking would be related to both propulsive efforts and control efforts (impact avoidance and absorption), these issues were not addressed in this study. Energy expenditure in cycling was also studied by Brooke and Davies (1973); Dill (1954); Pugh (1974); Swain, Coast, Clifford, Milliken and Stray-Gunderson (1987); Van Baak and Binkhorst (1981); and Whitt (1971). Mountain biking, impact absorption, or upper body movement were not mentioned in any of these papers, and the studies have no direct bearing on impact acceleration and suspension systems.

Various investigators have researched biomechanical aspects of cycling, but again their studies have been limited to the lower extremities. Topics have included optimization of bicycle (pedaling) design parameters (Yoshihuku and Herzog, 1990; Gonzalez and Hull, 1989); mechanical energy analysis during cycling (Hull, Kautz and Beard, 1991); goniometric measurement of hip angles during standing cycling (Hull, Beard and Varma, 1990); analysis of knee and hip load moments during cycle ergometry (Ericson, Nissell, Arborelius and Ekholm, 1986); pedal loading during cycling (Hull and Davis, 1981); body position and cadence during hill climbing in cyclists (Miller, Martin and Wells 1988); effectiveness and efficiency during cycling (LaFortune and Cavanagh, 1983); and pedaling technique improvement using real-time biofeedback (McLean and LaFortune, 1988).

Pedaling rates have been investigated extensively by a number of researchers. Boning, Gonen and Maassen (1984) investigated the interrelationships of fitness, pedaling rate and work load; optimal pedaling rate experiments have been published by Coast and Welch (1985); Coast, Cox and Welch (1986); Dickenson, (1929) Ericson and Nissell (1988); Hagberg, Mullin, Bahrke and Limburg (1981); Hull and Gonzalez (1988); Hull, Gonzalez and Redfield (1988); Jordan and Merrill (1979); Redfield and Hull (1986); Seabury, Adams and Ramey (1977); and Widrick, Freedson and Hamil (1992). No mention of upper body position, impact attenuation or mountain biking was made in any of these papers.

The effects of cycling position (standing and seated on level and incline) on energy cost of cycling have been studied (Ryschon and Stray-Gunderson, 1991), and there are some implications here for mountain biking. Since standing occurs in mountain biking a great deal of the time, both for reasons of increased climbing capabilities and impact attenuation during descents, information concerning energy cost of standing cycling might be of some value as a basis for further research into energy costs of mountain biking. While this research may someday prove valuable, it is beyond the scope of this project.

In a far reaching attempt to quantify elite cycling characteristics, Coyle, et al., (1991) expanded on the work of Burke, Cerny, Costill and Fink (1977);

Burke (1980); Coyle, Coggan, Hopper and Walters (1988), Hagberg, Mullin, Bahrke and Limburg (1979); and Kuntslinger, Ludwig and Stegeman (1985) comparing *good* -to *elite-class* cyclists on a broad range of physiological and biomechanical parameters including VO_2 max, blood lactate threshold, muscle enzyme analysis, myoglobin, fiber type, fiber area, capillarization, 1 hour time trial, cycling economy, torque throughout pedal range, average pedal angle, and horizontal and vertical force during pedaling. While this research is valuable in identifying characteristics of road cyclists and providing training goals for elite cyclists, it does not address characteristics that identify elite mountain cyclists.

Clearly, cycling-related scientific literature has been concerned with the forces affecting road cyclists: aerodynamic drag and wind resistance, pedaling efficiency and energy costs. Since impacts have never been of much concern to road cycling, it is expected that little work has been done on this topic. It appears from this literature review that scientists have studied cycling only from the waist down.

With the advent of mountain biking, a whole new realm of forces must be dealt with by cyclists, most of these relating to impact attenuation, fine manual control, traction and balance. The effect of impact forces incurred during mountain biking on frame vibration and rider motion has not been investigated. The reduction of these forces by suspension forks is also unknown.

Despite the fact that cycling-related scientific research has neglected mountain biking, there has been considerable research on the effects of impacts and vibration on humans within the field of industrial biomechanics, ergonomics, and engineering.

Mountain biking falls somewhere between the categories of *hand-arm* and *whole-body* exposure to vibrations. This is due to the bicycle's interface with the rider which involves the feet, buttocks, and hands. In most situations, a single impact incurred while seated on a mountain bike is enough to convince the rider to stand on subsequent impacts. Therefore mountain biking is dissimilar to whole body vibrations such as those incurred during driving, flying, and similar seated conditions. However, mountain biking is also different from hand-arm vibration in that the feet are also subjected to impact loading and shock. Therefore research in each of these areas has some application, but is incomplete.

A study investigating the effectiveness of tennis racquet grips in reducing vibration transfer to the subjects' hand and arm was performed by Hatze (1992), and may have some implications for vibration control in mountain biking. While the study involved tennis racquets and grips, the hand–grip interface is not unlike mountain bike handlebar–hand interface. Hatze found a statistically significant reduction in vibration transferred to the hand and arm when comparing the uncovered hard grip to a cushioned grip. Some questions remains as to whether the reduction in vibration was biologically relevant, since it was slightly less that 9% (Hatze, 1992). No comparisons to other similar hand-grip situations or sports was made, and conclusions drawn from this study concerning vibration control in mountain biking are tenuous. Still this suggests that the long-standing policy of using hand grips on mountain bike handle bars may be effective in reducing some vibration transmission to the rider's hands, however only high frequency-low amplitude vibrations are likely dissipated by this system.

Vibration control has long been a subject of concern and interest to the field of industrial biomechanics and ergonomics and various investigations have focused on human exposure to vibrations. One of the more relevant papers was conducted by Bovenzi, Zadini, Franzinelli and Borgogni (1991) and deals with affects of vibration on musculoskeletal disorders of timber workers exposed to vibrations produced during chain sawing. This study evaluated various upper body joint ranges of motion (ROM) in a control group, manual forest laborers exposed to less than 7.5 m/s^2 average acceleration over four hours, and the experimental group, those forest workers exposed to more than 7.5 m/s^2 average acceleration over four hours (chain saw operators). Significant decrements in active ROM were found in numerous upper body joints of chainsaw vibration-exposed workers. Based on these results, it appears that forest workers are not at risk for cumulative trauma disorders of the upper body unless they are exposed to greater than 7.5 m/s^2 average acceleration over four hours.

While it is doubtful that mountain biking produces vibration at similar frequency and with similar contraction duration, there may be some important information to glean from this study. Bovenzi et al. make some interesting comments concerning the function of the hand/wrists as a low pass filter of vibration, citing the work of Abrams and Suggs (1969), and Pyykko, Farkkila, Toivanen, Korhonen and Hyvarinen (1976). Apparently the mid- and high-frequency vibrations are dissipated by soft tissue motion in the hands (Reynolds, 1977), and low frequencies pass to the upper arm (Abrams and Suggs, 1969; Pyykko, et al., 1976; Pyykko, et al., 1986). The mechanism of vibration-induced injury is still debated among researchers, however some aspects are clear. The vibration sets up resonance frequencies within the soft tissue of the body and high shear forces are thought to occur at the nodes of this resonance. Stretch receptors in the vascular system may be activated by vibration, inducing constriction of blood vessels, reduced blood flow, edema and ultimately necrosis. Numbness and loss of manual control may also occur due to effects of vibration on the nervous system (Pyykko, et al., 1986). Bovenzi (1991) concluded that the combined risk factors of mechanical stress, hard physical effort, constrained postures, and strong grip force accounted for the elevated presence of musculoskeletal disorders in forestry workers. Mountain biking with rigid forks involves all of these risk factors, and the potential risk to mountain cyclists needs to be determined.

Much of the research into vibration exposure has concentrated on discomfort levels associated with whole-body vibration (for example, Mistrot et al. (1990)), or on the effect of vibrations on fine manual control, (studied by Nakamura and Haverkamp (1991)). Mistrot assessed the effect of sinusoidal multi-axial 2 to 16 Hz vibrations on seated subject discomfort and attempted to develop a procedure for predicting discomfort. Schmidtke notes in *Ergonomic Data for Equipment Design* (1984) that vibrations which produce pathological response in work settings are often tolerated without injury in recreational settings, perhaps due to breaks taken more frequently or the perception that the activity is fun.

Nakamura and Haverkamp (1991) investigated the effects of whole body shock-type vibration on fine manual control. The procedure was designed to simulate driving heavy earth-moving vehicles, and assessed the ability of the subjects to maintain a cursor within the parallel lines of a simulated "road" on a computer screen during vibration sprinkled with symmetric and asymmetric shocks. The results of the study indicated that drivers had similar tracking errors regardless of the symmetric or asymmetric occurrence of shock, provided the total shock was below 1.25 m/s^2 average acceleration and shock amplitudes were below 8 m/s^2. Additionally, Nakamura and Haverkamp showed that subjects had greater tracking error during symmetric shocks of 6.0 and 10.0 m/s^2 than during 8.0 m/s^2 symmetric shocks. Although the authors did not comment on the experience of the subjects other than to say that they were all experienced earth-moving equipment drivers, it is interesting to note that the 8.0 m/s^2 shock amplitude produced these results. It would be valuable to find out if this amplitude of shock was present in the earth-moving equipment which the subjects were experienced in driving. This is a fascinating development and at least suggests the possibility that subjects may be able to maintain fine manual control during certain shock amplitudes to which they have become accustomed. From empirical evidence observed while mountain biking, there appears to be a corollary adaptive process which occurs in all riders as experience increases.

Although this study involved steering-wheel control during single-axis vibrations, the application to mountain biking is obvious: if impact amplitudes are kept within certain ranges control might be improved. While it is the contention of many manufacturers of suspension forks that control is improved with their devices, published scientific evidence on this assertion is absent. While this claim is interesting, supported by logical assumptions, and in need of testing, it is beyond the scope of this thesis.

Shea, K., Shumsky and Shea, O. (1991) published a case study involving a patient with DeQuervian's disease, a nerve pathology resulting in numbness and loss of control. The etiology of the condition was traced to the individual's use of a mountain bike, and rest was prescribed which eventually brought relief. This case study indicates that others with similar mountain biking experience may be at risk for this condition. Munnings (1991) reported on cyclists palsy, and citing the large numbers of cyclists in the United States, advocated educating consumers on appropriate choices in bicycle size and rider position to minimize vibration exposure to sensitive tissues in the hands, wrists, arms and buttocks. It is interesting to note that both these physicians chose to reduce exposure to vibration as the treatment.

There have been no scientific publications to date concerned directly with assessing the vibrations associated with mountain biking. The review of literature related to this subject has revealed numerous collateral investigations but nothing exactly centered in this area. However, many publications touch on some aspect of this thesis project, and with the synthesis of some aspects of this literature along with logical choices based on empirical information, effective data collection and evaluation protocols are possible.

CHAPTER 3 METHODS

To analyze the effect of rigid and suspension forks on acceleration of the axle and frame, quantitative measures of specific variables must be made. Since a study of this nature has not been published in the research literature, determining the variables that will best answer the questions of interest must involve empirical analysis and logical choices rather than duplicating accepted scientific protocols and data collection procedures.

Fortunately, the rationale for choosing appropriate dependent measures is reasonably straightforward. Since the suspension forks are designed to attenuate shock, comparing peak acceleration values at the axle and frame as a bump impact takes place would determine to what extent this attenuation occurs. To determine the acceleration at the frame and axle, two small accelerometers were mounted, one on the axle and the other on the frame at the head tube. The output from these sensors was telemetered to a microcomputer and stored for later analysis.

Suspension forks are designed to reduce bump impact acceleration transmitted to the rider. Therefore, the first peak acceleration (P1—bump impact, see figure 2 below) is a variable of interest, and the difference between the axle value and the frame value best approaches the question of whether the suspension forks actually attenuate acceleration transmitted to the rider upon bump impact.

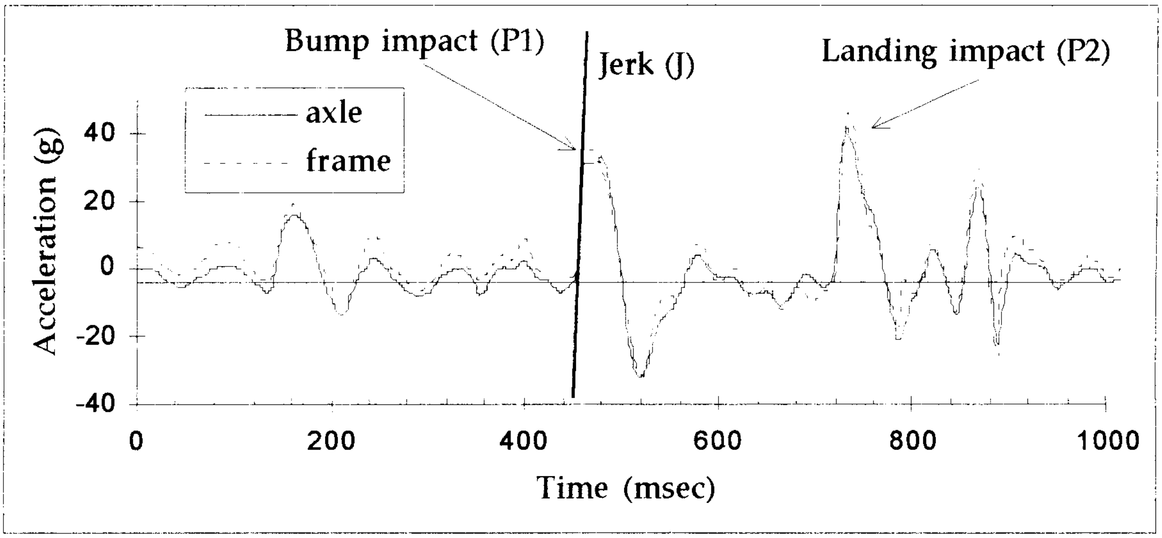

Figure 2. Accelerometer output for a typical impact event.

After a bump is incurred, the front wheel becomes airborne for a short time, landing just beyond the bump. At this point a second impact (P2) occurs. Between these two positive peaks is a negative acceleration peak of unknown origin. While the suspension forks are designed to "absorb" shock, it is important to determine how the forks will respond to rapidly encountered impacts. The second impact may not be "absorbed" the same as the first. Therefore, the difference between axle and frame values would determine the ability of suspension forks to attenuate shock upon landing. Unfortunately, since the bump shapes were different this measure is confounded somewhat. Not only does this value assess the ability of the fork to respond to rapidly occurring bumps, but also involved is the fork's ability to attenuate the acceleration from a mainly vertical ground reaction force (landing impact) as opposed to a mixed vertical and braking shear force as was incurred on bump impact. Since the landing force is not directed along the compressive axis of the suspension forks, acceleration attenuation effects may be altered. In addition, landing impacts have additional forces from

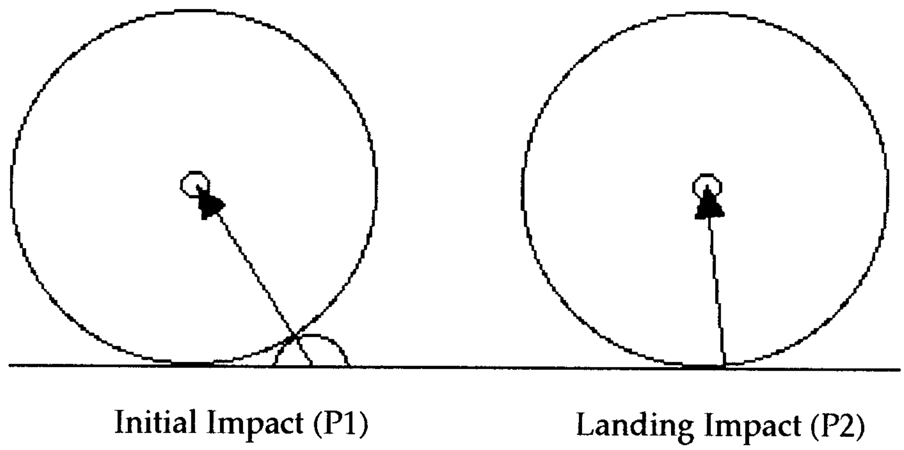

Figure 3. Theoretical force vector for bump and landing impacts.

acceleration due to gravity on the mass of the rider/bike system. Fractionating this measure into more specific values is beyond the scope of this thesis.

Since it was hypothesized that the suspension forks would allow the wheel to follow the contours of the surface more closely, axle motion should be more rapid. More rapid front wheel motion would lead to a more rapid rate of acceleration at the axle with suspension forks—with reduced transmission of this acceleration to the frame—than with rigid forks. The rate of acceleration increase from 20% to 80% of the first peak acceleration (J—jerk) differentiates the effects of the rigid and suspension forks on the ability of the wheel to follow changes in terrain. This variable compares the rate of acceleration of the system at the axle and frame. More rapid axle acceleration with suspension forks would lend support to the notion that traction may be improved with suspension forks.

In order to assess the effect of fork stiffness (resistance to compression) on acceleration reduction characteristics on different bump sizes, these three variables, P1, P2 and J, were determined across four fork conditions and three bump types: The forks were rigid forks (FR); suspension forks with low resistance to compression (F1); suspension forks with moderate resistance to compression (F3); and suspension forks with high resistance to compression (F6). The three bumps were a 4 cm cylinder (B1); a 40 cm ramp with a 15 cm drop-off at the end (B2); and a 12 cm rounded timber (B3).

To control for bike speed, a ramp was constructed to ensure similar speeds for each trial (5.4 m/s ~ 12 mph). A bump was placed at the end of the ramp for the bike to contact. The suspension forks were adjustable, allowing for fork stiffness to be changed rapidly. The bumps were also easily swapped, allowing for fully randomizing across suspension forks, bump types and subjects.

Seven subjects rode across the different bump types simulating typical impacts during mountain biking using the same bicycle (19 inch Klein Pinnacle, Chehalis, Washington) fitted with either rigid forks or a suspension fork set to one of the three stiffness settings (F1, F3, F6). Tire pressure was maintained at 40 psi, oil viscosity was stock 10 weight, (oil viscosity influences the rate oil can pass through the valve which is controlled by the dials on the fork crown) and ambient temperature did not fluctuate during data collection. Internal air pressure on the suspension, which influences the rate of return to the extended position after compression, was maintained at 45 psi. The accelerometers attached to the front wheel axle and bicycle frame provided information on the acceleration of these areas as each bump was incurred.

Experimental Environment

Each subject rode the bicycle down a ramp, constructed for the experiment, 4.19 m long at an angle of 20°, which resulted in a velocity of 5.4 m/s (~12 mph). Speed of each pass was controlled by starting each trial from a consistent location on the ramp, resulting in nearly identical speeds for each trial. The subject coasted through the test without pedaling, while in a crouched, standing position. Subjects passively rolled across the bumps without lifting the wheels or moving in ways that would affect the impact characteristics.

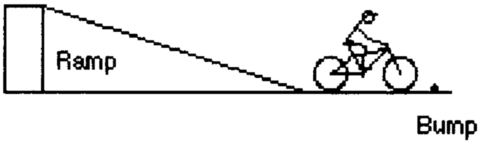

Figure 4. Experimental environment.

To measure the suspected high-frequency vibrations of the front wheel (D. Wooten, personal communication, October 17, 1993), two low-mass (2 gram) accelerometers (PCB model 3032A) were used: one mounted to the axle (A1) and another at the head tube (A2) on the bicycle frame (see figure 5).

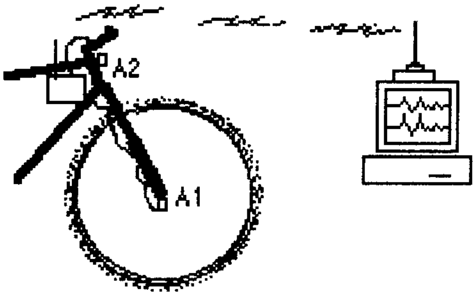

Figure 5. Accelerometer mounting and data telemetry.

The output from both accelerometers was transmitted via radio telemetry to a microcomputer using Noraxon software and hardware (Noraxon, Tempe, AZ), sampled at 1000 Hz and stored for later data analysis. When converting analog signals to digital signals, there is a risk of under-sampling. Under-sampling a signal can result in aliasing errors (Winter, 1990), a term relating to the inappropriate assignment of a digital value to an analog signal. Based on pilot studies of the frequency spectrum of the acceleration signal, a substantial drop in power occurred above 300 Hz, indicating that frequencies greater than this value were mainly noise. Therefore a 1000 Hz sampling frequency seemed sufficient to capture all possible data.

Accelerometer Data Processing

Using a spreadsheet program (Excel) the data were converted from Noraxon units to gravitational units (g) using a regression equation determined from calibration of the telemetry system (see figure 6 below). Data were then smoothed using a zero-lag, fourth-order, recursive Butterworth filter with an F_{sample}/F_{cutoff} ratio of 20 (50 Hz cutoff). The smoothed data were plotted and the variables impact peak acceleration (P1) and second peak acceleration (P2) were identified by searching specific ranges for the maximum. The jerk (J) was determined by searching for the two samples where 20% and 80% of the P1 maximum acceleration value occurred and calculating the slope by determining the change in acceleration divided by the time between the 20% and 80% values.

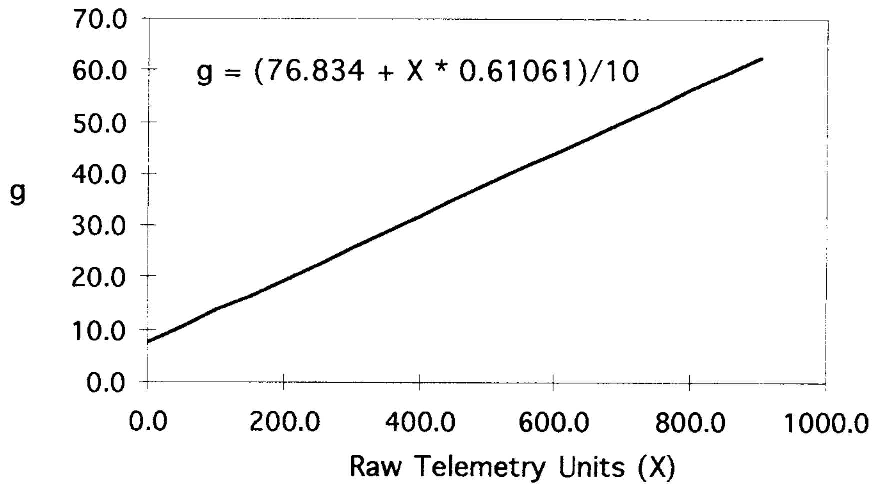

Figure 6. Conversion equation developed during calibration of the telemetry system.

Subjects

Seven experienced male mountain bikers served as subjects for this study after their informed consent was received in accordance with the Institutional Review Board for Human Subject Research at Oregon State University. The subjects were all of a stature appropriate for the bicycle (mean height 1.75 ± 0.025 m; mean weight 81.6 ± 2.8 kg). As it was suspected that rider motion and position would influence impact acceleration, riders were instructed to do nothing to influence the impact with the bump, and to ride as if this was one of many bumps.

Experimental Design

This study involved comparing acceleration at the frame and axle with four fork conditions on three types of bumps. The subject, suspension fork stiffness and bump size were selected at random, and rigid fork data were collected subsequently with bump size and subject randomized. Each subject completed one acceptable trial over each bump with each fork.

Bump Types

A bump was placed 2.3 m from the base of the ramp (figure 4). The three bump types were a rod 4 cm in diameter (B1), a 40 cm ramp with a 15 cm drop-off (B2) and a 12 cm diameter rounded timber (B3). The bumps were selected to mimic three types of impacts commonly experienced during mountain biking. B1 was designed to mimic a single unit of the frequent, small bumps that are present in all off-road conditions; B2 was similar to a pothole in a surface, with a gradual impact slope and a drop-off at the end; B3 was a large bump similar to a large rock or log which may occasionally be encountered.

Fork Conditions

The suspension forks (Rock Shox Mag 20, Boulder, CO) were adjustable by means of two small dials on the crown that alter the opening of a valve that allows oil to escape a reservoir as an impact is incurred and thus allowing compression of the fork. Suspension forks were tested on settings 1 ("soft"), 3 ("moderate") and 6 ("stiff") of the six possible settings resulting in three suspension conditions and one rigid fork condition. Other suspension fork conditions were controlled by maintaining oil viscosity at 10w, ambient temperature ≈ 70° F, and shock internal air pressure at 45 psi for consistent return to the extended position following compression. Rigid fork data were collected after replacing the suspension forks on the bicycle with a Koski big-radius fork (Keith Koski, Inc., Los Angeles, CA) and bumps were randomly assigned. Tire pressure was maintained at 40 psi.

Data Filtering

Data were filtered using a Butterworth recursive filter to remove random noise from the data that is introduced in the measurement process. It is generally accepted that errors occur mainly in the upper frequencies and are commonly filtered out in studies of this nature using low-pass filters.

These algorithms allow the true signal to pass relatively unaltered while removing high frequency noise from the signal.

A pilot study indicated that the most appropriate cutoff value was 50 Hz for the accelerometer data (F_{sample}/F_{cutoff} ratio of 20—1000 Hz sampling frequency/50 Hz cutoff frequency). Choosing this cutoff frequency involved filtering data at different cutoff values from F_s/F_c 8 to F_s/F_c 25 and comparing the residual—the average of the difference between the filtered value and the raw value over a period of time containing a typical event (Winter, 1990). A linear regression was calculated from the most asymptotic portion of the residual graph. At the point where this line intersected the Y-axis, a

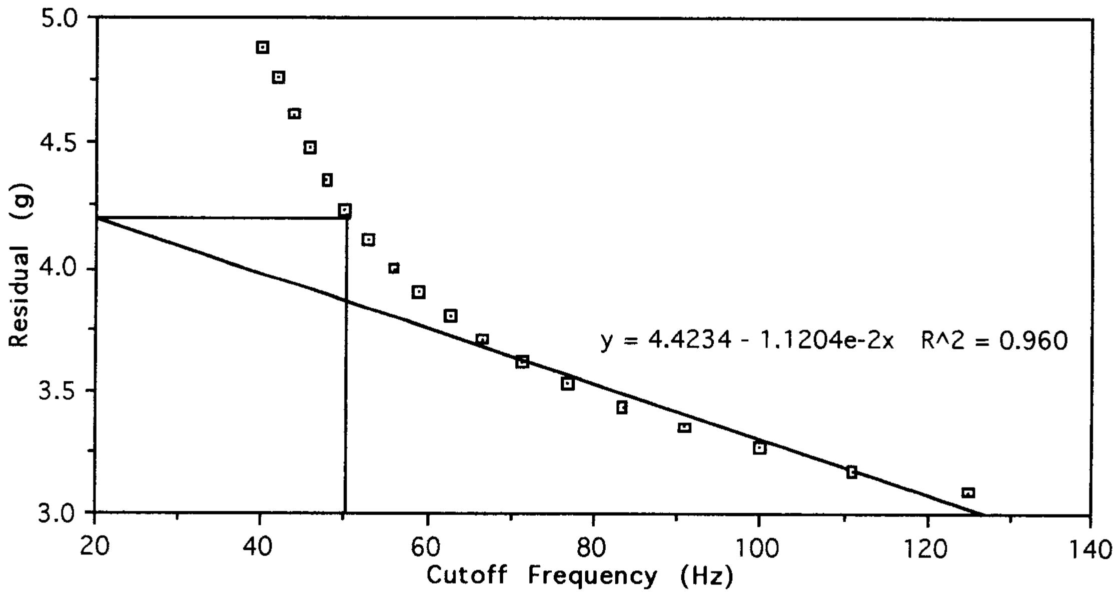

Figure 7. Residual analysis of accelerometer data showing 50 Hz cutoff frequency chosen for smoothing.

horizontal line was reflected back until the average residual curve was intersected and this represented the cutoff value for data filtering.

A sample graph of raw axle data and axle data filtered at 50 Hz is shown below.

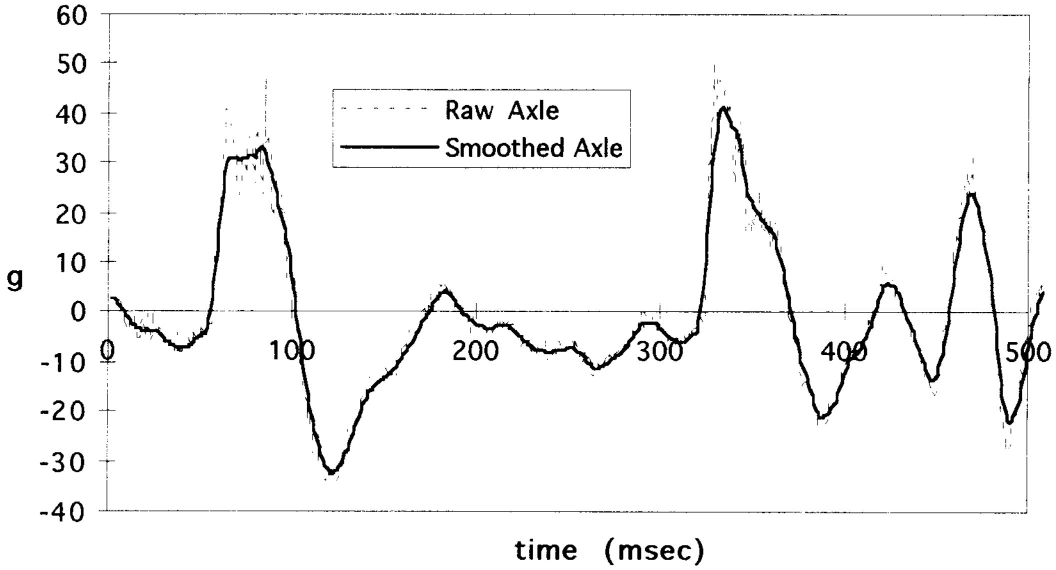

Figure 8. Raw and smoothed axle acceleration data (g).

Statistical Analysis

A 3 factor (2 accelerometers x 3 bumps x 4 forks) ANOVA with repeated measures on two levels was utilized for each dependent measure (P1, P2 and J). The level of significance was set at $p = .01$. Since many post-hoc tests are not suitable in repeated measures experiments, linear contrasts were used as follow-up tests when significant interactions were detected. Statistical analysis was performed using SuperANOVA (Abacus Concepts, Inc.).

CHAPTER 4 RESULTS AND DISCUSSION

The purpose of this investigation was to determine the effect of rigid fork and suspension fork stiffness (resistance to axial compression) on impact acceleration at the axle and frame on three types of bumps. Axle and frame values were compared across fork conditions to determine if axle acceleration and frame acceleration remained constant across fork conditions. The bicycle was fitted with either a rigid fork (FR) or a suspension fork set on soft (F1), medium (F3) or firm (F6) stiffness for a total of 4 different fork conditions. There were three bump types, a rod 4 cm in diameter (B1), a 15 cm drop-off (B2) and a 12 cm diameter rounded timber (B3). Accelerometers were placed on the axle and on the frame of the bicycle.

The complete results are summarized in table 1 below. The ANOVA tables are shown in the appendix. As expected, there was significant fork by bump by accelerometer interaction, and linear contrasts were used as follow-up tests for the within-fork and between-fork analyses.

The results are organized from small bump, to medium bump and then to large bump. Within each of these sections are between-fork analyses and then within-fork analyses with text, tables and histograms, and conclude with a summary of the findings for each bump.

Table 1. Complete results for P1, P2 and J across 4 forks and 3 bumps at the axle and frame (Mean ± SD).

	F1	F3	F6	FR
P1 (g)				
Axle				
B1	14.0 ± 3.0	13.3 ± 2.2	13.6 ± 1.7	12.2 ± 1.7
B2	31.0 ± 2.4	28.4 ± 1.9	28.7 ± 1.8	22.8 ± 2.6
B3	45.3 ± 6.6	45.8 ± 3.5	40.5 ± 3.5	35.2 ± 3.4
Frame				
B1	14.7 ± 2.3	11.1 ± 1.0	15.7 ± 2.0	12.0 ± 1.7
B2	25.3 ± 1.6	21.9 ± 2.1	27.2 ± 2.1	25.7 ± 3.0
B3	35.1 ± 1.9	28.3 ± 3.9	36.8 ± 3.4	36.8 ± 3.0
P2 (g)				
Axle				
B1	22.5 ± 5.0	26.9 ± 3.2	22.2 ± 5.0	18.7 ± 3.2
B2	25.0 ± 7.9	33.1 ± 5.8	30.4 ± 6.2	31.4 ± 8.6
B3	45.6 ± 9.6	48.3 ± 14.7	48.0 ± 9.2	44.2 ± 14.8
Frame				
B1	25.5 ± 8.6	20.4 ± 2.5	23.5 ± 5.7	18.2 ± 5.0
B2	28.0 ± 4.8	29.5 ± 2.4	30.2 ± 6.6	30.9 ± 9.1
B3	43.5 ± 7.3	34.8 ± 11.5	45.5 ± 8.8	45.5 ± 15.2
J1 (g/msec)				
Axle				
B1	1.8 ± 0.5	1.8 ± 0.4	2.1 ± 0.4	1.8 ± 0.3
B2	4.1 ± 0.5	3.8 ± 0.6	4.4 ± 0.6	3.6 ± 0.7
B3	3.8 ± 0.6	3.9 ± 0.4	3.7 ± 0.5	3.2 ± 0.6
Frame				
B1	1.2 ± 0.7	0.7 ± 0.8	1.4 ± 0.9	1.4 ± 0.5
B2	2.1 ± 1.1	2.2 ± 1.1	2.2 ± 1.0	3.3 ± 0.8
B3	2.7 ± 0.5	2.3 ± 0.6	2.7 ± 0.4	3.2 ± 0.4

Small Bump (B1) Fork Comparisons

On the small bump (B1), there were no statistically significant differences in the values at the axle versus the frame within any of the forks, except for F3 which showed a significant lower jerk (J) at the frame compared to the axle. (p =.0035). On small bumps, the amount of acceleration at the axle and at the frame was similar within all forks.

Table 2. Small bump (B1) within-fork axle versus frame values for P1, P2 and J (mean ± SD) with linear contrast p values shown on right.

F1		Axle	Frame	Contrasts p-value
	P1	14.0 ± 3.0	14.7 ± 2.3	.6537
	P2	22.5 ± 5.0	25.5 ± 8.6	.4944
	J	1.8 ± 0.5	1.2 ± 0.7	.1087
F3				
	P1	13.3 ± 2.2	11.1 ± 1.0	.1543
	P2	26.9 ± 3.2	20.4 ± 2.5	.1478
	J	1.8 ± 0.4	0.7 ± 0.8	.0035
F6				
	P1	13.6 ± 1.7	15.7 ± 2.0	.1718
	P2	22.2 ± 5.0	23.5 ± 5.7	.7655
	J	2.1 ± 0.4	1.4 ± 0.9	.0621
FR				
	P1	12.2 ± 1.7	12.0 ± 1.7	.9077
	P2	18.7 ± 3.2	18.2 ± 5.0	.9177
	J	1.8 ± 0.3	1.4 ± 0.5	.3239

Although there was a trend for the suspension forks to have slightly higher axle acceleration for the impact peak (P1) on the small bump (B1), no significant differences were seen between forks at the axle. At the frame, P1 values on B1 were lowest for F3 and highest for F6 and a significant difference was found only between these two (p =.0029). Since the within-fork analysis showed no difference at the axle across the forks on the small bump, this leads to the conclusion that suspension forks do little in the way of acceleration attenuation on impacts with small bumps.

When landing (P2), it was surprising to find that FR had slightly less acceleration at the frame than F1, but not a statistically significant reduction. No significant between-fork differences were detected at the axle or at the frame for the landing peak (P2) on the small bump (B1).

There were no significant differences detected in jerk between forks for values at the axle, or between forks for values at the frame on B1.

Small Bump (B1) Summary

It was hypothesized that suspension forks would have higher axle acceleration than rigid forks, providing support for the assertion that suspension forks allow better tracking of the front wheel with changing

Table 3. Small bump (B1) between-fork contrasts for impact peak (P1) at the axle and at the frame (mean ± SD) with linear contrast *p* values.

Axle	F1	F3	F6	FR
	14.0 ± 3.0	13.3 ± 2.2	13.6 ± 1.7	12.2 ± 1.7
F1	•	.6463	.8045	.2353
F3	•	•	.8326	.4658
F6	•	•	•	.3271
Frame	**F1**	**F3**	**F6**	**FR**
	14.7 ± 2.3	11.1 ± 1.0	15.7 ± 2.0	12.0 ± 1.7
F1	•	.0203	.5011	.0806
F3	•	•	.0029	.5605
F6	•	•	•	.0159

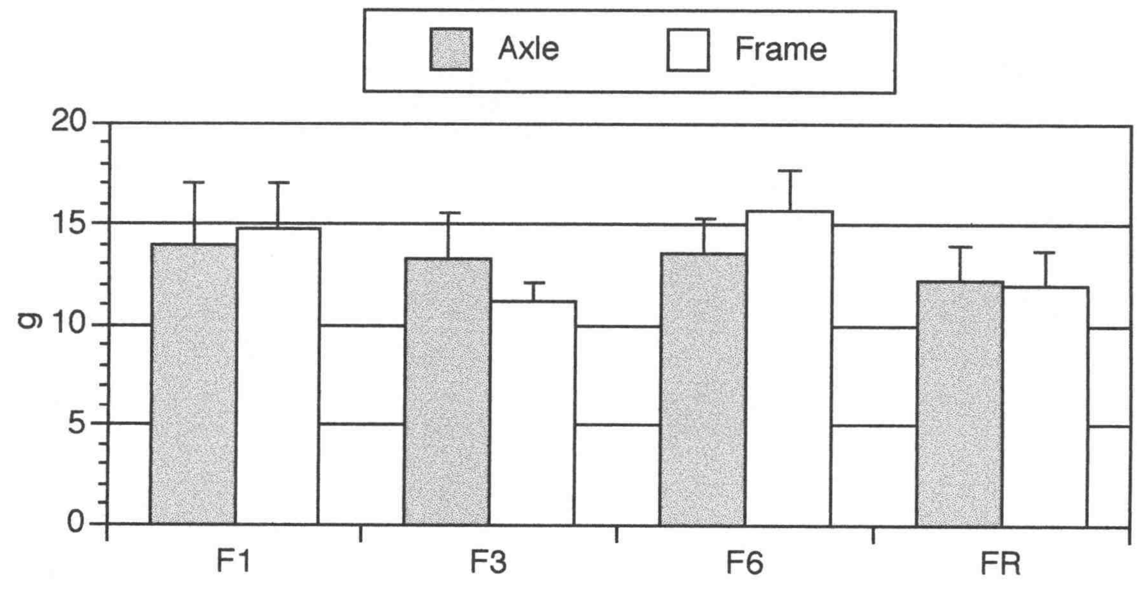

Figure 9. Small bump (B1) impact peak (P1) values (mean with SD) at the axle and frame shown across forks. No significant differences were found within forks.

Table 4. Small bump (B1) between-fork contrasts for landing peak (P2) at the axle and at the frame (mean ± SD) with linear contrast p values.

Axle	F1	F3	F6	FR
	22.5 ± 5.0	26.9 ± 3.2	22.2 ± 5.0	18.7 ± 3.2
F1	•	.3233	.9470	.3715
F3	•	•	.2919	.0559
F6	•	•	•	.4095
Frame	**F1**	**F3**	**F6**	**FR**
	25.5 ± 8.6	20.4 ± 2.5	23.5 ± 5.7	18.2 ± 5.0
F1	•	.2526	.6514	.0896
F3	•	•	.4880	.6073
F6	•	•	•	.2180

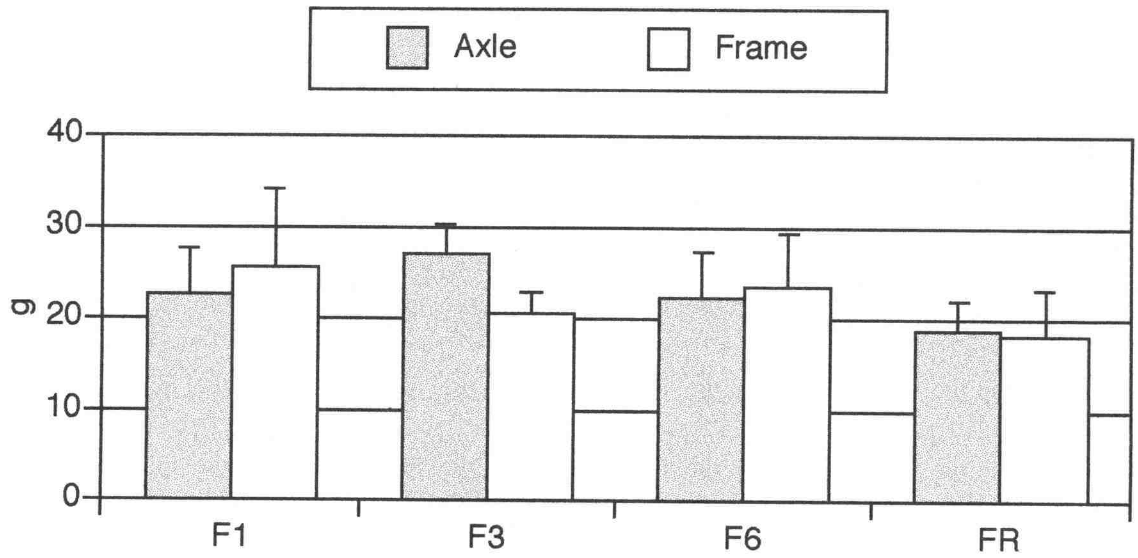

Figure 10. Small bump (B1) landing peak (P2) values at the axle and frame shown across forks.

Table 5. Small bump (B1) between-fork contrasts for jerk (J) at the axle and at the frame (mean ± SD) with linear contrast p values.

Axle	F1	F3	F6	FR
	1.8 ± 0.5	1.8 ± 0.4	2.1 ± 0.4	1.8 ± 0.3
F1	•	.8525	.3953	.9161
F3	•	•	.5063	.9358
F6	•	•	•	.4563
Frame	**F1**	**F3**	**F6**	**FR**
	1.2 ± 0.7	0.7 ± 0.8	1.4 ± 0.9	1.4 ± 0.5
F1	•	.2506	.4320	.9161
F3	•	•	.0834	.0538
F6	•	•	•	.8418

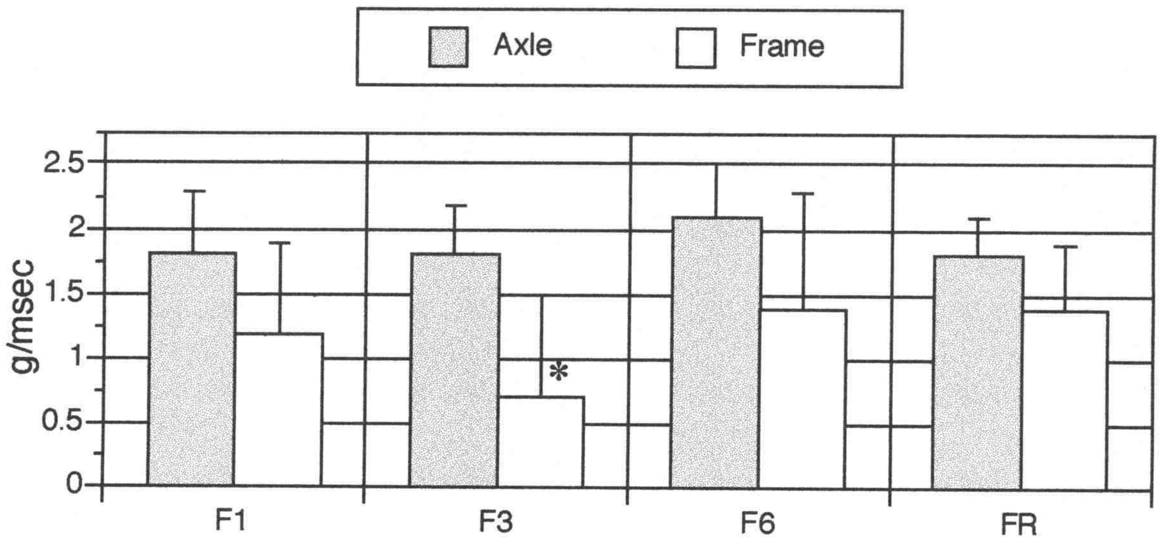

Figure 11. Small bump (B1) jerk (J) values at the axle and frame shown across forks. * indicates a statistically significant within-fork reduction (p < .001) in frame value compared to axle value.

surface contours. To support this assertion, softer forks would have to produce higher acceleration values at the axle than stiffer ones. However, when comparing small bump (B1) axle acceleration between forks, no differences were detected at either P1 or P2. Therefore, it does not appear that these suspension forks improved the ability of the front wheel to track small (4 cm) contour changes in the riding surface at this speed.

Frame and axle acceleration were not significantly different between or within any forks on either P1 or P2, and this suggests that on the small bump (B1), most of the acceleration occurring at the axle was transmitted directly to the rider. The rigid fork showed almost identical values at the axle and frame on the small bump.

Combined, these data suggest that on small bumps, suspension forks make little difference on how the front wheel tracks the surface, or how much impact is transmitted to the rider.

Medium Bump (B2) Fork Comparisons

On the medium bump, the advantages of suspension forks become evident with significant differences found within-forks when comparing axle to frame acceleration. F1 and F3 both had significant reductions in acceleration at the frame compared to the axle on the impact peak (P1) ($p < .0001$).

However, when comparing within-fork values at the axle to values at the frame on the landing peak (P2), none were significantly different. Possible reasons for this include the suspension forks' compressed position upon landing decreasing acceleration attenuation properties; differences in surface shape producing fork bending rather than compression; and off-balance landing increasing variability and decreasing statistical power.

F1, F3 and F6 also had significant within-fork reductions in jerk (J) values at the frame compared to the axle ($p < .0001$). This suggests that on moderate bumps, movement of the front wheel is similar regardless of fork stiffness, although with suspension forks, the axle acceleration is not transmitted to the rider.

Table 6. Medium bump (B2) within-fork axle versus frame values for P1, P2 and J (mean ± SD) with linear contrast *p* values shown on the right.

	Axle	Frame	Contrasts *p*-value
F1			
P1	31.0 ± 2.4	25.3 ± 1.6	.0003
P2	25.0 ± 7.9	28.0 ± 4.8	.4547
J	4.1 ± 0.5	2.1 ± 1.1	.0001
F3			
P1	28.4 ± 1.9	21.9 ± 2.1	.0001
P2	33.1 ± 5.8	29.5 ± 2.4	.4233
J	3.8 ± 0.6	2.2 ± 1.1	.0001
F6			
P1	28.7 ± 1.8	27.2 ± 2.1	.3391
P2	30.4 ± 6.2	30.2 ± 6.6	.9643
J	4.4 ± 0.6	2.2 ± 1.0	.0001
FR			
P1	22.8 ± 2.6	25.7 ± 3.0	.0587
P2	31.4 ± 8.6	30.9 ± 9.1	.9224
J	3.6 ± 0.7	3.3 ± 0.8	.4174

In the between-fork comparisons, each suspension fork was significantly different from the rigid fork when comparing P1 axle acceleration in the medium bump (B2) ($p < .001$); none of the suspension forks were significantly different from one another. When comparing the frame values for P1, F3 was lowest and was significantly different only from F6 ($p < .0006$). For the impact peak (P1) on the medium bump, suspension forks appear better at attenuating impacts transmitted to the rider than the rigid forks.

There were no significant differences in P2 acceleration values between any of the forks at either the axle or the frame for the medium bump (B2). Possible reasons for this finding have been discussed above. It is interesting to note that in all cases except F1, the P2 value exceeded the P1 value at both the axle and at the frame for each fork. This is to be expected due to the shape of B2, a 40 cm ramp up to a 15 cm drop-off.

The B2 jerk values at the axle were not significantly different between any of the forks; at the frame, each suspension fork had significantly lower jerk values when compared with the rigid fork (F1 versus FR $p < .0027$; F3 versus FR $p < .0046$; F6 versus FR $p < .0053$). This reduction in transmission of the jerk to the frame is noteworthy from both a statistical and practical standpoint.

Medium Bump (B2) Summary

On the medium bump (B2), a 40 cm ramp up to a 15 cm drop-off, all suspension forks did appear to allow the axle higher initial impact (P1) acceleration than the rigid fork, but only the softer suspension forks (F1 and F3) did not appear to transmit this increased axle acceleration to the frame. But the advantages of suspension forks appear limited to the initial impact with the bump (P1); in landing impacts (P2) no differences were found

Table 7. Medium bump (B2) between-fork contrasts for impact peak (P1) at the axle and at the frame (mean ± SD) with linear contrast *p* values.

Axle	F1	F3	F6	FR
	31.0 ± 2.4	28.4 ± 1.9	28.7 ± 1.8	22.8 ± 2.6
F1	•	.0966	.1365	.0001
F3	•	•	.8616	.0003
F6	•	•	•	.0002
Frame	**F1**	**F3**	**F6**	**FR**
	25.3 ± 1.6	21.9 ± 2.1	27.2 ± 2.1	25.7 ± 3.0
F1	•	.0255	.2232	.8081
F3	•	•	.0006	.0134
F6	•	•	•	.3290

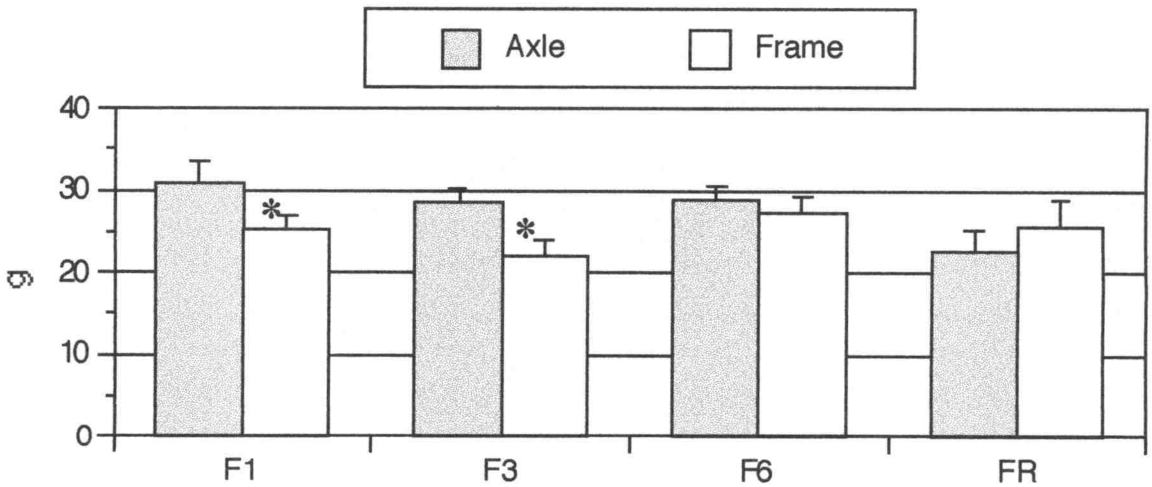

Figure 12. Medium bump (B1) impact peak (P1) values at the axle and frame shown across forks. * indicates significant within-fork difference ($p < .001$) (frame value less than axle value).

Table 8. Medium bump (B2) between-fork contrasts for landing peak (P2) at the axle and at the frame (mean ± SD) with linear contrast p values.

Axle	F1	F3	F6	FR
	25.0 ± 7.9	33.1 ± 5.8	30.4 ± 6.2	31.4 ± 8.6
F1	•	.0573	.2019	.1324
F3	•	•	.5434	.6997
F6	•	•	•	.8243
Frame	**F1**	**F3**	**F6**	**FR**
	28.0 ± 4.8	29.5 ± 2.4	30.2 ± 6.6	30.9 ± 9.1
F1	•	.7197	.5921	.4712
F3	•	•	.8760	.7386
F6	•	•	•	.8532

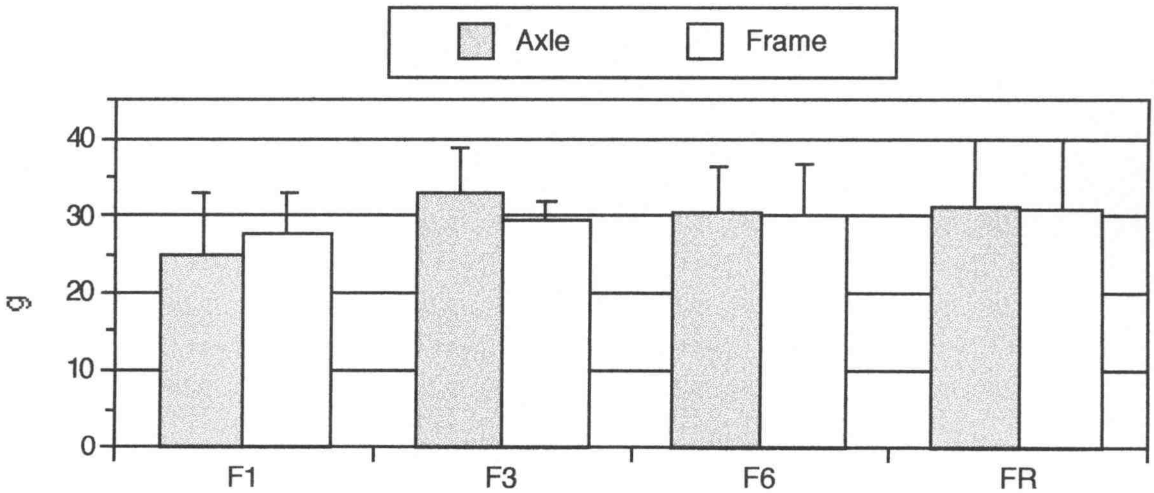

Figure 13. Medium bump (B2) landing peak (P2) values at the axle and frame shown across forks.

Table 9. Medium bump (B2) between-fork contrasts for jerk (J) at the axle and frame (mean ± SD) with linear contrast p values.

Axle	F1	F3	F6	FR
	4.1 ± 0.5	3.8 ± 0.6	4.4 ± 0.6	3.6 ± 0.7
F1	•	.4549	.4948	.1878
F3	•	•	.1535	.4487
F6	•	•	•	.0462
Frame	**F1**	**F3**	**F6**	**FR**
	2.7 ± 0.5	2.2 ± 1.1	2.2 ± 1.0	3.2 ± 0.4
F1	•	.8651	.8302	.0027
F3	•	•	.9645	.0046
F6	•	•	•	.0053

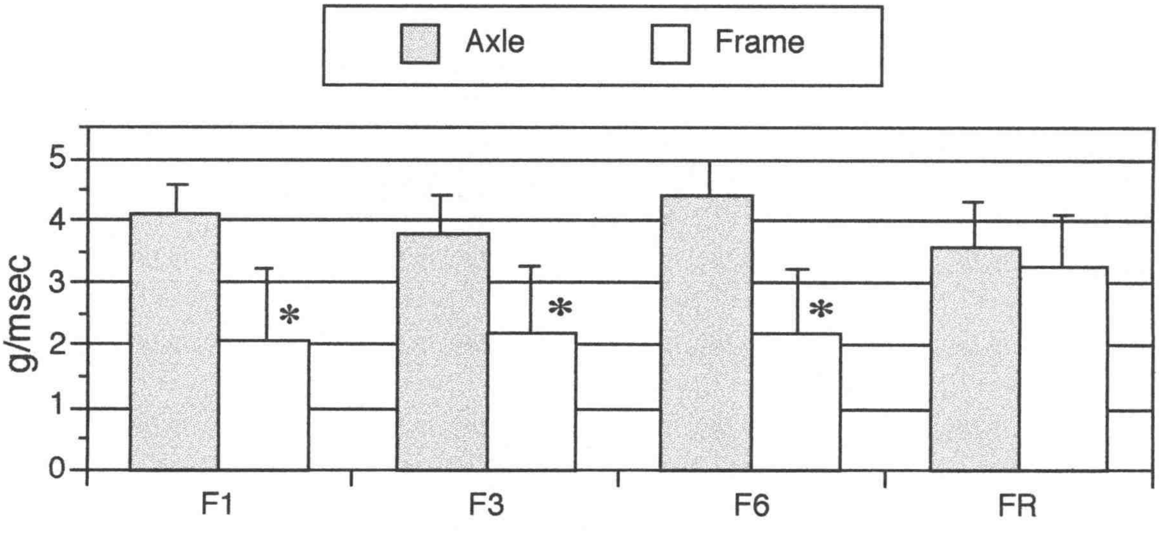

Figure 14. Medium bump (B2) jerk (J) values at the axle and frame shown across forks. * indicates significant difference ($p < .001$) within-fork (frame value less than axle value).

between- or within-forks. The suspension forks showed similar axle jerk compared to the rigid fork, but unlike the rigid fork, suspension forks reduced the jerk transmitted to the frame. Thus, on medium bumps rigid forks probably allow the wheel to track the surface changes of bump impacts similarly to suspension forks, however with rigid forks the impact is fully transmitted to the frame and ultimately to the rider.

Large Bump (B3) Fork Comparisons

On the large bump (B3), the within-fork analysis revealed that initial contact peak acceleration (P1) was significantly lower at the frame compared to the axle for F1 ($p = .0001$) and for F3 ($p = .0001$). F6 and FR each showed no significant difference between axle and frame acceleration for P1 on the large bump (B3). These data suggest that softer forks attenuate initial impact acceleration better than stiffer forks. For the landing peak (P2), within-fork comparisons show significant differences in axle versus frame acceleration only for F3 ($p = .0012$). Jerk (J) was significantly reduced at the frame compared to the axle for all suspension forks; the rigid forks showed nearly identical values at the axle and frame.

Table 10. Large bump (B3) within fork axle versus frame contrasts for P1, P2 and J (mean ± SD) with linear contrast p values.

F1	Axle	Frame	Contrasts p-value
P1	45.3 ± 6.6	35.1 ± 1.9	.0001
P2	45.6 ± 9.6	43.5 ± 7.3	.5950
J	3.8 ± 0.6	2.7 ± 0.5	.0060
F3			
P1	45.8 ± 3.5	28.3 ± 3.9	.0001
P2	48.3 ± 14.7	34.8 ± 11.5	.0012
J	3.9 ± 0.4	2.3 ± 0.6	.0001
F6			
P1	40.5 ± 3.5	36.8 ± 3.4	.0154
P2	48.0 ± 9.2	45.5 ± 8.8	.5353
J	3.7 ± 0.5	2.7 ± 0.4	.0067
FR			
P1	35.2 ± 3.4	36.8 ± 3.0	.2971
P2	44.2 ± 14.8	45.5 ± 15.2	.7543
J	3.2 ± 0.6	3.2 ± 0.4	.8392

The P1 acceleration at the axle on the largest bump (B3) was significantly higher on all suspension forks compared to the rigid fork ($p < .0007$). P1 axle acceleration for F3 and F1 was similar and both were significantly greater than the F6 axle values ($p < .0021$). At the frame, P1 acceleration was lowest for F3 and was significantly different from all other forks (p <.0001). No other forks had significantly different acceleration at the frame on the impact peak (P1) on the largest bump (B3).

On P2, the landing peak, no significant differences were found between any of the forks at the axle, all allowed similar acceleration upon landing. At the frame, F3 shows a trend to be lower than F1, F6 and FR but this was not significant.

Jerk (J) did not show any significant differences between any forks at the axle or frame. Perhaps the maximum rate of compression was exceeded for even the softest fork (F1) and all were accelerated at a similar rate based on the inertia of the rider/bike system. In any case the suspension forks were unable to significantly increase the rate of acceleration at the axle, or decrease it at the frame for the largest bump.

Large Bump (B3) Summary

Based on these data it appears that F3, with moderate resistance to compression, performed better than all other forks. It allowed similar axle acceleration as the softer fork, F1, and this acceleration was significantly greater than the stiffer forks (F6 and FR). Despite having the high axle acceleration, F3 did not transmit this acceleration to the rider as was the case with F1. On impacts with large bumps it appears that a moderate degree of resistance to compression is advantageous.

Table 11. Large bump (B3) between-fork contrasts for impact peak (P1) at the axle and at the frame.

Axle	F1	F3	F6	FR
	45.3 ± 6.6	45.8 ± 3.5	40.5 ± 3.5	35.2 ± 3.4
F1	•	.7519	.0020	.0001
F3	•	•	.0007	.0001
F6	•	•	•	.0006
Frame	**F1**	**F3**	**F6**	**FR**
	35.1 ± 1.9	28.3 ± 3.9	36.8 ± 3.4	36.8 ± 3.0
F1	•	.0001	.2681	.2599
F3	•	•	.0001	.0001
F6	•	•	•	.9845

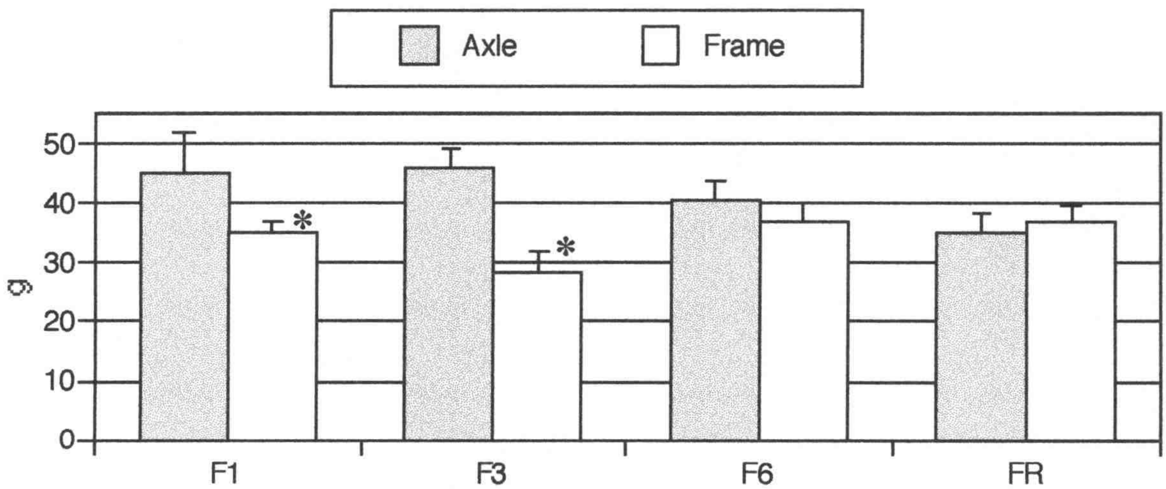

Figure 15. Large bump (B3) impact peak (P1) values at the axle and frame shown across forks. * indicates a significant difference ($p < .001$) within-fork (frame value less than axle value).

Table 12. Large bump (B3) between-fork contrasts for landing peak (P2) at the axle and at the frame.

Axle	F1	F3	F6	FR
	45.6 ± 9.6	48.3 ± 14.7	48.0 ± 9.2	44.2 ± 14.8
F1	•	.5219	.5634	.7215
F3	•	•	.9501	.3192
F6	•	•	•	.3505
Frame	**F1**	**F3**	**F6**	**FR**
	43.5 ± 7.3	34.8 ± 11.5	45.5 ± 8.8	45.5 ± 15.2
F1	•	.0368	.7215	.6254
F3	•	•	.0102	.0103
F6	•	•	•	.9989

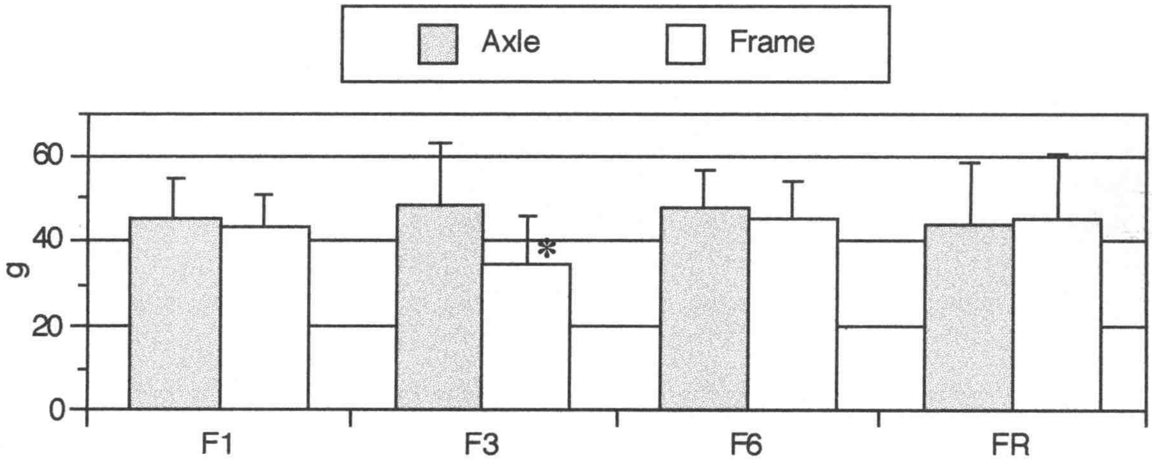

Figure 16. Large bump (B3) landing peak (P2) values at the axle and frame shown across forks. * indicates a significant difference ($p < .001$) within-fork (frame value less than axle value).

Table 13. Large bump (B3) between-fork contrasts for jerk (J) at the axle and at the frame.

Axle	F1	F3	F6	FR
	3.8 ± 0.6	3.9 ± 0.4	3.7 ± 0.5	3.2 ± 0.6
F1	•	.8100	.8826	.1033
F3	•	•	.6980	.0619
F6	•	•	•	.1382
Frame	**F1**	**F3**	**F6**	**FR**
	2.7 ± 0.5	2.3 ± 0.6	2.7 ± 0.4	3.2 ± 0.4
F1	•	.7197	.5921	.4712
F3	•	•	.8760	.7386
F6	•	•	•	.8532

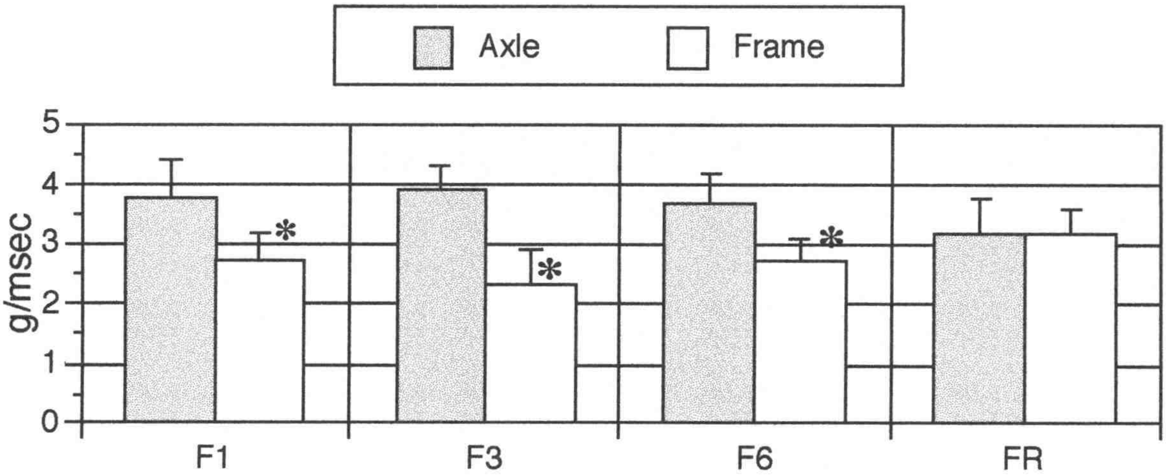

Figure 17. Large bump (B3) jerk (J) values at the axle and frame shown across forks. * indicates a significant difference ($p < .001$) within-fork (frame value less than axle value).

CHAPTER 5 SUMMARY

Mountain bikers are subjected to substantial impacts while riding, and suspension forks are designed to attenuate the impacts transmitted to the rider. Suspension forks are alleged to allow faster speeds, with better control and with less fatigue. Before these assertions can be evaluated, more basic questions about the ability of suspension forks to attenuate acceleration must be examined, and this was the goal of this investigation.

This experiment was designed to compare the acceleration at the axle and frame of mountain bike forks of different stiffness (resistance to axial compression). Accelerometers were placed on the axle and frame of a bicycle that was ridden down a ramp and across three sizes of bumps. Seven subjects participated after giving their informed consent. The bicycle was fitted with either rigid forks (FR), or suspension fork set on stiff (F6), medium (F3), or soft (F1). The bump impact consisted of two distinct peaks, one at bump impact (P1) and another at landing impact (P2) after a brief airborne period. The rate of acceleration (J) for P1 was also calculated and compared. A 2 x 3 x 4 ANOVA with repeated measure on two levels was used to analyze the data, with linear contrasts post hoc.

The design of suspension forks is based on assumptions about some of the most basic aspects of a wheel rolling over a surface. While this experiment was designed to assess suspension fork function across a range of stiffness and bump sizes, a brief outline of the assumptions underlying the functional goals of suspension forks is needed.

Riding on a bumpy surface causes slowing in many different ways. First, when riding a mountain bike from point A to point B, a straight line will get you there faster, all other things being equal. Straying from a straight line will increase the time it takes and will decrease the average velocity between point A and point B. In other words, any displacement of the center of mass from given straight line decreases straight-line velocity.

A bump causes both vertical and horizontal displacement which are influenced by the bump's shape. The vertical component displaces the bike/rider system upward and it returns to the surface due to the acceleration of gravity. As a bike goes up and down, straight line velocity decreases. The horizontal component slows the bike/rider system further by applying a braking force on the system. If the bump were high enough (a wall), the system would stop altogether, causing the cyclist to crash.

Riders therefore avoid bumps which are big enough to threaten control, and better riders also avoid bumps which slow them due to increased vertical excursion. Riders avoid bumps by turning and this increases the lateral displacement of the center of mass resulting in decreased straight-line velocity. Suspension forks are supposed to reduce the impact acceleration of these bumps and reduce the need of the rider to avoid bumps, which is claimed to increase speed.

It is apparent from this investigation that suspension forks are generally effective in reducing the acceleration transmitted to the frame during initial impact with a bump, provided that the bump is large enough. These data do not contradict the assertion that suspension forks should increase speed, provided that the bump impacts are large enough to elicit suspension fork impact attenuation.

Surprisingly, in this investigation the landing impact showed no significant reductions between forks; only F3 showed a significant within-fork reduction in frame acceleration compared to axle acceleration, and only on the largest bump. It is possible that the other suspension forks were not able to extend rapidly enough to be prepared for the landing impact, and upon contact in their compressed state, unable to attenuate the acceleration of the landing impact. It is also possible that the landing impact was similar among rigid and suspension forks due to the more vertical force vector of the contact surface, resulting in bending of the forks rather than compression. The effect of rider position may also have influenced these results, since off-balance landings may have increased the variability of the data and decreased the statistical power. It is also possible that the acceleration of the riders' mass due to gravity after being airborne from the initial impact may have applied more force at the landing impact than at the initial impact, altering the acceleration attenuation properties of the suspension forks. In the continuing development of suspension forks, acceleration attenuation of an impact following an airborne period appears to be an area where improvements could be made.

A complex equation is always being computed by mountain bike riders to find the best (easiest and fastest) path through bumps. The algorithm determines if a bump is large enough to avoid by steering around it. In essence, is the loss due to increased lateral excursion less than the loss due to the sum of the increased vertical excursion, the increased braking force, and the effort to regain the lost speed and control? This takes a tremendous amount of rapid visual assessment of the surface just ahead and cognitive processing, both of which are based upon prior experience.

On small bumps, 4 cm or less, suspension forks appear no better than rigid forks in attenuating initial or landing impact acceleration, suggesting that is unlikely that suspension forks would make any difference in the path a rider chose through a course of small bumps. Further refinements in suspension fork function on small bumps may be warranted, but it seems likely that high-frequency, low-amplitude impact absorption is an area where tires will always have significant advantage over suspension forks, due to the tire's low mass, rapid response and easy adjustability. Tires after all have been around since Dunlop invented them in 1876, and were in fact the first shock attenuation device widely used in bicycles.

Whenever bumps are encountered the rider must do something to absorb the impact acceleration. Large impacts tend to cause the trunk to flex due to braking forces and vertical forces imparted to the system. The rider must resist this trunk flexion with the back extensors, elbow extensors and other muscle groups, and mainly by eccentric contraction. The handle bar rises with each bump and if the rider wishes to hold on, he must grip it with greater force than if the bar was stationary. If a bump is avoided, force is required to turn the bike. All of these factors require muscular force and ultimately contribute to the rider's fatigue at the end of a long ride.

There is evidence that suspension forks do reduce delayed onset muscle soreness while mountain biking. Seifert, Leutkemeier, Spencer, Miller and Burk, (1994) showed that riders completing a course on mountain bicycles with rigid forks had serum creatine kinase levels—a marker of muscle breakdown related to high-force eccentric contractions—that were ten times of the levels of weight matched controls riding with suspension forks over the same course. Suspension forks are alleged to reduce the muscular force needed for mountain biking by attenuating the impact acceleration that reaches the rider.

The present investigation showed that impact attenuation did occur with suspension forks, but only on larger bumps and only on the initial impact. Suspension forks do little to reduced the acceleration transmitted to the rider during the landing impact. Only F3 on the largest bump showed a statistically significant decrease in frame acceleration compared to axle acceleration. Suspension forks may significantly reduce fatigue by the reduction in initial impact acceleration alone, but the lack of effective reduction in acceleration transmitted to the rider on landing impacts means that suspension forks offer only part of the possible advantages generally granted to them. Reductions in acceleration transmission during landing impacts would improve the reduction of fatigue apparently available at present.

Nevertheless, knowing that some impacts will be attenuated may improve a rider's confidence. Riders may be more likely to reach and maintain high speeds when they know that some portion of the larger bumps ahead will be attenuated by the suspension forks. Although the present investigation did not directly measure the speed of riders with suspension forks, the data do appear to support the contention that suspension forks allow riders to ride faster over large bumps. Clearly, further investigation is necessary to determine if impact attenuation by suspension forks results in mountain biking at higher speeds.

Besides increasing speed and reducing fatigue, suspension forks are also alleged to allow the wheel to move somewhat independently of the handlebars and is therefore better able to follow changes in the surface without forcing the rider's mass to also follow them. The separation of the front wheel from the bike/rider system reduces the effective mass of the front wheel; this allows the front wheel to move more rapidly and farther when a given force is applied to it.

By design, suspension forks should have greater acceleration at the axle than rigid forks. If it exists, this alleged difference should make the suspension fork front wheel have better traction because it should be in contact with the surface for a greater time than a rigid fork front wheel over a given stretch of ground. Less airborne periods translates into more contact time for braking and turning.

The wheel's surface is generally spinning at a rate so that the instantaneous contact point has a zero velocity relative to the surface over which it is traveling. If it is not, the tire has exceeded the static coefficient of friction and is skidding. If the front wheel is being braked by the rider as it becomes airborne, it is likely to stop spinning and be stationary as it returns to the surface again. This causes a brief period of skidding each time the front wheel returns to the surface. Suspension forks are supposed to reduce the airborne periods and therefore reduce skidding.

If the wheel is turned by the rider to make the bike go right or left, the airborne period reduces the effect of the turn on the bike's path, and forcing the rider to oversteer to accomplish a given radius. In this situation, the bike follows a jerky path around a corner, and the lateral static coefficient of friction is more likely to be exceeded leading to skidding. Suspension forks' effect on reducing airborne periods should also improve cornering capabilities.

However, no significant differences in axle jerk were found between the forks on any of the bumps. Suspension forks do not appear to allow the front wheel to accelerate upward more rapidly upon bump impact. Only at the frame on B2 was a significant difference found between suspension forks and the rigid fork. This suggests that the front wheel will accelerate at similar rates for rigid and suspension forks, the only apparent advantage being that with suspension forks this jerk is not transmitted to the rider.

Within forks, F1, F3 and F6 each had significantly lower frame jerk compared to their respective axle jerk on B2 and B3; F3 also showed significant within-fork reductions in frame jerk compared to axle jerk on B1. In essence, all forks had similar jerk but F3 transmitted less to the rider over a broader range of bumps.

After showing that there were specific advantages to suspension forks, many will wonder which fork performed best, resulting in the greatest axle acceleration, greatest attenuation of acceleration transmitted to the frame and allowing the highest axle jerk while limiting jerk to the frame. F3, with moderate stiffness, appeared to perform the best of all suspension forks. When comparing axle versus frame values within-forks, F3 showed six occasions where significant reductions in frame values versus axle values occurred: P1 on B2†, P1 on B3†, P2 on B3, J on B1, J on B2† and J on B3 ($p <.01$ in all cases). Those measures marked with † are especially important because significant reductions were also seen between the suspension forks and the rigid fork. F1, with the lowest stiffness, showed four within-fork significant reductions: P1 on B2†, P1 on B3†, J on B2† and J on B3 ($p <.01$ in all cases). F6, with the highest stiffness of the suspension forks, showed two significant reductions: J on B2† and J on B3 ($p <.01$ in all cases). FR showed no significant reductions in frame values compared to axle values on any of the dependent measures.

It is unclear how these result generalize to other riding conditions. Mountain biking is by nature over unpredictable surfaces which are extremely difficult to quantify, so conclusions about optimal stiffness for all possible conditions is unwise until further study is completed.

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APPENDIX

ANOVA tables for Peak 1, Peak 2 and Jerk

PEAK 1	df	Sum of Squares	Mean Square	F-Value	P-Value
FORK	3	588.016	196.005	23.646	.0001
BUMP	2	8170.490	4085.245	492.833	.0001
LOCATION	2	48344.817	24172.408	2916.093	.0001
FORK * BUMP	6	146.404	24.401	2.944	.0088
FORK * LOCATION	6	1683.687	280.614	33.853	.0001
BUMP * LOCATION	4	10128.429	2532.107	305.466	.0001
FORK * BUMP * LOCATION	12	819.273	68.273	8.236	.0001
Residual	216	1790.492	8.289		

PEAK 2	df	Sum of Squares	Mean Square	F-Value	P-Value
FORK	3	395.811	131.937	2.240	.0847
BUMP	2	7478.155	3739.078	63.487	.0001
LOCATION	2	59846.180	29923.090	508.072	.0001
FORK * BUMP	6	702.047	117.008	1.987	.0690
FORK * LOCATION	6	1290.410	215.068	3.652	.0018
BUMP * LOCATION	4	7052.722	1763.181	29.937	.0001
FORK * BUMP * LOCATION	12	222.075	18.506	.314	.9864
Residual	206	12132.450	58.895		

JERK	df	Sum of Squares	Mean Square	F-Value	P-Value
FORK	3	12.762	4.254	8.219	.0001
BUMP	2	52.812	26.406	51.017	.0001
LOCATION	2	806.626	403.313	779.211	.0001
FORK * BUMP	6	3.231	.539	1.040	.4000
FORK * LOCATION	6	20.726	3.454	6.674	.0001
BUMP * LOCATION	4	68.820	17.205	33.240	.0001
FORK * BUMP * LOCATION	12	7.500	.625	1.208	.2792
Residual	216	111.800	.518		