Masters of Science (M.Sc.) in Kinesiology Thesis

Impact Force Testing of Long Distance Running Shoes

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Abstract

The primary purpose of the study was to calibrate and validate a shoe impact machine designed to replicate heel strike impact force produced during running. The secondary purpose was to compare impact force attenuation magnitudes of four selected brands of running shoes. A major focus of footwear research has been on heel strike impact force due to its link to pain and injury (Frederick, 1984; Nigg, 1986; Nigg, Cole, Bruggemann, 1995). However gross participant gait variation during testing has made it difficult to consistently measure and compare impact forces between shoes. To correct for this variance, an ideal testing method would be mechanical simulation of heel strike to validate actual human response (Frederick, 1986, B). Eleven healthy male participants performed 25 trials of barefoot force platform running at 3 m·sec. Using the vertical ground reaction force (VGRF) curves generated, mean barefoot impact force values were calculated. An impact machine was calibrated to the mean barefoot impact force scores produced from the force platform running for each participant. The impact machine then duplicated 5 heel strikes using four selected brand name running shoes. All impact force data was represented in percent body weight to normalize each shoe's performance magnitude. Impact machine validity was established through a paired sample t-test. No significant differences were found between barefoot running and the barefoot impact machine results where, $t_{(11)} = .222$, $p > .05$. The results demonstrate that the impact machine generated equivalent impact force results compared to running over a force platform using multiple trials. A One-Way analysis of variance

(ANOVA) revealed significant differences between midsole attenuation rates between the four pairs of running shoes; where, $F(3,40) = 5.766$, $p < .05$. Scheffe's post hoc comparison determined that Nike was significantly different from Adidas and New Balance. No other significant differences were found. Nike had the greatest attenuation rate absorbing 7.9% of the impact force per step followed by Saucony 6.5%, then Adidas 4.6%, and finally New Balance 4.5%.

Key Words: Running, Ground Reaction Force, Impact Force, Footwear, and Midsole

Introduction

The demand for high performance running shoes continues to grow at an unprecedented rate. It has been speculated that the number of joggers in the United States alone had reached 30 million by 1980, which was more than 10% of the total population (Kristoff, Ferris. 1979). In Canada, approximately 18% of the population were utilizing running as a form of physical activity (Nigg, Cole, Bruggeman, 1995). Once utilized as a minor form of health maintenance by a low percentage of the population, running has become a major recreational activity practiced worldwide. The magnitude of the running domain is illustrated through magazines, textbooks, radio, television, and the worldwide web. A major focus of running innovation and technology has concentrated on footwear. Undisputedly the running shoe is the single most important piece of running equipment (Cavanagh, 1990). Considering that 2 out of 3 runners will be affected by injury each year it is clear that proper shoe selection is imperative (Nigg, 1986). The origin of many injuries is caused by excessive loads, which are produced during heel contact. Vertical ground reaction force (VGRF) is produced on each step where the transmission of a sharp resultant force to the human locomotor system. Due to an extended leg on heel strike, humans promote a stiff jarring effect that produces a shock wave traveling from the foot to the head. It is not uncommon for the amplitude of vertical impact forces in heel-toe running to range between 2 to 4 time's body weight (BW) depending on velocity, surface, and running style (Nigg, 1986).

In an attempt to combat excessive impact force values, shoe companies have employed various cushioning systems in the midsole. The use of various foams such as ethylene, vinyl, and acetate (EVA), molded polyurethane, gel, or air-cushioning systems can be located in the midsoles in each of the major name brands on the market today. The repeated trauma of impact forces causes intense vibration in the lower leg creating a wide variety of injuries. Common running injuries include stress fractures, patellofemoral stress syndrome, heel spurs, tendonitis, bursitis, shin splints, plantar faciitis, Morton's neurome, and tarsal tunnel syndrome (Marshall and McNair, 1994). The overall yearly incidence rate for running injuries varies between 37 and 56% depending on the running demographic examined. From epidemiological studies, it has been concluded that running injuries lead to a reduction or cessation of training in about 30 to 90% of all injuries, 20 to 70% lead to medical consultation and treatment, and 0 to 5% result in the absence from work (van Mechelen, 1992).

Although brand name companies proclaim that their midsoles attenuate shock, it is still highly equivocal as to which shoe performs best. Resourceful marketing schemes and flashy shoe design has further camouflaged which running shoes perform best to attenuate VGRF. The shoe industry is driven by two major factors: function and fashion. Undoubtedly function is the most important consideration for sport shoe companies, however an underlying influence of fashion cannot be disregarded (Sheperd, 1997). All major shoe companies employ the service of the top athletes to help design and improve their footwear line at the highest level. This alone is a testament to functionality. Nonetheless Adidas still makes their Galaxy running shoe in over 20 different aesthetic color schemes (Sheperd, 1997). With thousands of running shoes to choose from, it is logical to utilize ostentatious designs to help influence shoe purchases. Nike running shoes in fact require two years of aesthetic design before being placed on the market after model renovations (Sheperd, 1997). The research utilized for these designs subsequently leads to an increased shoe cost. Ironically consumers are often lead to believe that an increased cost is indicative of increased shoe quality and performance. When purchasing a leading brand name associated with quality, one would hope the shoe is not a product of resourceful marketing, rather functional performance innovation. Many factors such as price, durability, comfort, aesthetics, protection, weight, performance, and purpose play a role in the criteria for shoe selection (Nigg, 1986). Currently though the consumer is often sold on aesthetics and a technical sales pitch.

Quantitative recognized research on brand name running shoes has been limited in nature (Cavanagh, 1990). Furthermore, minimal empirical evidence is available to quantify the shock absorbency magnitudes existing between midsoles on running shoes. The competitive footwear industry maintains this trend as experimental research is conducted behind closed doors. Another reason for finite research resources is the complexity of finding reliable and valid results using human participants. The human population is highly variable in size and movement characteristics. This fuels participant variation on ground reaction force values and the ability to achieve statistical significance when measuring running shoe performance. Within the biomechanics community, footwear research has been a relatively neglected domain (Cavanagh, 1990).

Investigators who attempt to overcome these difficulties must perform studies with increased sample sizes combined with large trial numbers. This is not always a feasible option, as increased time and costs are an issue for performing research. Several methods of ground reaction force data collection have been utilized to combat these dilemmas. Standard force platform running has been utilized as the "gold standard" for collecting ground reaction forces. Collecting a sufficient number of good trails is however a difficult task due to human error. For example an accepted trial is identified as an attempt that is: free from altered running technique, a foot strike landing within the platform boundary, and a velocity maintained within a 5% error range. The culmination of these factors forges a highly tedious process in order to collect satisfactory trials numbers. Mechanical testing instruments to measure vertical ground reaction forces have received minimal use due to ecological validity constraints. Mechanical replication of impact forces would be a sound alternative solution if the instrument were designed to characterize accurate ground reaction forces. The intrinsic control and speed at which they collect data would prove to be fruitful, however conventional mechanical testing has not effectively modeled human ground reaction forces. The development of an impact machine that could effectively replicate and measure vertical ground reaction forces would have substantial implication for the researcher and consumer. The device would provide the necessary control to test midsole materials in currently marketed running shoes. The results of the midsole comparison would supply consumers an indication of relative shoe cost and attenuation performance.

Purpose

The primary purpose of the study was to calibrate and a validate shoe impact machine to replicate heel strike impact force produced during running. The secondary purpose was to compare impact force attenuation magnitudes of four selected brands of running shoes.

Delimitations

This study only attempts to replicate the event of heel strike impact force within the stance phase of the gait cycle. The Impact force resultant was measured only in the vertical plane. All other forces (mediolateral and anterio-posterior) acting upon an individual during the gait cycle are not being measured or replicated in this research. The remainder of the gait cycle (midstance, toe-off and swing phase) is not being simulated by the shoe impact machine. The impact force values are also limited to a gait velocity of 3 m·sec. Finally the results of this study are delimited to the four band name running shoes selected for examination.

Definitions

Force: Push or pull; the product of mass and acceleration (Hall, 1999).

Ground Reaction Force (GRF): A force acting from the ground on an object that is in contact with the ground (Nigg, et al, 2000).

Impact Force: The force produced from the landing phase as a result of the collision between the foot and the ground at heel strike (Nigg et al, 1995).

Shock Absorption: The dampening of vibrations generated in a system (Watkins, 1999).

Attenuation: The reduction of the amplitude of impact forces (Nigg, et al 1995)

Heel Strike: The beginning of the stance phase. Results in an impact between the heel and the ground.

Midsole: The shock-attenuating portion of the shoe between the upper last and outsole (Esterling, 1993).

Dorsiflexion: rotation of the foot about a transverse axis through the ankle joint in which the dorsal surface is drawn closer to the shin (Watkins, 1999).

Pronation: Rotation of the foot about the subtalar joint involving simultaneous abduction, dorsiflexion, and eversion (Watkins, 1999).

Supination: Rotation of the foot about the subtalar joint involving simultaneous adduction, plantar flexion, and inversion (Watkins, 1999).

Review of Literature

Epidemiology

Running as a form of exercise provides excellent cardiovascular health benefits. However this simple form of fitness promotes various musculoskeletal injuries to the human locomotor system, which can have an incapacitating effect. Inspection of the epidemiological research on factors causing running injuries yields several conclusions. Hoeberigs (1992) found that in particular, distance run per week, previous running injury, being a novice runner, and running speed were key factors in the etiology of running injuries. Many of the risk factors implicated as sources of injury have not been included in epidemiological research. This does not mean they are not responsible for causing running injuries; rather the literature base has not been sufficiently developed to draw definitive conclusions (Hoeberigs, 1992). Examples of some of the excluded risk factors were: the role of shoes, personality type, and anatomical factors. Since the footwear domain is a relatively new area of research, it is logical that running injury epidemiology is also in a premature state (Hoeberigs, 1992). Research by van Mechelen (1992) found the same factors were significantly related with running injuries with the exception of running to compete rather than running speed. Also included were the risk factors that were not significantly related with running injury due to equivocal or limited research. Some of these highlighted factors include running surface, basal metabolic index, shoes, in-shoe orthoses, and malalignment.

Another epidemiological investigation by Cook, Brinker, and Mahlon (1990) revealed a greater number of risk factors associated with running injury. Included were the same factors presented by Hoeberigs (1992) and van Mechlen (1992), however an increased number of etiological risk factors were included. These were change in weekly distance, poor technique, stretching, surface type, hill running, and shoe cushioning. Particular emphasis was placed on the cushioning of heel strike impact forces due to heel strike being the most critical stage of the gait cycle due to the impending shock wave traveling up the axial skeleton (Cook et al, 1990). This intense energy transfer is responsible for acute and chronic injury mechanisms. After an examination of the epidemiological literature, the most significant origins of running injury can be classified into five distinct categories: 1) the distance run per week, 2) previous running injury, 3) novice runners, 4) biomechanical abnormalities, and 5) shoes. Although the origin of musculoskeletal injury has been established, the etiology specifically causing running injury requires further investigation.

Ground Reaction Force (GRF) and Loading

One confirmed link between all the major injury sources is the applied load called ground reaction force (GRF) sustained from running. Increased mileage leads to increased GRF's, novice runners often utilize poor running technique maximizing GRF's, biomechanical abnormalities increase GRF's, and footwear attenuation rates determine the magnitude of GRF's. Ground reaction force is a three dimensional force with varying magnitude in each direction. VGRF produced on heel strike can result in immense magnitudes, which could ultimately surpass musculoskeletal stress limits. For example, a 70kg individual with a stride length of 1.5m would make foot contact 670 times per kilometer, at approximately 2.5 times their bodyweight would cause a net force of 60 tonnes per kilometer. Immense loading magnitudes of such high proportion illustrate why injuries are so prominent in the running population. Decreasing ground reaction force using superior footwear may significantly reduce running induced injuries since footwear is designed to attenuate impact loading. Figure 1 presents the interaction of the events leading to running injury due to ground reaction forces.

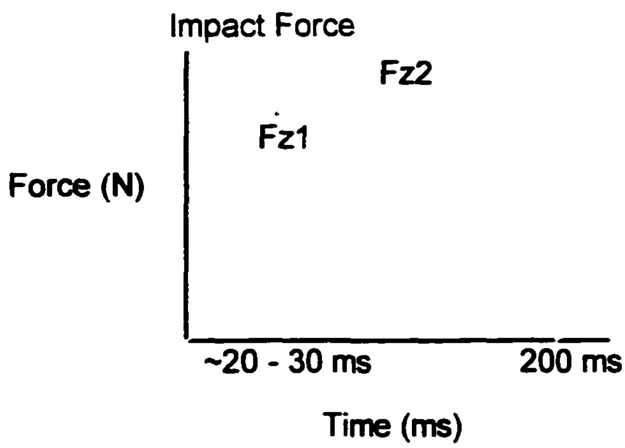
Figure 1.

Impact Force

Within a vertical ground reaction force curve, an impact force peak is produced which has been implicated as a primary source contributing to running injuries (Chu, Yazdani-Ardakani, Gradiser, Askew, 1986; Voloshin, Wosk, 1980; Voloshin, Wosk, Brull, 1981; MacLennan, Vyvyan, 1981). An example of a typical ground reaction force curve and the corresponding impact force produced from running is display in Figure 2.

Figure 2.

Vertical Ground Reaction Force Curve (Fz)



Greater attention and research has been focused on the vertical aspect of the reaction force component. This is due to a composite rating of 85% of the total impulse being applied to the foot vertically, where as 15% of the impulse results medio-laterally (Cook et al, 1990). This composite rating applies only to a normal gait pattern within the running population. A normal gait pattern is defined as a heel strike landing in a neutral position deviating between $+7^{\circ}$ of supination and -11° of pronation on heel contact (Barnes and Smith, 1994). This operationalization is necessary as individuals exhibiting excessive mediolateral movement are prone to increased injuries not induced by vertical impact force.

The high frequency impact peak occurs directly after heel strike, typically between 20 to 30 milliseconds after contact (Frederick, 1986 A; Hamill, 1996). During heel-strike, the straight skeletal alignment of upper and lower leg causes an impact load much like a rod subject to compression. Consequently, gravitational potential and kinetic energy are directly transferred to the runner leading to high levels of shock (Watkins, 1999). It is for this reason that impact force is assumed to be linked to pain and running injury (Frederick, 1984; Nigg, 1986; Nigg, Cole, Bruggemann, 1995).

Running Injuries

The majority of running injuries due to impact force are located in the lower extremity, particularly from the knee down. Many injuries have a minor effect, which do not limit daily routine or performance. These injuries primarily include blistering, calluses, and chafing (Bridge, 1980). More significant overuse injuries that have various grades of debilitation are: stress fractures, patellofemoral stress syndrome, achilles tendonitis, retrocalcaneal bursitis, posterior tibialis tendinitis, iliotibial band friction syndrome, shin splints, plantar faciitis, metatarsaglia, Morton's neuroma, and metatarsal tunnel syndrome (Agostini, 1994). Other maladies runners experience at a decreased incidence rate include: chondromalacia of the patella (runner's knee), and lower back pain (Anderson, Hall, 1995). These overuse injuries result from unattenuated impact force surmounting human joint and tissue limits, particularly in the recreational runner.

High mileage runners are prone the previously mention injuries, however these athletes are also subject to micro-traumatic injuries affecting the integrity of the hematological system. Often these changes from endurance training have been misinterpreted as "sports anemia". Rather research by Falsetti, 1983 suggests that the hematological damage is a result of the impact forces generated while running. The repeated trauma from foot strikes has been found to cause transient changes in red blood cells (RBC), hemoglobin, and hematocrit (Falsetti, 1983). Furthermore, the material used in the midsole of shoes has been shown to intervene in the amount of cellular damage due to impact force. Softer air-cushioned shoes were more effective than firm soles in reducing the acute erythropietic stress that occurs with endurance training (Falsetti et al, 1983). The results of the study "indicate that: 1) material properties of running shoes may be correlated with physiological measurements, and 2) appropriate cushioning reduces the RBC abnormalities experienced in long distance running" (Falsetti, 1983).

Since increased RBC destruction is related to the trauma caused by impact force through heel striking, appropriate midsole cushioning would also help to reduce erthrocyte abnormalities such as reticulocytosis. Reticulocytosis is an erythropoietic response due to acute RBC destruction. Premature red blood cells (called reticulocytes) are quickly excreted to replace the increased demands of RBC damage due to heel strike hemolysis. These cells have no oxygen carrying capacity and therefore circulate without purpose. Research by

Dressendorfer, Wade, and Frederick (1992) found that the severity of heel strike hemolysis might be influenced by the cushioning properties of the midsole. Although both test groups observed reticulocytosis, the soft-soled group produced significantly less erythropoeisis compared to the firm-soled group.

Running Shoe Design

It is generally accepted that attenuating impact force is the business of sport shoe manufacturing (Frederick, 1986, B). The single most important functional component of the shoe is the midsole, and its fundamental purpose is cushioning (Hamill, Bates, 1988). Midsole construction is made from a wide range of viscoelastic materials. Some examples are polyurethane elastomers, polyurethane foams, polyvinyl chloride foams, ethylene vinyl acetate, synthetic rubber foams, and silicone rubber. More complex midsoles utilize combinations of these foams plus additional air bladders, or gel sacs. Each of these materials responds differently under compression conforming to the principals of absorption. The two mechanisms that exist to attenuate impact force are rigidity and loss tangent. Rigidity is the materials ability to deform under load, where as loss tangent refers to the ratio of energy dissipated and not transmitted to the applied body (Forner, et al, 1995). From a design perspective it is currently unknown which attenuation method works best to decrease impact force. Other portions of a running shoe consist of an outsole, wedge, insole, heel counter, quarterlining, heel counter support, upper last, sock liner, ankle collar, heel tab, and lacing system (Cook et al, 1990). Figure 3 shows the various parts of a running shoe.

Figure 3.

Impact Force Measurement Systems

Research using participants to measure midsole function are usually associated with reliability problems and highly time consuming. This promotes the use of materials tests, which are not affected by these problems (Nigg, 1986). Test results must be valid if they are to be effective for consumer information. This requires a knowledgeable approach on the material properties and the movements involved (Nigg, 1986). Numerous investigative approaches have been utilized to develop a greater comprehension of the foot and shoe interface (Barnes, Smith, 1994). The result of the previous research however has been equivocal for both *in vivo* tests and materials tests.

In Vivo Tests

In vivo experiments thus far have had difficulty performing materials tests due to participant variation. Force platform running has been classified as the gold standard for ground reaction force data collection (Nigg, 1986). Nonetheless collecting reliable data on any given variable has been difficult. Clarke, Frederick, and Cooper, 1983 collected ground reaction force data for a variety of dependent force measures. Their results revealed that force platform running could measure attenuation differences depending on the footwear used for certain parameters. Time to impact peak was measurable and significantly different, however force magnitudes due to footwear could not be assessed (Clarke et al, 1983). The research suggests that impact force magnitudes are decreased due to an adaptive proprioceptive response. The reliability of this research however may be questionable as only 5 footfalls were collected per condition. "Based upon interdependent parameter reliability and minimum sample size evaluations, a sample size of 25 trials was identified as necessary to provide accurate ground reaction force data describing a subject's performance" (DeVita, Bates, 1988). Participant variation from trial to trial, day to day, and week to week is large and is caused by fatigue, changes in muscle activation, and the orientation of human joint segments.

Further *in vivo* investigation by Bates and Dufek (1991) on impact force midsole attenuation found subtle differences between footwear shoe conditions. A comparison between basketball, volleyball, and running shoes revealed basketball shoes as the best footwear condition (Bates, Dufek, 1991). The investigation results only found significance when employing a within-subject analysis. This was primarily due to low statistical power and minor attenuation differences between each shoe condition.

Midsole Materials Tests

Mechanical tests are a necessary reference point for the *in vitro* shock absorbing properties of various running shoe designs (Frederick, 1986, B). The impact peak is produced when the center of pressure is under the plantar surface of the calcaneous (Frederick, 1986, B). The observed magnitude during heel strike provides the rationale to develop an impact tester to measure midsole attenuation qualities (Frederick, 1986, B). Based on the current literature however, a materials testing instrument that accurately replicates impact force has yet to be developed.

The majority of impacters are weighted shafts, missiles or swinging pendulums that strike the outer heel surface. The calibration method designed to replicate heel strike produced in running is often questionable. In many cases the materials tests do not attempt to simulate heel strike, rather simply perform a compression test. Research by Foti and Hamill 1993 performed a materials test and compared the results to forces produced during running. Naturally the results of the study found that materials tests and human subject tests did not produce the same result (Foti, Hamill, 1993). The impacter involved was an 8 kg mass dropped from a 5 cm height. The velocity of the mass was not measured, and the diameter and shape of the missile head was unreported. The ecological validity of this research is suspect when trying to simulate human conditions with such a simple design. In addition, only ten ground reaction force trials were collected from the participants. Twenty-five trials are required if the mean data is attempting to characterize human impact forces (DeVita, Bates, 1988).

A similar testing protocol by Marshall and McNair (1994) revealed significant differences in midsole characteristics. An impacter was used to measure midsoles and compared to human response characteristics collected by a force platform. A 9 kg mass, 2.5 cm in diameter, with a 9.0 cm radius of curvature was dropped from a height of 5 cm. The shoes were clamped to prevent movement. The results from the materials test found that the midsoles only differed from the barefoot trials. The differences observed between the shoes and materials tests were not sufficient to elicit changes in absorption magnitudes (Marshall and McNair, 1994).

Other materials tests used to replicate impact forces are pendulum tests. The impact was delivered to the plantar aspect of the foot by a swinging pendulum. Individual tests were performed by fixing the lower leg with straps at a 90° angle. Participants are fitted with shoes and are measured on various force dependent measures. Lawless and Lafortune (1995) utilized this impact testing method comparing footwear in relation to barefoot on reaction force values. The materials test results found significant differences on reduced peak variables, transient rates, and mean power frequency when compared to barefoot. Smaller but significant differences existed between midsoles except for peak impact force (Lawless, Lafortune, 1995). The research provides evidence that cushioning differences can be measured under controlled conditions, however absorption magnitudes still have not been recorded.

Since observations in peak force between footwear comparisons have not been measured effectively by force platform running, Aerts and De Clecq (1993) performed a materials tests on midsole density. Heel strike impact force was simulated through the use of a pendulum. The results displayed an inverse relationship when compared to human participant response. During materials tests, the harder the footwear, the higher the impact frequency. However participants recorded lower impact force values for harder midsoles and higher impact force values for softer midsoles. A possible explanation for this trend is a "bottoming out" effect (Hamill, 1996). If the softer materials excessively deform under compression, the midsole will lose its ability to attenuate impact force. When comparing soft versus hard midsole materials in general, a linear relationship between time to peak impact and impact force peak as material become harder (Hamill, 1996). Human tests will not follow this linear impact pattern if the materials examined are too soft.

Method

Purpose

The primary purpose of the study was to calibrate and validate a shoe impact machine to replicate heel strike impact force produced during running. A secondary purpose was to compare the impact force attenuation magnitude of four different brands of running shoes.

Participants

Eleven healthy male participants were selected to participate in the study. Only males were selected to decrease the total number of shoes needed to perform the experiment. To meet participant inclusion criteria, each individual exhibited a pronounced heel-toe gait pattern. The necessary pattern was evaluated by exhibiting two distinct peaks in the vertical ground reaction force

(VGRF) curve as previously demonstrated on Figure 2.

Procedure and Apparatus

The experiment was performed in the biomechanics laboratory at Lakehead University's Kinesiology Research Center. Each participant performed 25 trials of barefoot running at a velocity of 3 m·sec. All of the VGRF data was collected though Advanced Mechanical Technology Incorporated (AMTI) force platforms. The output signal was managed using AMTI's BioDataAquisition (BioDaq) processing software. Light beam sensors (Archer, Co.) were positioned at shoulder height to monitor running velocity. Accepted trials were free of altered running technique, a foot strike landing within the platform boundary, and a velocity maintained within a 5% error range. From the barefoot GRF curves produced for each condition, impact force scores (Fz_1) were extracted and meaned using BioAnalysis (version 1.0) gait processing software. The mean barefoot impact force values were then used as a baseline to calibrate the impact machine.

The impact machine was calibrated for each participant to match individual impact force characteristics collected during force platform running. The impact device used to replicate these forces consisted of a loaded aluminum sled mounted with an adjustable prosthetic foot sized 9, 10, or 11. Refer to Appendix A to view photos of the impact machine. The prosthetic foot (Otto Bola, Pedilan) were made from a wood interior, molded with a dense foam heal pad encapsulated in a rubber exterior. The heel of the prosthetic was designed to simulate the fat pad under the calcaneous of the foot. During impact testing, prosthetic foot sizes were changed to match participant foot sizes recorded during force platform running. Throughout impact testing, the prosthetic foot angles were fixed at a neutral 5° supination and 10° dorsiflexion position for all impact tests.

The sled was fitted to an incline track that was set at a vertical incline of 10°. Impact force data was collected by an AMTI force platform fixed at the base of the track. The sled load was altered using nylon sand bags ranging between .5 kilograms to 30 kilograms to simulate participant's body masses. Participant masses were converted to match the track slope angle using a trigonometry equation (sin 10° x subject mass). Increasing or decreasing the sleds runway length calibrated the magnitude of impact force output. Trial and error was used to locate the correct runway distance needed to replicate the impact force values produced during force platform running. A calibration chart was developed for mass conversions and runway distances used to reproduce participant's impact forces. See Appendix C.

Once calibrated, the impact machine performed 5 trials with the prosthetic barefoot, and 5 trials in each of the four shoe conditions. Four pairs of running shoes in 3 sizes (U.S. 9,10, and 11) were selected for analysis. Shoes measured for attenuation included: Nike, Saucony, Adidas, and New Balance. Refer to Appendix B to view model specifications. The shoes selected were all designed for cushioning with a mild anti-pronation device in the midsole. Each shoe had similar midsole lasting (i.e. shape), however the midsole construction design was different for two groups. Nike and Saucony (Group 1) abided to the rigidity principal of absorption, whereas Adidas and New Balance (Group 2) abided to the loss tangent principal of absorption. These two midsole construction designs were selected for examination to reveal future design implications.

From the barefoot GRF spike produced for each condition, impact force scores (Fz_1) were extracted and meaned using BioAnalysis (version 1.0) gait processing software. Footwear absorption scores were calculated to reveal the total shock absorbed due to the addition of active footwear for four different pairs of running shoes. The shoe absorption percentage was calculated using the following computation:

$$\frac{\text{mean shoe score - mean barefoot score}}{\text{mean barefoot score}} = \text{Absorption \%}$$

Statistical Design

Confirmation of reliability was assessed by super-imposing several force curve trials (n=25) and comparing impact force standard deviations for the participants on the impact machine. To establish validity, a paired sample t-test between force platform barefoot running and the impact machine was used to reveal whether the modalities are producing the same impact force result. A one-way analysis of variance (ANOVA) was employed to detect significant midsole attenuation differences between four brands of running shoes. Scheffé's post hoc comparison was used to locate any significant mean differences.

Results

The paired sample t-test used to compare impact forces collected during force platform running versus the impact machine yielded no significant differences ($t_{(11)} = .222$, $p > .05$). See Table 1. An acceptance of the null hypothesis (H_0) is warranted were $H_0 : \mu_d = 0$. The results conclude that the impact force values produced during force platform running are equivalent to the impact machine.

Table 1.

Paired Samples Test: Running – Impact Machine (Newton's)

Mean	Std Dev.	Std. Mean Error	95% Confidence Interval		t	Df	Sig. (2-tailed)
.4464	6.6550	2.0066	-4.0245	4.9172	.222	10	.828

Since the impact machine provided valid results when compared to force platform running, shoe attenuation comparisons were conducted to measure midsole performance. The one-way ANOVA revealed significant differences between the shoes measured ($F(3,40) = 5.766$, $p < .05$). See Table 2. There is enough available evidence to reject the null hypothesis that all midsoles are equal ($H_0 : \mu_1 = \mu_2 = \mu_3 = \mu_4$), and accept the alternative hypothesis (H_1). It is possible to conclude consequently, that the four pairs of shoes do not absorb the same amount of mean impact force.

Table 2.

One-Way ANOVA: Percentage of Absorbed Force (Newton's)

	Sum of Squares	df	Mean Square	F Ratio	Significance
Between Groups	89.194	3	29.731	5.766	.002
Within Groups	206.238	40	5.156		
Total	295.432	43			

Scheffé's Post Hoc comparison was utilized to reveal which shoes were significantly absorbing greater impact forces within the footwear group. See figure 3. Examination of the Post Hoc comparison finds that Nike is significantly different from New Balance (p = .013), and Nike is also significantly different from Adidas (p = .016). See Table 3. No other significant differences between shoes were found.

Table 3.

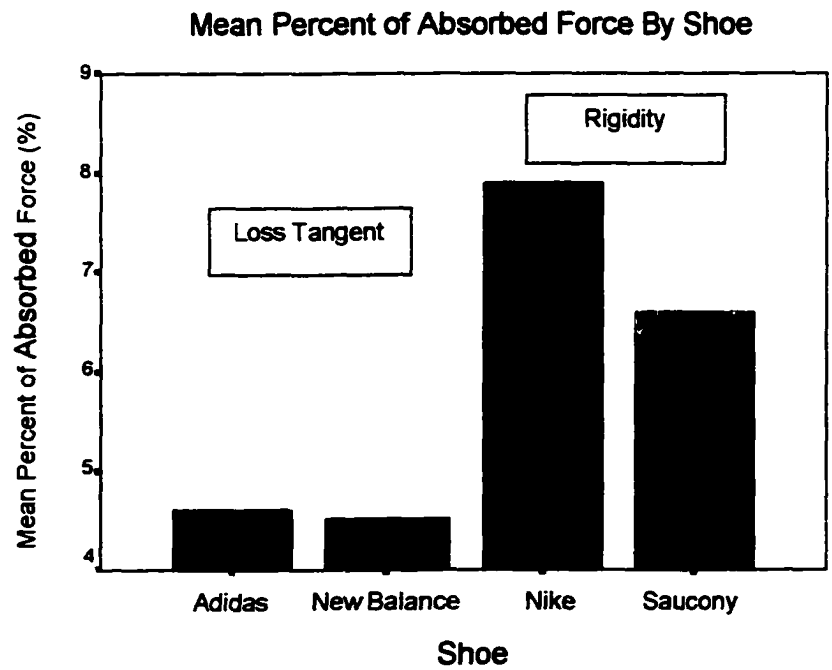
Scheffé Post-Hoc (Multiple Comparisons): Percentage of Absorbed Force

Number Assigned to Group (I)	Number Assigned to Group (J)	Mean Difference (I-J)	Standard Error	Significance	95% Confidence Interval Lower	95% Confidence Interval Upper
Adidas	NB	9.690	.968	1.00	-2.7286	2.9224
	Nike	-3.2965*	.968	.016	-6.1220	-.4710
	Saucony	-1.9937	.968	.253	-4.8192	.8318
NB	Adidas	-9.6901	.968	1.00	-2.9224	2.7286
	Nike	-3.3934*	.968	.013	-6.2189	-.5679
	Saucony	-2.0906	.968	.216	-4.9161	.7349
Nike	Adidas	3.2965*	.968	.016	.4710	6.1220
	NB	3.3934*	.968	.013	.5679	6.2189
	Saucony	1.3028	.968	.617	-1.5227	4.1283
Saucony	Adidas	1.9937	.968	.253	-.8318	4.8192
	NB	2.0906	.968	.216	-.7349	4.9161
	Nike	-1.3028	.968	.617	-4.1283	1.5227

* The mean significant difference is at the α = 0.05 level.

Research results indicate that footwear designed using a rigidity midsole design, absorb a greater percentage of impact force compared to shoes designed using loss tangent. To illustrate this, Figure 1 shows the average absorption percentage for each shoe from the 11 male participants. Nike is the best attenuating midsole absorbing 7.9% of the applied impact force, Saucony is second absorbing 6.6%, Adidas is third absorbing 4.6%, and New Balance is last absorbing 4.5% of the impact force. As a rigidity group, Nike and Saucony absorb 7.25% of the applied impact force; whereas the loss tangent group, Adidas and New Balance, absorb 4.55% impact force.

Figure 1.



Discussion

Heel strike impact force research during running gait is of the upmost importance due to its close association with injury (Agostini, 1994). Conventional impact tests using force platform running has been ineffective in the measurement of midsole attenuation. Participant variability during the dynamic gait phase is chiefly responsible for this obstacle (DeVita, Bates, 1988). Reliable mechanical simulation and reproduction of the heel strike phase would provide the necessary control to test midsole absorbency magnitudes existing between currently marketed running shoes. The primary purpose of the study was to calibrate and validate a shoe impact machine to replicate heel strike impact force produced during running. The secondary purpose was to compare the impact force magnitude of four selected brands of running shoes.

In order to achieve the research rationale, reliability and validity tests were necessary to provide evidence that the impact machine could accurately reproduce human impact force. Previous research established reliability using successive impact force curves, which were superimposed and inspected for variation (Bauer, Valjakka, 1999). Analysis of the impact force curves yielded minimal standard deviations (SD) for each participant (see Appendix D). In the present study reliability measures were reaffirmed, where group (n=11) peak barefoot impact force values averaged a SD = 8.87 N (0.91 kg) on the impact machine. A SD rate of 0.91 kilograms for the group is highly reliable when compared to the force platform SD's, which were double by comparison when collected over 25 trials (DeVita, Bates, 1988). Minimal SD levels provide conclusive evidence that the impact machine can successfully perform multiple indistinguishable trials in a controlled environment. These results help eliminate the predicament of washed effects from participant variation previously associated with force platform running.

Since reliability had been ascertained, validity measures were performed to demonstrate that the impact force data was consistent with the impact force data produced from force platform running. In order for the impact machine to be valid the mean impact force scores produced during running should be identical to the mean impact force score produced on the impact machine. To measure this, a paired sample significance *t*-test was used. Paired sample *t*-tests assess the reliability of the observed difference between the two modalities on peak barefoot impact force. They also provide increased power associated with repeated measures due to decreased idiosyncrasies in variability resulting from the matched pairs. The results of the *t*-test revealed no significant differences where, $t_{(11)} = .222$, $p > .05$. This confirms a 95% probability that the impact force values produced during force platform running and the impact machine are equivalent. Therefore the impact forces collected during running are the same as the impact force collected on the impact machine. The success of the barefoot comparison served as the baseline validation measure before progressing to the midsole phase of testing on the running shoes.

The secondary purpose was to measure shock absorption magnitudes for four selected brands of running shoes. A one-way ANOVA revealed a significant difference between the footwear measured where, $F(3,40) = 5.766$, $p < .05$. Based on the results of the footwear impact force data, there is sufficient evidence to conclude that all midsoles do not absorb equally. Nike was significantly different from New Balance ($p = .013$), and Nike was also significantly different from Adidas ($p = .016$). Saucony approached significance when compared to New Balance ($p=.216$). No other significant differences between shoes were found.

Research results indicate that footwear designed to collapse like a shock absorber (rigidity), absorb a greater percentage of impact force compared to shoes designed using the loss tangent principal. Nike and Saucony were designed using the rigidity principal; whereas, Adidas and New Balance were designed using loss tangent. Nike and Saucony combined to absorb 7.25% of the impact force sustained during running. Adidas and New Balance absorbed 4.55% of the impact force, a difference of 2.7%. Considering that the average individual predisposes themselves to impact forces 2 to 3 times their body weight while running, a 2.7% impact force reduction rate is significant (Nigg, 1986). For example, a 175 pound male would eliminate between 95 to 142 pounds of impact force per step depending on the individual's running style simply through shoe selection. A saving of this magnitude would help decrease some of the injuries previously associated with running. Thus consumers who select a running shoe based on performance, should consider purchasing midsoles that employ a rigidity midsole design. However footwear made using rigidity tend to cost significantly more than the loss tangent counterpart. This is due to the increased cost in the molding process involved in creating multi-encapsulated (rigidity) midsoles (Esterling, 1993). Therefore if cost is a variable when selecting footwear, purchasing shoes designed with the rigidity principle may not be a feasible option.

Recommendations

Future research on the impact machine should test a larger sample of shoe types to draw inferences on current midsole design. A greater sample of shoes will also provide an indication of cost and relative performance. A repetitive impact materials endurance test on the impact machine would provide empirical information regarding midsole life spans during distance running. Finally to improve the impact machine design, a damper could be installed above the prosthetic foot to further simulate musculoskeletal attenuation characteristics in the lower extremity.

Conclusions

The impact machine was a reliable and valid device for replicating impact force produced during running. It provided fast, accurate test results. Nike was found to be the best performing midsole for force attenuation, Saucony was second, while Adidas and New Balance finished third and fourth. Research findings suggest that footwear designed with the rigidity principal absorb a greater percentage of impact force compared to shoes designed using loss tangent. From the shoes tested, a retail cost comparison found that an increase cost was consistent with increased midsole performance.

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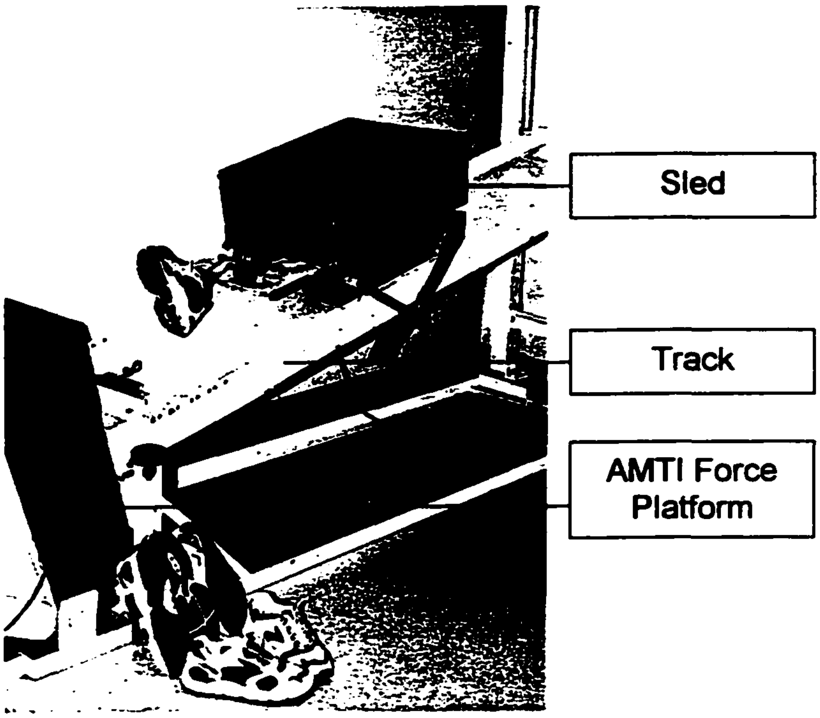
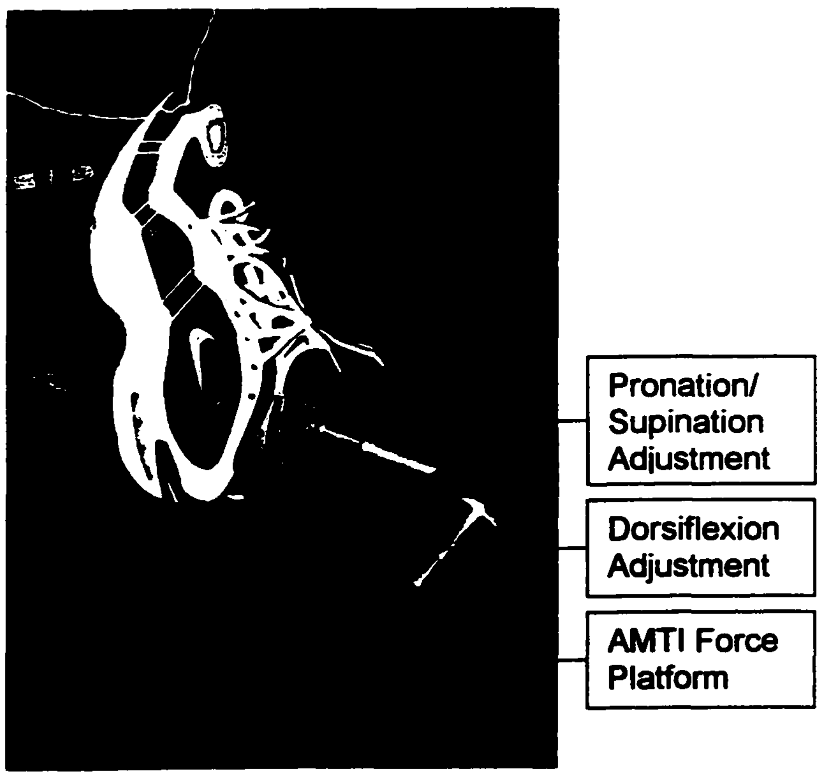
Appendix A

Impact Machine





Appendix B

Shoe Specifications

Rigidity

Nike
Sirocco: retail $189.99
Gender: Male
Usage: Training
Footstrike: Rearfoot
Width: Medium
Midsole Characteristic: Single-density EVA, with full-length Air unit
Outsole: Blown rubber and carbon rubber
Weight Range: 140-190
Added Features: None
Shoe Weight: 13.9 oz.

Saucony
Web Grid: retail $145.00
Gender: Male
Usage: Training
Footstrike: Rearfoot
Width: Wide
Midsole Characteristic: Two-density EVA, with Grid unit in rearfoot
Outsole: Carbon rubber
Weight Range: 140-180
Added Features: Grid
Shoe Weight: 13 oz.

Runners World Magazine (2001) Fall product review. www.runnersworld.com United States of America.

Appendix B Continued

Shoe Specifications

Loss Tangent

New Balance
762: retail $130.00
Gender: Male
Usage: Training
Footstrike: Rearfoot
Width: Narrow, Medium, Wide
Midsole Characteristic: Two-density EVA, Abzorb pads in forefoot and rearfoot
Outsole: Blown rubber and carbon rubber
Weight Range: 140-180
Added Features: Abzorb
Shoe Weight: 12.8 oz.

Adidas
Supernova: retail $130.00
Gender: Male
Usage: Training
Footstrike: Rearfoot
Width: Medium
Midsole Characteristic: Two-density EVA, adiPRENE in forefoot and rearfoot
Outsole: Blown rubber and carbon rubber
Weight Range: 130-180
Added Features: Torsion system
Shoe Weight: 12.3 oz.

Runners World Magazine (2001) Fall product review. www.runnersworld.com United States of America.

Appendix C

Calibration Factors

Participant	Foot Size	Participant Weight (N)	Participant Weight at 10° (N)	Added Sled Mass (N)	Impact Force Running Barefoot	Sled Distance (Inches)
1	11	876.49	152.20	32	1234.23	4 ½"
2	9	733.76	127.42	17.4	1195.98	4 ¾"
3	9	790.65	137.29	23.2	921.48	2 ¾"
4	9	620.00	107.66	5.8	953.48	3 15/16"
5	10	921.47	160.01	36.5	1534.86	5 3/8"
6	10	750.83	130.38	19.1	950.04	3 1/8"
7	9	853.21	148.16	26.6	1208.61	4 ¼"
8	11	739.45	128.40	18	1150.33	5 "
9	10	853.21	148.16	26.6	1383.06	5 ¼"
10	10	864.59	150.13	30.7	1447.96	5 3/8"
11	9	800.50	139.01	24.2	952.78	2 7/8"

Note: Sled empty weighs 57.5 kilograms

Midsole Height

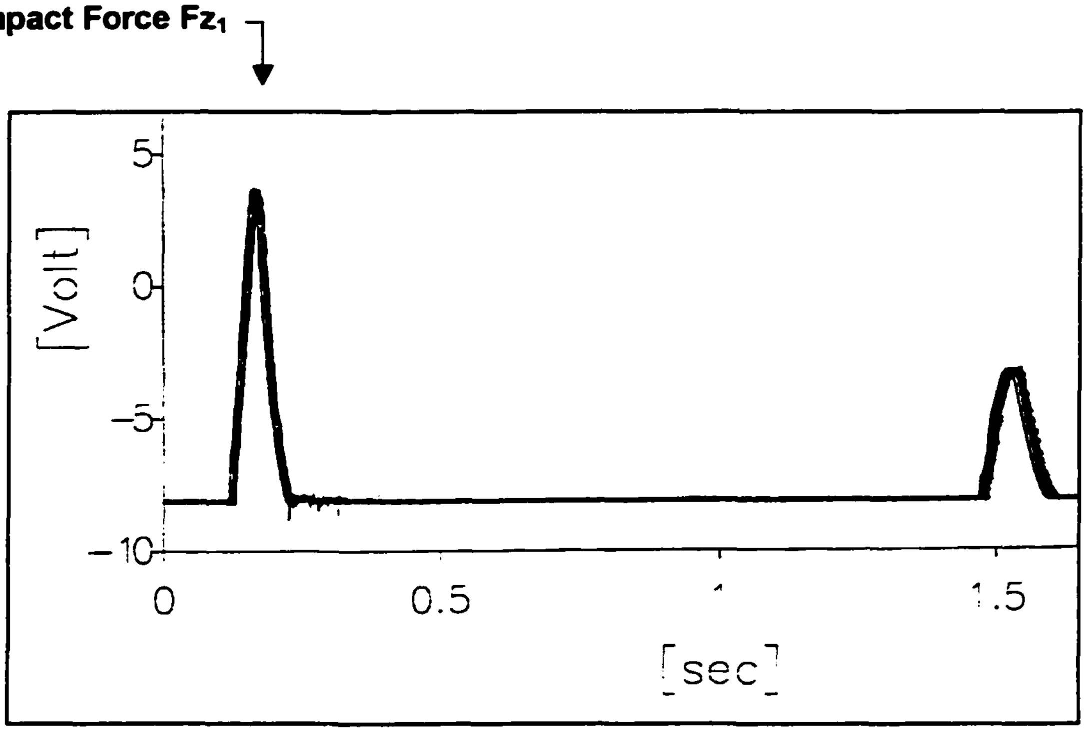
Shoe	Size 9	Size 10	Size 11
Nike	1 5/8"	1 7/8"	1 11/16"
Saucony	1 7/16"	1 11/16"	1 7/16"
New Balance	1 ½"	1 5/8"	1 5/16"
Adidas	1 3/8"	1 5/8"	1 3/8"

Total drop height = Sled distance + Midsole height

Appendix D

Twenty Stacked Heel Strikes Using the Shoe Impact Machine

Impact Force Fz_1



Note: Average impact force standard deviation < 5 Newton's.

1999 Bauer, T., Valjakka, K. A system for the measurement of the Energy in the Soles of Running Shoes. *XIV th Proceedings in International Symposium for Biomechanics in Sport.* 194-198. Perth, Australia.