THE DYNAMICS OF RUNNING AND THE POSSIBILITIES OF DAMPING

BY

SHAUN P. O'NEILL

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Signature of Author ______________________________
Department of Mechanical Engineering
May 7, 2004

Certified by ______________________________
Ernesto Blanco
Professor of Mechanical Engineering
Thesis Supervisor

Accepted by ______________________________
Ernest Cravalho
Professor of Mechanical Engineering and VanBuren N. Hansford Faculty Fellow
Undergraduate Officer and Chairman, Undergraduate Thesis Committee

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Submitted to the Department of Mechanical Engineering
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ABSTRACT

Running and jogging (a slower, more rhythmic form of running) have become increasingly popular today. An unfortunate by-product of this broad interest in running has been the growing incidence of overuse injuries (the result of repetitive microtrauma to the tendons, bones and joints). The increase in the number of people who run in order to improve their physical fitness has been accompanied by an increase in the prevalence of musculoskeletal injuries due to running. Laboratory studies that analyzed an athlete s gait (pattern of walking or running) have determined that when running on level surfaces, the initial impact forces exerted on the lower extremities are two to three times the individual s body weight.

This report aims to address the problem of running and jogging injuries by examining the forces exerted on the body and developing a foot attachment that would minimize the possibility of injury. These impact force peaks may be accompanied by high stresses on bones and joint surfaces. A major shock absorbing creation will allow these runners to continue to train and prepare when they might otherwise be injured by either preventing such injuries or by providing enough cushion to allow the runners to maintain training when injured. In this report a product was developed that would improve the wide world of sports. This product, comprised of a spring and damper system, was designed to address the detrimental consequences of the harsh impact force while restoring energy that is usually lost in impact. Preliminary testing has shown that this product has a high potential for successfully fulfilling this purpose. Further testing would be necessary to develop this product into a truly revolutionary advancement to the world of running as we know it.

Thesis Supervisor: Ernesto Blanco
Title: Professor of Mechanical Engineering

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1 INTRODUCTION

Aerobic exercise has become one of the most popular forms of endurance training today. In the United States, the most popular forms of aerobic exercise are running and jogging (jogging is a slow, rhythmic form of running — See **Figure 1** below). In fact, it is estimated that 15% of Americans run, jog, or walk regularly [1]. The aim of aerobic conditioning is to improve the function and efficiency of the cardiovascular system. Some of the benefits of jogging or distance running include: prevention or postponement of coronary disease, personal gratification and enjoyment, and a low cost sport that both sexes can enjoy. An unfortunate by-product of this broad interest in running has been the growing incidence of injury. The primary causes seem to be a lack of adherence to proper training techniques, wearing improper footwear, and poor initial conditioning, which then leads to overuse injuries.

a) b)

Figure 1. **(a)** Running through a field. **(b)** Jogging down the street.

Most running injuries tend to be caused by a few recurring factors including shoe problems, training errors, environmental factors, or anatomic abnormalities that can predispose an athlete to certain injuries. As a result, runners can directly prevent the majority of running and jogging injuries. An appropriate running shoe is very important in training and may help prevent running injuries. Shoes should provide shock absorption, motion control, and stability for the runner. When selecting a running shoe, the athlete should look for a style that will provide all of the above benefits as well as fit comfortably. Fortunately, all of the major show brands make a shoe appropriate for the vast majority of runners. Laboratory studies that analyzed an athlete s gait (pattern of walking or running) have determined that when running on level surfaces, the forces exerted on the lower extremities are two to three times the individual s body weight (See **Figure 2**).

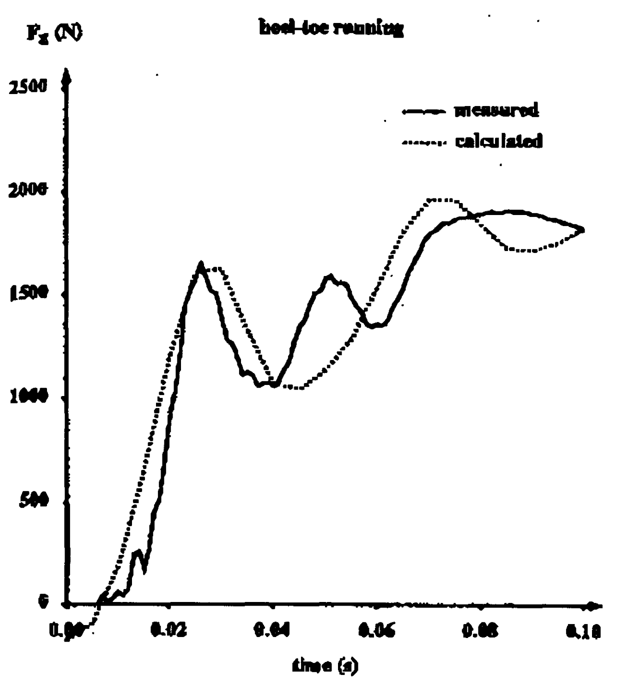

Figure 2. Time histories of vertical ground reaction force. The mass of the subject was 71 kg. Note that the

maximum force is about 1500 to 2000 N (about 2 to 3 times the weight of the subject).

Under this heavy pounding, shoes will lose approximately 60% or more of their shock absorption capability after 250-500 miles of use. A runner who puts in 10 miles per week, therefore, should consider buying new shoes after nine to 12 months. When a shoe s mileage exceeds 500-600 miles, it should be discarded for running purposes. Resoling will not revitalize the dead shoe [1].

In regards to training errors, the best advised rule is the rule of too s : too much, too fast, too soon, and too little rest appear to be the hallmarks of training errors. Every runner has a physiologic limit and trying to exceed that limit can lead to injury. The mileage one runs should be gradually increased, on an individual basis. Overall, injuries are most likely to occur in one or more of the following situations: over-distancing without adequate stretching, rapid changes in mileage, an increase in hill training, interval training (going from slow speeds over long distances to fast speeds covering less ground), and insufficient rest between training sessions.

2 PROBLEM ASSESSMENT

This section discusses the problem addressed by this report, including an explanation of overuse injuries and the focus of the problem.

2.1 OVERUSE INJURIES

The increase in the number of people who run in order to improve their physical fitness has been accompanied by an increase in the prevalence of musculoskeletal injuries due to running. Most of these injuries are classified by clinicians as overuse injuries. There are basically two types of injuries: acute injuries and overuse injuries. Acute injuries are usually the result of a single, traumatic event (macrotrauma). Common examples include wrist fractures, ankle sprains, shoulder dislocations, and hamstring muscle strain. Overuse injuries are more subtle and usually occur over time. They are the result of repetitive microtrauma to the tendons, bones and joints. Common examples include tennis elbow (lateral epicondylitis), swimmer s shoulder (rotator cuff tendonitis and impingement), Little League elbow, runner s knee, shin splints, jumper s knee (infrapatellar tendonitis), Achilles tendonitis and shin splints. In most sports and activities, overuse injuries are the most common and the most challenging to diagnose and treat.

Overuse injuries can often happen when one is first beginning to participate in a sport or activity and try to improve rapidly by over-immersing. A new runner may have poor technique and may not allow his or her body adequate time to rest which would predispose them to runner s knee for example. Training errors are the most common cause of overuse injuries. These errors involve a too rapid acceleration of the intensity, duration or frequency of one s activity. A typical example is a runner who has run several miles three times a week without any problem. That runner then begins advanced training for running in a marathon, running a longer distance every day at a faster pace. Injury or break down is inevitable. Overuse injuries also happen in people who are returning to a sport or activity after injury and try to make up for lost time.

There are also technical, biomechanical and individual factors. Proper technique is critical in avoiding overuse injuries. Slight changes in form may be the culprit. Some people are more prone to overuse injuries and this is usually related to anatomic or biomechanical factors. Imbalances between strength and flexibility around certain joints predispose runners to injury.

2.2 Focus of Problem

In running, the most common injuries include runner s knee, shin splints, Achilles tendonitis, lower back pain, and muscle strain or fatigue. Two of these injuries will be the focus of this study: runner s knee and shin splints.

Runner s knee (see **Figure 3 (a)** on next page) is generally a sprain involving the ligaments of the knee, which is a common occurrence among runners. This sprain produces pain upon movement and local swelling. The swelling can be reduced by packing the knee in ice, but more sever sprains may be associated with tears in the cartilage, which require immediate medical attention. To prevent runner s knee, it is often advised that runners should invest in a good pair of shoes with adequate support and cushioning. Running on soft surface as much as possible will also minimize the jarring forces on one s knees.

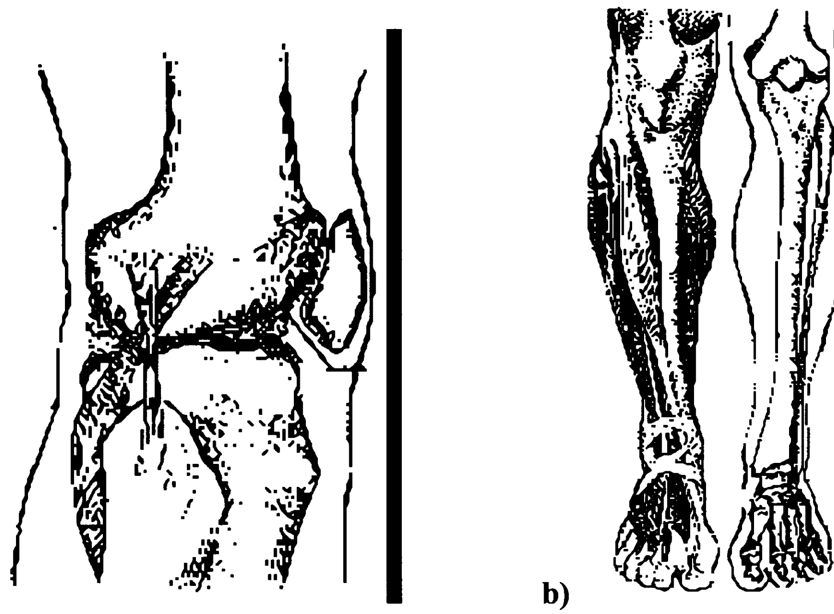

Figure 3. **(a)** Runner s knee. **(b)** Shin splints. Note the areas of where injury occurs in each type of running injury.

Shin splints (see **Figure 3 (b)**) are an inflammation and swelling of the tough, fibrous membrane surrounding the bone and attaching it to the muscles along the tibia (the main bone in the lower leg). Shin splints may result from improper conditioning or running on a very hard surface such as concrete. The suggested treatment usually includes rest and heat to relieve the pain. Specific lower-leg conditioning exercises and stretches can help as well. To avoid shin splints, stretching is necessary after each workout. Also, like runner s knee, running on soft surfaces such as grass, dirt, or padded track and wearing running shoes with adequate cushioning will help to prevent such injury.

Runners with these handicaps usually need to rest until their injury has healed. However, when training for a set event such as a marathon, a break in training will be very harmful to one s overall preparation for the event. A major shock absorbing creation will allow these runners to continue to train and prepare by either preventing such injuries or by providing enough cushion to allow the runners to maintain training when injured. This report will aim to address the problem of running and jogging injuries by examining the forces exerted on the body and developing a foot attachment that would minimize the possibility of injury.

3 ANALYTICAL BACKGROUND

In this section, the biomechanical factors behind jogging injuries, the past experimental findings, and further necessary analysis are discussed.

3.1 BIOMECHANICAL FACTORS

In biomechanical terms the development of an overuse injury to an anatomical structure may be formulated as follows. During each running step, the stress developed within the structure is so high that biological reactions take place which, in the long term, reduce the maximal stress that can be sustained without failure. When this maximal stress drops below the stress actually encountered during running, microtraumata or macrotraumata occur, which constitute an injury.

It may be useful in the search for methods of preventing injuries to compare the variables under various experimental conditions. Varying shoe construction could be an important means of creating different experimental conditions since the choice of footwear is probably all that can be influenced in recreational runners. It seems reasonable to assume that some running injuries are related to phenomena that occur during the landing phase of a running stride. In this phase, the muscles involved in reducing the momentum of the body segments are forcibly lengthened, which could cause them to develop large stresses. Also in this phase, runners who strike the ground first with their rear foot produce an impact force peak (See **Figure 4** on next page). These force peaks may be accompanied by high stresses on bones and joint surfaces.

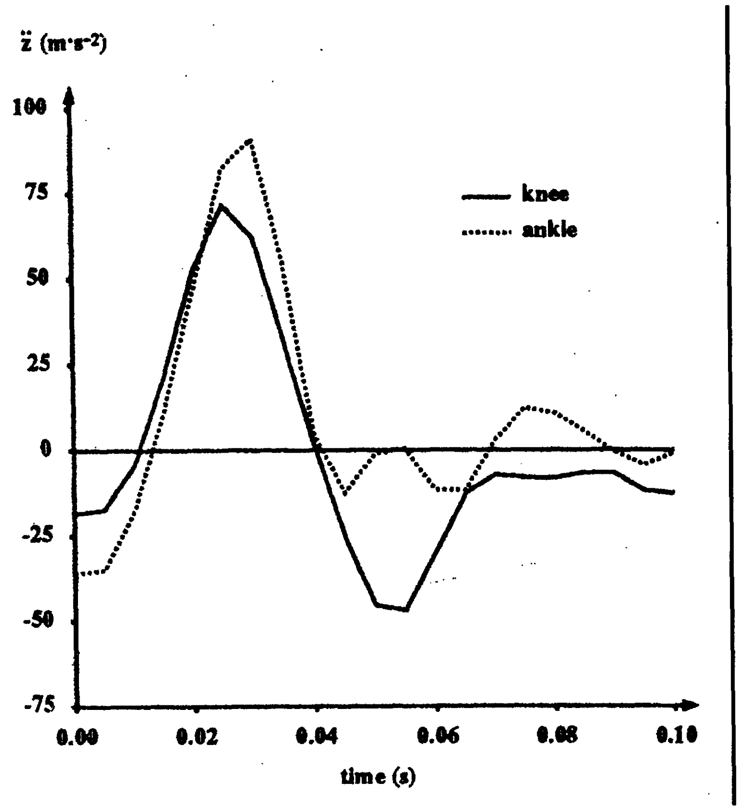

Figure 4. Time histories of acceleration at knee and ankle. Note the large peaks between 0.02 s and 0.04 s, which denote large impact force peaks.

3.2 Experimental Findings

Typical time-histories of vertical ground reaction forces during heel-toe running show a high-frequency peak (impact force peak) in the first part of the impact phase. It seems reasonable to assume that some running injuries are related to this impact phase during which the body collides with the ground. There is some indirect evidence that impact forces may be harmful. Repeated impulse loadings can produce degenerative changes in cartilage. Running shoes can be regarded as a means to cushion such impact forces, and therefore prevent overloading of the body.

However, it was unexpectedly found that the cushioning properties of shoes did not produce detectable changes in the magnitude of impact forces. It was hypothesized that subjects had adapted their running style to different shoe conditions. To address this issue, the impact phase in running has also been investigated theoretically. The scientist B. M. Nigg [2] used a two segment model (thigh and shank), connected by one hinge joint. To represent muscles, springs were included on each side of the joint. Surprisingly, the stiffness of these springs had no effect on impact peak force. The question arises to what extent this result was influenced by shortcomings of the model used. Stacoff [3] simulated the influence of shoe material properties on rearfoot movement in the frontal plane during touchdown. Shoe stiffness had little effect on impact peak force (1550 vs 1600 N), but influenced the rearfoot movement greatly.

In a recent experimental study on the impact phase [4] it was implied that runners have no opportunity to control the rotations of the body segments during the impact phase, other than by selecting a certain geometry of the body and muscular activation levels prior to touchdown. Also Nigg [2] stated that the runner is not able to react with a change in activity in the relatively short duration of the impact phase.

3.3 Necessary Further Analysis

To study impact forces further, a theoretical (simulation) approach is required to quantify the effects of initial conditions and other parameters on impact force, since in an experimental setting it is difficult to manipulate humans in such a way that the effect of one isolated variable can be studied by varying it systematically. In fact, changes in the measured ground reaction forces will be the combined result of all factors together. For instance, when shoe properties are changed, experimental subjects may adapt their gait pattern and thus mask any changes in impact peak forces. It is probably even impossible to induce controlled variation in muscle activity in experimental subjects.

For successful simulation of impact, providing a realistic quantitative assessment of the influence of variables that play a role, it is necessary to improve on the theoretical models used previously. In particular, muscles are known to have both force-length and force-velocity relationships, depending on activation, and these should be included. The utility of such musculo-skeletal models has been successfully demonstrated in studies of coordination in vertical jumping using direct dynamics simulations [5]. Through this analysis, it would be possible to systematically examine the effects of changes in muscle activation, position and velocities of body segments at touchdown and surface characteristics on impact forces during heel-toe running in order to minimize related injuries.

4 FUNCTIONAL REQUIREMENTS

The functional requirements for any shock absorbing creation should include the following provisions.

4.1 ELIMINATE PEAKS OF IMPACT EFFECT

This product should be able to lower the peak; however the same area will remain under the impact curve (See **Figure 5** on the following page). The base of the foot attachment will be broader so that the energy does not disappear.

This decrease in maximum impact force can be accomplished through the use of a system involving springs and dampers. The material used must be able to absorb impact and restore its shape very quickly (before the next step is taken). In closed pore cells, air will compress, gas reacts to the compression, but then the shape reforms immediately to its initial state. Permanent deformation must be avoided.

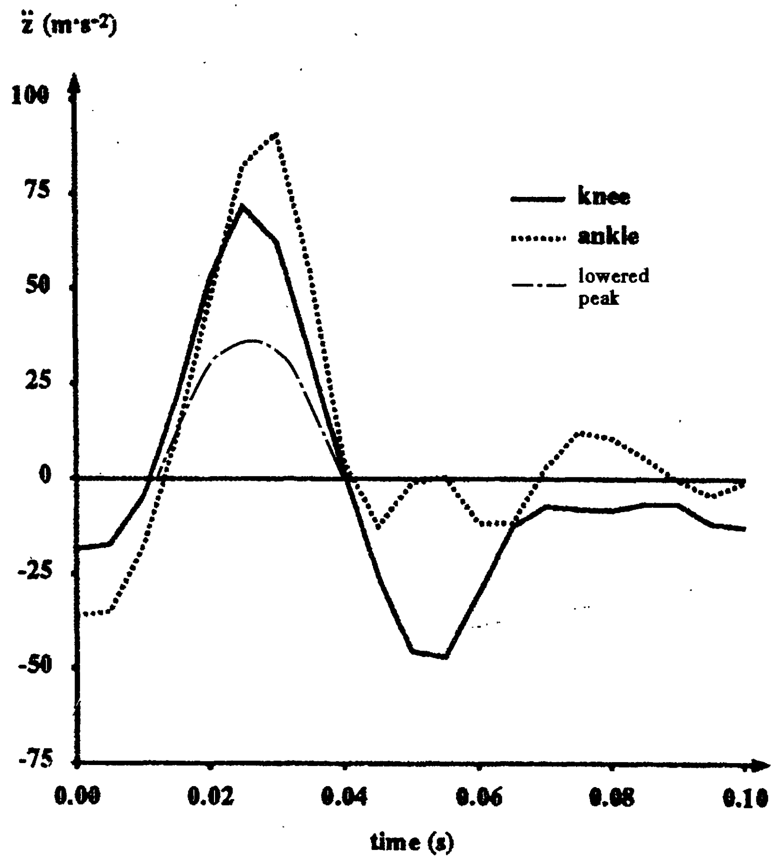

Figure 5. Lowering the impact force. Note that the peak of the impact force is lowered, but the time interval of the peak remains the same.

The foot attachment must also have spring-like properties. This will allow some of the energy the runner exerts downward to be put back into his or her step. By using an elasto-kinematic design, it would be possible to store energy from the loading and then use it to propel a runner forward.

4.2 Stability and Durability

This product must have the ability to provide complete stability in the x-y axes with no serious deformation in the z-axis. Such movement will impede the runner s speed by absorbing all the energy instead of exerting most of it forward. Serious deformation may be extremely tiring, much like running in sand on a beach.

The foot attachment must also be able to support the energy of the whole body. The product will need to support the entire body as well as the additional shock from running on a material like concrete. The product must be able to support all of the energy while maintaining its shape and ability to absorb shock.

4.3 Marketability

Attach to regular shoes outside. There exist many shoe inserts to absorb shock, but an enhanced shock absorber on the outside of the sole would allow for greater shock absorption. In addition, many runners buy shoes that fit their feet perfectly. An internal insert may obstruct this ideal fit. However if the shoe provides room (the runner intentionally left extra room in his shoe for an insert), the outer shock absorber may even be used in conjunction with an insole.

The product must also be waterproof and rugged. Since the product is to be worn outside the shoe, it must also be resistant to water and extreme temperature conditions. Since the product is to be worn outside the shoe, it must be able to withstand running on rocks, glass, and any other type of debris found in the runner s path.

5 DESIGN IDEAS

This section describes the preliminary design ideas, including the ideas generated in the brainstorming process and the exploration of an idea involving a pure elasto-kinematic design.

5.1 BRAINSTORMING DESIGN IDEAS

An initial idea suggested the possibility of employing dirt as a shock absorber. Runners are often told that it is better to run on soil than concrete because the soft ground works better to absorb the impact force. Hence a shock absorber with dirt as the key elements of shock absorption was briefly explored. However as a runner travels over dirt, the dirt is compacted, and over time it restores its shape as more dirt is disturbed and then settles. Hence since dirt is easily compacted, problems with dirt arose including its compatibility and inability to restore its shape.

Other preliminary ideas which were not extensively explored included air pockets that would behave similar to springs and the possibility of storing other gases within these air containment devices. However these ideas were not explored in favor of a more mechanical design.

5.2 PURE ELASTO-KINEMATIC MODEL

An idea which was explored in a rather extensive manner was the incorporation of pure elasto-kinematic device. This model would incorporate springs with little damping for the purpose of restoring lost energy back into one s stride. It seemed reasonable to explore a foot attachment that would be used to conserve energy while maintaining stability. By using an elasto-kinematic design, it would be possible to store energy from the loading and then use it to propel a runner forward.

Such a design would include a large spring apparatus. The spring setup would need to have such a large deflection that a great amount of the energy spent in the impact with the ground could be restored back into the step. The simple idea that was explored was that of a single large spring that would protrude form the bottom of the shoe positioned at the heel. This would create a simple way of restoring energy back into the stride without creating huge instability issues, provided that the spring would be stable enough. To examine the instability of such a device it was necessary to consider the ground reaction force vector throughout the stride (See **Figure 6** and **Figure 7** on the following page).

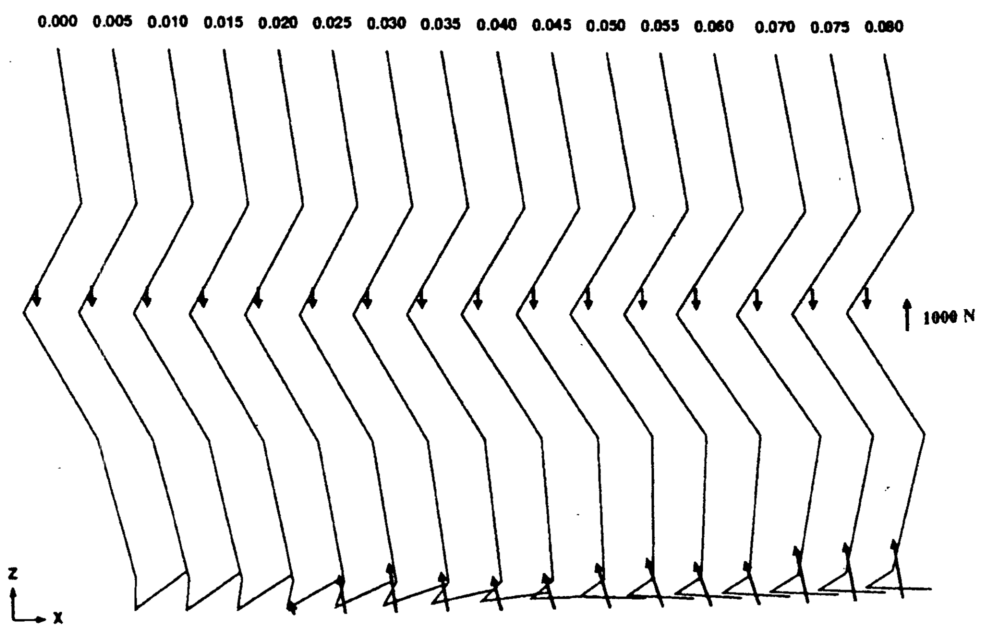

Figure 6. Ground reaction force vector and force of gravity vector. Note the peaks just after touch-down and just before take-off.

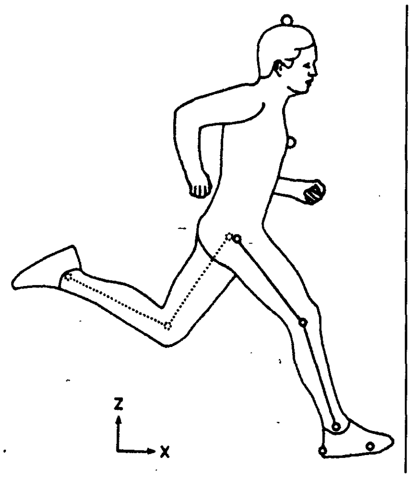

Figure 7. Location of markers to define position of body segments. These markers were used to generate the body position points used plotted in Figure 6..

As can be noted from **Figure 6**, the ground reaction force vector was hardly ever perpendicular to the foot. This would mean that the spring would feel not only a compression axially, but also a moment from the lateral forces exerted on it by the ground. This moment would cause great instability for the runner, and hence the idea was shot down for a more rigid spring-incorporated design.

6 FINAL DESIGN

This section describes the design parameters for the final design, the design itself, and the manufacturing process associated with such a design.

6.1 DESIGN PARAMETERS

The key design parameter to consider was force density on the foot as a result of the ground reaction forces. **Figure 8** below displays in three dimensions the density of forces on the foot during a usual stride.

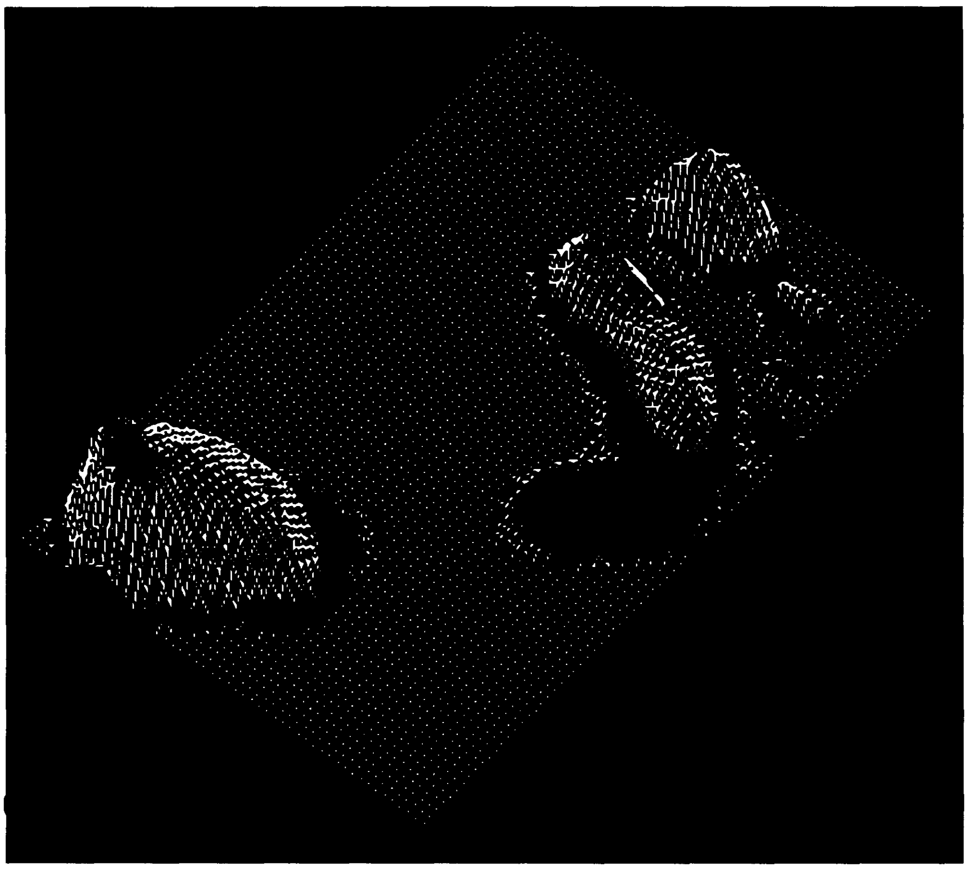

Figure 8. Force density on foot during gait. Note the high peak on the heel, correlating to a high impact force.

The next issue of concern was the path of contact with the ground along the foot. **Figure 9** shows the force density along with the central line of contact as the foot rolls along the ground.

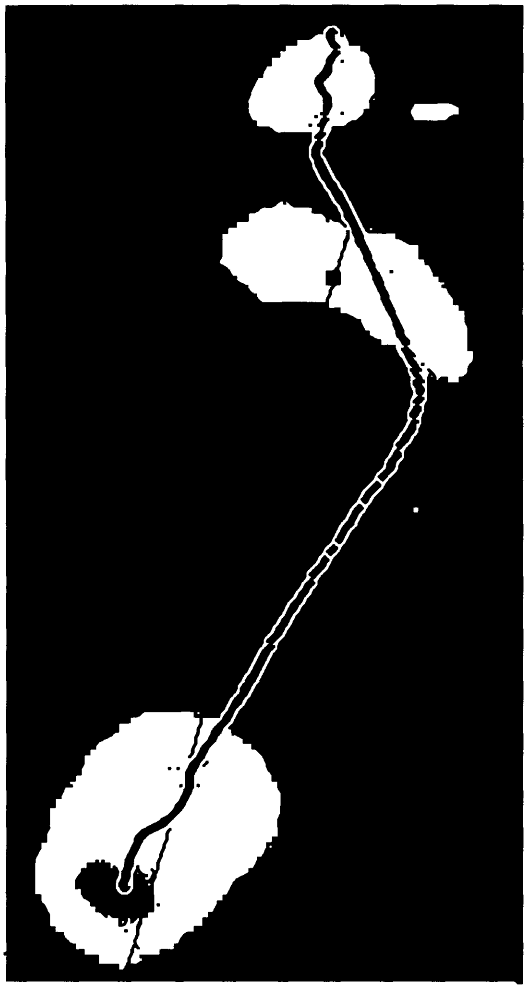

Figure 9. Force density on foot and central path of contact during gait. Note the large line that traces the central path of contact of foot with ground.

Hence the optimum design would incorporate the density of force on the foot with the ground as well as the path of contact in order to effectively support the foot as maximum energy that was lost in impact is restored into the stride.

6.2 DESIGN OF PRODUCT

The final design of the product consisted of a spring and damper system that is to be attached to the outside of the shoe. This device was comprised of a series of small springs placed strategically throughout a foam rubber core, which would act as a damper (See **Figure 10**). The springs were placed along the central path of contact outlined in **Figure 9** and distributed according to the force density described in **Figure 8**. Stiffer springs and a higher number of the weaker springs were placed in the areas of high force density, namely the heel, ball, and big toe areas. The rubber core would be cut in half, with a space in between the two halves to allow the springs to have maximum deflection.

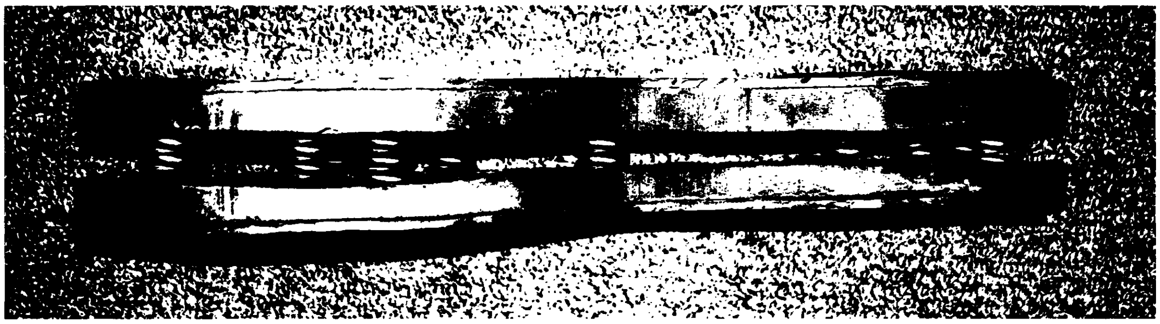

Figure 10. Side view of final design mockup. Note the springs enlaced in the soft rubber core and the thin layer of hard rubber which protects and encapsulates the product.

See **Figure 11** on the next page for a viewing of the product with a running shoe fitted on top.

Figure 11. Product with a shoe fitted on top. Possible interfaces include Velcro attachments or straps.

6.3 Manufacturing Processes

The thin outer layer of rubber could be made from a mold, using a process known as injection molding. Injection molding is a common manufacturing process where material is melted and injected under pressure to solidify in a mold. The mold incorporates two moving parts that are clamped together to form the cavity. Material (usually a plastic, or in this case a rubber) is melted in a barrel. The material is then injected under high pressure into the mold. The material is allowed to cool, after which the mold is opened and the part removed. These basic steps can be seen in **Figures 12** and **13**.

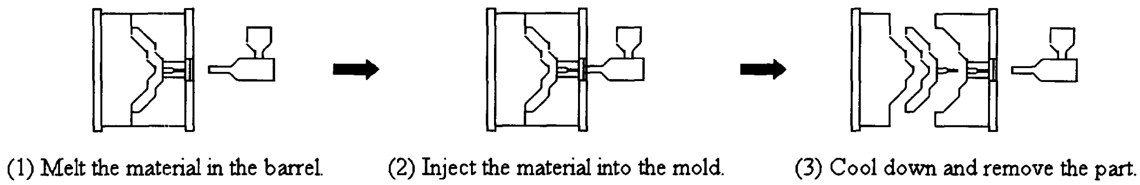

Figure 12: Basic steps of the injection molding process.

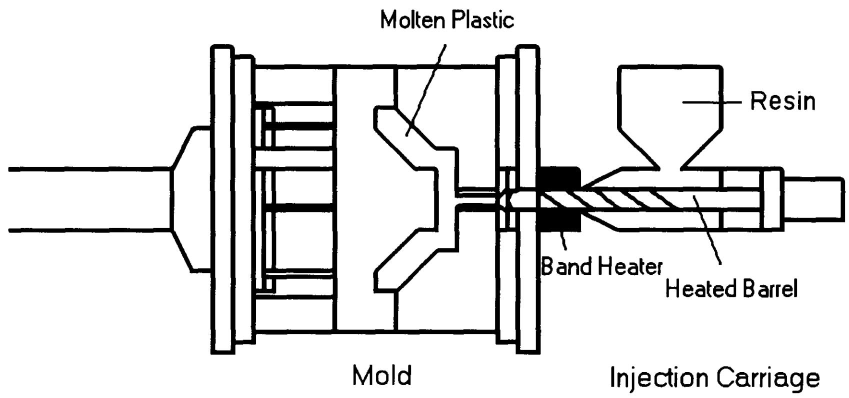

Figure 13: Mold (left) being filled with molten plastic by means of the Injection Carriage (right).

7 Conclusion

In this day and age, when running and jogging has become such a popular form of aerobic exercise, innovations have become almost an expectation in providing those participants an even more enjoyable experience. Athletic gear has been advanced in several ways. In particular, shirts have been modified to provide more efficient transports of sweat, in attempts to keep runners drier while still maintaining an effective system of cooling. Shorts have been altered by using increasingly lighter material for a looser fit. However the problem of overuse injuries in the sport of running and jogging due to the harshness of the initial impact force with each stride has left much room for improvements and advancements.

Guided by past experimental findings concerning the natural gait of humans and the forces involved in this gait, this project has been able to produce a product that would improve the wide world of sports. This product, comprised of a spring and damper system, was designed to address the detrimental consequences of the harsh impact force while restoring energy that is usually lost in impact. Preliminary testing has shown that this product has a high potential for successfully fulfilling this purpose. Further testing would be necessary to develop this product into a truly revolutionary advancement to the world of running as we know it.

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