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ABSTRACT

The purpose of this investigation was to compare the effectiveness of two types of mountain bike front fork suspension systems for controlling ground reaction vibration at the handlebar upon impacting a raised surface. A second purpose was to investigate the effectiveness of these two suspension systems at maintaining ground-wheel contact following impact.

This investigation provided a direct measurement of handlebar vibration and ground reaction forces at the front wheel. A rigid front end was compared to an elastomer and a hydraulic suspension system each tested at their stiffest and softest settings. A single subject was chosen to perform repeated trials over an AMTI force platform modified with a 3 cm raised surface. Velocity and riding technique were controlled for reliability and rider weight displacement was measured using strain gauges mounted on the handlebar.

A shear quartz mode piezoelectronic accelerometer mounted to the handlebar provided vibration measurements and the AMTI force platform measured ground reaction forces. Mean curves for acceleration and ground reaction force were recorded and calculated from repeated trials and used system comparison.

Results from the mean curve comparison of the suspension systems showed reduced amplitude and frequency of vibration at the handlebar and improved ground/wheel contact time for both elastomer and hydraulic systems when compared to the mean curves for the rigid front end. Statistical analyses supported the mean curve results indicating significant differences between the rigid and the suspension systems on all variables analysed at the .05 alpha level.

It was concluded that the hydraulic and elastomer systems reduced handlebar vibration and improved ground-wheel contact when compared to the rigid systems for this particular subject and bike combination. This investigation supports claims made by manufacturers of suspension systems, that front suspension improves ground/wheel contact and reduces transmission of impact energy to the rider at the handlebar.

ACKNOWLEDGEMENTS

I would like to express my gratitude to those individuals who provided assistance in the completion of this document. I extend thanks to Mr. Carlos Zerpa for his invaluable technical assistance and support throughout the duration of this project. I would also like to thank Dr. Tony Bauer, Dr. Jocelyn Farrell and Dr. Jim Mcaulliff for acting as my thesis committee.

A special thank you to my father, Mr. Werner Laser for his technical assistance in building and donating the power supply unit used for data collection purposes and for his continued motivational support.

I would also like to express my sincere appreciation to Mr. Farzam Etemadi of Petrie's Cycle and Sport Shop for supplying the bike, the suspension systems and his mechanical expertise for this project.

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CHAPTER ONE

Introduction

The sport of mountain biking is quite possibly one of the fastest growing recreational and professional sporting activities in the world today. As the sport develops so too must the equipment required in order to meet the ever increasing demands of the athletes involved. Mountain bikes are no longer considered to be a heavier version of the sleek road and track racing cycles but are hybrid, technologically developed vehicles which are constantly undergoing refinement, redesign, and development. The most significant technological modification to the mountain bike has been the development of a suspension system modelled after those developed for motorbikes, or more specifically moto-cross bikes.

The first mountain bike suspension systems appeared at the elite racing level in response to the overwhelming performance demands placed on the bike and rider. Mountain bikes have undergone a significant metamorphosis in the past decade and the main change has been the implementation of the front suspension system. There are numerous manufacturers of front suspension systems each with their own performance standards. The underlying objective for an efficient front suspension is to decrease the amount of shock transmitted to the rider while maintaining ground/wheel contact (Orendorff & Smith, 1995). The objective is to improve bike handling and conserve impact energy transfer to the rider while reducing the effort required to keep the bike on course. With the appearance of at least five types of suspension system designs and at least ten different manufacturers, comparative assessments of the performance benefits are quite complicated. There are numerous engineering criteria for system evaluation but little biomechanical research has been completed to assess the effects of front suspension systems designed for the reduction of shock vibration. Vibration transmitted to the hands and upper body during the use of vibrating tools creating specific levels of vibration exposure, has been cited as the cause of numerous hand and upper limb disorders (National Institute of Occupational Safety and Health [NIOSH], 1989). It is reasonable to consider that the vibration exposure to the hands and upper extremity during mountain bike riding may also be of a sufficient level to present a safety risk. Vibration can lead to the development of any one of the many disorders related to hand transmitted vibration such as: white finger, Renauds phenomenon, carpal tunnel syndrome, or repetitive strain disorder to name a few (International Organization for Standardization [ISO], 1986). Measuring the effectiveness of suspension systems in terms of their capacity to reduce the transmission of impact vibration to the upper body is one method of evaluating suspension systems. The results of this study will provide an evaluation of the effectiveness of two types of mountain bike suspension systems currently available to the consumer.

Other than private commercial testing, there is relatively little published research available that provides for the comparison of different suspension systems. This research will provide information on the effectiveness of two suspension systems to reduce vibration at the handlebar, and improve ground-wheel contact. In addition, the measurement techniques provide an effective methodology for future investigations. Much of the research available on suspension systems is based on engineering concepts and deals with the mechanical nature of the bicycle system without taking into consideration the resulting effects on the rider operating the vehicle (Orendorff & Smith, 1995). An investigation focussing on the interaction between the vehicle and the operator requires consideration of two separate systems: the mechanical system (the bike) and the human system (the rider). This investigation attempts to evaluate the interaction between these two interdependent systems. In this particular study, the rider will be included for specificity but will be controlled as much as possible using monitoring methods to measure the operators consistency. This investigation addresses an isolated impact event that could occur while riding a mountain bike and attempts to provide a better understanding of the interaction between human and machine. The study also gives insight into the hand/bike interface to provide information for design efficiency for control of vibration transmission to the hands and upper body. One objective was to substantiate or refute the manufacturers claims that suspension does significantly reduce the amount of shock transmitted to the hands. This factor seems to be one of the more common advertising tools or sales pitches used to target the recreational rider market for mountain bike suspension systems.

The evaluation of vibration transmitted to the handlebar is also useful for making comparisons between the levels of vibration known to cause detrimental effects in the hand and upper limb in industry. Critical vibration exposure levels may also be experienced by mountain bike riders (Gerr, Letz, & Landrigan, 1991, Mishoe & Suggs, 1977; Ranny, 1993; and Wasserman & Taylor, 1991).

Mountain Bike Suspension Systems

Mountain bike suspension systems are an evolutionary product transferred from moto-cross racing technology. Front suspension systems were initially developed to improve bike handling and performance with respect to steering and keeping the front wheel on the ground for improved traction and maintenance of forward velocity. Without the damping effect of suspension, when a wheel hits a bump of considerable size, the wheel bounces off the bump and loses contact with the ground. Each time the wheel is off the ground, the rider has less control and loses angular momentum which is normally conserved when the wheel is rolling on the surface. While in the air the wheel slows its rate of revolution or stops turning all together depending on how long it is suspended. Maintaining ground contact allows for improved bike handling on rough terrain.

When suspension systems were first developed for mountain biking (Poole, 1991), less consideration was given to the rider's physical comfort than to the bike's performance. The effect of decreasing the level of shock transmitted to the rider is a convenient by-product of the shock absorber development, rather than a design objective. In mountain biking, because the source of locomotive power is the rider, the quality of the ride must be closely evaluated to minimize fatigue. Unnecessary energy expenditure, such as absorbing impact shock, will have a negative performance effect on the rider. Mountain bike suspension manufacturer's were quite aware of potential problems and exploited this theory as an advertising tool to sell suspension systems. The sales pitch is that suspension systems reduce the reaction force at impact. Less force is absorbed by the arms, legs, and body, leaving more energy available for pedalling faster or riding longer.

Purpose

The purpose of this research is to investigate the effectiveness of front fork suspension systems for controlling ground reaction vibration in the handlebar of a mountain bike when impacting a raised surface. A second purpose is to investigate the effectiveness of the suspension systems in maintaining ground-wheel contact following impact.

Definitions

Vibration	The oscillation or periodic motion of a rigid or elastic body from a position of equilibrium.
Oscillation	The variation in position of an object over time in reference to its starting position.
Frequency	The rate of oscillation; number of oscillations per unit time; the number of complete cycles per unit of time. One Hertz (Hz) is one cycle/second.
Spring rate	The measure of a spring's stiffness, expressed by how much weight is required to compress a given spring one inch, for example; a "100 lb spring" will compress 1 inch under a 100 lb weight.
Damping	The process of controlling energy loss from a compressed suspension following an impact which initially compressed the system, storing energy in it. The process by which the amplitude of the crest of a vibration is decreased.

Preload	A form of spring tension loaded into a suspension system. It puts the suspension in equilibrium with the rider's weight so it can support the rider's weight without compressing and causing a loss in available travel. If preload is too high the suspension will be stiff and unresponsive, if too little preload the suspension will bounce with the rider's movements.
Travel	The amount of distance the shock can move from minimum to maximum compression to absorb impact; in general the more travel the better absorption.
Elastomer	The material used to store energy in suspension system, usually urethane, may be solid or foam and can be designed to stiffen with compression.
Recoil	The release of energy from the compressed system, allowing it to return to it's resting length.
Stiffness	The ratio of force or torque to the resulting change in displacement of an elastic body.
Acceleration	The time rate of change in velocity (m/sec^2 or gravity). The second derivative of displacement with respect to time.
G's	The acceleration produced by the force of gravity/(1g=9.81m/s^2).
Accelerometer	A transducer used to measure acceleration or time rate of change in velocity.
Hertz (Hz)	A unit of frequency (cycles/second).

Spectrum, vibration	The distribution of frequencies that describes the frequencies that are present in a vibrating system.

Limitations

This research was conducted recognizing the following limitations:

1. The effect of only one impact on the suspension system was measured and not the effects of multiple impacts as might occur in the natural environment.
2. The impact effect of only one size of bump rather than variable sized bumps which may influence the performance of the suspension system was assessed.
3. The effects of the suspension were only measured at one velocity.
4. The use of a single subject limits the degree to which inferences may be made to other riders.
5. The findings are not representative of all suspension system designs available on the market.
6. The laboratory conditions do not allow for consideration of natural surface ie: gravel, sand, mud, etc. .
7. One bike was used in order to adopt the system to fit one somatotype.
8. The accelerometer and force platform were both factory calibrated outside of the laboratory and were assumed to be accurate. .

CHAPTER TWO

Literature Review

The purpose of this research was to investigate the effectiveness of vibration control at the handle bar and maintenance of ground/wheel contact for selected mountain bike front suspension systems. Much of the research regarding suspension systems is deemed to be of a proprietary nature and was not available for this investigation, however there is a considerable amount of research regarding hand-arm vibration and the use of vibrating tools/devices that provided valuable information with respect to the testing and measuring procedures for this study. As the sport is still in its infancy, research is currently in progress on many aspects of mountain biking.

Development of Suspension Systems

Bicycle suspension has been utilized since the late 1880's (Poole, 1991) but has not been in common use until recent adaptation by mountain bike racers. After the introduction of suspension in 1880 there were no significant developments until the 1950's and 1960's. At this point in time, Alex Moulton designed a system which was sold to the Raleigh Bicycle Company. Raleigh owned the patent but ceased production of the suspended bicycles in 1967 (Poole, 1991). It was not until 1983 that Moulton began to design another suspension system. During the 1970's suspension systems were introduced to the sport of bicycle moto-cross (BMX). The BMX bikes resembled scaled down versions of motorcycles but the suspension systems proved to be too heavy and unreliable (Poole, 1991).

With the development of mountain bikes in the late 1970's, popularity for the sport has grown so that mountain bike sales now dominate bicycle sales worldwide. With this boom, manufacturers have developed methods for differentiating their products from the competition. One way of achieving this was to produce a technically superior bike."The hottest trends in the mountain bike industry are lighter bikes and suspension" (Poole, 1991, p. 11). Today's suspension systems are due almost entirely to the influence of mountain bike racing, a sport still in its infancy. According to frame builder and designer, Keith Bontrager, "the book is still being written on mountain bike design because off-road riding creates so many conflicting demands on both the rider and the bike" (Roosa, 1990, p. 82).

The development of mountain bike suspensions in the early 1980's resulted in response to the ever increasing demands for a better handling bike. At this point motorcycle technology crossed into the mountain biking industry in the form of front suspension systems (Roosa, 1988). Initially, suspension was not about increasing or improving rider comfort, it was about performance. The focus was not on transforming a bumpy ride into a glide, but to keep the tire on the ground.

Bicycles have always had suspension to a certain degree. There has always been a "passive" suspension which includes the tires, the spokes, the rims, the padded gloves, and seats. The shock from impact will travel through a bicycle deflecting everything in its path including the wheels, forks, frame tubing, handlebar, and stem. These small deflections attenuate the shock a small amount before it is transmitted to the rider. "Every frame member interconnects and different materials react to shock in different ways" (Roosa, 1990, p. 75).

The new "active" suspension being added to today's mountain bike is thought to improve rider comfort by reducing the shock transmitted to the rider (Olsen, 1993; Poole, 1991; & Roosa, 1990). Another advantage thought to be gained by using suspension is the ability to ride faster. The rider gains increased control and will not have to work the arms and upper body to absorb shock as much. "It is the fine corrections that one does with hands and arms that prevents the rider from being able to absorb bumps and make steering corrections simultaneously" (Roosa, 1990, p. 82).

The greatest benefit of riding with front suspension is thought to be experienced when riding over rough terrain which should be less punishing to the body because less shock should be transmitted to the rider, leaving more energy for pedalling (Burke, 1994). The wrist and upper body will take much less abuse and the wheel will stay on the ground (Price, 1989). It is vital that the wheel remain in contact with the ground for the rider to maintain velocity. If the wheel leaves the ground at any point there are losses in forward momentum. A wheel coming into contact with the leading edge of a bump experiences an upwards force. If the force is great enough to lift the wheel or even just to reduce the force between the wheel and the ground then a portion of the forward momentum is lost (Roosa, 1990). The result is that the bike slows down. On rough terrain, momentum losses can be severe. Loss of ground contact also causes diminished rider control and off-road riders are continually wrestling with the handlebar to keep the front wheel on the chosen line, thereby expending muscular energy that could be used for pedalling.

Mechanics of Suspension

Suspension acts to smooth the ride as well as add a more controllable compliance by introducing a spring and a mechanism to control its motion via damping (Langley, 1992a). Suspension has been designed to keep the wheels in contact with uneven surfaces, smoothing the ride to decrease fatigue in the rider, and in the vehicle structure (Price, 1989).

Springs support the weight of the vehicle (bicycle) but once set in motion, the springs may oscillate for many cycles before arresting (Price, 1989). Springs are constantly excited when the vehicle is moving. Shock absorbers or dampers are associated with a suspension unit to eliminate or decrease the oscillation to within a few cycles.

In the design of motor vehicles, suspension systems are considered with respect to sprung and unsprung weight (Price, 1989). Sprung weight consists of all parts of the vehicle including passengers that sit above the springs. The wheels and their support structures that attach to the underside of the spring comprise the unsprung weight. "The springs serve to isolate the sprung weight from road vibration and shock as well as minimize extraneous vehicular motions like swaying, bobbing and pitching." (Price, 1989, p. 21). In contrast to stabilizing the sprung weight the springs allow the wheels to move freely, rising and falling to follow the contours of the ground. Since the unsprung weight is usually small compared to the sprung weight, the wheels can move quickly to maintain traction and directional control. In a bicycle without suspension the situation is quite different. The rider is the vehicle and the entire bicycle becomes the unsprung mass.

The arms and legs serve as suspension members working as shock absorbing levers (Roosa, 1988).

Springs make the bicycle wheels more responsive to a host of vertical and lateral forces. The wheels are therefore able to trace the contours of the ground more precisely and maintain better traction. Suspension systems are commonly referred to as springs and these springs are commonly constructed of one of three materials:

1. Steel-coil springs, a simple reliable wire wound into a coil often designed to stiffen as it becomes compressed.
2. Gas, trapped in a cylinder, is compressed by a piston offering steeply increasing stiffness as full travel is approached.
3. Fluid-hydraulics, usually oil is forced to flow through small holes or 'ports'. Viscous fluids resist movement and mechanical energy is converted to heat.

The mechanics of the active suspension are as follows; when the wheel encounters a bump, the impact causes an increase in the kinetic energy through the system. The springs of the system are compressed to absorb the shock energy of the impact. The compressed spring is essentially storing this kinetic energy from the impact. Damping refers specifically to the process of controlling the energy absorption and rebound damping refers to the energy loss from the compressed suspension system.

There are three methods by which damping is achieved, they are:

1. Friction This occurs in all types of suspension systems (springs) to some degree however, energy losses due to friction are difficult to control.

2.	Hysteresis	This is found to occur in elastomer or rubber bumper systems. Elastomers have an inherent energy loss due to mechanical deformation of material. Energy is lost as heat. Different materials offer varying amounts of damping.
3.	Hydraulic	This occurs when a viscous fluid resists flow and mechanical energy is converted to heat. The size and number of ports may be varied as may the viscosity of the fluid to alter the degree of damping.

Front Fork Suspension Designs

Active front suspension systems may be found anywhere between the front axle and the hand grips. There are many motorcycle style telescoping forks, some using steel coil springs and friction, some using elastomers for both spring action and damping, some hydraulic (see Figure 1), and some systems combine hydraulic with elastomers. There are also an increasing number of linkage forks available on the market.

The most common mountain bike suspensions are the telescoping forks. The bike designers believe that "suspension ideally belongs at the front wheel to create the most favourable ratio between sprung and unsprung mass" (Roosa, 1990, p. 79). Not as common in elite racing, but gaining popularity with recreational riders, is the stem suspension unit which supports the argument that suspension is not as much about bike handling but rather, rider comfort.

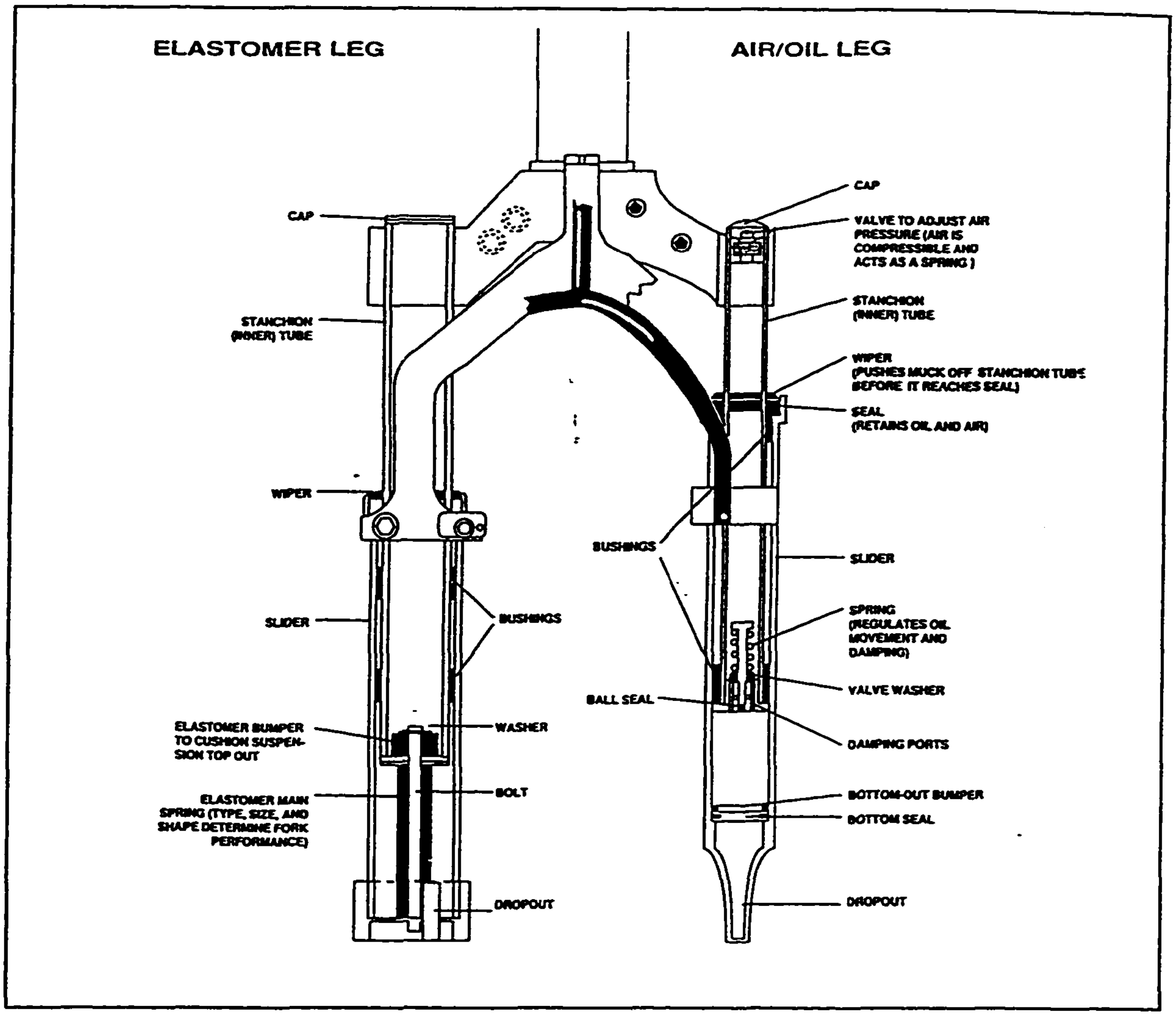

Figure 1. Diagram illustrating two types of front suspension being tested. The left leg represents an elastomer bumper system which compresses to cushion bumps and the right leg shows a hydraulic system where oil is forced upward in the stanchion tube to reduce shock.
Note: Adapted form "Suspension Comprehension: A Guide to this Year's Shocking Array of Forks and Swing Arms." by J. Olsen, 1993, Bicycling, 34, 60-65.

The telescoping forks to be evaluated in this research include an elastomer bumper style fork and a hydraulic fork (see Figure 1) each being tested at its stiffest and softest settings which will be compared to a rigid fork being tested as the control. Each system has inherent weaknesses but each is thought to be effective in improving the quality of the ride. Travel, preload, spring stiffness, type and strength of damping, and handling factors must be considered when discussing different types of suspension. (Olsen, 1993).

Elastomer Systems

Elastomer systems rely on urethane bumpers for the spring action that produces the damping effect on impact. The degree of preload of an elastomer system depends on the material characteristics of the bumper itself. The bumpers are available in varying densities, some designed to stiffen with compression. The softness or stiffness of the elastomer is referred to as the durometer (Zinn & Nicol, 1992). Friction damping is achieved with the sliders, wipers and legs slowing down the recoil, or bounce back of the elastomer bumpers. Some friction damping is built into the elastomer itself to counter their tendency to behave like springs. However, elastomers are ‘location sensitive’ which means that the harder the system is compressed, the harder it will push back until it reaches its original position. This makes recoil difficult to control in elastomer systems (Nicol, 1992).

In an elastomer bumper suspension system, a limitation is spring travel. With the elastomer system being evaluated in this study, the amount of travel is limited to 3 cm. However, in light of this fact it must be considered that the travel is limited because the fork has been designed to have the same length as the bikes originally designed rigid forks. This characteristic limits any geometry changes that may occur when an after market suspension system is installed which may affect bike handling.

Hydraulic Systems

The mechanical action damping characteristics of a hydraulic system offer greater control over compression and recoil of the suspension system. The hydraulic recoil is speed sensitive therefore the system will always return to its resting position at a constant rate of speed no matter how much force had been applied to compress it. The rate of damping and recoil can be finely tuned to the riders preference however, hydraulic systems do have higher stiction than elastomer systems meaning that they have a greater resistance to initial movement or a higher preload.

The hydraulic system being tested in this investigation provides up to 5 cm. of travel but this causes changes in the bicycle head angle, of up to 2 degrees altering the bikes handling and responsiveness (Poole, 1991). After market suspension systems placed on a frame not designed for the extra length will slow steering by causing changes in the bikes handling (Roosa, 1990).

The preload contributes to performance variations in different types of telescoping forks. Increasing the preload will cause an increase in the amount of force necessary to activate the compression of the system. If there is too much preload the system will not absorb smaller impacts and/or washboard type surfaces and only significant impacts will activate the system. Too little preload will cause the system to behave like a pogo as the weight of the rider alone would be enough to compress the system and any additional impact would start the system bouncing.

Controlling preload in elastomer systems is achieved by changing the density or the shape of the elastomer bumper. The bumper is similar to a plug that fits inside the fork leg as shown in Figure 1. However, the rider is limited to a small selection of different bumpers. With a hydraulic system the preload setting may be finely tuned. Adjusting the size or the number of the ports or changing the viscosity of the oil in the system acts to control the rate at which the compressed system rebounds. As well, the amount of air pressure in the pneumatic chamber may be adjusted to suit the rider's weight, style, and preference. One of the problems often encountered with hydraulic systems is that the damping may be too strong to allow the wheel to react to a series of smaller impacts. The strong damping prevents the wheel from moving fast enough as the hydraulic fluid can only move so quickly. If this happens the suspension will behave as a solid/rigid fork without any absorption.

The main argument between using hydraulic or elastomer systems is dependent upon the type of terrain over which the bike will travel. For terrain with frequent small bumps, washboards, gravel, roots, and rocks the better system would be the one which is easily activated and responds quickly, such as the elastomer systems. However, if the ride will be mainly on smooth surface with occasional fallen trees, boulders, big ruts or rocks, a more suppressed system response like that of a hydraulic system is required to manage the greater impact forces without running out of travel.

The pros and cons for each system must be considered with the type of terrain and style of riding for which the bike will be used. The hydraulic systems may require more maintenance work and are heavier, adding additional weight to the bike than the elastomer system. However, hydraulic systems do have the advantage of allowing for a customized preload and damping for the rider. Each system is claimed to be the most effective at decreasing the amount of shock vibration transmitted to the rider but there has been little biomechanical research published to support this contention.

Previous Research

The theoretical advantages of suspension systems have been considered to be concerned with improving vehicle handling and the quality of the ride. Actual data to support these advantages is limited, however, research is ongoing and some interesting investigations have been published to support the advantages of using front suspension. In a 1994 article Burke reported that physiologist, Dr. M. Berry (1994) attempted to quantify the physiological advantages of using suspension in a project that required the subject to ride a bike with and without suspension on a treadmill with 2 x 4 inch boards attached, set at a 2% grade, running at 6.5 mph. The purpose of this investigation was to compare energy expenditure and physical stresses between riding suspended versus rigid (unsuspended) bikes (Burke, 1994).

The findings reported that under suspended conditions the energy expenditure was significantly lower than when riding with a rigid bike (Burke, 1994). The rigid trial resulted in an energy expenditure that was 13% higher than the front suspension trial. It was also reported that 1.8 calories/minute could be saved in energy cost using suspension which adds up to over 100 calories/hour. Ratings of perceived exertion were also reported as being significantly higher for the rigid versus the suspended trial.

Other physiological research performed to support the theory that suspension reduces fatigue in the rider has been performed at the University of Utah. Investigators had 12 trained cyclists ride on an outdoor single track course with an average velocity of

10 mph for one hour under three different bike conditions including a front suspended bike, a fully suspended bike, and a rigid bike. The results indicated the average heart rate for the two suspension bikes was 146 heart beats per minute (bpm) while the average heart rate for the rigid bike was 154 bpm. Perceived exertion was also reported to be lower for the suspended bike trials than the rigid trial. One of the most interesting measure taken in this study examined the serum creatine kinase in blood samples taken from the subjects 24 hours after they performed the exercise. Creatine kinase is the enzyme found in the muscle tissue that will increase in the blood when muscle damage occurs (Seiffert, Leutkemeier, Spencer, Miller, & Burke, 1994). An increase in the serum creatine kinase is indicative of muscular cell trauma, and exposure to repeated high amplitude shock or vibration as occurs during mountain biking is great enough to cause damage to the musculature of the upper extremity resulting in measurable changes in post riding creatine kinase levels. Attenuating the shock or vibration that the upper extremity is exposed to during mountain bike riding is one method of decreasing the amount of muscular damage sustained to the upper extremity of the rider. Riding a suspended mountain bike has been shown to reduce the amount of muscle cell damage as measured using serum creatine kinase levels as an index for the amount of damage that has occurred.

Seiffert et al. 1994, reported that when the athletes rode the suspended bike the amount of serum creatine kinase was nearly ten times lower than when the athletes rode a rigid bike. Conclusions from these results were that the body will receive much less muscle damage and trauma if one selects a suspension bike while riding a tough course.

Further observations made on these systems indicated that riding front suspension bicycles resulted in faster finishing times in cross country time trials and also accounted for lower average heart rate and creatine kinase levels. These findings lend support to the theory that trail shock detracts from speed and endurance (Seiffert et al., 1994).

These two physiological studies provide evidence that suspension systems are an effective component in improving the rider's performance but they do not offer any advice on how to select the most effective system from the overwhelming selection of suspension systems available for the consumer. Although annual reports on various suspension systems appear in numerous mountain biking/cycling magazines there is little scientific data presented to support the decision to purchase one particular system over another.

Bicycling magazine in its October 1994 issue produced a listing of numerous suspension systems evaluated on their exclusive fork tester known as 'the Monster'. Initially this testing device was called the mobile on bike suspension tester because it was originally designed to be carried on the bike and measure the g-forces that the rider experienced when encountering terrain variations such as bumps, dips, or washboards. The monster used to evaluate front suspension systems for the article in the October 1994 issue was a stationary system modelled from the mobile on bike suspension tester to create a controlled environment that would allow for comparisons of different systems. The testing device had a pivoting arm loaded with 68 lbs. of force (the approximate weight of a 150 lb. person distributed over the front wheel), a rotating drum with various sized bumps attached, and a pair of accelerometers mounted at the handlebar. The results were reported in G's measured for 1, 2, and 3 inch bumps (Dr. Z, 1994).

The most relevant scientific data to this current investigation was reported by Orendurff, Fujimoto, and Smith (1994) from Oregon State University. Orendurff's first investigation suggested that acceleration on the frame increased with fork stiffness. This single subject design lacked a control condition so comparison between suspended and rigid was not possible. In a subsequent investigation Orendurff and Smith (1995), examined the effect of rigid fork and suspended fork stiffness on impact acceleration with three different size bumps. Using two accelerometers, one mounted at the axle and the other on the frame, the results were reported for initial peak and landing peak acceleration, and the slope of the initial peak. The findings indicated that the suspension forks reduce large impacts transmitted to the rider through the front wheel (Orendurff & Smith, 1995). However, the acceleration at the bike-rider interface of the handlebar was not measured so the degree to which shock absorption effects the amount of shock being transmitted to the rider was not assessed. By placing the measuring device on the handlebar it is possible to measure the amount of vibration that is potentially being transmitted to the riders upper body.

Measurement Techniques

In order to evaluate the amount of vibration transmitted to the rider from the bike it is necessary to interpret the characteristics of vibration. Vibration is an oscillatory motion which means that the motion is not constant but alternatively more and less than an average value. The degree of the oscillation determines the magnitude of the vibration and the rate of the repetition (cycles of oscillation) determines the frequency of the vibration. Vibratory motion may be defined as being either deterministic or stochastic. Deterministic motion is characterized by a constant periodic wave form following a sinusoidal wave pattern. Stochastic motion is best described as random characterized by non-periodic wave forms when plotted as may be seen with shock or impact (Griffin, 1990).

The majority of research performed on vibration focuses on sinusoidal or deterministic vibration while less research has examined responses to non-periodic or shock motion. In performing vibration measurement one must take into account the fact that vibration conditions vary from one moment to the next. Vibration that is sampled over a period of time is independent of the period of time over which it was sampled (Griffin, 1990). Therefore, it is incorrect to assume the motion is stationary and that a representative average value can be used to indicate severity over the full sampling period. For this reason one must consider maximum values and ranges when assessing vibratory motion, particularly so when the nature of the vibration is non-deterministic and does not follow a sinusoidal pattern.

Hand Vibration

The investigation proposed in this study is concerned with evaluation of the vibration at the handlebar that may be transmitted to the bike rider's upper body. Hand-transmitted vibration is a term commonly used to denote vibration entering the body at the hand. The principle causes of hand transmitted vibration involve situations where the hands and fingers grasp or push some type of vibrating object such as motorcycle handlebars (Griffin, 1990).

Hand transmitted vibration by definition may be concerned with effects that occur only in the fingers or hand but this vibration may be transmitted further into the body and the effects it produces there may also be of interest in vibration measurement research. Measurement of hand-transmitted vibration has traditionally been done in an attempt to better understand the adverse effects on the hand and upper limb from various vibration exposures. The principal causes of severe hand vibration are identified in the literature (Wasserman 1987; NIOSH 1989; ISO 1986; and Burstrum & Lundstrom, 1994) as being the tools and processes in agriculture, mining, and construction where the hand and fingers grasp or push vibrating objects (Griffin, 1990). The quantification of the extent of the adverse effects of hand transmitted vibration has been ill-defined and incomplete (Griffin,1990). A wide range of disorders caused by vibration exposure may be classified into five separate types of disorders. The diagnosis of each of the five types requires different procedures and some types are associated with specific sorts of vibration. The five possible disorders include, vascular disorders, bone and joint disorders, peripheral neurologic disorders, muscle disorders, and other disorders including; whole body and central nervous system (Taylor 1989; Taylor & Brammer 1982; Pykko & Stark 1986; Wasserman 1987; NIOSH 1989).

In assessing hand transmitted vibration one must be aware of the complex interactions between the relevant variables making it very difficult to discern a simple cause-effect relationship between vibration and detrimental effects to the hand (see

Appendix A). The relative importance of shock and continuous vibration in the production of various vibration induced injuries is not well understood however, there has been some evidence that injury to bone and joints is partially associated with low frequency shock (NIOSH, 1989; Brammer, 1986).

When assessing factors that affect hand transmitted vibration the type of tool or device used is not as important as the characteristic of the vibration exposure and those factors which affect its transmission to the hand or the susceptibility of the hand to adverse affects (Griffin, 1990). Exposure to hand-transmitted vibration is very complex and is difficult to quantify. Vibration entering the hand will often occur in three translational axes and even then the amount of vibration may vary between the hands or along the length of the handle. The magnitude of vibration will likely change from one instant to the next and may contain both low magnitude vibration and high magnitude shock. The vibration may extend over a wide frequency range and is also dependent on the condition and usage of the device being held (Griffin, 1990).

Measurement Units

Components of vibration that have been measured in previous research include acceleration reported in m/sec^2 or g's, frequency reported in Hertz (Hz), and duration of exposure reported as min/day or hours/day (NIOSH, 1989). Vibration acceleration is commonly measured in three orthogonal basicentric axes at the point on the handle as close as possible to where vibration enters the hands (see Figure 2).

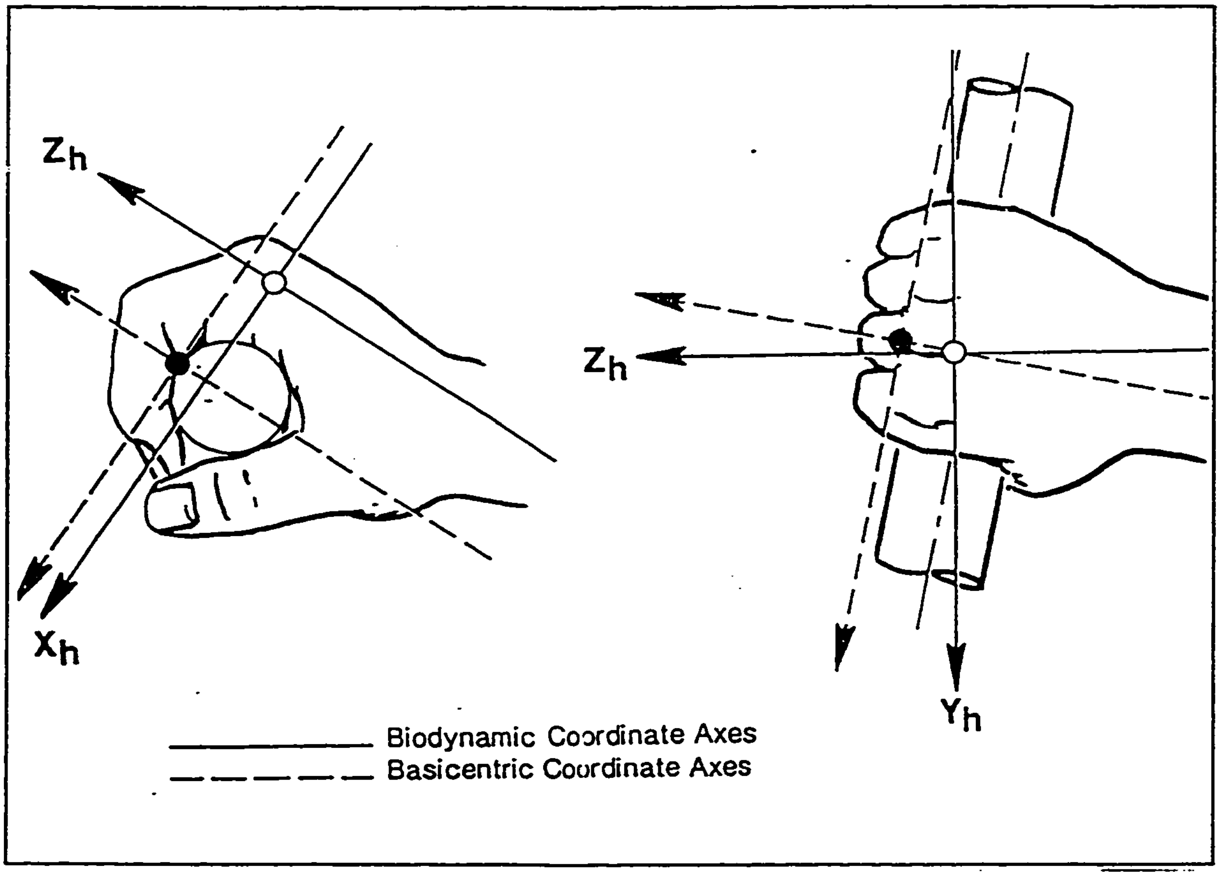

Figure 2. Basicentric Axes (x, y, z) for the hand (h).

NOTE: Adapted from the Handbook of Human Vibration (p.16), by M.J. Griffin, 1990, London, Academic Press.

The basicentric axis of greatest acceleration may be used to calculate acceleration levels. In order to understand the relevance of a vibration measurement one must be aware of the three components of a vibrating system. These are mass, elasticity, and damping (Griffin, 1990).

The kinetic energy of a system is a function of the mass and motion of the system. The potential energy of the system is a function of the mass and elasticity of the back and forth between kinetic and potential energy. In the absence of any mechanism to take energy out of the system, a system will theoretically vibrate forever once it begins to oscillate. Damping is the mechanism that transforms the kinetic and potential energy into heat and thereby takes energy out of the vibrating system. Thus if no energy is directed into a system to keep it vibrating, the damping will dissipate the initial energy in the system and all motion will stop (NIOSH, 1989, p.12).

Shock absorbers provide a means for taking energy out of the system via a damping mechanism that absorbs kinetic energy and stores it as potential energy. The damping is achieved through deformation of elastomer bumpers or by fluid being forced to flow through ports in the hydraulic suspension system. Following the impact the elastomers decompress and the fluid moves back through the ports thereby releasing the stored potential energy.

Acceleration. Measurement of acceleration is most commonly used to assess vibration. The three parameters which describe the amplitude of vibration as a function of the frequency are; displacement, velocity, and acceleration. Acceleration is used to specify vibration as both velocity and displacement can be calculated by integrating the acceleration signal over time. As well, accelerometers are commercially available and allow for ease of measurement. A third reason for using acceleration as a measure of vibration is that the amplitude of acceleration at higher frequencies is considerably higher than either displacement or velocity making it easier to take an accurate measure.

Commercially available accelerometers are capable of measuring the amplitude of vibration associated with hand-transmitted vibration. Piezoelectric accelerometers can be designed to measure vibration within a frequency range of 1 to 50,000 Hz (NIOSH,1989). The accelerometer reacts to vibration with a small mass that moves across the face of a crystal element. When vibration impinges on a piezoelectric accelerometer, the movement of the mass across the crystal creates an electrical voltage proportional to compression of the mass against the crystal. The resulting voltage is proportional to the acceleration. The voltage signal is often amplified to overcome signal loss problems by measuring changes in the electrical charge of the crystal caused by vibration.

As vibration is a vector quantity it is often necessary to make measurements in each of the three orthogonal axes. These three measurements can be obtained by use of a triaxial accelerometer or by three regular accelerometers that are oriented along three orthogonal basicentric axes attached to a small metal cubic block (Hempstock and O'Conner, 1977; Reynolds & Angevine,1977; Wasserman &Taylor, 1991; Wasserman 1987).

Of the three orthogonal basicentric axes, the dominant single axes vibration directed into the hand is used in assessing the vibration measured (ISO, 1986). In other words, the basicentric axis of greatest acceleration may be used to calculate acceleration levels (NIOSH, 1989)

The vibration levels that are measured at the handle do not necessarily represent a true measure of the energy that is directed into the hand and upper body. Consideration must be given to the effects of coupling between the hand and handle as the degree of vibration energy transmitted to the hand from the handle may be influenced by any combination of these factors: grip force exerted by the hand around the handle, axial or static force exerted by the hand on the handle, size of vibrating surface in contact with the hand, body position associated with respect to handle

The most important of these are the axial force and the grip force exerted by the hand on the handle (Griffin, Macfarlane, & Norman, 1982).

If one were to attempt to obtain a true measure of the energy that is directed into the hand, the coupling that occurs between the hand and the handle must be evaluated by measuring grip force as well as acceleration. This can be accomplished by breaking the vibration that is directed into the hand into its harmonic components. One can also determine the amount of energy that is stored in the hand as kinetic and potential energy and is consequently transferred back and forth between the hand and vibrating handle (Brammer & Taylor, 1982; Wasserman &Taylor, 1991).

Mathematical models of the hand and arm that have been developed generally imply that the vibration energy directed into the hand at frequencies below 80 Hz is transmitted to and can be perceived by the arm. From these models it was also determined that vibration energy directed into the hand at frequencies above 100 Hz is more local to the area of the hand in contact with the vibrating surface. Radwin, Armstrong, and Chaffin (1987) reported that vibration can affect the operators hold and use of the vibrating device which is then reflected in altered work performance and risk of injury.

With increased vibration, grip force on the handle is increased and tactile sensitivity is decreased (NIOSH, 1989).

Force Measuring the ground reaction forces of the front wheel as it crosses over the force platform allows one to evaluate how effectively the suspension systems behaves to maintain wheel contact with the ground following impact with a bump. The force platform measures the amount of force imparted in the vertical axis. As the wheel crosses the plate and rolls over the bump it gains potential energy, some of this energy may be absorbed into the tire, the front fork, and the frame of the bicycle. Some of this energy will be expended as kinetic energy, expressed by a period of flight or decreased pressure contact with the ground. One of the primary functions of a front suspension system is to maximize ground/wheel contact so that the rider may maintain steering control as well as being able to maintain forward propulsion. Once the wheel loses ground contact, any energy being imparted via pedalling is lost as there is no way for the energy to get to the ground. Once airborne, the wheel will lose angular momentum and stop spinning which translates into a loss of energy that could have been directed at propelling the bike forward. The magnitude of this energy loss is even greater if one considers that the rider must recover from this loss by exerting an even greater pedalling effort to compensate for this reduction in forward momentum.

Having a front suspension system should decrease or eliminate the degree to which ground/wheel contact may be compromised because the systems are designed to absorb the kinetic energy imparted on impact. Some of the absorbed energy is dissipated as heat while the remainder is stored via compression of the system. For example the compressed elastomer, or the movement of fluid through the ports in a hydraulic system. It is this stored potential energy that allows for maintained ground /wheel contact. As the system releases this stored energy (decompresses) it exerts a downward force, pushing the wheel back against the ground and thus avoiding decreasing levels of contact with the surface.

CHAPTER THREE

Methodology

The main purpose of this research was to evaluate the effectiveness of two types of mountain bike front suspension designs for reducing the levels of vibration transmitted to the handlebar when impacting a bump. A secondary purpose to this investigation was to evaluate how effectively these same front suspension systems maintain ground/wheel contact when impacting the bump.

Vibration reduction and improved bike handling are considered to be the two benefits achieved through a front suspension system. There is however, little published scientific data available to support the degree of suspension effectiveness. Two suspension systems will be compared to a rigid control system utilising variables indicative of the level of vibration at the handlebar and the amount of ground reaction force created while riding over a 3 cm. bump.

Apparatus

The testing will be performed in a gymnasium. A ramp measuring 1 m in height with an angle of descent of 60 degrees was placed 2.7 m in front of an AMTI force platform as illustrated in Figure 3. The size of the test space limited the size of the ramp and testing velocity. The force platform was mounted into the gymnasium floor according to factory specifications. A 1/4 inch plate of aluminum measuring 33 x 38 cm. was mounted directly on top of the force platform and to this plate is mounted the bump that

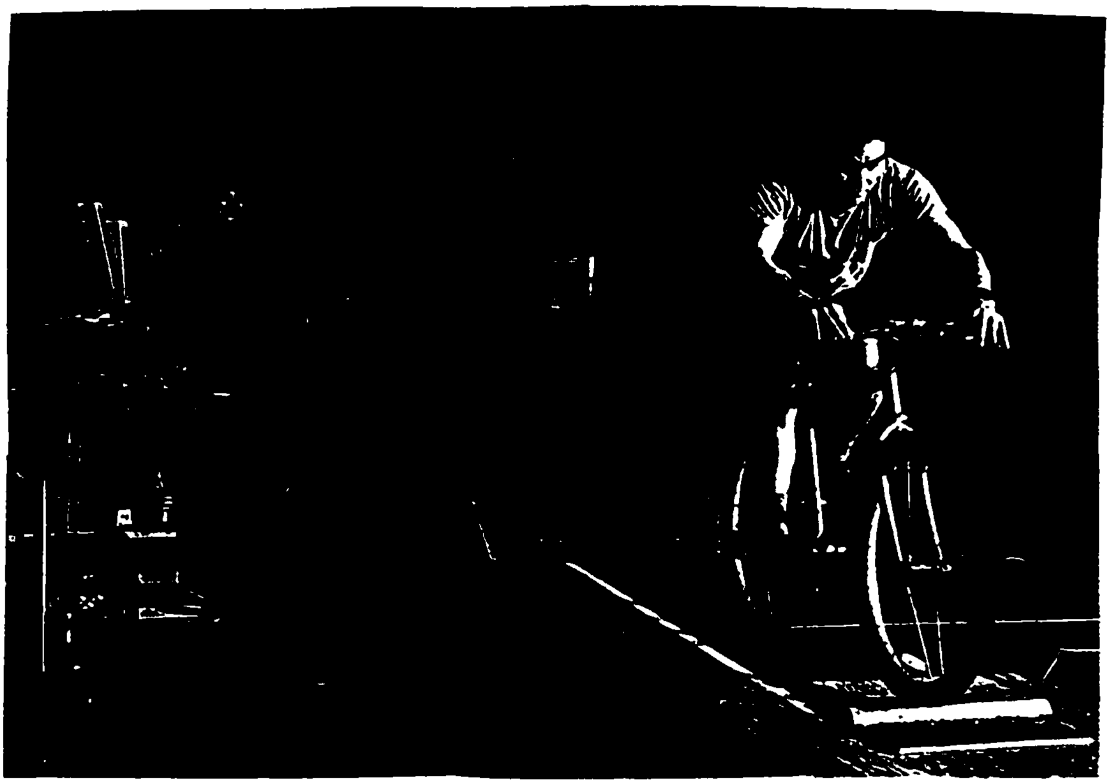

Figure 3. Photograph of apparatus set up for Accelerometry and Ground Reaction Force measures.

that was 3 cm. in diameter but was cut longitudinally and mounted at right angles to the subject/riders direction of travel across the plate. The leading edge of the plate was bevelled to 60 degrees so as not to create an impact response when the bike wheel rolls onto the plate.

Vibration measures was recorded using a triaxial accelerometer mounted at the stem of the handlebar. The accelerometer is mounted in the Fx plane according to the basicentric axis system illustrated in Figure 2. A shielded cable connected the accelerometer basicentric axis system illustrated in Figure 2. A shielded cable connected the accelerometer to an amplification system and a personal computer. Data was acquired and processed using the Global Lab data acquisition software (Data Translation, Inc., 1993).

Strain gauge measurements are recorded from eight strain gauges. Four strain gauges are mounted orthogonally about the handlebar at 2.5 cm to the left and the right of the centre of the handlebar. The strain gauge output is amplified and linked to a personal computer using a shielded cable and all data is computed through the data acquisition software. Data collection for both the accelerometer and the strain gauge was initiated using a light beam mechanism .25 m in front of the force platform at the base of the ramp.

Force plate data was collected on a second computer using the AMTI force platform software (Advanced Mechanical Technology, Inc., 1993). Only data in the Fz plane was used for analysis of the ground reaction forces created when riding over the platform. The Fz plane was the only plane of interest considering that this is the plane where vertical forces are measured and would best indicate any loss of ground contact.

Technical Development

The development of the measurement instrumentation is the result of a series of experimental trials resulting in the adoption of three simultaneous measures; strain gauges for the rider's weight distribution, accelerometry for handlebar vibration, and the force plate for ground reaction forces. Initially the strain gauges were used as a tool to evaluate the vibration at the handlebar. The force/time output from the strain gauges was applied to the relationship F = Ma. However, determining the proportion of the rider's mass that was acting on the handlebar presented difficulties. The use of an accelerometer to measure vibration then became an option. With the accelerometer to measure vibration the strain gauges were then incorporated as a control to record the consistency of the riders weight transfer onto the handlebars. The control measure was necessary to provide a reliability measure of the rider's mass force displacement over multiple trials.

Strain Gauge Control Measurement

Eight strain gauges were mounted orthogonally about the handlebar at 2.5 cm to the left and right of the centre of the handlebar. The strain gauges were used to measure the total bending forces applied to the handlebar using a summed resultant force output. Attachment of the strain gauges was performed according to manufacturers instructions. A Wheatstone bridge connected each set of four strain gauges linked by a shielded cable to a custom built power supply unit. The power supply provided 12 Volts DC to drive the Wheatstone bridge and the power supply unit was also equipped with two amplifiers with gain of 52.25 to manipulate the signal. The amplified signal was processed through an analog to digital converter. The digital signal is processed by the Global Lab program which converts the signal from volts (V) to Newtons (N) using an established calibration factor. This measure was recorded by hanging a 16 kg load off the handlebar. The calibration factor is expressed by the relationship; 16 kg x 9.8 N = .243 V/channel.

Acceleration Vibration Measurement

The accelerometer utilized in this investigation was manufactured by Piezotronics Inc., it is a quartz shear mode ICP accelerometers designed for high precision shock and vibration measurements. Mounting of the accelerometer was achieved following the manufactures instructions. Initially three accelerometers were mounted at the centre of the handlebar to record vibration activity in each of the three orthogonal axes. The accelerometers were connected to the same power supply unit as the strain gauges via a shielded cable. The signal from the accelerometer was amplified as was the signal from the strain gauges. The amplified software signal was processed through an A/D converter and then processed by the Global Lab data acquisition software. The computer output was graphically presented as a millivolts/time curve. Using manufacturer calibration data, the millivolts (mv) signal was converted to units of g-forces/time (10.41 mv/g) which was subsequently converted to an acceleration value of m/s^2 by applying the calibration factor of 0.102 $g/m/s^2$ (Appendix C).

Pilot study data revealed that the magnitude of the signals obtained in the Z and Y planes was negligible compared to the magnitude of the signal obtained in the X plane. Therefore data obtained in the X plane was utilized for this investigation.

Analysis of the accelerometer data required manipulation of the original signal in order to determine the frequency range of the vibration occurring in the handlebar itself. The raw signal was processed using a Fast Forward Fourier Transformation (FFT). The FFT is a smoothing technique used for reducing random noise in signals and produced a power spectrum of the signal. The power spectrum depicted the wave frequencies and corresponding amplitudes on the x and y axis respectively. The power spectrum signal was run through a magnitude analysis on the Global Lab signal analysis software which allowed for the determination of the cut off frequency for the type of vibration being analysed. From this magnitude analysis it was apparent that all of the vibration activity being recorded by the accelerometer was occurring below 50 Hz. Determination of this cut off frequency provided an index for the level at which the raw signal could be filtered to remove any extraneous noise. A cut off frequency of 50 Hz was selected and signals were processed through a Butterworth low pass filter. This frequency was selected as the cut off to remove any low level noise that may have contaminated the original signal.

Ground Reaction Force Measurement

The suspension system should absorb a portion of the impact energy and store it within the damping mechanism, resulting in lower impact forces than the rigid system. A similar difference between systems was also expected to be seen on examination of landing force values because of the absorption capability of the suspension systems. The degree of energy absorption responsible for the variation in impact and landing forces may be represented by the impulse value calculated as the area under the force/time curve. Impulse was calculated for the point of maximum impact force to the maximum landing force. The suspension system that is best able to absorb and store the initial impact energy by converting kinetic to potential energy and subsequently releasing this stored energy on landing will show a higher impulse value. It is the release of the stored potential energy in the system that is responsible for creating the greater impulse values. The kinetic energy imparted to the rigid system is dissipated through a flight phase when the front wheel actually loses contact with the ground. This same energy is stored, to some degree, in the suspension mechanisms and upon a controlled release of this energy, force is exerted downward onto the platform, eliminating the flight phase and maintaining pressure on the force platform so that there will be a greater area under the curve indicating a greater impulse and a greater degree of ground/wheel contact.

The rate at which stored energy from the impact is dissipated from the compressed suspension system can be measured using the slope from the peak impact force to the following minimum. The steeper the slope the more quickly the energy is being dissipated and the greater the rate of change of force being applied to the floor. The suspension system should produce a flatter slope as the rate of change of force being applied to the floor will be decreased due to the decompression or releasing of energy in an attempt to maintain ground/wheel contact. The rigid system should show a much steeper slope as there will have been very little energy absorbed and the wheel will quickly be entering a flight phase to dissipate the kinetic energy of impact. The slope will also be measured for the landing impact, from the point of maximum impact to the following minimum.

Control Variables

Control measures were recorded to limit the variance between and within trials. The measures included the subject's velocity while crossing the force platform and the subject's riding technique. The control measures were taken to account for subject/rider skill level, riding technique, and velocity. The variance attributed to riding style and rider skill level was controlled by using a single subject. The single subject ensured that the bike dimensions and specifications were appropriate to the riders somatotype as the bike was set up to fit one particular rider. Rider weight also affected velocity as gravity was the major force acting on the bike and rider down the ramp. Subject velocity control was addressed by rolling down the ramp without applying any external force through pedalling or pushing off. The assumption was that there would be a negligible effect on velocity due to rolling resistance. The potential energy of the bike and rider at the top of the ramp was considered to be equivalent to the kinetic energy of the bike and rider at the bottom of the ramp over all trials.

Velocity of the bike was measured using reflective light beams to calculate time over a standard displacement. Tire pressure was maintained at 60 pounds per square inch and checked after every fifteen trials. Subject weight was consistently measured at 81 kg.

Riding technique was controlled for consistency through pre test practice prior to pilot data collection. The consistency of the subjects weight force displacement was measured using the strain gauges mounted on the handlebar.

Test Measures

Accelerometry

The level of vibration at the handlebar resulting from the impact with the bump was measured by an accelerometer mounted at the handlebar. The accelerometer was calibrated for compliance with national standards using the mounting and recommended operating instructions.

The accelerometer data was acquired using Global Lab software which presents the signal in millivolts. The signal was filtered using a Butterworth low pass filter with a cut off frequency of 50 Hz and a Nyquist fraction of 0.25 to allow for the removal of any low level noise that may have contaminated the original signal. The raw signal was converted using the factory calibration quotient (10.41 mv/1g) to produce an output expressed in m/s^2. The standard value at sea level is 9.80665 m/s^2. The output was then converted using the relationship 0.102 $g/m/s^2$ to produce an output expressed in units of acceleration, m/s^2. These conversions may be performed directly in the global lab environment.

The data collection for the accelerometer was initiated when the rider broke the light beam located 2.5 m in front of the force platform. Data collection time was set for one second and sampling frequency at 200 Hz.

Ground Reaction Forces

Ground reaction forces for the front wheel rolling over the bump were collected on the force platform. The collection of force data was initiated as the rider contacted the edge of the force platform and collection time was set for one second. The AMTI software package for gait analysis (Advanced Mechanical Technology, Inc., 1993), was used for force data collection. The vertical axis was analysed to determine the ground reaction forces created as the bike rides over the force plate and bump. Raw data was acquired through the AMTI software and was expressed in Newtons (N). The platform had been factory calibrated prior to installation and zeros taken before each set of data collection trials. Data from the AMTI gait program was exported to the Hz software (Lakehead University, Biomechanics Lab, 1993) for analysis and computation for a mean curve over fourteen trials.

Test Procedures

Subject

The subject who performed all trials for this investigation was an accomplished cyclist with ten years experience riding mountain bikes. The subject weight remained consistent through the testing at 81 kg. The bike used for testing was fitted to the subject to ensure a proper riding position. The subject was encouraged to perform numerous pre-trial sessions on the bike with each of the suspension systems to enable a learning response to occur prior to actual data collection.

Two types of front suspensions systems were selected for this investigation with the rigid fork serving as the control system. An elastomer system and a hydraulic system were be tested at their stiffest and softest settings and compared to the rigid system.

The subject rode the bike down the ramp and over the force plate and bump. The rider had been instructed to perform all trials as consistently as possible. The rider was provided with a tape marking to indicate exactly where on the ramp the front tire must be prior to rolling down the ramp.

Prior to data collection, the subject performed numerous trials with each suspension systems and setting to become familiar with the different set ups and the response each has on impact with the bump. Once the rider was comfortable testing began. The subject/rider began each trial with the left foot on the pedal and right foot on the floor and both front and back brakes applied. Once given a go ahead signal from the tester, the subject/rider mounted the bike and released the brakes. Data collection for the accelerometer and strain gauges began once the light beam was broken and for the force platform on initial contact with the plate. As the rider descended down the ramp, the feet remained in the three o'clock and nine o'clock position with the right foot always in front. During the descent, the shielded cable from the accelerometer and strain gauges was guided by an assistant to ensure that it did not become damaged during testing. The cable attached to the bike measured 12 m in length, requiring that the subject/rider to begin braking as soon as the platform was crossed. A braking marker placed just after the force platform indicated where the subject/rider was to begin braking. Data collection was carried out over three consecutive days. The first system tested was the rigid front end, and fifteen trials were collected. The following day the elastomer suspension system was installed by a certified bicycle mechanic and set at its softest setting following completion of fifteen trials the system was reset to the stiffest setting by exchanging the elastomer plugs and fifteen more trials performed. After all trials were completed with the elastomer forks, the bicycle mechanic installed the hydraulic system and fifteen trials were performed at the softest setting followed by fifteen trials at the stiffest setting. All front end system changes were performed according to manufacturer installation instructions by a certified bicycle mechanic to ensure that the bike and shocks were set up correctly.

Data was saved to a diskette at the end of each trial for subsequent analysis. A graphical display of each trial was checked prior to saving the data to ensure that all the data collection systems were working correctly.

Data Analysis

Control Measures

Rider Weight Displacement. The strain gauge data output for each set of four strain gauges were recorded on two separate channels and summed using the Global Lab software to produce a millivolts/time output. This electronic output was converted to a force /time curve using a calibration factor of .243 mv/N for each channel (Appendix B). The force/time curve was then integrated to produce an impulse/time curve to allow for comparison of areas under the force/time curve at specific instances during trials. Each system was tested for ten trials and analysed at the 100 ms. interval indicative of the instance just prior to impact. The 100ms. time interval represents the impulse just prior to impacting the bump on the platform and provides the pre-impact rider weight displacement on the handlebar. Consistency at the 100 ms. point is an indication that the rider was approaching the bump with the same weight displacement and therefore the same technique for each trial (see Figure 4).

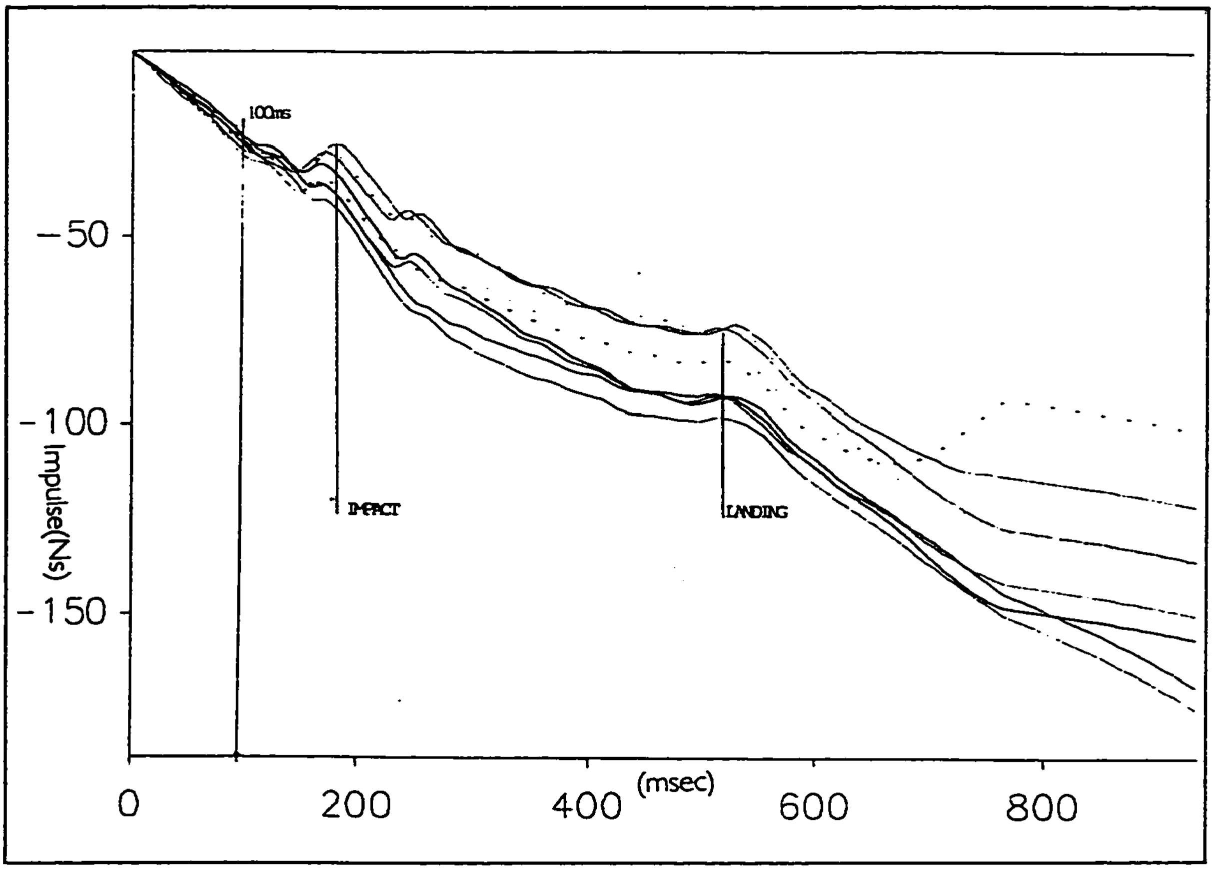

Figure 4 Sample Impulse versus Time curve from strain gauge data during rigid bike trials illustrating the 100ms. instance used for data analysis.

The weight displacement control system data collected during the pilot study shows consistency and indicates reliable rider technique as the bike approaches the bump.

Accelerometry.

Analysis of accelerometer data required some manipulation of the original signal collected from the pilot testing in order to determine the frequency range of the vibration occurring in the handlebar itself. The pilot accelerometer data was initially run through a Fast Forward Fourier Transformation (FFT) analysis, a smoothing technique for reducing random noise in signals. The FFT yielded a power spectrum of the signal which had been originally recorded. From this analysis, it was apparent that all of the activity being recorded by the accelerometer was occurring below 50 Hz. Determination of this cutoff frequency provided an index for filtering the raw signal. Subsequently, all raw data was processed through a Butterworth low pass filter, with a cutoff frequency of 50 Hz and a Nyquist fraction of 0.25, to remove any low level noise that may have contaminated the original signal.

The filtered signals for each set of trials were summed and averaged using the Global Lab software to produce a mean output of the trials performed for each particular system being tested. The mean output was in units of volts but was converted to millivolts. The millivolts signal was converted to an acceleration unit of m/s^2 to produce an acceleration/time curve. From the acceleration curves for each of the systems tested, comparisons were made on the following variables: peak impact and peak landing acceleration, the frequencies at which each of these occur, the range of the peak impact and peak landing acceleration and the slope of each of these peaks.

The Peak Acceleration values for impact and landing were obtained directly from the Global lab output using the statistics option. The acceleration curves were used to compare the amplitude of vibration occurring in each of the systems tested (see Figure 5). The frequency at which these amplitudes or peak accelerations occur must also be considered when comparing systems. The greater amplitude and the higher the frequency at impact indicates greater vibration at the handlebar.

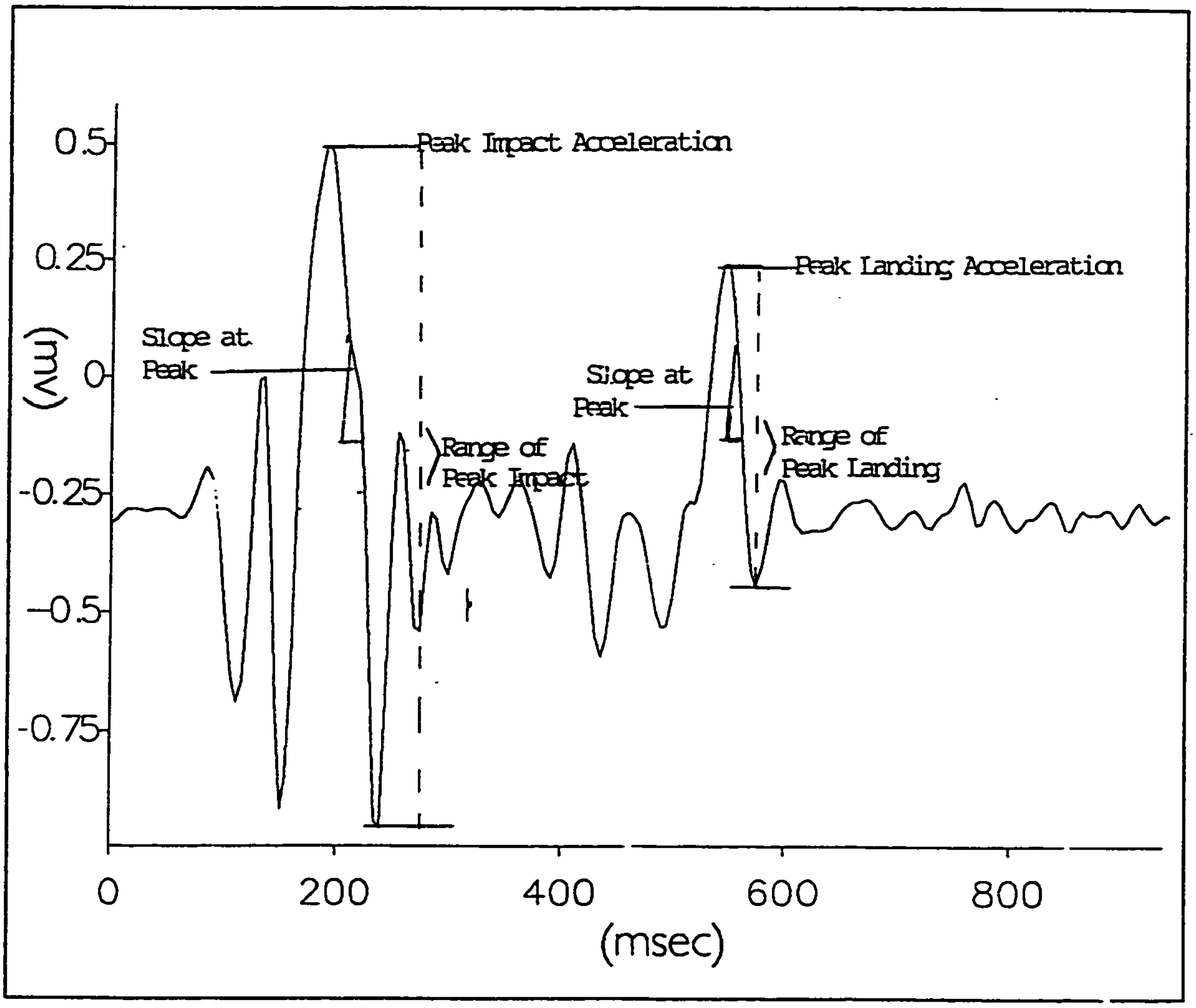

Figure 5. Sample curve of mean acceleration data indicating event variables.

The slope on the acceleration/time curve at peak impact and landing amplitudes is a measure of the rate of change of the acceleration. The slope indicates how quickly the acceleration is changing from one instant to the next. The suspension system is designed to absorb impact energy so that one would expect that the rate of change in acceleration would be less depending on the effectiveness of the suspension system. The rigid system should respond instantly to the impact and the rate of change of acceleration would therefore be higher than when energy is being absorbed through the suspension .

Comparing the slopes of the peak landing and impact acceleration indicates how much influence the suspension systems, at various settings, have on the rate of change in acceleration. The more the suspension is able to absorb the impact energy the less the slope.

The range of peak acceleration values for impact and landing provide information on the amplitude of the vibration associated with striking the bump and the subsequent landing. The range indicates to what extent the impact and landing vibration amplitudes vary from the normal vibration associated with riding the bike over the flat ground just prior to impact. One would expect that the suspension systems would act to reduce the level of vibration not only at impact but also at landing. The ranges of the peak acceleration values demonstrate the variation between systems. The range is measured as the difference between the maximum positive peak acceleration value and the subsequent minimum value on the mean acceleration/time curve.

Ground Reaction Forces

Measuring the ground reaction forces created as the bike travels across the force plate and bump provides insight into what is occurring at the wheel with respect to ground reaction forces. The force platform provides a method of measuring the amount of force generated between the wheel and the ground and is therefore a tool for evaluating how each system behaves in order to maintain ground contact following impact. Ground reaction data was collected using the AMTI "gait" software program. Vertical ground reaction forces were analysed to provide graphical force/time curves of the front wheel crossing the platform and bump. The area under the force/time curve represents the impulse of the system at any given instant. Integration of the force/time curve produces impulse measures for comparison of mean trial curves (see Figure 6).

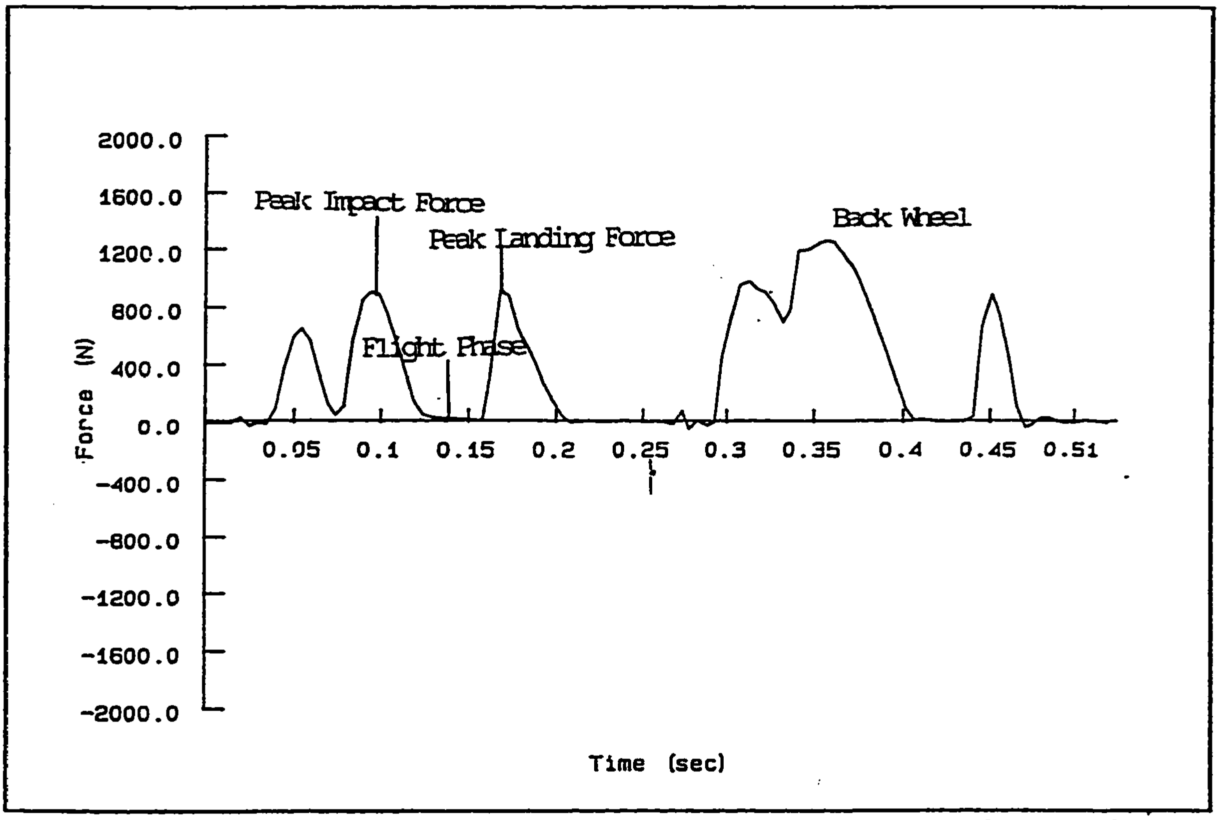

Figure 6. Sample curve of ground reaction forces produced using AMTI force platform and software package.

Each suspension system was tested to provide the mean force/time curve using a Meangait program. This program allowed for a maximum of fourteen trials to be averaged, producing a single mean force/time curve. The Meangait output also included a listing of the cumulative impulse at each of the maximums and minimums measured in the curve. This measure allowed for comparisons of impulse at particular points during the front the front wheel's course across the bump on the platform. Force platform ground reaction force variables that will be used for comparing the various systems include:

1. The peak impact and peak landing force.
2. The slope of the peak impact force to the following minimum value.
3. The slope from the peak landing force from the previous minimum value.
4. Loss of ground contact.
5. The impulse measured from the peak impact to the final minimum following landing.

Research Design

Mean Curves - Descriptive Analysis

Mean curves were produced for the accelerometry and ground reaction measurements taken on each of the five systems tested. From these mean curves the values for each of the independent variables were obtained allowing for comparison between the five conditions tested.

Statistical Analysis

A one by five analysis of variance (ANOVA) was performed for each of the variables except for frequency of vibration and loss of ground contact. The raw data was obtained by visually marking the appropriate value from each of the ground reaction and accelerometry curves. A one by five ANOVA was generated for each of the relevant test variables and a Tukey's HSD post hoc test was performed to determine where any significant differences did exist at the .05 alpha level.

CHAPTER FOUR

Results

The results for the control data and each of the variables of interest are presented in the following sections. The control variables, velocity and impulse are summarized in the first section and the test variable data are summarized in sections concerned with accelerometry measures taken at impact and landing and with ground reaction force measures at impact and landing.

Control Data

Velocity

To ensure the velocity of the bike and rider had been effectively controlled, velocity was measured under three testing conditions; 30 pre-testing trials were performed for the rigid bike, and for each of the suspension systems at the soft setting. The soft setting was chosen because it presents the greatest mechanical difference from the rigid system and would have more of an effect on the bike and the rider's performance and reaction to the impact. If the different front ends on the bike were to affect velocity it would be most apparent by comparing the velocity of the bike and rider under these three conditions. The results of the velocity data, summarized in Table 1, demonstrate that the velocity was controlled. The raw data are presented in Appendix D.

Table 1

Summary of velocity data from timing trials

	Rigid	Elastomer-soft	Hydraulic-soft
Mean velocity m/s	9.13	9.07	9.01
S.D.	0.79	0.68	0.62
Range	3.03	2.35	2.30

Rider Technique

Strain gauges measuring weight force transfer were utilized to evaluate the consistency of the rider's technique. For each of the five test conditions 10 trials were recorded and the impulse was calculated up to the 100 ms point representing impact. The impulse values allowed for a comparison of the total amount of force the rider had placed on the handle bar approaching the bump. The results of the mean strain gauge measures taken for each of the test conditions are summarized in Table 2. The raw data is presented in Appendix B.

Table 2

Summary of mean Impulse calculated at 100ms. for each test condition (Ns).

	Rigid	Elastomer Stiff	Elastomer Soft	Hydraulic Stiff	Hydraulic Soft
Mean Impulse	25.43	23.68	12.81	17.38	10.81
Standard Deviation	1.95	2.52	2.96	2.85	2.36
Range	6.75	8.70	9.64	9.30	9.46

The greatest impulse at 100 ms was measured for the mean curve of the rigid trials which also demonstrated the least deviation about the mean and the lowest range of values over the ten trials. The elastomer system at the stiff setting produced the second greatest impulse value at 100 ms with the second lowest standard deviation and range of values over the ten trials. The mean impulse at 100 ms was third highest for the stiff hydraulic system followed by the soft elastomer system and finally the soft hydraulic system. The standard deviations for each mean impulse follow this same trend except for the hydraulic system at the soft setting which was observed to have the third lowest standard deviation about the mean. These values are all within a reasonable range for each system indicating that weight transfer was consistent prior to impact in all trials.

The mean curves produced from the strain gauge data for each of the five test conditions are presented in Figure 7.

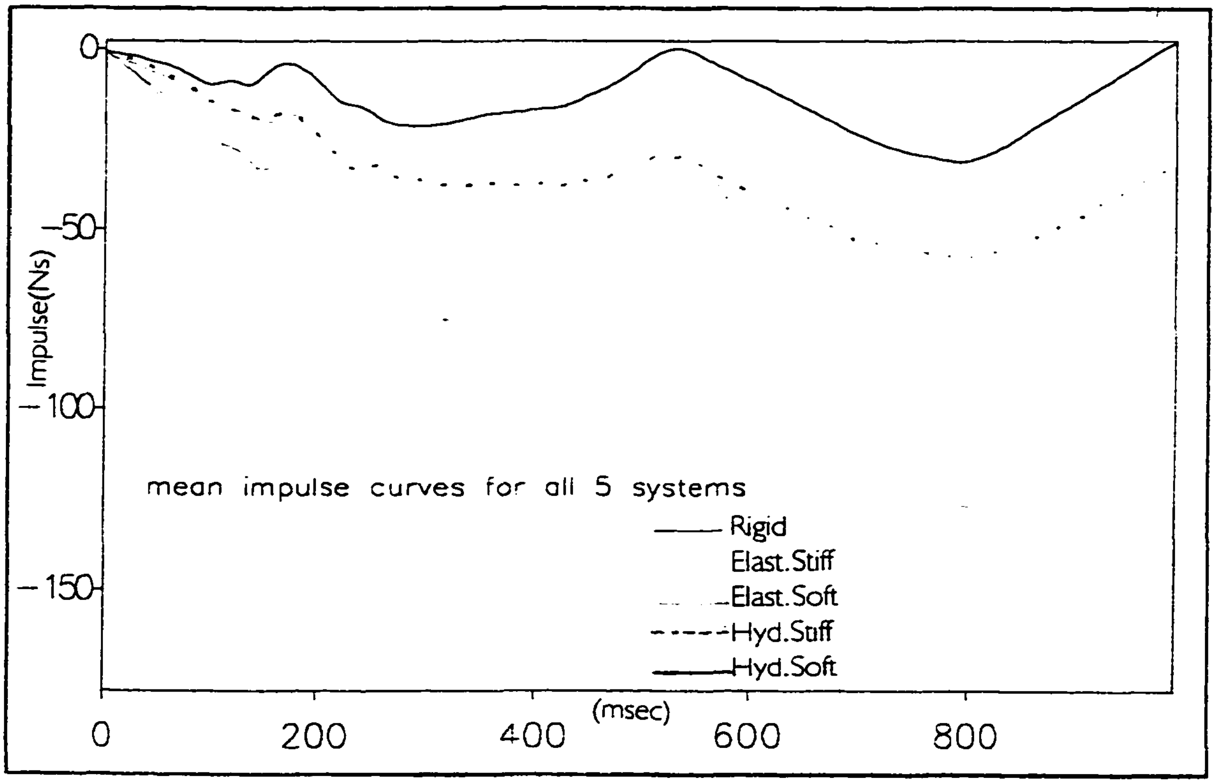

Figure 7. Mean Impulse curves from strain gauge data illustrating the 100ms. instant used for comparisons between rigid, elastomer and hydraulic at the stiff and soft setting.

Mean Curve Results

The test variables for accelerometry and ground reaction forces are presented in the following sections; peak acceleration, frequency, range and slope of peak acceleration are presented as impact and landing acceleration.

The ground reaction variables for peak impact and peak landing forces and the respective slopes and impulses generated are presented with the mean curves from which these values were obtained.

Accelerometry

Acceleration measures taken at the handle bar upon impact are reported in ms^{-2} and are representative of the acceleration measured in the x-axis of the basicentric axis of the hand (Figure 2). In addition to the mean acceleration values determined for peak impact and landing, frequencies, slopes, and ranges at each of these peaks are reported for comparison of the five test conditions. The values obtained from the mean curves presented in Figure 8 allowed for comparison between systems for; mean peak impact and peak landing acceleration, the mean frequencies, slopes and ranges of these peaks.

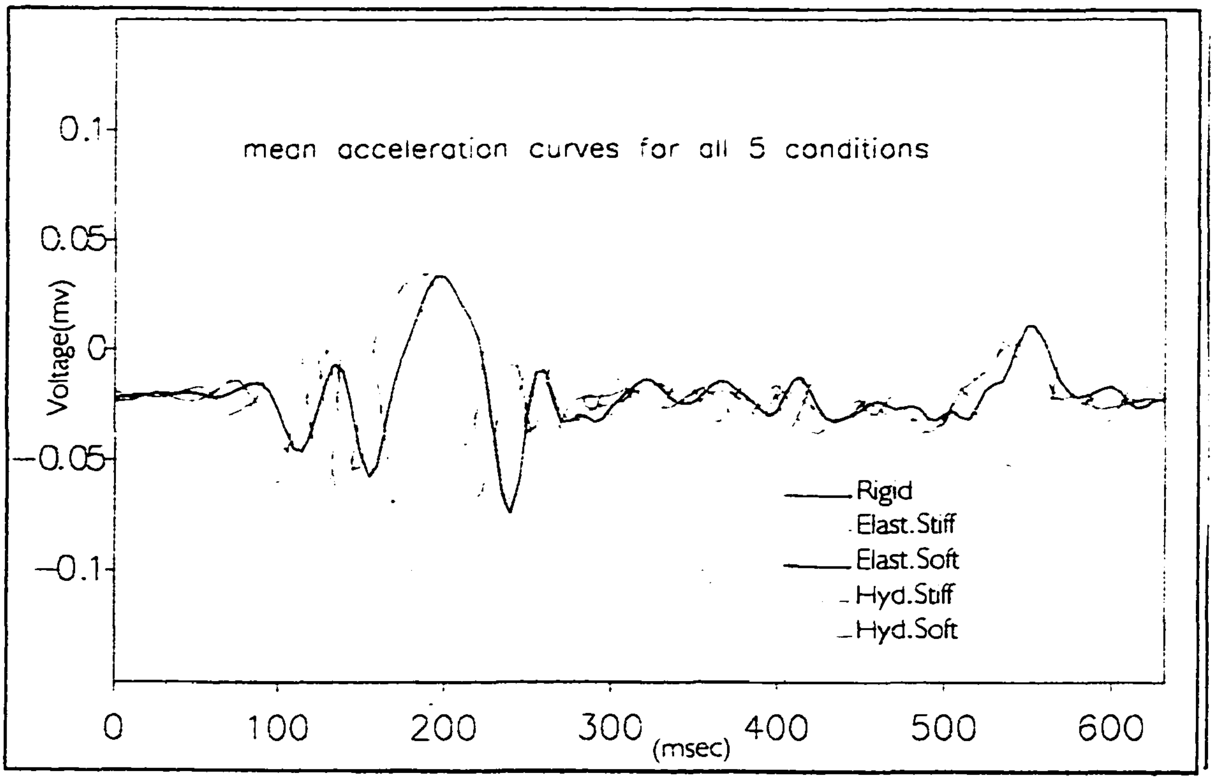

Figure 8. Mean Acceleration vs. Time curves for each test condition

Impact. The mean curve values recorded for the peak impact acceleration are summarized in Table 3. The raw data is presented in Appendix E. The mean acceleration curves are presented in Figure 8.

Table 3

Summary of impact accelerometry data from mean curves of each test condition.

	Rigid	Elastomer Stiff	Elastomer Soft	Hydraulic Stiff	Hydraulic Soft
Peak Accl. (ms^{-2})	51.42	33.51	31.74	33.81	29.43
Frequency (Hz)	22.00	11.10	12.50	12.50	12.50
Range (ms^{-2})	137.31	96.53	95.59	115.94	92.20
Slope (ms^{-2}/ms)	4577.00	1930.60	1917.85	2318.00	1844.04

Results of the mean curve accelerometry measures taken at the peak impact of the wheel on the bump indicate that the greatest impact acceleration occurred with the rigid system. The mean acceleration measured for the rigid front end was 51.42 ms^{-2} which is 17.6 ms^{-2} greater than the next highest impact acceleration observed for the hydraulic suspension system at the stiff setting. The elastomer system at the stiff setting had a peak impact acceleration within 0.3 ms^{-2} of the hydraulic stiff setting. The elastomer soft setting had a mean impact acceleration slightly lower than the elastomer stiff setting and the hydraulic system at the soft setting produced the lowest peak impact acceleration.

The mean curve peak impact acceleration values for all of the suspension trials were within a range of 4.38 ms^{-2}. When evaluating vibration at the handle bar the frequency at which the mean curve peak acceleration occurs must also be taken into account. A more thorough examination of the mean curve peak impact acceleration data indicates that the rigid system not only produced an impact acceleration approximately 35% greater than the suspended trials (51 ms^{-2} to 33 ms^{-2}) but that this greater acceleration occurred at nearly twice the frequency of the suspension trials.

The range of the mean curve acceleration from peak impact to the following minimum value for each test condition corresponds with the trend seen when comparing peak acceleration values. The greatest maximum to minimum range was observed for the rigid trial with the stiff hydraulic system producing the second greatest range. The stiff elastomer setting had a slightly greater maximum-minimum range than the soft elastomer setting and the soft hydraulic setting exhibited the lowest range from peak impact acceleration to subsequent minimum.

In comparing mean curve values of the slope from the peak impact acceleration to the following minimum value, a similar trend to that seen when comparing the frequencies was observed. The slope of the acceleration measured for the rigid system was found to be almost twice that of the slope measured for the suspension conditions. This difference in slope values is not surprising if one takes into consideration the frequency values observed. In order for the rigid system to have a greater amplitude of oscillation at twice the frequency of the suspension systems the slope of the amplitude must be much greater.

Landing. The mean values for the landing acceleration variables are summarized in Table 4 and raw data are presented in Appendix E.

Table 4

Summary of mean landing accelerometry variables

	Rigid	Elastomer Stiff	**Elastomer Soft**	Hydraulic Stiff	Hydraulic Soft
Peak Accl. (ms^{-2})	**46.06**	29.90	**20.47**	22.91	20.44
Frequency (Hz)	**20.00**	12.50	**12.50**	12.50	11.10
Range (ms^{-2})	**51.42**	45.95	**30.23**	34.49	25.45
Slope (ms^{-2}/ms)	**2571.00**	1531.99	**1007.70**	699.62	635.71

The mean curves generated by the Global Lab (see Figure 8) also provided the landing acceleration data for the five test conditions. Peak landing acceleration, the frequency, range, and slope that occurred at this peak were recorded to allow for comparison of each system's response to landing following impact. The results indicate that the greatest peak landing acceleration was observed for the rigid system mean curve; this peak acceleration was 35% greater than the next closest peak landing acceleration (46.06 ms^{-2} to 29ms^{-2}) which occurred with the elastomer system at the stiff setting. The hydraulic system at the stiff setting produced the third greatest landing acceleration followed by the elastomer soft setting and finally the hydraulic soft setting. The two soft setting trials produced peak landing acceleration values that were within .03 ms^{-2} of each other.

The rigid system oscillated at a frequency of 20Hz which was almost double that of the other four test conditions. The elastomer system exhibited an oscillation frequency of 12.5Hz for both the soft and stiff setting while the hydraulic system had a frequency of 11.1Hz for the soft setting and 12.5Hz for the stiff setting.

The rigid system demonstrated a slope value from peak landing acceleration to a subsequent minimum at almost twice the value of the slope measured for the elastomer system at the stiff setting. The elastomer system at the soft setting exhibited the third greatest slope value followed by the hydraulic system at the stiff setting and finally the hydraulic system at the soft setting.

The greatest mean range (amplitude of oscillation) occurred with the rigid system followed by the elastomer stiff, the hydraulic stiff, the elastomer soft, and then the hydraulic soft system settings.

Ground Reaction Forces

The force platform measurements allowed for comparison of mean values for peak impact and landing forces as well as a comparison of the slopes occurring at these peaks. The Meangait software program produced mean force/time curves for each of the five test conditions, presented in Figure 9. The mean curve values for peak impact and landing forces are summarized in Table 5. The raw data collected from the force platform is presented in Appendix F.

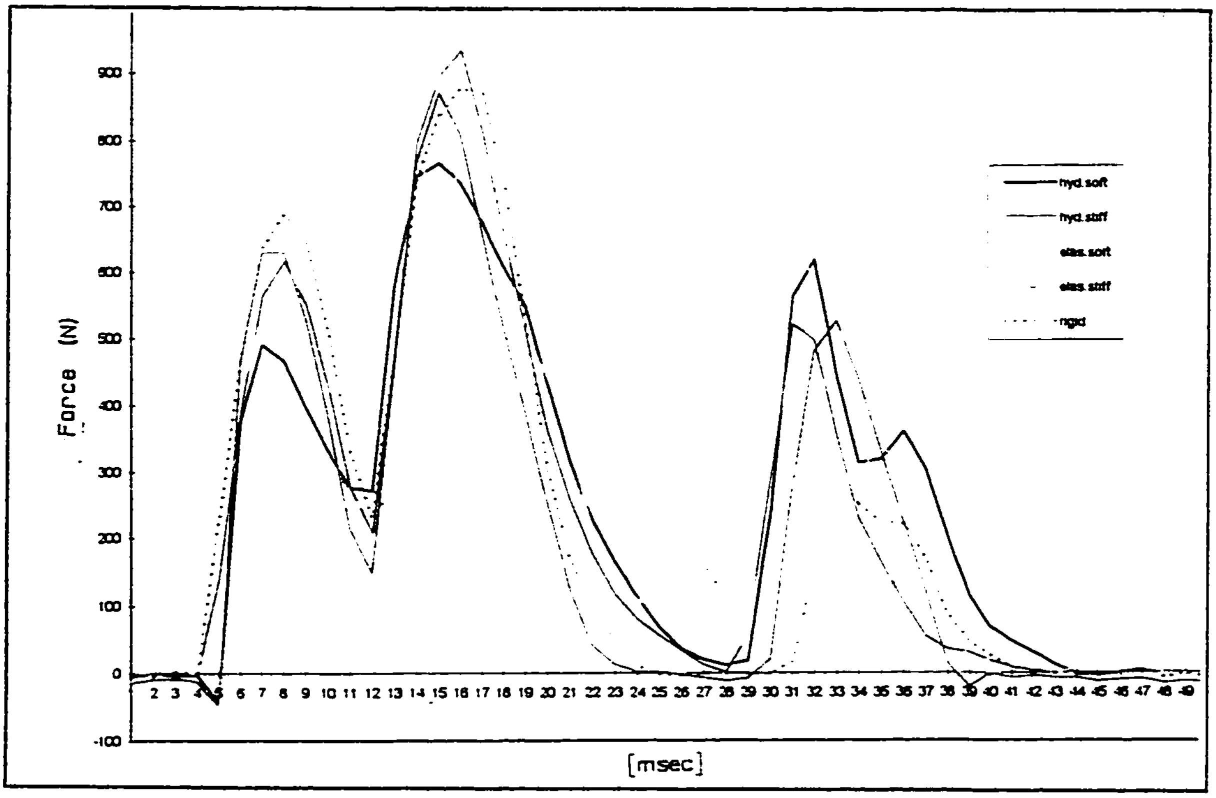

Figure 9. Mean Force vs. Time curves from AMTI force platform software package.

Table 5

Summary of Ground Reaction Force variables.

	Rigid	Elastomer Stiff	Elastomer Soft	Hydraulic Stiff	Hydraulic Soft
Peak Impact (N)	874.55	871.07	811.26	920.65	764.86
Slope Imp. (N/s)	15475.83	15837.64	14750.18	15344.17	13906.55
Peak Land (N)	283.81	526.63	626.04	518.19	617.40
Slope Land (N/s)	1957.31	3631.93	4637.33	3838.44	4410.01
Impulse (Ns)	35.94	37.20	46.40	42.44	48.30

Impact. The results in Table 5 indicate that the greatest mean curve peak impact force was measured for the hydraulic system at the stiff setting. The second greatest impact force was observed for the rigid system followed by the elastomer system at the stiff setting and then the elastomer at the soft setting. The lowest peak impact force was measured for the hydraulic system at the soft setting.

The slopes measured from the peak impact force to the following minimum value reflect the rate of unweighting of the front wheel in response to the impact. The greatest slope was measured on the mean curve for the elastomer system at the stiff setting. The next highest slope value was measured for the rigid trial and then the hydraulic system at the stiff setting. These three slope values were within a range of 493 N/ms while the next slope value for the elastomer system at the soft setting was approximately 594 N/ms lower then the next greatest slope value. The lowest slope value was observed for the hydraulic system at the soft setting, 790 N/ms lower than the slope for elastomer system at the soft setting.

Landing. The peak landing force values indicated that the greatest ground reaction force occurred for the elastomer system at the soft setting. The next greatest mean landing force was measured for the hydraulic system at the soft setting followed by the elastomer and then the hydraulic system at the stiff settings. The lowest landing force was measured for the rigid system which was less than half the magnitude of the greatest landing force observed.

The rigid system also demonstrated the lowest slope value measured from the minimum force following impact to the maximum ground reaction force of landing. The hydraulic and elastomer systems at the soft settings produced the greatest slope values followed by the hydraulic and then the elastomer at the stiff setting. The slope values observed from these mean curves reflect the differences observed when comparing the landing forces themselves. The slope measured for the rigid system was less then half that of the slopes measured for the hydraulic and elastomer systems at the soft setting.

Loss of ground contact following the impact with the bump occurred for the rigid system and for the elastomer system at the stiff setting. There was no loss of ground contact observed for the mean curves of the other three conditions (see Figure 9).

Impulse measured from the peak impact force to the peak landing force was determined by calculating the area under the force/time curve produced by the AMTI software. The impulse measured for the hydraulic system at the soft setting was greater than that measured for the elastomer system at the soft setting. The third greatest impulse was observed for the hydraulic system at the stiff setting followed by the elastomer at the stiff setting. The lowest impulse was measured for the rigid system.

Statistical Analysis

The results of the one by five ANOVA performed on each of the independent variables except for frequency of oscillation and loss of ground contact are presented in Table 6. The Tukey's Honestly Significant Difference (HSD) post hoc analysis with the alpha level set at p<.05, was run subsequent to the ANOVA to determine exactly where any significant differences between systems tested did occur.

Table 6
Summary one by five ANOVA results for Dependent variables

Independent Variable	F Ratio	Probability
Peak Impact Acceleration (PIA)	F(4,56)=134.726	p<.05
PIA Slope	F(4,56)=28.145	p<.05
PIA Range	F(4,56)=16.483	p<.05
Peak Landing Acceleration (PLA)	F(4,56)=181.311	p<.05
PLA Slope	F(4,56)=15.367	p<.05
PLA Range	F(4,56)=8.432	p<.05
Peak Impact Force (PIF)	F(4,63)=18.837	p<.05
PIF Slope	F(4,63)=25.408	p<.05
Peak Landing Force (PLF)	F(4,63)=25.257	p<.05
PLF Slope	F(4,63)=30.506	p<.05
Impulse	F(4,63)=7.322	p<.05

Accelerometry

Statistical analysis of the raw data collected indicated that there were significant differences for each of the accelerometry variables tested. Post hoc analysis for peak impact acceleration indicates significant differences between the rigid system and all of the four suspension conditions as well as between the stiff hydraulic system and the soft elastomer system ($p<.05$). Peak impact acceleration slope and range for each suspension condition tested were significantly different to the slope and range of the rigid system ($p<.05$).

Post-hoc analysis of the peak landing acceleration data indicated significant differences between the rigid system and each of the suspension conditions tested ($p<.05$). As with the impact results, the slopes for each of the suspension conditions on landing, were also found to be significantly different from the slope for the rigid system, ($p<.05$). Range values for peak landing acceleration indicated the significant differences occurred between the rigid system and the soft elastomer, soft and stiff hydraulic system. Significant differences were also found between the stiff elastomer and the soft hydraulic system ($p<.05$). In summarizing these acceleration results a generalized statement may be made that in light of the significant differences between the suspended and the rigid systems tested, the suspension systems did act to effectively reduce handlebar vibration for this particular subject under these specific testing conditions.

Ground Reaction Forces

The Tukey's HSD post hoc analyses were also run for each of the ground reaction force variables to determine where significant differences occurred. Analysis of the peak impact ground reaction forces indicated significant differences between the stiff hydraulic system and each of the other systems as well as between the soft hydraulic system and all other systems (p<.05). Analysis of the slope values corresponding to the peak impact forces, indicated that significant differences occurred between the two soft suspension conditions and the stiff suspension and rigid system.

The results of the post hoc analysis for landing indicated significant differences in peak landing force between the rigid system and the four suspension conditions tested as well as between the soft suspension conditions with the two stiff suspension conditions (p.<05). Analysis of the slope values for the peak landing forces indicated significant differences occurred between the rigid and the stiff/soft hydraulic as well as the soft elastomer. Significant differences were also found between the stiff elastomer system and the other three suspension conditions, and finally, the slope value for the soft hydraulic system was found to be significantly different from all other conditions (p.<05). The significant differences between the rigid and the suspended conditions on these ground reaction variables indicate that the suspension systems do effectively act to reduce the force of impact and that the softer suspension systems do improve ground wheel contact to a rigid system for this particular subject under these test conditions.

CHAPTER FIVE

Discussion

Mountain bike front suspension has become standard equipment for most high end mountain bikes available on the market today. Initial development of suspension systems occurred in response to the demands placed on the equipment by elite mountain bike racers. The technology has developed to the level that front suspension products are now available for all mountain bikers who wish to experience the benefits of a front suspension fork. Manufacturer's of front suspension systems have claimed that suspension systems improve the quality of any ride by decreasing the amount of impact shock energy transmitted to the rider as well as enhancing the bikes handling over rough terrain. The physiological benefits that have been linked to the improved quality of ride with suspension include a decrease in perceived exertion and fatigue (Burke, 1994), a decrease in energy expenditure, and a decrease in muscular damage due to the trauma of repeated impacts (Seiffert et al.,1994). These benefits are due to the mechanical properties of the suspension unit that absorb a portion of the shock energy of impact acting not only to decrease the amount of shock energy transmitted to the rider but also acting to improve ground/wheel contact on impact.

One purpose of this investigation was to evaluate the effectiveness of two types of front suspension systems at reducing handlebar vibration when compared to a rigid system on impacting the same bump under controlled conditions. The second purpose was to compare the effectiveness of the two front suspensions systems with the rigid system at maintaining ground/wheel contact following impact with the same bump under controlled conditions.

Control Variables

Velocity

Controlling for the subject/bike approach velocity is imperative as the suspension systems response to the impact are directly affected by the velocity of travel. Velocity was effectively controlled for by removing the application of any external forces on the bike and rider other than gravity. The results of the pre-test timing trials performed on three different test conditions demonstrate the affectiveness of using the ramp to control for velocity. Trials were compared between the rigid system and the soft settings on both the elastomer and hydraulic system. These two suspension conditions were chosen for comparison as they so mechanically different from the rigid system. Any variation in velocity that may be due to the different front ends on the bike would be most apparent when comparing a very soft suspension system with the rigid system. As the mean velocities for the two systems evaluated are within .12 ms^{-1} with similar standard deviations and ranges of values one can assume that velocity during actual testing was controlled (Table 1).

Strain Gauges

Results from the handlebar strain gauge measures demonstrate the degree of consistency of riding technique as the subject approached the bump for each of the five test conditions. From each set of test trials, 10 trials of strain gauge data were recorded, the mean value of the impulse calculated at 100 ms. from the start of data collection was used for comparisons among test conditions (see Table 2 and Figure 7).

Examination of the raw data (Appendix B) for the ten trials under each of the five conditions demonstrates the consistency of riding technique for each condition. Variation in impulse values seen in Table 2, may be in part due to the nature of the suspension system itself. The suspension systems have pre-load response to the force the rider places on the handlebar by leaning on it to support the upper body. Some of the force being placed on the handlebar by the rider may be absorbed by the suspension as the system becomes compressed. This is most evident at the soft suspension settings. The soft setting for the elastomer and hydraulic system demonstrate the lowest values for impulse at 100 ms. The more rigid the system becomes the less force is absorbed into the system. The stiff setting on the hydraulic system demonstrates that there is some force being absorbed by the system but this is less evident for the stiff elastomer setting. This difference in pre-compression on the suspension unit is due to the mechanical difference between the hydraulic and elastomer system. The elastomer system becomes stiffer by changing the elastomer bumpers within the fork to a much denser material with a higher threshold for compression. The hydraulic system has a pneumatic chamber that resists movement with a threshold of air pressure that must be overcome to allow the hydraulics to become activated and absorb energy being placed on the system. The air pressure in this particular system was set to suit the subject's weight and allowed some initial compression of the suspension unit under the weight of the rider's upper body alone. The stiff elastomer system allowed less compression under the weight of the rider than the hydraulic system for both the soft and the stiff settings.

The increase in variability of the mean impulse values as the system is set softer is probably due to the inherent variability in response of each system. The softer the system is set, the less likely it is to respond to loading in a consistent manner. The soft setting alters how the rider respond to the system itself. If the system has a greater degree of response variability load this will be reflected in how consistently the rider can perform repeated trials. The greater the variability in the system at the softer settings results in a greater variance about the mean and a slightly greater range of values over the ten trials. From each set of trials, ten trials were used to evaluate impulse values. Only ten were used because of technical difficulties during data collection. Each set of trials demonstrates a consistent curve shape although the impulse values at any instance following impact show an increased variability. Curves for each set of trials are presented in Appendix B. Although there is some variance in the impulse values for each of the mean curves the within trial variability did remain consistent across trials as indicated by the range of values about each mean. The similar values seen for the range of values about each mean demonstrates that the subject rode with a similar degree of consistency for each test condition indicating the riding technique was reliably controlled for.

Test Variables

Accelerometry

One purpose of this investigation was to evaluate the effects of mountain bike suspension on handlebar vibration following impact. The accelerometer provided the measurements required to compare handlebar vibration between the suspension systems tested. The mean curve results summarized in Table 3 and Table 4 and the significant differences found between the rigid and suspension trials on post hoc tests support the theory that suspension systems reduce the amount of vibration at the hand-bike interface.

In comparing the five systems it is important to consider the peak acceleration values together with the ranges and frequencies of these peak values. The rigid system not only demonstrated the greatest peak impact acceleration as well as the greatest range from peak to minimum but, more importantly, peak values occurred at twice the frequency of the peak impact acceleration measured for the four suspension systems tested (see Table 3 and Figure 8).

The fact that the frequency of vibration measured for the rigid system was almost twice the frequency measured for any of the suspension systems provides evidence that the suspension systems tested, did act to reduce the amount of impact energy transmitted through the bike to the handlebar. The slope values measured from the peak impact acceleration also support the findings from the comparison of the frequency measures and vice versa. The slope, indicating rate of change of the acceleration displays how quickly the acceleration is changing from one instant to the next. The suspension units are designed to absorb impact energy and would affect the rate of change of acceleration by decreasing it compared to the rate of change of acceleration seen with a rigid system. The slope for the rigid trial mean curve was found to be nearly twice the value of the slope for the next greatest peak impact acceleration measured on the mean curves generated. One-way ANOVA and post-hoc analysis of the raw data collected also indicated that the rigid system produced a significantly different slope at the .05 alpha level compared to the other four test conditions.

A trend for the mean curves indicated that the stiff settings exhibit responses more like the rigid system (see Figure 8). Stiffer suspension settings behave more like a rigid system as demonstrated by the results for the ranges from maximum acceleration to the following minimum. The greatest mean curve range was observed with the rigid system followed by the hydraulic stiff, elastomer stiff, elastomer soft then hydraulic soft system. Similar trends are observed through the statistical analysis.

The greater range and impact acceleration observed for the rigid system on both the mean curve and raw data analysis are due to the fact that the energy from the impact is not able to be dissipated to the extent that it is with the suspension systems. The suspension units dissipate the impact energy by absorbing a portion through the deformation of the elastomer bumper or by forcing the oil to flow through the ports in the hydraulic system. Any energy that is not absorbed by the suspension system is transferred to kinetic energy creating the vibration at the handle bar as well as an unweighting or flight phase of the front wheel. The rigid system does absorb some of the impact energy by passive damping through the materials of the bike. However, there is no active damping to absorb impact energy, resulting in more of this energy being transferred to kinetic energy, creating greater acceleration amplitudes and frequencies. This is not only true for the impact acceleration values observed but also for the landing acceleration values recorded. The order of the mean curve landing acceleration results indicate that the suspension systems actively damp the landing energy as well as that of impact. The mean curve values for landing acceleration demonstrate that the suspension systems can respond to a second impact, as the landing is a subsequent impact. If the suspension system is to be an effective modification to the mountain bike, it must prove to be effective at responding to a series of sequential impacts without becoming locked up and responding as a rigid system. The two suspension systems tested in this investigation had the capability to respond effectively to the landing or second impact. However, this may not be the case for all suspension systems. It is possible that when some systems become compressed in response to the initial impact they may not be able to decompress quickly enough to be able to respond to subsequent impacts. The velocity of the bike and the size and shape of the bump would also affect how the system responds to impact.

Benefits of Suspension. One of the benefits of reducing the amount of vibration energy at the handlebar is that less impact energy will be transmitted to the rider's hands. This may decrease the risk of sustaining hand-arm vibration induced injury and may decrease the fatigue of the musculature of the upper extremity.

Vibration induced injuries to the hand and upper extremity have been well documented in industry, specifically mining and forestry. The International Standards Organization has published a set of guidelines pertaining to vibration exposure and the potential hazardous effects to the hand-arm (ISO, 1986). Vibration exposure is known to have detrimental effects not only to the musculature of the hand and arm but also to the vasculature, the bones and joints as well as specific neurological effects (Griffin, 1990). The assessment of risk of injury requires more detailed measures not included in this investigation. Consideration of factors altering the transmissibility of vibration into the hand must also be given. These factors include; grip force, hand size, musculature, somatotype, wrist, elbow and shoulder angle, ambient temperature, airflow, and physiological effort (Griffin, 1990).

The detrimental effects to the hand-arm system are, in part, dependent upon the vibration energy that is absorbed by the hand-arm which is not equivalent to the amount of vibration energy transmitted to the hand. The hand and arm are elastic systems capable of storing potential and kinetic energy. Potential energy is stored as the result of the relative compression or extension of tissues. Kinetic energy results from the motion of tissues in the hand and arm. The hand-arm system has been found to be a highly damped system having the effect that much of the vibration energy transmitted is absorbed (Reynolds & Angevine, 1977).

The results of this study indicate that the impact energy that is transmitted to the rider's hand through the handlebar can be reduced when a suspension system, as opposed to a rigid front end, is in place. This may in turn reduce the risk of the rider developing vibration induced injuries.

Ground Reaction Force

A second purpose to this investigation was to evaluate how well the suspension systems tested would function to maintain ground/wheel contact following impact. Values of peak impact from the mean curves generated on the AMTI software package for each of the five test conditions indicate that the greatest ground reaction force occurred with the hydraulic system at the stiff setting (Table 5). This peak force value is approximately 15% greater than the peak impact forces measured for the rigid or the elastomer system at the stiff setting which were within 3 Newtons of each other (Table 5). Post-hoc analysis at the .05 alpha level between the stiff hydraulic and all other systems confirms that this system did produce the greatest ground reaction force on impact (Table 6). It is not surprising that the stiff elastomer and the rigid system had such similar mean values, as the elastomer system is designed to behave more as a rigid system when stiffer elastomer bumpers are used. The greater value observed for the stiff hydraulic system may be explained by the fact that the hydraulic system has a greater initial resistance to movement. This resistance is known as stiction. This property of the hydraulic system requires that a greater initial force must be applied before the system responds. By overcoming the static friction of the pneumatic chamber and allowing the hydraulic fluid to move through the ports absorbing and storing impact energy the system responds to the force of impact. The elastomer system does not have any initial pressure to overcome before the system can begin absorbing energy. The elastomer bumper simply begins to compress under the load of impact. Due to the fact that the stiff hydraulic system requires a greater initial force to begin absorbing energy, a greater peak ground reaction force is observed. This greater ground reaction force (see Table 5), represents the greater amount of force applied against the hydraulic suspension forks before absorption and unweighting occur. The rigid system responds to impact with a minimal amount of passive damping via the tires, spokes, rims, frame, etc. until there is no further absorption at which point the energy from the impact is transferred to the kinetic energy of the flight phase or an unweighting (see Figure 9).

The soft setting for the elastomer and hydraulic systems produces much lower peak impact values than the stiff settings on the mean curves (see Table 5). These lower values indicate that each system is actively absorbing energy on initial contact with the bump. The stiffer the setting the more force required by the system to begin absorbing impact energy. The lower impact value for the soft hydraulic than the soft elastomer system may indicate that the soft hydraulic setting is more effective at absorbing impact energy than the soft elastomer setting under the conditions of this investigation. The hydraulic system at the soft setting required a lower activation force to begin absorbing impact energy resulting in the significantly lower ground reaction force indicated through the ANOVA and post hoc analysis (Table 6) and measured from the mean curve (see Table 5).

The storing of potential energy in either of the suspension systems may be evaluated by examining the values for the slope of the peak impact force to the following minimum force value (see Figure 9). The greater the slope the greater the rate of change of force being applied to the platform. A very steep slope indicated that the wheel is quickly reducing contact pressure with the force platform. The greatest slope value was recorded for the elastomer system at the stiff setting, followed by the rigid system and then the stiff hydraulic system. These three mean curve slope values are within 3% of each other, and are significantly different from the soft settings when looking at the raw data. This lends support to the finding that, stiffer settings behave more like the rigid.

The soft settings for the hydraulic and elastomer system produced lower mean curve slope values which were found to be significantly different on post-hoc analysis than the other three systems. This finding is probably due to the compression of the system to store the energy from impact (kinetic energy). As the systems compress, they resist losing contact with the ground by allowing the wheel to trace the surface. The compression of the system causes the suspension fork to move, allowing the wheel to remain on the ground. The softer the system the more energy that will be absorbed and the greater the compression resulting in a lower rate of unweighting on the force platform represented by a lower slope value. The effectiveness of the suspension systems at maintaining ground/wheel contact is best observed by evaluating whether or not there was an actual loss of ground contact measured following impact (see Figure 9). Loss of ground contact was recorded for the rigid and the stiff elastomer systems but not for the other three suspension systems (see Table 5). This supports the claim that suspension systems do act to maintain ground/wheel contact and allows for improved bike handling.

The peak landing forces measured produced a very different order of results than the peak impact forces (see Table 5). The soft suspension settings produced significantly greater ground reaction forces on landing than the stiff systems which were still much greater than the peak landing force for the rigid system. A significant one-way ANOVA followed by subsequent post hoc analyses indicated that there are significant differenced between the soft systems and the stiff and rigid systems as well as between the stiff systems and the rigid system (Table 6). The higher landing forces are due to the force of decompression of the suspension unit. The softer the system is set, the greater the compression of the system and the more potential energy stored in it. This energy is released as the kinetic energy of decompression resulting in greater ground reaction force values. The peak landing values for the soft elastomer system are greater than for the soft hydraulic indicating that more energy was absorbed and subsequently released on decompression of the elastomer system. The same is true of these two systems at the stiff settings. The slope values for the peak landing are indicative of the rate of change of force on the platform, in this case a weighting of the platform. The systems demonstrated a similar rate of decompression with the soft settings producing a significantly greater slope value than the rigid system. The decompression of the suspension unit is referred to as rebound and is controlled for in some suspension units by rebound-damping. The suspension systems tested in this investigation demonstrated similar rates of decompression or rebound.

The peak impact to peak landing impulse was determined to allow for comparisons of the amount of ground reaction force generated. The greater the total ground reaction force between these two points the greater the ground/wheel contact. The mean curve results indicated that the soft hydraulic and soft elastomer systems produced the greatest impulse values (see Table 5). This may be attributed to the fact that these two soft settings were able to absorb greater amounts of impact energy and release this energy through decompression of the suspension unit to maintain ground/wheel contact. The stiff hydraulic system produced the third greatest impulse value which was significantly greater than the impulse values for the stiff elastomer and the rigid system. These two systems with the lowest impulse values were the only two systems to have a loss of ground contact following impact with the bump. Statistically significant differences were found to occur on post hoc analysis between the rigid system and the two hydraulic conditions as well as the soft elastomer system. Significant differences were also found between the stiff elastomer and the two hydraulic and soft elastomer system (Table 6).

CHAPTER SIX

Conclusions

The controlled laboratory conditions under which this investigation was performed allowed for the consistency and reliability of the results recorded but, the controlled conditions also limit the extent to which conclusions regarding these results may be generalized. The purpose of this investigation was to compare the effectiveness of front suspension systems at reducing handlebar vibration and at improving ground/wheel contact following impact with a bump. In drawing conclusions from the results one must keep in mind that the results are specific to the conditions under which the testing was performed, in particular; controlled velocity, one rider, one size bump, one bike.

Vibration Control

Shock energy is partially transmitted to the rider through vibration at the handlebar. One purpose of this investigation was to evaluate the effectiveness of two types of front suspension compared to a rigid front end at reducing the amount of vibration at the handlebar following impact with a bump. From the results of this investigation we can conclude that the two systems tested did reduce handlebar vibration following impact with a standardized bump at a controlled velocity for this particular rider compared to the rigid system. The amplitude of oscillation from the mean curve data for the rigid system was found to be approximately 30% greater than the suspension trials. Another finding was that the frequency of vibration was reduced by almost 50% with the suspension systems in place compared to the rigid system. These results support the marketing claims made by manufacturers of front suspension systems that suspension does decrease the amount of impact shock energy transmitted to the rider. The results from this investigation also provide support to the findings of the physiological studies that evaluated the effects of suspension on energy expenditure and muscle cell damage. Muscular damage due to vibration exposure would be reduced with suspension, as lower amplitudes at lower frequencies would be transmitted to the rider's hands. Decreased energy expenditure may be accounted for in part by the fact that as the level of vibration increases the grip strength about the vibrating handle also may increase in an attempt to control the vibration. The lower the vibration the lower grip strength required and less energy is expended. The softer settings for both systems tested produced the lower amplitudes of oscillation but the frequency remained relatively constant for all four suspension conditions.

Even though the two suspension systems tested did prove to effectively reduce handle bar vibration compared to the rigid, it has not yet been established whether or not the level of vibration with or without suspension presents a hazardous risk of inducing hand-arm vibration injury. Further investigation to evaluate this level of risk is required.

Ground Control

The impetus for designing a suspension system for the mountain bike was to improve bike handling. A rigid system that has no active damping often loses contact with the ground as the shock energy of impact is transferred to the kinetic energy creating a flight phase where the front wheel losses contact with the ground. Through absorption of impact energy, suspension systems convert some of this energy into potential energy through a 'compression' of the system. The system compresses as the wheel moves up the bump and decompresses as the wheel rolls off the bump. The decompression or rebound is the release of the potential energy stored in the system. This rebound creates a downward force to keep the wheel against the ground maintaining ground/wheel contact and counteracting the flight phase seen with the rigid system.

A second purpose to this study was to evaluate the effects of front suspension on maintaining ground/wheel contact compared to a rigid front end following impact with a bump. As loss of ground contact occurred with only the rigid and the stiff elastomer system we can conclude that the suspension systems are effective at improving ground/wheel contact following impact with the particular bump at the specific velocity set for this investigation. The ground reaction forces measured indicated that the two suspension settings at the soft settings produced lower impact force values than the rigid system. Lower forces were due to compression of the suspension unit, and much greater landing force values due to decompression of the suspension unit.

Increasing the ground/wheel contact would partially account for the decreased energy expenditure reported by Berry in an investigation that compared the energy cost of riding rigid versus suspended bikes(Burke,1994). The increased ground contact following impact provides the rider with greater steering control and less wrestling with the handle bar to keep the bike on the chosen line of travel. Less wrestling with the handle bar would decrease the energy expenditure required to continue travelling on the chosen path at a specific velocity. This would also account for the faster time trial results for the suspension trials (Seiffert et al., 1994) in combination with the fact that less momentum is lost when the wheel remains in contact with the ground, conserving momentum requiring less pedalling energy to maintain velocity.

Recommendations

To further validate the benefits of mountain bike suspension observed in this investigation it is recommended that:

"1. A larger sample size be used in order to attempt to generalize findings.

2. Testing be performed at various velocities to measure the effect that velocity has on suspension system performance.

3. Testing be performed with various size and shaped bumps to evaluate to response of different systems to different types of impact.

4. 2-D video analysis be incorporated as a control measure to determine consistency of riding technique.

5. The summed acceleration value for triaxial measures taken in each of the axis of the hand be used for comparison of systems rather than only one accelerometer..

Recommendation for further study include addressing the following questions:

1. Does the level of vibration exposure from mountain bike riding present a risk of developing hand-arm vibration injuries?
2. What are the typical vibration exposure levels associated with an average mountain bike race?

3. Are certain types of suspension units more effective than others at decreasing handlebar vibration and at maintaining ground/wheel contact?

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APPENDICES

Note: **Inconsistancies between mean curve data and raw data presented in the appendices are due to variations in computer generated mean curves as opposed to raw data generated means which may be less accurate due to the fact that maximum and minimum values were chosen from curves for each trial which introduces human error into the selection of these values.**

Appendix A

Factors affecting hand-transmitted vibration.

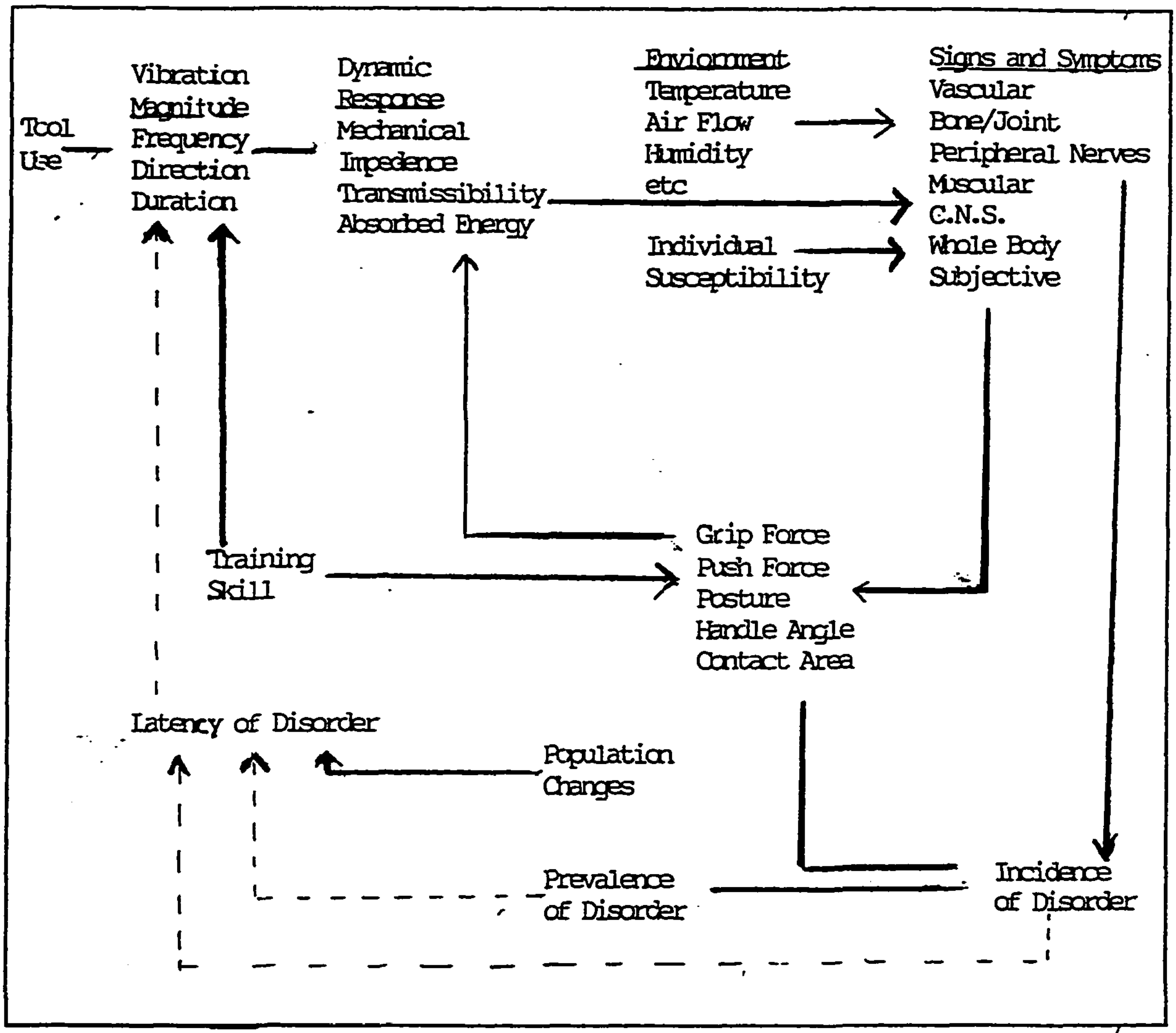


Figure 10 Diagram illustrating factors influencing the cause-effect relationship for hand-transmitted vibration.

Adapted from Handbook of Human Vibration (P.533), by M. J. Griffon, 1990, London, Academic Press.

Appendix B

Strain gauge raw data

Table 7 Impulse values from strain gauge data collected at 100ms (Ns)

trial #	Rigid	Elast. Stiff	Elast. Soft	Hyd. Soft	Hyd. Stiff
1	23.82	21.69	9.29	13.21	22.21
2	25.99	24.04	12.76	7.43	15.87
3	28.77	23.77	12.74	9.34	14.30
4	23.31	23.12	13.18	11.87	12.91
5	25.51	25.19	15.79	8.89	16.55
6	27.09	23.93	18.11	12.62	16.26
7	25.92	27.21	14.81	11.85	17.21
8	26.29	18.51	12.66	6.13	19.03
9	22.02	22.51	8.47	11.20	18.59
10	24.72	26.85	10.24	15.59	20.86
mean	25.34	23.68	12.81	10.84	17.38
S.D.	1.95	2.52	2.96	2.86	2.85
range	6.75	8.70	9.64	9.46	9.3

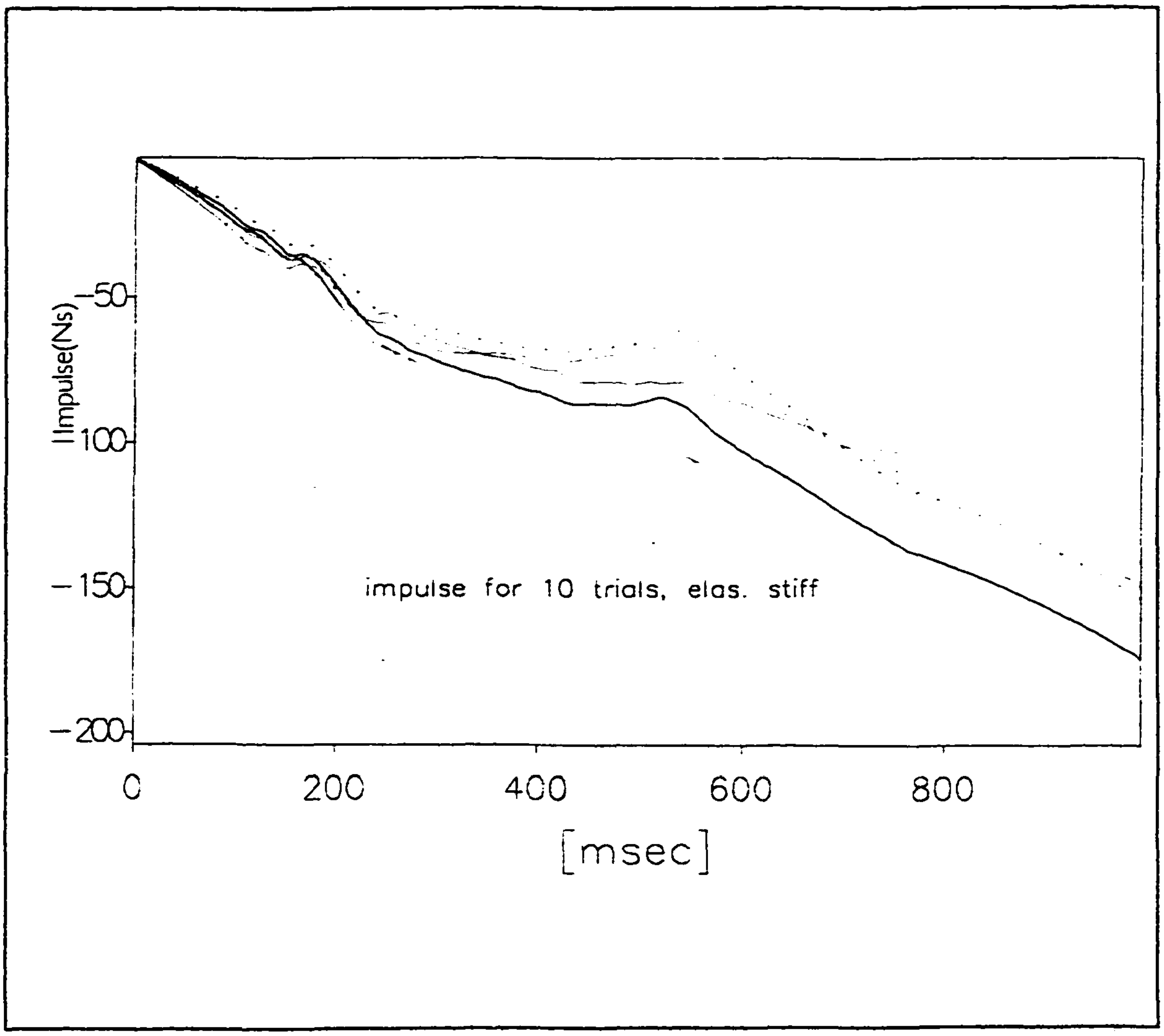


Figure 11 Impulse Curves (Ns vs. Time) for stiff elastomer trials

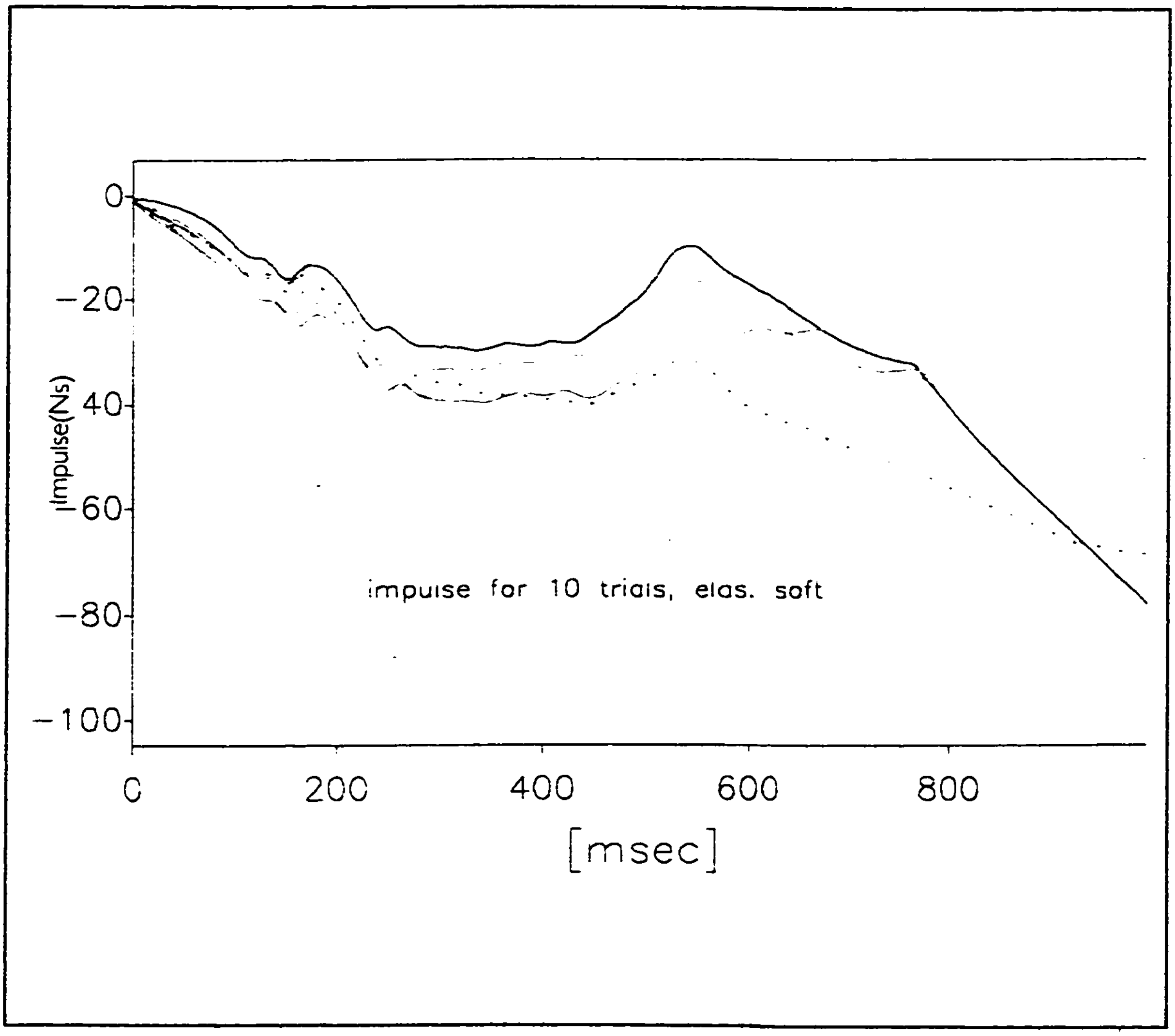


Figure 12 Impulse Curves (Ns vs. Time) for soft elastomer trials

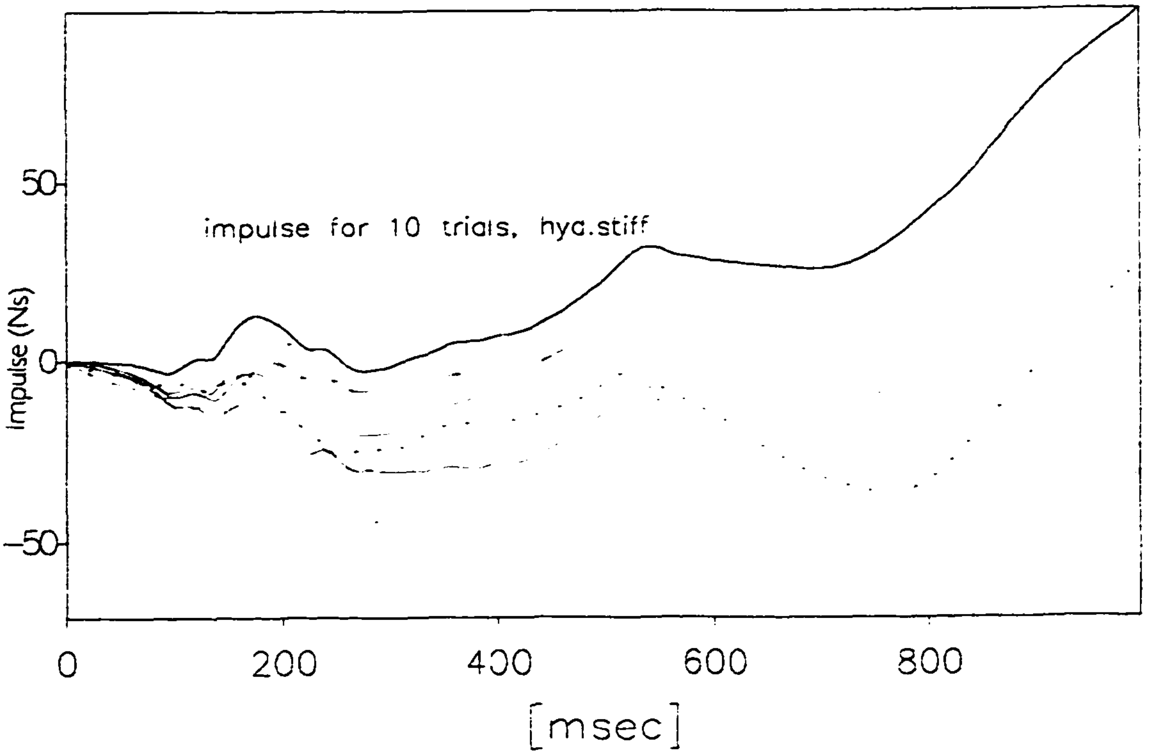


Figure 13 Impulse curves (Ns vs. Time) for stiff hydraulic trials

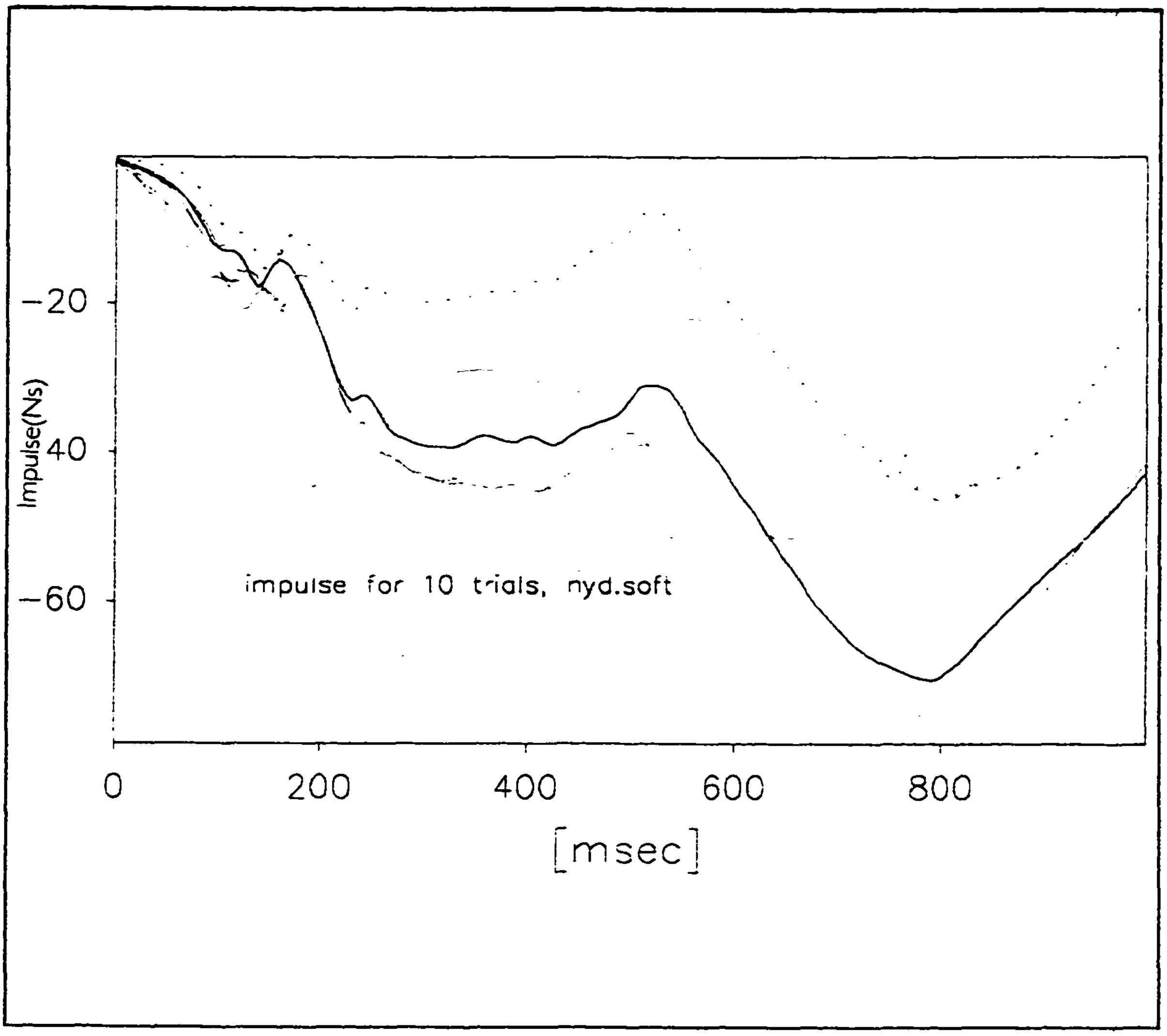


Figure 14 Impulse curves (Ns vs time) for soft hydraulic trials

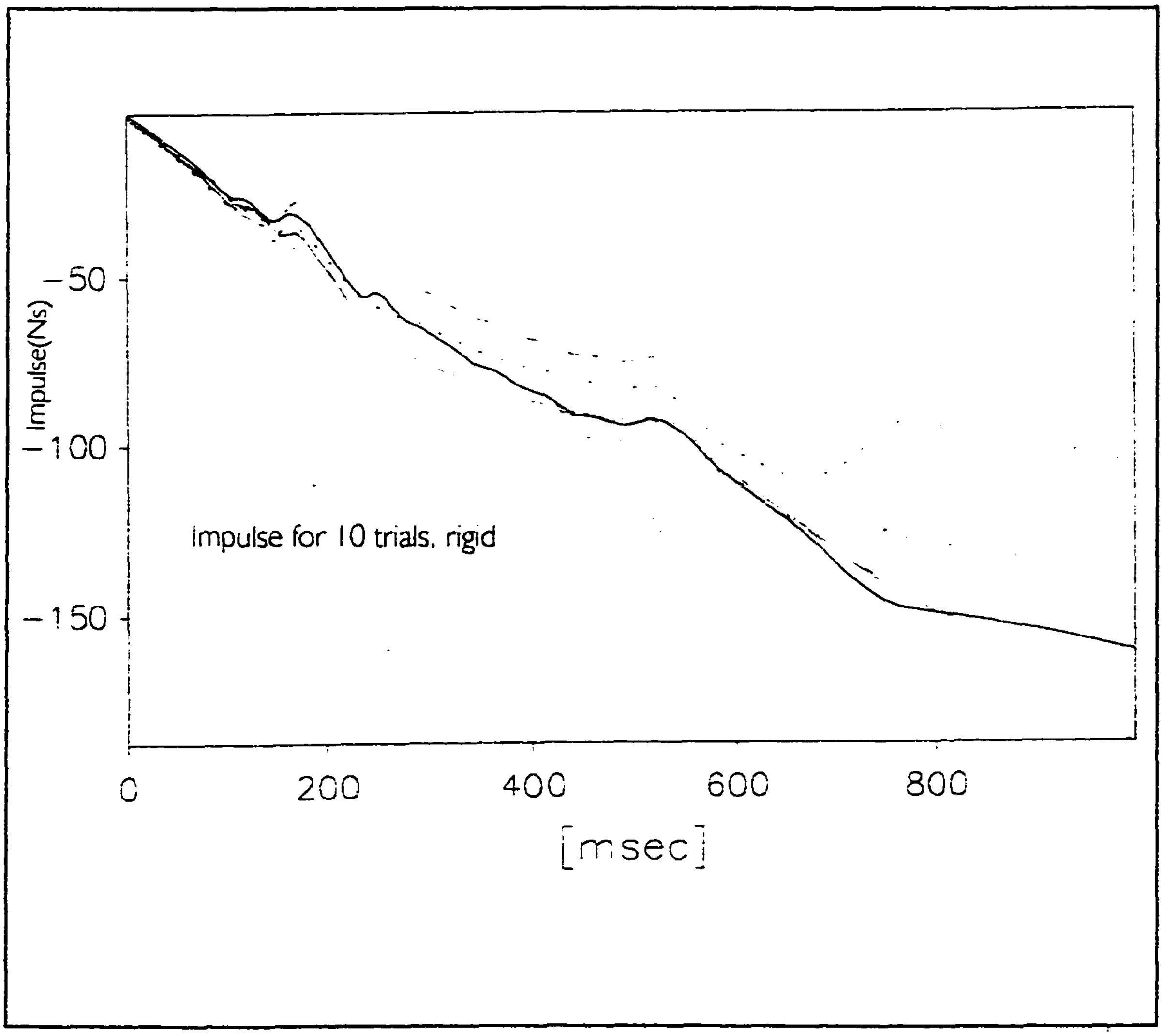


Figure 15 Impulse curve (Ns vs time) for rigid trials

Appendix C

Accelerometer Calibration Certificate

Calibration Certificate

Per ISA-RP37.2

Model No. V353B17/035

Serial No. 11168

PO No. ______ **Customer** ______

Calibration traceable to NIST thru Project No. 822/253168

ICP® ACCELEROMETER
with built-in electronics

Calibration procedure is in compliance with MIL-STD-45662A and traceable to NIST.

CALIBRATION DATA

Voltage Sensitivity	10.41	mV/g
Transverse Sensitivity	2.9	%
Resonant Frequency	80	kHz
Time Constant	1.0	s
Output Bias Level	8.9	V

KEY SPECIFICATIONS

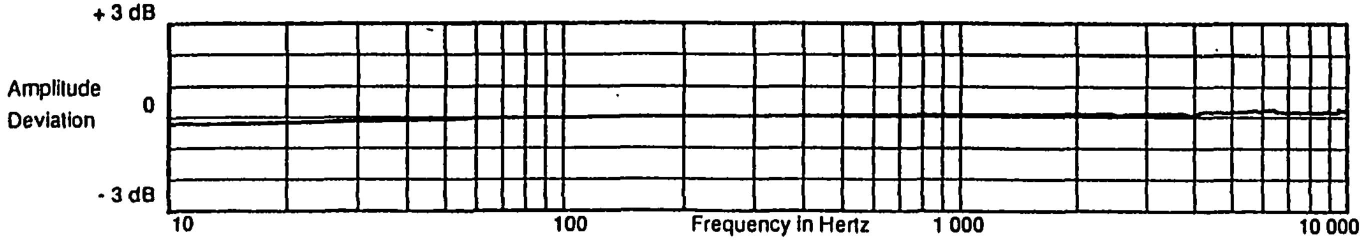
Range	500	±g
Resolution	0.01	g
Temp. Range	-65/+250	°F

METRIC CONVERSIONS:
ms⁻² = 0.102 g
°C = 5/9 x (°F -32)

Reference Freq.

Frequency Hz	10	15	30	50	100	300	500	1000	3000	5000	7000	10000
Amplitude Deviation %	-2.2	-2.2	-1.2	-.7	0.0	.6	1.1	1.1	1.5	2.3	2.1	2.9

FREQUENCY RESPONSE



PCB Piezotronics, Inc. 3425 Walden Avenue Depew, NY 14043-2495 USA
716-684-0001

Date 4/22/94

Calibrated by ______

CODE CC ENG

Appendix D

Velocity Raw Data

Table 8 Velocity trials raw data (m/s).

trial #	Rigid	Elast. Soft	Hyd.Soft
1	9.46	9.14	9.46
2	7.97	8.49	7.97
3	10.8	8.82	9.01
4	10.23	7.92	9.23
5	8.26	8.51	8.26
6	9.07	8.26	9.27
7	8.97	8.97	8.97
8	9.99	9.14	9.99
9	9.0	9.75	9.00
10	8.66	9.02	8.66
11	9.38	9.27	9.83
12	8.48	8.95	8.48
13	10.1	8.67	9.43
14	10.67	10.27	10.1
15	8.62	10.1	10.27
16	8.95	9.23	8.67
17	7.77	8.48	8.95
18	9.02	9.38	9.27
19	9.75	9.46	9.07
20	9.84	10.01	9.75
21	8.97	7.97	9.14
22	8.51	10.23	8.97
23	9.07	8.26	8.26
24	7.92	8.66	8.51
25	8.82	8.97	7.92
26	8.99	9.00	8.82
27	9.14	9.99	8.49
28	9.85	9.07	9.54
Mean	9.13	9.07	9.01
S.D.	.79	.68	.62

Appendix E

Accelerometry Raw Data

NOTE: Difference between mean curve values and mean values are due to the fact that the Global Lab produces a mean curve by summing points for each sampling period and not by summing the maximum or minimum values for each trial. This variation between mean curve and mean values occurs for all test conditions.

Table 9 Accelerometry impact values for rigid system

	Max. (mv.)	time (ms)	Range (mv.)	Slope (mv/ms)
mean curve	.0457	.15	.1458	4.86
trial 1	.1575	.235	.2081	11.63
trial 2	.1337	.24	.2550	9.55
trail 3	.1281	.24	.1672	8.44
trial 4	.9227	.2	.1898	7.08
trial 5	.1740	.25	.1794	9.11
trail 6	.1868	.23	.2111	10.35
trial 7	.1208	.23	.2323	6.69
trial 8	.1708	.145	.1818	4.24
trial 9	.2271	.225	.2509	14.21
trial 10	.0567	.15	.2148	4.69
trial 11	.1251	.23	.2563	7.94
trial 12	.1757	.14	.1949	5.16
trial 13	.1971	.23	.1624	10.46
trial 14	.1671	.145	.1824	5.47
mean	.1652	.206	.2080	8.216
SD	.0308	.042	.0326	2.891

Table 10 Accelerometry impact values for stiff elastomer system

	Max. (mv)	time (ms)	Range (mv)	Slope (mv/ms)
mean curve	.0356	.19	.1025	2.05
trial 1	.0415	.19	.1408	2.81
trial 2	.0409	.18	.1477	2.95
trial 3	.0519	.145	.1831	4.57
trial 4	.0488	.195	.1593	3.19
trial 5	.0439	.185	.1495	3.32
trial 6	.0439	.195	.1641	3.65
trial 7	.047	.19	.1532	2.79
trial 8	.0464	.185	.1495	2.49
trial 9	.0586	.195	.1532	2.55
trial 10	.0452	.18	.1434	2.39
trial 11	.0433	.185	.1147	2.29
trial 12	.0409	.19	.1459	2.92
trial 13	.0446	.195	.1624	3.25
Mean	.046	.185	.151	3.013
S.D.	.005	.013	.016	.613

Table 11 Accelerometry impact values for soft elastomer system

	Max. (mv)	Time (ms)	Range (mv)	Slope (mv/ms)
mean curve	.0337	.195	.1015	2.03
trial 1	.0391	.190	.1514	3.03
trial 2	.0336	.195	.1428	3.57
trial 3	.0391	.205	.1483	3.71
trial 4	.0446	.210	.1709	3.8
trial 5	.0403	.190	.1465	3.26
trial 6	..0464	.200	.1678	3.73
trial 7	.0476	.200	.1495	2.99
trial 8	.0500	.190	.1471	2.94
trial 9	.0415	.185	.1528	3.82
trial 10	.0439	.200	.1752	3.89
trial 11	.037	.190	.1447	2.89
trial 12	.0542	.195	.1624	3.25
trial 13	.0433	.205	.1575	3.50
Mean	.043	.197	.155	3.144
S.D.	.006	.007	.011	.369

Table 12 Accelerometry impact values for stiff hydraulic system

	Max. (mv)	Time (ms)	Range (mv)	Slope (mv/ms)
mean curve	.0359	.185	.1231	2.46
trial 1	.0769	.165	.1408	3.47
trial 2	.0861	.170	.1477	4.25
trial 3	.0562	.185	.1831	3.72
trial 4	.0482	.170	.1593	3.16
trial 5	.0671	.170	.1495	2.99
trial 6	.0677	.185	.1641	3.84
trial 7	.0604	.190	.1592	4.41
trial 8	.0653	.155	.1495	3.31
trial 9	.0568	.190	.1532	4.18
trial 10	.0525	.185	.1434	4.3
trial 11	.0623	.185	.1147	4.66
Mean	.064	.177	.1513	3.845
S.D.	.011	.012	.0618	.558

Table 13 Accelerometry impact values for soft hydraulic system

	Max. (mv)	time (ms)	Range (mv)	Slope (mv/ms)
mean curve	.0313	.180	.0979	2.18
trial 1	.044	.185	.1459	4.73
trial 2	.0397	.185	.1624	4.1
trial 3	.0519	.170	.1367	3.03
trial 4	.0433	.180	.1677	4.2
trial 5	.0477	.180	.1965	4.37
trial 6	.0562	.160	.1385	2.31
trial 7	.072	.1950	.1697	3.77
trial 8	.0586	.185	.1825	4.06
trial 9	.0452	.180	.1831	3.66
trial 10	.0579	.180	.1247	4.09
Mean	.052	.180	.1610	3.932
S.D.	.01	.009	.0236	.70

Table 14 Accelerometry landing values for rigid system

	Max. (mv)	time (ms)	Range (mv)	Slope (mv/ms)
mean curve	.0489	.575	.0546	2.73
trial 1	.1220	.575	.0903	3.6
trial 2	.1677	.580	.0783	3.37
trial 3	.1710	.575	.0879	2.62
trial 4	.1832	.575	.0880	3.52
trial 5	.1653	.575	.0953	4.4
trial 6	.1289	.570	.0958	4.27
trial 7	.1953	.580	.0969	3.83
trial 8	.1957	.565	.0897	3.45
trial 9	.1556	.575	.0714	3.59
trial 10	.1676	.580	.0677	4.86
trial 11	.1321	.570	.0915	4.71
trial 12	.1556	.550	.0690	4.22
trial 13	.1492	.565	.0739	5.3
trial 14	.1208	.580	.0842	3.96
Mean	.1578	.572	.843	4.009
S.D.	.0250	.008	.0103	.5539

Table 15 Accelerometry landing values for stiff elastomer system

	Max. (mv)	time (ms)	Range (mv)	Slope (mv/ms)
mean curve	.0173	.55	.0488	1.63
trial 1	.0378	.540	.0610	2.40
trial 2	.0507	.545	.0958	3.19
trial 3	.0403	.540	.1117	3.72
trial 4	.0348	.555	.0818	2.73
trial 5	.0378	.540	.0689	2.30
trial 6	.0244	.555	.0677	2.26
trial 7	.0323	.560	.0781	3.12
trial 8	.0330	.560	.0732	2.44
trial 9	.0372	.565	.0633	3.73
trial 10	.0378	.550	.0313	2.16
trial 11	.0415	.575	.0824	2.12
trial 12	.0293	.535	.0665	1.9
trial 13	.0348	.55	.0806	3.22
Mean	.036	.552	.0668	2.7371
S.D.	.006	.012	.0228	.5984

Table 16 Accelerometry landing values for soft elastomer system

	Max. (mv)	time(ms)	Range (mv)	Slope (mv/ms)
mean curve	.0217	.575	.0321	1.07
trial 1	.0195	.57	.0427	1.71
trial 2	.0244	.58	.0537	1.53
trial 3	.0275	.58	.0555	1.59
trial 4	.0958	.595	.01251	3.57
trial 5	.0452	.565	.0891	4.46
trial 6	.0372	.575	.0696	2.32
trial 7	.0464	.585	.0598	2.99
trial 8	.0467	.575	.0824	3.29
trial 9	.0476	.56	.0745	2.98
trial 10	.0616	.47	.0751	3.76
trial 11	.0629	.575	.0897	3.59
trial 12	.0403	.585	.0684	2.28
trial 13	.0299	.59	.0514	1.71
Mean	.045	.57	.063	2.752
S.D.	.02	.031	.021	.963

Table 17 Accelerometry landing values for stiff hydraulic system

	Max. (mv)	time (ms)	Range (mv)	Slope (mv/ms)
mean curve	.0217	.575	.026	.743
trial 1	.0427	.550	.0653	1.18
trial 2	.0579	.560	.0397	2.18
trial 3	.0374	.565	.0470	1.59
trial 4	.0421	.560	.0586	2.59
trial 5	.0397	.550	.0598	2.93
trial 6	.0391	.570	.0647	2.39
trial 7	.0305	.530	.0610	2.59
trial 8	.0360	.545	.0641	4.07
trial 9	.0347	.560	.0830	3.21
trial 10	.0342	.580	.0574	3.32
trial 11	.026	.565	.0470	2.3
Mean	.038	.558	.059	2.577
S.D.	.008	.013	.012	.806

Table 18 Accelerometry landing values for soft hydraulic system

	Max. (mv)	time (ms)	Range (mv)	Slope (mv/ms)
mean curve	.0217	.56	.026	.74
trial 1	.021	.56	.0452	1.92
trial 2	.0256	.57	.0543	2.17
trial 3	.0226	.55	.0378	1.51
trial 4	.0287	.56	.0482	1.93
trial 5	.0256	.555	.0464	2.32
trial 6	.0311	.545	.0494	1.98
trial 7	.0366	.57	.0574	1.91
trial 8	.0256	.55	.0372	1.49
trial 9	.022	.565	.0366	1.46
trial 10	.0354	.565	.0568	2.27
Mean	.027	.559	.047	1.896
S.D.	.005	.009	.008	.318

Appendix F

Ground Reaction Force Raw Data

NOTE: Differences between mean curve values and calculated mean values are attributable to the fact that the Meangait program produces mean curves by summing points for each sampling period rather that summing specific maximum and minimum points as for the calculated mean values.

Table 19 Ground reaction force values for rigid system

	Impact			Landing			Impulse
Trial #	Peak (N)	Time (s)	Slope (N/s)	Peak (N)	Time (s)	Slope (N/s)	Pk-Pk (Ns)
1	978.19	.06	11031.1	398.98	.14	5336.5	38.73
2	872.45	.06	9429.11	449.12	.14	6590	35.33
3	1128.17	.06	8053.21	353.14	.14	4620.13	32.69
4	1103.82	.06	12320.33	351.7	.16	4122.67	37.71
5	1036.49	.06	8011.54	278.36	.15	3506.38	41.19
6	990.64	.05	10529.7	251.42	.16	3312.88	32.59
7	1043.65	.06	8440.42	271.48	.16	3056.22	39.50
8	949.1	.06	7480.21	523.62	.14	6319.44	29.51
9	1039.35	.07	7974.83	212.74	.14	3172.14	33.61
10	972.02	.05	13072.51	242.54	.15	3672.64	39.87
11	966.29	.06	8141.92	366.03	.14	3561.75	39.81
12	1073.73	.06	13855.29	275.63	.14	4469.7	37.83
13	941.93	.06	11970.11	423.33	.14	4589.9	35.7
14	1033.62	.06	13773.43	432.49	.16	3577.43	31.75
mean	1028.70	.059	10291.69	345.04	.147	4279.06	36.13
S.D.	57.91	.005	2359.36	92.57	.009	1127.25	3.63
mean curve	874.55	.06	15475.83	283.81	.14	1957.31	35.94

Table 20 Ground reaction force values for stiff elastomer system

	Impact			Landing			Impulse
Trial #	Peak (N)	Time (s)	Slope (N/s)	Peak (N)	Time (s)	Slope (N/s)	Pk-Pk (Ns)
1	976.67	.06	7581.69	671.53	.13	2977	45.41
2	856.34	.06	9709.89	614.23	.13	5503.58	34.65
3	863.5	.05	9860.67	559.79	.14	3406.39	31.74
4	879.26	.05	5959.6	910.78	.15	3260.41	36.22
5	935.13	.05	7907.08	598.9	.14	2105.93	35.08
6	856.34	.05	6711.23	714.51	.14	4114.72	40.33
7	959.48	.05	6079.56	1167.21	.13	4972.29	53.4
8	824.82	.06	5996.43	598.47	.13	3732.72	33.58
9	849.17	.05	7198.75	470.97	.14	3025.35	31.56
10	879.26	.05	6853.77	731.7	.14	6315.33	40.05
11	949.46	.06	9641.4	588.44	.13	3648.91	34.49
12	905.04	.05	7063.77	737.43	.13	4550.59	35.29
13	979.86	.05	5258.47	412.23	.13	4312.11	28.9
14	844.78	.05	5720.87	565.52	.13	3691.18	37.37
mean	889.9	.053	7253.67	667.34	.135	3974.06	37.04
S.D.	188.99	.005	1522.98	47.56	.007	1099.07	6.31
mean curve	871.07	.05	15837.6	526.63	.14	3631.93	37.2

Table 21 Ground reaction force values for soft elastomer system

	Impact			Landing			Impulse
Trial #	Peak (N)	Time (s)	Slope (N/s)	Peak (N)	Time (s)	Slope (N/s)	Pk-Pk Ns
1	839.15	.05	5615.8	751.76	.13	7006.73	44.28
2	892.12	.06	5578.19	721.67	.12	8436.44	44.82
3	899.31	.06	5696.13	889.29	.13	10537.55	51.09
4	919.37	.05	6569.5	776.12	.13	10081.13	46.82
5	912.21	.05	6036.07	940.86	.14	8738.82	53.96
6	874.96	.06	6730.74	597.04	.13	6796.88	35.31
7	940.86	.06	5334.35	1018.22	.12	11906.44	61.0
8	932.26	.05	5855.75	853.47	.12	8781.8	47.99
9	842.01	.06	6016.93	781.84	.13	6038.92	42.33
10	814.79	.05	5121.56	777.54	.14	8165.8	39.2
11	870.66	.06	6221.57	842.01	.15	8481.0	41.77
12	925.1	.05	6169.73	655.17	.14	6160.18	41.49
13	886.42	.05	6832.39	849.07	.12	7996.46	49.36
mean	888.4	.055	6003.98	804.21	.131	8394.48	46.13
S.D.	38.92	.005	515.79	113.32	.01	1714.71	7.72
mean curve	811.26	.05	14750.18	626.04	.13	4637.33	46.4

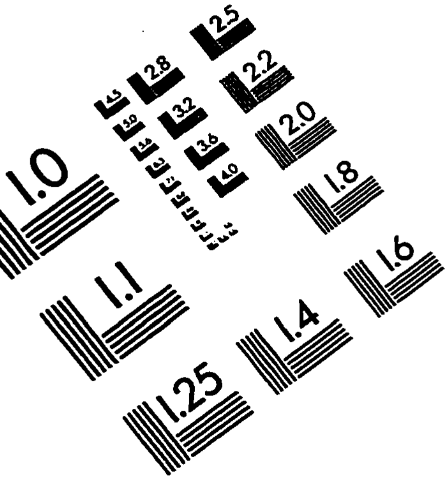
Table 22 Ground reaction values for stiff hydraulic system

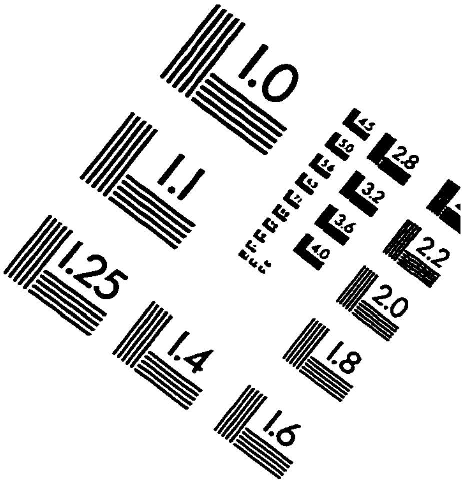
	Impact			Landing			Impulse
Trial #	Peak (N)	Time (s)	Slope (N/s)	Peak (N)	Time (s)	Slope (N/s)	Pk-Pk (Ns)
1	1101.67	.06	7979.29	737.79	.13	9455.13	49.18
2	1091.79	.06	8408.85	739.68	.14	8343.56	44.49
3	988.81	.06	8250.85	718.2	.13	7320.1	35.19
4	987.57	.06	8260.25	596.68	.14	6705.22	34.84
5	1118.79	.05	8616.77	732.83	.13	8262.78	46.39
6	998.16	.05	8321	730:27	.13	7506.8	44.82
7	1078.39	.06	7725.79	783.27	.13	7936.6	48.23
8	1052.6	.06	9585.36	450.91	.13	9311.82	35.44
9	975.24	.06	7559.69	417.4	.14	8469.3	38.09
10	998.16	.05	8356.83	544.03	.15	6930.25	34.05
11	978.26	.05	8927.46	572.78	.14	6496.78	34.76
12	1128.53	.05	7531.93	771.81	.13	8722.89	48.98
13	946.59	.06	6322.54	842.01	.13	6119.24	44.62
mean	1034.2	.056	8142.21	664.44	.135	7813.92	41.47
S.D.	62.8	.005	781.18	133.62	.007	1066.73	6.10
mean curve	920.65	.06	15344.17	518.19	.13	3838.44	42.44

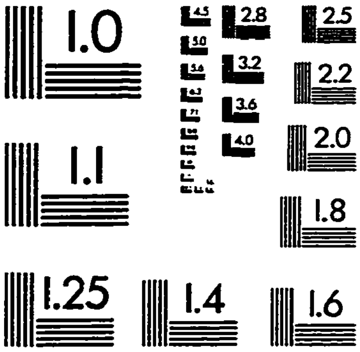
Table 23 Ground reaction force values for soft hydraulic system

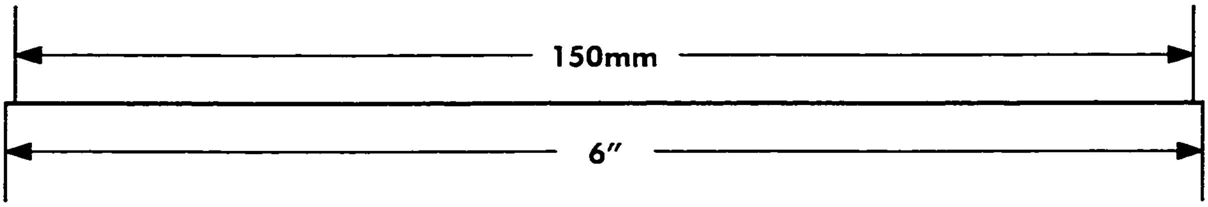
	Impact			Landing			Impulse
Trial #	Peak (N)	Time (s)	Slope (N/s)	Peak (N)	Time (s)	Slope (N/s)	Pk-Pk (Ns)
1	1018.22	.05	12982.75	690.15	.14	7177.3	37.56
2	956.82	.06	13855.29	863.28	.14	14688.5	39.53
3	943.73	.06	11999.25	897.88	.14	10155.56	44.34
4	1094.15	.05	10959.4	897.08	.13	8191.82	52.48
5	999.6	.06	14326.0	723.1	.14	7334.9	39.47
6	1021.09	.05	12839.77	512.51	.14	7981.57	38.41
7	1018.22	.06	14612.57	1042.57	.14	11667.67	36.56
8	1016.79	.06	12781.13	1108.47	.13	10158.36	57.12
9	955.19	.05	18129.0	607.06	.14	10314.66	38.62
10	950.89	.05	8712.82	1135.69	.13	16788.82	49.85
11	920.8	.06	11621.88	969.15	.14	8992.88	44.06
12	900.75	.06	9011.1	917.94	.14	10298.77	47.06
13	1002.46	.06	9090.46	925.1	.14	11711.5	48.93
14	1028.25	.06	9311.91	1076.96	.13	12224.89	51.3
mean	991.92	.056	11444.89	883.41	.137	9135.66	44.66
S.D.	56.0	.005	2241.14	189.16	.005	4362.16	5.54
range	193.5	.01	6483.57	623.18	.01	8754.16	20.56
mean curve	764.86	.05	13906.55	617.4	.14	4410.0	48.3

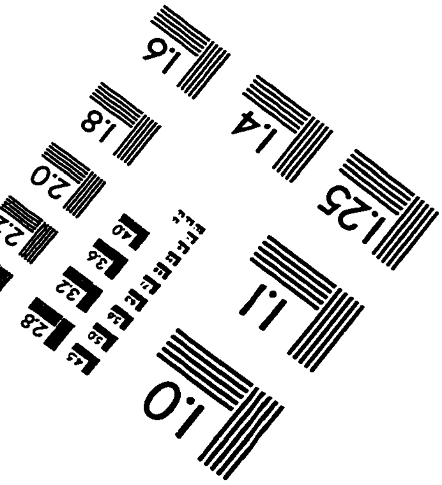
IMAGE EVALUATION TEST TARGET (QA-3)

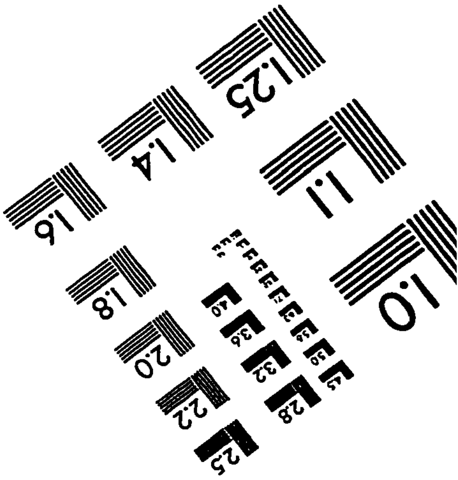












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