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The role of intrinsic foot muscles in three running footwear conditions

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The Role of Intrinsic Foot Muscles in Three Running Footwear Conditions

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An Honors Program Project Presented to

The Faculty of the Undergraduate

College of Integrated Science and Engineering

James Madison University
_____

In Partial Fulfillment of the Requirements

For the Degree of Bachelors Science in Engineering
_____

by Brian Thomas Groener

May 2016

Accepted by the faculty of the Department of Engineering, James Madison University, in partial fulfillment of the requirements for the Honors Program.

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PUBLIC PRESENTATION

This work is accepted for presentation at the MadE xChange on April 16, 2016 and the SIEDS Conference at the University of Virginia on April 29, 2016.

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Acknowledgements

I would like to thank Dr. Pierrakos, Dr. Wunderlich, Dr. J Nagel, the participants in the experiment, Trish Brown, Ameera Teal, and my family for their wonderful support, guidance, and encouragement. I would also like to thank the Honors Program for awarding me with the Achievement scholarship as well as the Department of Engineering for developing well-rounded problem solvers. The completion of this project would not have been possible without you.

Abstract

Running has grown tremendously in popularity and so has running with minimalist shoes. Injuries such as plantar fasciitis (pain and inflammation of a thick band of tissue that runs across the bottom of the foot) are prevalent in runners despite efforts to design footwear to alleviate the impact of running and to reduce the number of injuries. In the past decade, minimalist running shoes have received considerable attention, causing debate amongst runners and scientists as to their utility in injury prevention. While running barefoot or in minimalist shoes reduces initial impact forces, the claim that they lower injury rates remains inconclusive. It is speculated that the intrinsic muscles of the foot have an increased workload in minimalist running due to the forefoot strike that usually accompanies the use of minimalist rather than traditional shoes. These muscles may be important in supporting the bony and soft tissue structures of the foot and may help prevent inflammatory conditions such as plantar fasciitis. It is the aim of this study to design an experiment to determine how minimalist runners, in contrast to traditional and barefoot runners, use mechanisms (e.g. foot kinematics and intrinsic muscles) that influence load on the plantar fascia and therefore the acquisition or prevention of plantar fasciitis. The experiment involves participants running on a treadmill for five minute intervals barefoot and wearing traditional and minimalist running shoes. Participants were equipped with electromyography (EMG) electrodes to measure muscle activity and pressure mapping insoles to measure the force exerted over the contact area. A motion camera system was used to capture foot and ankle kinematic data. Analysis of the results were used to suggest the changes taking place in each type of footwear.

Motivation

Over the past century and especially the past two decades, running has grown tremendously in popularity. From 1990 to 2013 *Running USA* reported 300% growth in competitive running with an all-time record of event finishers in 2013 (1). Along with the rise in popularity, the sport of running has also seen a rise in injuries. Some of the most common running injuries include Achilles tendonitis, runner's knee, shin splints, and plantar fasciitis (38). The likelihood of these injuries occurring has a variety of factors, but the overall yearly incidence rate for running injuries varies between 37 and 56% (2).

In response to minimizing these injuries, the running industry has attempted to create solutions including, but not limited to, different types of footwear that aim to alleviate the impact felt by the body when striking the ground. In the past 5 to 10 years minimalist running shoes have taken the market by storm, causing debate amongst runners and scientists as to their utility in injury prevention. Some studies for example, suggest that there is an increase in running injuries such as bone marrow edema after switching to barefoot or minimalist running (29, 30). Others however, claim that kinematic changes associated with running in minimalist shoes replicate barefoot running and that both are associated with a reduction in injuries (9, 31).

Running footwear can be broken down into three major categories; traditional shoes, minimalist shoes, and barefoot. Each one of these has unique properties that are compared below in Table 1. This is not to suggest that one is better than the other, but rather that they simply have different effects on runners. Within the three types of running, one of those differences is the change in a runner's strides and foot strikes. While it has been found that minimalist shoes generally do a good job of replicating barefoot running, the claim that the resulting shorter strides and forefoot landing reduce impact peak and lower injury rates remains inconclusive (21). It has been argued

that barefoot running produces a more natural stride and reduces the peak impact force on the foot when coming into contact with the ground (14). Minimalist shoes aim to imitate barefoot running yet also provide protection to the foot by creating a barrier between the runner and the ground.

There are several features that are typical of each type of footwear which differentiate it from the other. For example, traditional running shoes have laces, heavy cushioning, and thick soles (usually about ½" to 1" thick) while minimalist shoes generally do not have laces, have little to no cushioning, and the soles are usually less than 4mm thick. Examples of each type of footwear can be seen below, in the table.

Table 1. Comparison of different running footwear properties shows the diversity amongst each of the three conditions. The most suitable condition for each runner depends on personal preferences.

	Traditional	Minimalist	Barefoot
Typical landing style	Rear foot strike	Fore foot strike	Fore foot strike
Impact	Medium	Medium	Low
Comfort	High	Medium	Low
Foot pressure values	Low	High	High
Image	(24)	(23)	(39)

Most runners using traditional shoes, land on their heel with a rear foot strike (RFS). After switching to minimalist or barefoot running, runners regularly use a forefoot strike (FFS), which involves landing further anteriorly on the foot (8). During the FFS, the plantar structure of the

foot stretches further, loading it in tension. This may lead to inflammation of the abductor

hallucis, abductor digiti minimi, quadratus plantae, and plantar fascia if it stretches beyond what

it is ready to handle. An example of this can be seen in Figure 1, as well as different landing

positions. However, if those same muscles are used to resist the flattening of the arch and the

stretching of the plantar fascia, then training these intrinsic muscles might help prevent these

injuries. Figure 2 shows a different angle of the plantar fascia which can be viewed in relation to

the intrinsic muscles shown in Figure 3.
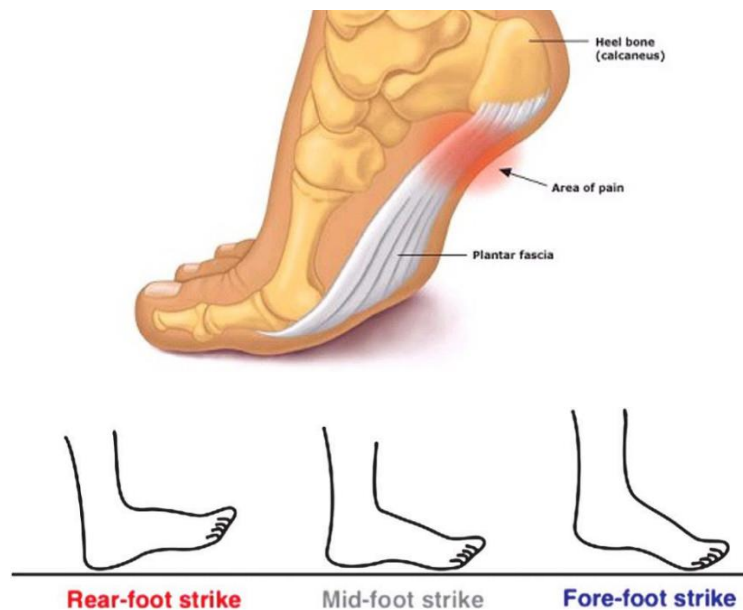
Figure 1. The plantar fascia attaches the toes to the heel, during a FFS at touchdown the arch

flattens causing increased stretch of the plantar fascia. Other landing positions can be seen as

well. (27, 37)
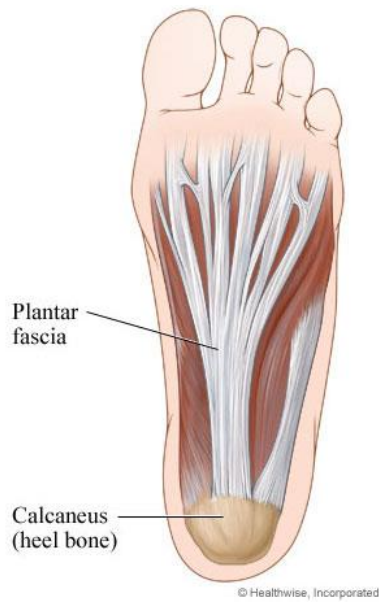
Figure 2. The location of the plantar fascia in relation to the toes and heel shows the close

proximity to intrinsic muscles. (44)
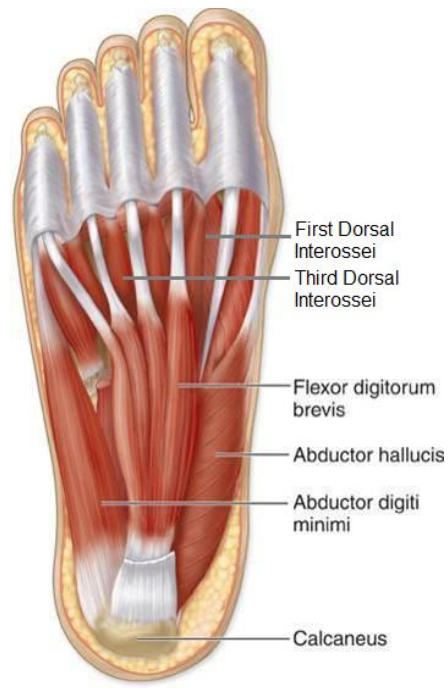
Figure 3. This displays the location of intrinsic foot muscles relevant to this study. The relative

size of each can be seen as well. (28)

Due to the changes in landing kinematics in various footwear conditions, it is hypothesized that the intrinsic muscles are used differently in minimalist than traditional footwear. It is predicted that greater ankle plantarflexion and foot dorsiflexion (arch flattening) at touchdown will be associated with greater pressure in the forefoot, and these will be associated with barefoot and minimalist shoe running. It is also predicted that these changes in movement will be associated with increased activation of intrinsic muscles that resist foot dorsiflexion, and that this increased intrinsic muscle activity will therefore be greater during minimalist and barefoot running than in traditional shoes.

While overuse and/or fatigue of intrinsic foot muscles may result in conditions such as plantar fasciitis, training may lead to strengthening of these muscles and prevention of plantar fascia injury. If these muscles are more active during minimalist or barefoot running, then these footwear conditions may provide an opportunity to train these muscles, allowing them to more successfully fulfill their role in support of the midfoot and forefoot, thereby possibly reducing the risk of injury. It is the aim of this study to determine if minimalist runners use the intrinsic muscles that may help prevent plantar fasciitis more when running in this type of footwear. The functions these muscles play during the running gait will also be observed to help make that determination.

The Problem

Although much has been studied about the extrinsic muscles of the foot (45), their intrinsic counterparts have not received the same attention. This is likely because they can be very difficult to test. This study strove to overcome that barrier using appropriate technology. An experiment was conducted with runners who have a history of running barefoot or in minimalist shoes in order to compare the role of footwear and determine if it changes the way the body's intrinsic foot muscles reacts during dynamic movement.

Intrinsic Muscles as they relate to Plantar Fasciitis

Intrinsic muscles are small and buried in the soft tissue of the foot making them difficult to isolate and test. However, it is generally postulated that intrinsic muscles give dynamic control to the foot, help to regulate the rate of pronation, and stabilize arches (26). Kelly conducted an experiment to determine this in 2014 using indwelling EMG electrodes. He asked participants to complete a series of balance tests and analyzed how each of the tested muscles responded. This is one of the few studies conducted specifically to address intrinsic muscle function.

Plantar fasciitis is one of the most common causes of heel pain. It involves inflammation of a thick band of tissue called the plantar fascia which runs across the bottom of the foot, connecting the heel bone to the toes. Plantar fasciitis causes a stabbing pain that typically occurs during an individual's first steps in the morning. Once the foot becomes active the pain of plantar fasciitis normally decreases, but it may return after long periods of standing or after getting up from a seated position. This injury is particularly common in runners. However, people who are overweight and those who wear shoes with inadequate support are at risk of plantar fasciitis as

well (20). Under normal circumstances, the plantar fascia acts like a shock-absorbing bowstring, supporting the arch of the foot. If tension on that bowstring becomes too great, it can create small tears in the fascia. Repetitive stretching and tearing can cause the fascia to become irritated or inflamed (20). The repetitive motion of running makes runners prone to this condition, although it is unclear if there is a higher prevalence in minimalist runners due to a FFS (32).

Barefoot Running and Injuries

Running footwear has evolved substantially, however some runners have always been barefoot and still prefer to run that way today. This affects how the runner's body moves and reacts to the ground. Barefoot runners are characterized by more efficient movements and lower overall forces and stress on the body. Studies have been conducted to substantiate these claims and researchers found that one year overall risk of injury for those wearing traditional running shoes was greater than for those running barefoot (40).

It must be understood however that all runners, barefoot and shod, vary in their form depending on a wide range of conditions such as speed, surface texture, surface hardness, and fatigue. There is no such thing as a single barefoot running form but, instead, a highly variable range of kinematic styles (19). However, there are some significant differences that have been repeatedly observed between shod and barefoot running. It has been found that about three quarters of shod runners RFS, while experienced barefoot runners are expected to land in a FFS on the ball of the foot below the fourth and fifth metatarsal heads. However, it is wrong to assume that runners will always land this way according to their footwear. It is reasonable to predict that runners who FFS though, regardless of whether they are barefoot or shod, incur fewer injuries caused by impact peaks for the simple reason that FFS landings do not generate an appreciable impact peak (19).

That said, FFS running places higher loads on the Achilles tendon and plantar flexors, possibly causing a trade-off in injuries (19).

Minimalist Running Shoes and Injuries

Running in minimalist footwear has been promoted as a means of reducing or eliminating running injuries by returning to a more natural gait, much like barefoot running (7). Once again, the minimalist running shoes emphasize landing towards the front of the foot which avoids a heel strike while also minimizing impact forces. In a study focusing specifically on running styles, FFS shod runners and barefoot runners were compared against rear foot strike shod runners. It was concluded that, a FFS landing style resulted in reduced lower extremity power, hip power and knee power while also shifting power absorption from the knee to the ankle (8). This is significant, considering minimalist running helps to prevent rear foot strike and suggests there is a basis for believing that probability of injury would decrease by switching to this style.

Analyzing the biomechanics of a runner's gait is a crucial step to determining causation of injury. A runner's stride will typically deteriorate over the course of a run as the individual gets tired, loses energy, and builds up lactic acid. Determining the forces, loads, and stresses a runner undergoes during their gait cycle and determining where those forces are acting specifically (i.e. what muscles are being most affected) is crucial in analyzing if they exceed what the body can handle at any point while running (12). The heel is of particular interest because as the load is increased on the heel, the more stress it puts on the rest of the body. Although minimalist shoes have less padding to absorb the impacts, the influence to land towards the front of the foot instead changes the loading dynamics (14). Seen in Figure 4 below is a graphical representation of forces a person experiences when walking as compared to running in traditional shoes. Analyzing the mechanical energy spent by the runner, the impact with the ground is easily

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noticeable and creates a distinct stop and start motion as compared to the more gradual motion of the person walking. The aim once again is to lower impacts and forces on the body by achieving a more gradual transition.
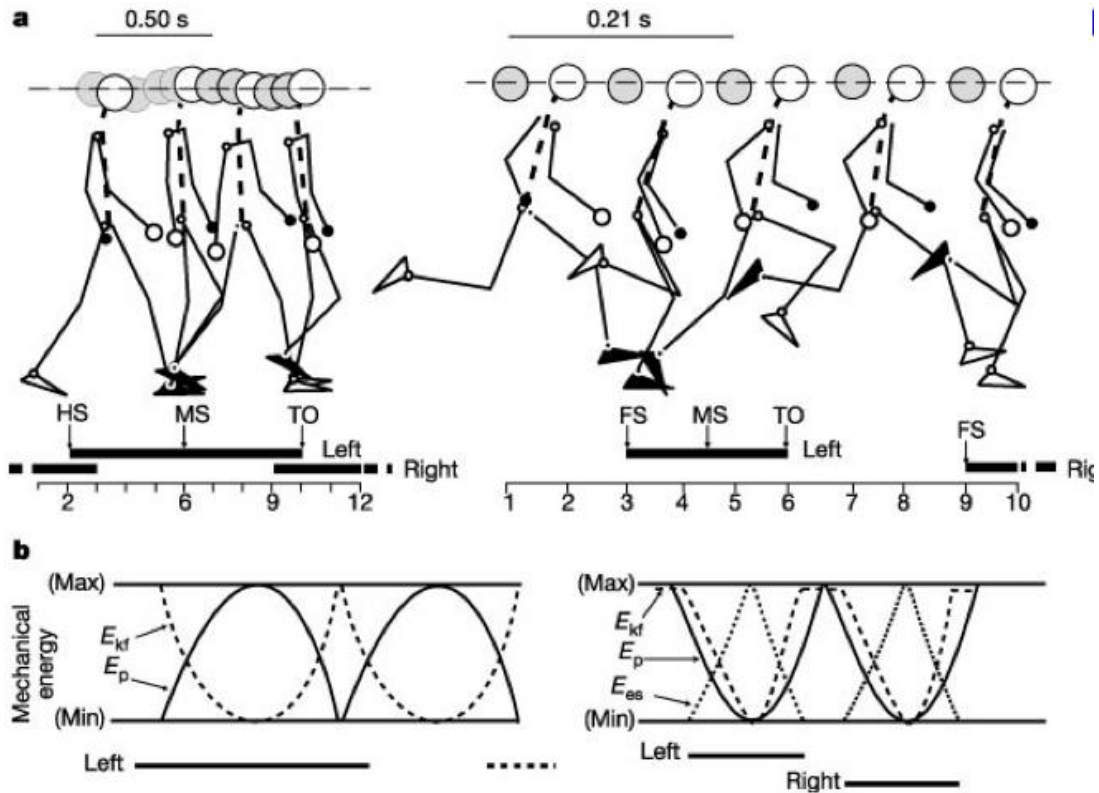
Figure 4. Comparison of gait analysis differences between walking and running illustrates the abrupt transfers of energy during rapid dynamic movement. This is more gradual in walking due to slower pace and lesser impacts on the body. (25)

In an experiment, minimalist shoes were studied to determine impact loads and their resultant forces on the body. A model of the lower extremity was analyzed to determine the magnitude of loads at common injury sites during running. Ankle and lower leg compressive forces were over 10 times the subject's body weight while the plantar fascia force recorded 1.3-2.9 times body weight (18). All peak loads recorded during the experiment were associated with the runner's

mid-stance and push-off when muscle activity is maximal. This test provides a way to normalize the information and addresses the common running injuries associated with impact forces.

Traditional Running Shoes

Traditional running shoes are not inherently bad as they have been developed to increase overall comfort and durability. However, with an increase in the number of runners worldwide and injury occurrence still near 50%, injury prevention has been brought into the spotlight and needs to be addressed. Because there is not much gear, running shoes immediately become the center of attention. In an effort to provide runners comfort and stability, the running footwear industry added cushioned heels and other padding to many of their shoes. Despite the cushioning however, it has been observed that landing with a rear foot strike still results in a defined impact peak upon contact with the surface (14). Due to the thick cushioning and tread in traditional shoes, the runner is being encouraged to land towards the heel of their foot which has the most padding. However the resultant force is still higher than both minimalist and barefoot running and can have damaging effects on the body.

Impact forces experienced by runners are not only distributed in the feet and legs but the rest of the body as well, making them important to consider. Contact with the ground creates a "…resulting 'shock wave', which passes up the limb, [and] may produce damage, leading to degenerative joint disease and a variety of other pathologies" (17). While many factors come into play, switching shoes is one of the easiest ways to avoid possible injury, thereby making it the leading candidate for analysis.

Summary

Different running styles (such as RFS and FFS) likely require unique levels of intrinsic muscle activation. FFS should almost always be different from a RFS for example, due to the changes in landing placement of the foot. As the heel is the primary point of contact during a RFS it generally absorbs all the impact at touchdown and disperses it through the body rather than dispersing that impact over a longer landing time during FFS. It is worth considering the effect a high level of intrinsic muscle activation may have on the foot in terms of possible injury.

Making comparisons between barefoot, minimalist, and traditional running shoes can be difficult. The margin of difference between each of these types of footwear can be slim and often variable. This means working with small changes to make observations and analysis successful while attempting to control a variety of external factors. There is research to suggest that minimalist shoes have potential for injury reduction. Not only do they emphasize a FFS as often seen in barefoot runners but they offer protection from rocks and other debris on the ground. Traditional shoes seem to have overcompensated for runners and are thereby encourage a more unnatural form of running which emphasizes a rear foot strike while contacting the ground which can cause higher impact forces and a greater likelihood of injury.

More studies need to be conducted to determine the benefits of each running condition and their effects on the foot, as well as the rest of the body. Problems arise with finding a way to collect accurate and consistent data and translating that into relevant and generalizable knowledge. Developing new testing methods and drawing comparisons across the three running conditions should help to provide a better understanding of the role footwear plays with intrinsic muscle activation. If repeatable data is realized, this could provide a scientific foundation for the causation of plantar fasciitis and possible reduction of injury occurrence in runners.

Research Predictions

The purpose of this study is to determine if runners in minimalist shoes activate their intrinsic foot muscles more or less than runners in other footwear conditions. It is predicted that pressure distribution will be greater in the forefoot during barefoot and minimalist running due to the tendency to FFS. Because there are different landing kinematics in traditional, minimalist, and barefoot running it is believed that the intrinsic muscles are used differently in minimalist than traditional footwear. More specifically, given current understanding of intrinsic muscle mechanics, the muscles tested are expected to change levels of activation under each condition in order to compensate for higher or lower peak impacts during touchdown of the foot while completing each stride. It is also predicted that this leads to increased intrinsic overall foot muscle activation in both minimalist and barefoot running.

<div align="center">**Methods**</div>

Due to the nature of the study, every aspect of the methodology had to be carefully considered and reviewed. The following sections break down each step to completing the experiment. This study received IRB approval (#16-0303).

Participants and Recruitment

In this study, participants with experience in either minimalist or barefoot running were recruited. In order to reach potential participants a bulk email request was sent to the engineering department, JMU cross country, and JMU triathlon club teams asking for willing individuals to volunteer. People expressed interest in participating by responding through email. As an incentive for participating, a dining voucher was offered. Upon recruiting the participants, a time was scheduled in the laboratory for them to come in and complete testing. Once the participant arrived to the laboratory, the protocol was explained and they were asked to sign informed consent papers. The experiment was then conducted as detailed in the following section.

Testing Explanation

The experiment consisted of two tests, a treadmill and pressure mat test, the first of which was completed under three conditions including traditional, minimalist, and barefoot running. The pressure mat was only completed in the barefoot condition. The treadmill test produced data to show if there were any changes in the intrinsic muscles across each of the conditions. The pressure mat test was meant to supplement pressure data for the barefoot treadmill test since pressure mapping insoles could not be worn for this condition. Table 2 below shows a comparison between the two tests.

Table 2. Comparison between the two tests completed in this study displays the differences in data collected, and how many times each test was executed.

	Treadmill Test	**Pressure Mat Test**
Number of Conditions	3 (Traditional, Minimalist, Barefoot)	1 (Barefoot)
Trials per condition	5	4
Data recorded	Kinematic EMG Pressure (Insoles – for traditional, minimalist)	Pressure

Kinematic, plantar pressure, and EMG data were collected directly to the laboratory computer. Kinematic data tracked the movement of subjects throughout the duration of the tests. Dynamic movements were captured by Qualysis motion cameras throughout the experiment which picked up only the reflective markers that were placed on the knees, ankles, and feet of the subject. Pressure mapped the impact from each step over the entire foot. EMG measured muscle activation by reading signals sent throughout the muscles of the foot. Anthropometric parameters (height, weight) and subject data (number, running tendencies from survey) were entered by hand into an Excel spreadsheet. As the tests occurred the researcher took physical paper notes as well.

To organize the data, a table was created indicating the trial number, landing style, trial type, and if the trial was counted. This allowed for comparison between each of the different conditions. The trial number indicated the video number be taken and counted chronologically from first to

last. The landing style was indicative of how the runner landed on average throughout the trial. Treadmill test trials lasted ten seconds while barefoot pressure trials were three seconds. The trial type was simply which test was being completed and in what condition. Finally, while there were a set number of trials to be completed for each test, there were some that were recorded but had issues so another trial had to be completed. For example, during the treadmill tests there were often 6-7 trials as opposed to 5 because a marker came loose or fell off during the test.

Participants were asked to bring their own footwear and wear shorts that stop well above the knee so that kinematic markers can be placed properly on the knee, leg, and foot. Surface electromyography (EMG) electrodes were then attached to their foot using standard skin preparation methods. Rubbing alcohol was applied to clean off any oils and the area was lightly sandpapered to insure stable electrode contact and enhance skin impedance. The transmitter was taped to the leg so it did not interfere during testing and it sent the electrode signals to the receiver that was connected to the computer. The EMG electrodes were placed on the abductor hallucis, first and third dorsal interossei, and abductor digiti minimi. Kinematic motion cameras tracked the motion of the subject in sync with the EMG data. Pressure mapping insoles were placed inside the traditional and minimalist shoes which were attached to a transmitter as well. This transmitter and battery were worn in a customized belt around the waist which sent signals to another receiver setup on a separate computer. The participant was then given 10 minutes to warm up on the treadmill in their choice of footwear. The tests began shortly after and can be broken down as follows.

Maximum voluntary contraction

Prior to starting, participants were asked to stand on their toes with EMG sensors attached in order to produce a maximum voluntary contraction (MVC) of the muscles being tested. They

were also asked to stand on the pressure mat and squeeze their toes as hard as possible. The result with the highest levels of activation provided a baseline with which to normalize subsequent measurements.

Treadmill test

The first test required the subject to run on a treadmill for 6 minutes at a self-selected comfortable running pace (around five-six mph), followed by a brief cool down. This test was completed three times, once with standard running shoes, once with minimalist running shoes, and once barefoot. For each participant the order of the three conditions was randomized to ensure that fatigue did not substantially affect the results. Subjects were given a resting period between each of approximately 5 minutes to recover and prepare for the next condition. The experimental setup can be seen in Figure 5.

Figure 5. The experimental setup of the treadmill test with subject in traditional shoes shows the equipment being used in action.

Barefoot test

The second test required subjects to run barefoot across a pressure platform embedded in the laboratory floor. Kinematic tracking markers were attached to their first metatarsal, navicular tuberosity, posterior calcaneus, fifth metatarsal head, fifth metatarsal base, lateral and medial malleolus, and lateral and medial tibial condyles. 3D kinematic tracking software recorded the movement of the individual as they ran. The markers were also used during the treadmill test, and the placement was the same. This can be seen below in Figure 6. The ratio of forefoot to hindfoot peak pressure (Figure 7 below) was calculated at landing. Figures 8 and 9 show the mat and insoles used to complete testing.

Figure 6. Display of the location for marker and EMG placement. There were a total of nine markers on each leg and four electrodes on one foot. (41)
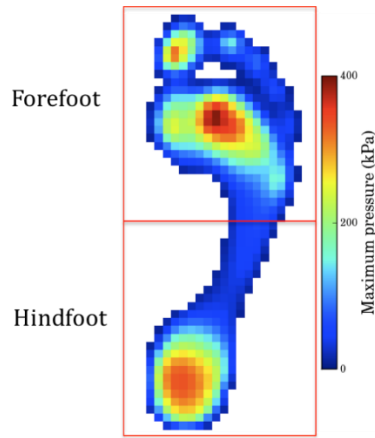
Figure 7. Example pressure distribution of the foot with separation of forefoot and hindfoot. This illustrates how the pressure data were separated and regions were compared.

All recorded data and statistics were associated with individual subject numbers so it remained anonymous. Subjects were not audio taped and the tracking software does not show the individuals, it only measures their general body movements. A follow up survey was given to determine information regarding the subject's running background. The survey can be seen in the appendix.

Figure 8. The Pressure mat used for barefoot testing, which was embedded in the laboratory floor. (42)

Figure 9. The pressure insoles used for testing and their placement within the shoe can be seen. To the left of the shoe is the transmitter which sent the data to the computer. (43)

Further details for completing the tests can be seen in the appendix as well, labeled chronologically and separated into steps taken before and after the subject arrives for testing.

Data Analysis

The sections below break down how the resulting data were analyzed. The six minute testing period was split into one minute intervals. The first minute was not recorded in order to allow the subject to get up to speed. The first ten seconds from each subsequent minute of the test was used for analysis. Each ten second interval was considered one trial for the treadmill test. After determining if any trials would be removed (due to equipment issues or other reasons) the remaining trials were exported to Matlab.

Kinematic Data

These data were used to observe and confirm landing styles which was completed by observing the dynamic movement of subjects throughout their trials. The impact point of the foot (forefoot or heel) was used as the indicator.

EMG

Root mean square averaging was completed to calculate average intrinsic muscle activation values. This involved squaring each value (to rectify the data), summing them, dividing by the number of values and taking the square root. The data were then normalized. While a maximum voluntary contraction test was completed in order to create a scale for the normalization, there were often values recorded during the trials that produced higher results. In order to account for this, the normalization was done according to the highest peak values in each trial. This way, the data could be scaled according to its true maximum output and the results would be meaningful. A butterworth filter (sixth order) was used to filter the data. The specifications from Matlab can be seen in Figure 10.

Figure 10. Specifications of EMG filter used to analyze data. Signal analysis was completed in Matlab using a sixth order Butterworth filter.

Pressure

The foot was separated into three main regions, the forefoot, midfoot, and hindfoot. Individual steps and averages of those steps across each of the trials were considered. One pressure mat trial (taking a few strides across the mat) lasted approximately three seconds whereas insole data was

collected during the treadmill test and one of these trials lasted ten seconds. In the Novel database, these three masks (regions) were applied and peak pressure, pressure time integral, and force time integral values were calculated. These data were then exported to excel. Time based files allowed for the pressure in each mask to be observed in reference to when it occurred during the course of the step, which was displayed as a percentage of 100. The three masks were compared over the same steps and plotted to visualize the differences. The pressure time integrals were plotted as well but rather as a bar graph, indicating average pressure values over the course of a series of steps and comparing each region of the foot (i.e. forefoot) to each other in minimalist and traditional shoes.

Design of Experiment

Intrinsic foot muscles can be difficult to isolate and there is a limited amount of information available regarding how to test them. Conducting a design of experiment analysis allowed for the interactions between variables to be better understood. This allows for the experiment to be executed under optimal conditions and minimize error. The independent variable, or factor, was set as the running footwear type. The dependent variables, or responses, included EMG, pressure, and kinematic data. The speed of the runner was determined to be a factor as well since the subjects were able to pick a comfortable running speed during the duration of their tests. The insole pressure values were also selected as the output data for analysis. Correlations between speed and pressure were investigated. As will be explained later a larger population size would be more telling, however, this indicates how a design of experiment type of analysis would be completed.

Using a 2^2 factorial test, data were entered according to low and high values. For the shoe type, the low value was traditional shoes and the high was minimalist shoes. The running speed low and

high values were 5 and 7 miles per hour, respectively. The corresponding pressure values were entered, which allowed for the calculation of a sum of squares, mean of squares, and f-test characteristic. This in turn produced probability values and graphs which visually illustrate any interactions between factors. In Figures 11 and 12, a steep slope shows an effect on the output as the initial benchmark changes from low to high. A horizontal line would indicate little, or no effect. Figure 13 shows both factors plotted. The lines crossing indicate an interaction between the two factors, showing an optimal point to run future tests. From the graph, this indicates a running speed of approximately 6.5 miles per hour. This can be discerned by where the lines intersect, in relation to the low and high scale at the bottom with 7 miles per hour being high.

The shoe type and running speed individual graphs show trends for pressure values as the initial metrics are increased from low to high. For example, in the shoe type, the pressure increases when runners switch to the high value, or minimalist shoes. This is expected because the reduced cushioning should increase the pressure the runner feels on impact. The running speed can be analyzed in a similar manner. As the speed of the treadmill rises there is clearly an increase in pressure values. Therefore, the runner should be running at the same pace throughout the experiment and this speed should be kept consistent across subjects. This issue was not anticipated when the experiment began, but has to be accounted for in all future trials and was factored into the data analysis.

The reasons for choosing pressure, kinematic, and EMG data as measures are due to their direct and/or indirect relation to the intrinsic foot muscles. The pressure data were assessed as the amount and location of stress on the foot during each footwear condition. The kinematic data were mainly used to assess the runner's gait and any changes in form. The EMG electrodes were focused on four distinct intrinsic muscles and used to determine the level of activation during locomotion.

Changes in the values across each footwear indicates a need for the body to respond differently and adapt accordingly.
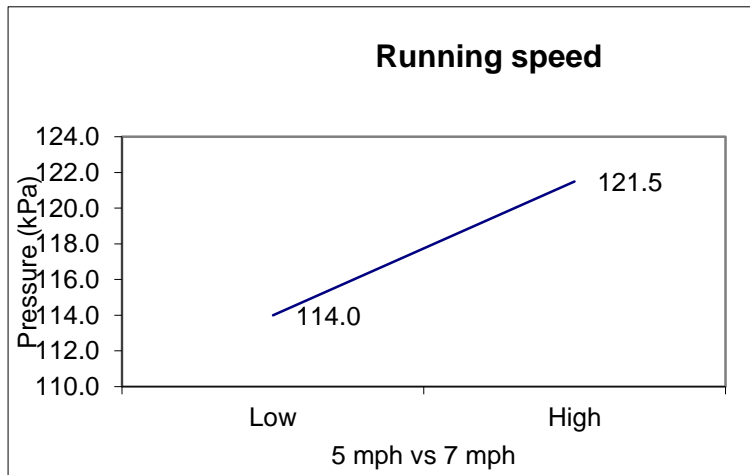
Running speed

Figure 11. An illustration of running speed versus pressure. This shows an increase of pressure values as the running speed is increased.
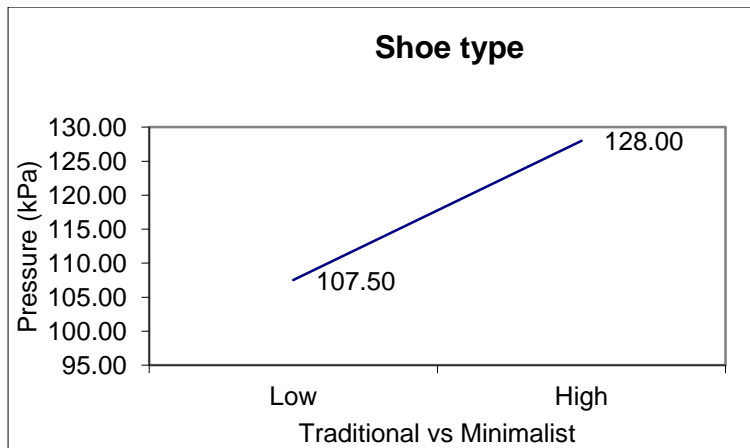
Shoe type

Figure 12. Shoe type versus pressure displays an increase in pressure values after switching from traditional to minimalist shoes.

Shoe type X Running speed
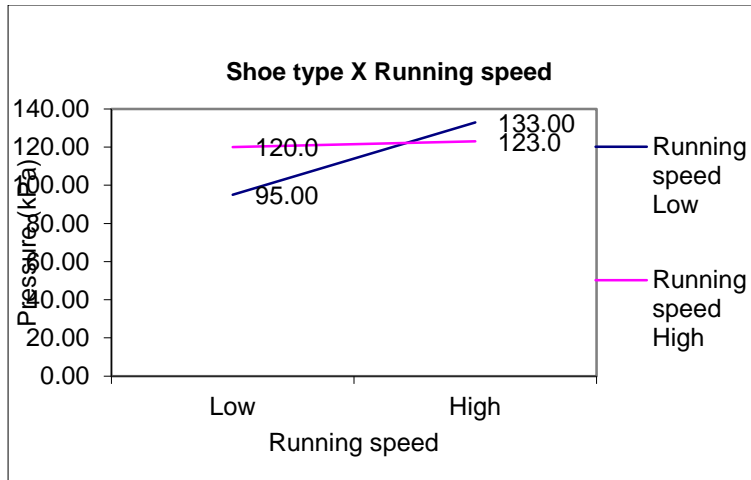
Figure 13. Shoe type and running speed versus pressure indicates an interaction between the two variables. The intersection around 6.5 miles per hour indicates an optimal point for testing.

Results

The results were broken down into the categories in which they were collected, including

kinematic data, pressure data, and EMG data. The pressure and EMG values were the main focus

due to their utility in addressing the research predictions. It should also be noted that only data

from one subject was used for analysis as proof of concept. Due to time limitations and

equipment issues this choice made the most sense.

Kinematic Data

The actual output from the software for one of the trials can be viewed in Figure 14. One of the

primary benefits of collecting these data was to synchronize the EMG results with the exact

movement of the runner at that time. However, it also allowed for the determination of the

landing style (RFS, MFS, FFS) during each of the trials, as mentioned earlier.
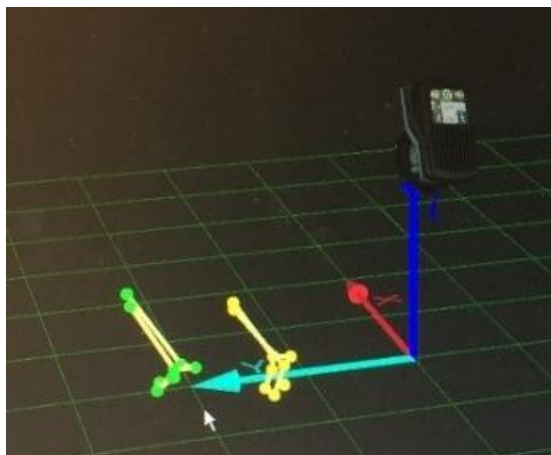


Figure 14. Software output of the motion cameras during a pressure mat trial shows how the

markers were visually displayed on the computer.

The data were initially analyzed and compared to findings from previous studies. Landing style

results were consistent with what was expected, corroborating results from other experiments (14).

There were definitive changes in gait when the subjects switched between traditional and minimalist shoes. It was found that with barefoot and minimalist shoes the subject landed with a FFS 85 percent of the time. On the contrary, a RFS was experienced 100 percent of the time using traditional running shoes.

With traditional running shoe's increased cushioning, the runner lands on their heel because the tread is so much thicker and there is more protection offered during contact with the ground. In minimalist and barefoot running, the same cannot be said and so the body must react differently to protect itself. Therefore the runner naturally lands on the ball of their foot in order to minimize the impact forces experienced and more evenly distribute the load across the foot. This creates a smoother stride and nearly eliminates pressure on the heel and midfoot which can be seen in the following sections.

Pressure Data

The pressure mat and insole readings were primarily used as indirect measurements to indicate how stretched the planta fascia was during a series of steps. If a subject were to heel strike across a series of trials, this would result in high ankle and low foot dorsiflexion, low stretch of the plantar fascia, and low movement of the intrinsic muscles. The opposite could be said regarding a FFS. The output - mean peak pressure values averaged over fourteen steps - from two pressure insole trials in different conditions can be seen below in Figures 15 and 16, along with barefoot data in Figure 17. The first trial is from the treadmill test in traditional shoes, while the second is from the same test in minimalist shoes, and the third is from barefoot running across the pressure mat. Similar pressure distribution patterns in each condition were evident.
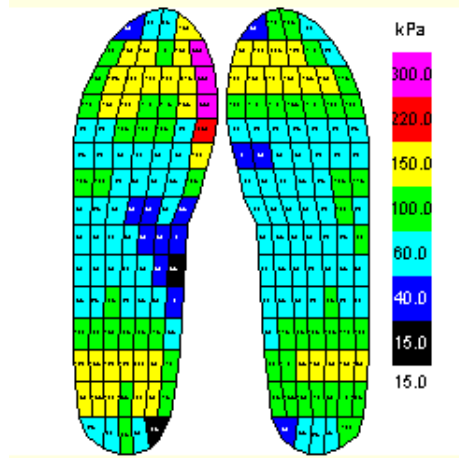
Figure 15. Traditional insole data shows generally low, even pressure across the foot. The areas of highest pressure were in the heel and forefoot.
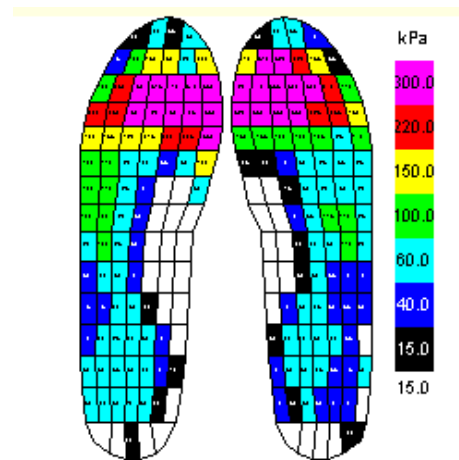
Figure 16. Minimalist insole data shows highly localized areas of pressure. This was concentrated in the forefoot and had values nearly twice of what was found in traditional shoes.
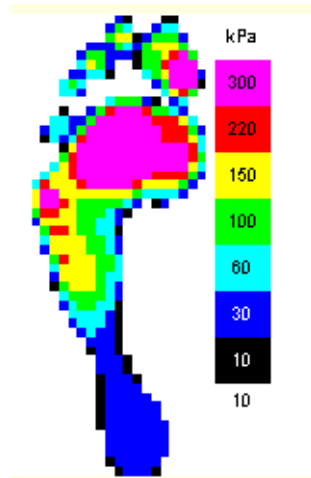
Figure 17. Barefoot data featured high forefoot pressure and low midfoot and hindfoot pressure. Values were similar to minimalist results and the medial midfoot often did not contact the mat, leaving that area largely empty.

The traditional running shoe results were characterized by localized pressure in the forefoot and heel regions and were typically in the range of 150-220 kPa. Minimalist shoes on the other hand had high pressures (normally 220+ kPa) on the forefoot and very low pressure on the midfoot and heel (around 15-60 kPa). The barefoot trials were characterized by a large area of high pressure (300+ kPa) across the forefoot and metatarsals along with a low pressure area (30-60 kPa) throughout the heel and parts of the midfoot. It was often found that the midfoot and heel would not even register pressure points during minimalist and barefoot running because the subject would never contact the ground with these parts of the foot.

These results also helped to determine where the impact was specifically being focused in each of the conditions and how the pressure compared relative to the other conditions. For example, the forefoot in minimalist shoes experienced nearly twice the amount of pressure as it did in traditional

shoes. Meanwhile the heel only received 25-30 percent as much pressure in minimalist shoes as compared to traditional. This affects how the body responds to the impact applied to the foot.

The barefoot data, all completed on the pressure mat, were very similar to the results of the minimalist insole pressure values. Analysis from a time series of steps confirmed the subjects were experiencing a fore foot strike in minimalist and barefoot running as opposed to a rear foot strike in traditional shoes. This was also found to occur in previous studies (8, 14). The barefoot pressure trials (red – in Figure 18) recorded the highest overall peak and average values, with minimalist shoes (blue) slightly behind and traditional shoes (green) with the lowest overall pressure as can be seen in Figure 18. This graph is a representation of data from five trials for each condition in one subject.
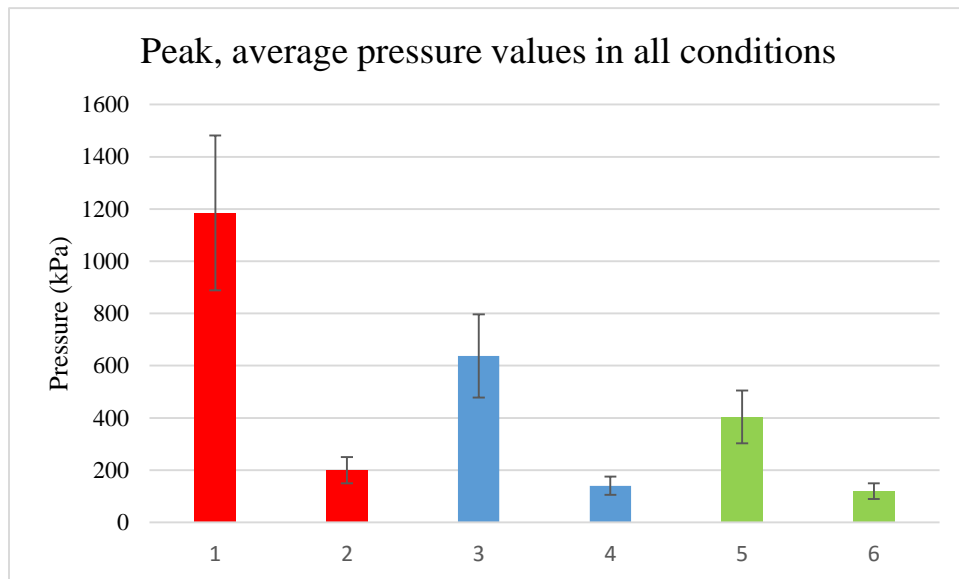
Figure 18. Peak and average pressure values were found to be highest in barefoot running (red) followed by minimalist (blue) and traditional (green), respectively. The bars represent an error of plus or minus 20 percent. Note that the average values do not vary significantly.

While pressure values across the trials are important to consider, analyzing individual steps can be even more telling. The foot was divided into hindfoot, midfoot, and forefoot regions to compare what areas were receiving the highest and lowest pressure, relative to each other. Figures 19, 20, and 21 show the course of pressure on each section of the foot throughout one step, in each running condition. Figure 22 represents a pressure time integral comparison for each section of the foot in minimalist and traditional trials. These were created by plotting pressure values for each section of the foot against the time at which they occurred during a single step. Each graph will be explained further.
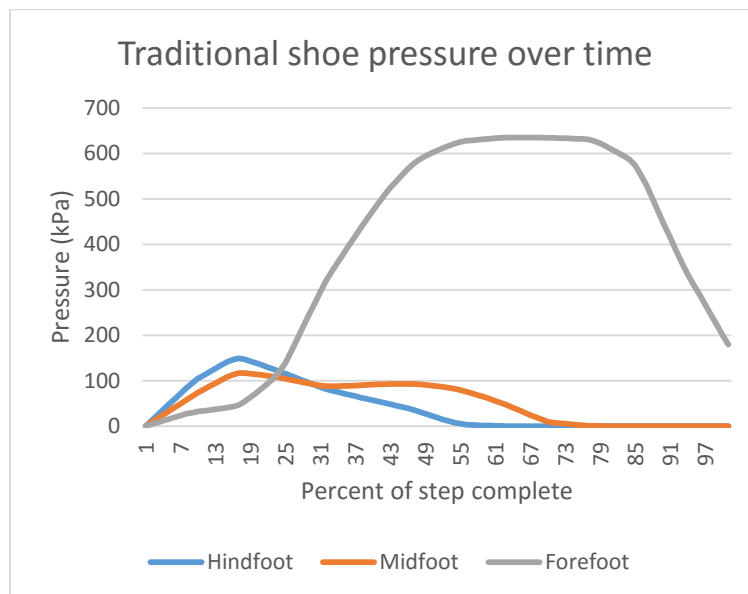
Figure 19. An illustration of traditional shoe pressure versus time over the course of one step. The initial peak from the hindfoot and midfoot represent an initial RFS and the sharp decline of the forefoot is due to takeoff during the completion of the stride.
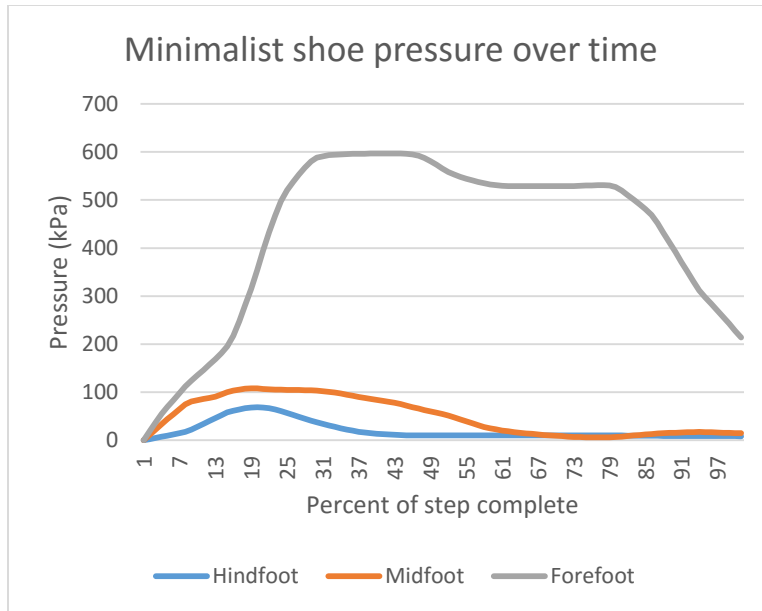
Figure 20. Minimalist shoe pressure versus time during one step shows an initial forefoot strike. The forefoot reaches its peak value the fastest in this condition.
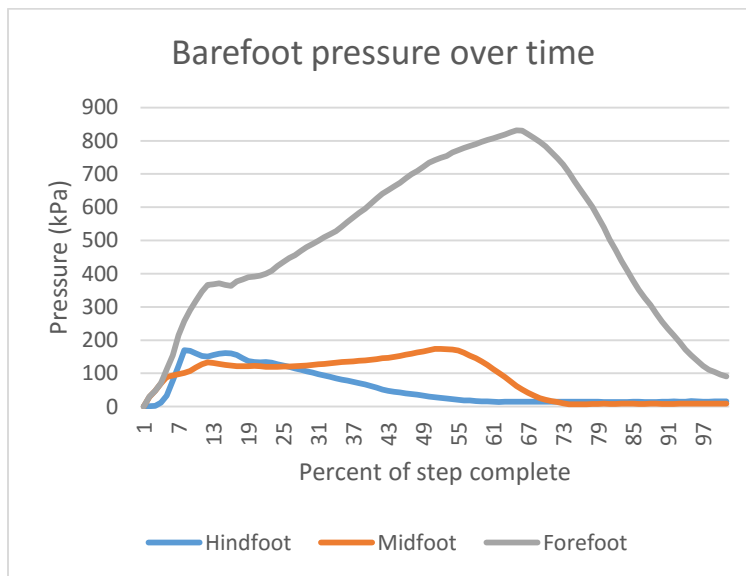
Figure 21. Barefoot pressure versus time illustrates a forefoot strike with higher midfoot and hindfoot values relative to the minimalist condition. There is also a delay in peak forefoot pressure which climaxes nearly 200 kPa greater than the other two conditions.
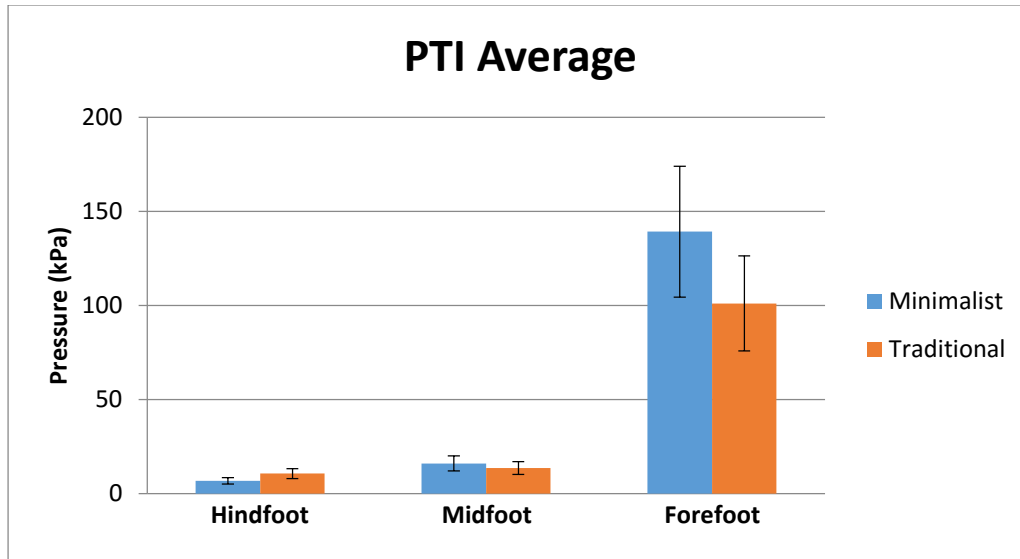
PTI Average

Figure 22. Comparison of pressure time integral (PTI) averages for hindfoot, midfoot, forefoot in minimalist and traditional shoes shows much greater activation in the forefoot than the other regions. It should be noted traditional hindfoot values were greater than minimalist.

In the traditional running shoe (Figure 19), the rear foot strike is immediately obvious with initial peak pressure in the midfoot and hindfoot nearing its crest of roughly 190 kPa before the first quarter of the step is complete. These values continue to diminish until they both approach zero before 75 percent of the step occurs. After the initial peak of midfoot and hindfoot values, the forefoot pressure increases rapidly, reaching its maximum value about halfway through the step. This pressure illustration shows an initial landing phase, or touchdown, on the hindfoot. The runner then transitions their foot to flat around 50 percent as the forefoot values continue to increase. The back of the foot then begins to raise off the ground, preparing for the next step, creating no pressure on the midfoot or hindfoot. Finally, the forefoot pressure remains near its max value until the takeoff phase where the foot completely lifts in order to complete the stride. This can be seen in the decline of the forefoot pressure towards 90 percent step completion.

The minimalist shoe data (Figure 20) appears similar at first glance, but there are important differences from the traditional shoe. The first major difference comes from the forefoot strike. This can be determined from the fact that the midfoot and hindfoot never cross the forefoot values but rather remain below the entire time. The forefoot also peaks much more quickly in this step, reaching its maximum value about 25 percent of the way through the step, as opposed to 50 in traditional shoes. It is worth considering as well that the midfoot and hindfoot values never peak as high in minimalist shoes and are both diminished to zero around 60 percent through the step which is earlier than in traditional as well. The forefoot values peak during the touchdown phase, diminish slightly through the step as pressure is distributed throughout the foot and the runner moves their foot towards the metatarsals. Forefoot pressure again declines quickly during the takeoff.

The barefoot graph (Figure 21) exhibits a mixture of traditional and minimalist patterns. While there is still a decidedly forefoot landing style, there is more of the hindfoot and midfoot contacting the ground than in minimalist shoes, which is evident by the higher initial pressure values. The midfoot and hindfoot then show similar trends to the traditional shoe through the step as the pressure diminishes until it is nonexistent around 65 percent. The forefoot however takes longer to reach its maximum value than in either pair of shoes, peaking near 800 kPa around 70 percent of step completion, about 200 kPa higher than both of the other conditions.

The pressure time integral (PTI) graph (Figure 22) is a different visualization of similar information. Data for this graph represents an average of fourteen steps across five trials in traditional and minimalist running shoes. It is important to remember the previous graphs discussed were for a single step. While the traditional and minimalist pressure values were very similar in the steps shown, the averages in the PTI graph give a better representation of the

expected overall results. The PTI determines the area under the curve for each section of the foot and compares the averages for traditional and minimalist shoes. As can be seen the forefoot is the highest followed by the midfoot and hindfoot, respectively. The minimalist shoe values on average were higher in the midfoot and forefoot while the hindfoot in traditional shoes surpassed minimalist, as expected.

EMG Data

By reviewing the muscle's location and level of use during specific movements, EMG values may indicate a particular function being executed. Comparing their levels of activation across each condition is significant as well and may indicate a change in task or performance.

Peak, minimum, and average EMG values were recorded for each individual trial and a standard deviation and confidence interval were calculated. This indicates the level of variability across a series of trials. Table 3 below shows the ratio of root mean square (RMS) EMG data relative to maximum contractions for each muscle and condition. The values were normalized according to the highest peak each muscle elicited in any of the tests completed. RMS will be explained further.

Table 3. Ratios of RMS EMG data relative to maximum contractions. All muscles varied in relation to the footwear being worn except for the Abductor digiti minimi which remained consistent across conditions.

	Abductor Hallucis	Ab. Digiti Minimi	First dorsal interossei	Third dorsal interossei
Traditional	55%	39%	13%	36%
Minimalist	48%	37%	22%	56%
Barefoot	12%	38%	70%	47%

There was no specific muscle tested that proved to be the most active across all conditions but the abductor digiti minimi was relatively low and consistent in each condition. The other three varied according to the footwear being worn. This indicates that the changes in running footwear did affect the level of activation of intrinsic muscles.

An RMS analysis was completed for all trials in each of the three conditions. Table 4 shows the average of this data for barefoot, minimalist, and traditional trials. RMS averaging allows for a more accurate representation of the "normal" value throughout the course of a trial. This test squares each value (to rectify it), sums the data points, divides by the number of values, and takes the square root. The values diminish greatly from the peaks shown above because these calculations include periods of inactivity, such as when the foot is in the air. Each of the calculations were completed using matlab and once again were calculated from all five trials in each condition for one subject. Figure 23 graphically represents this data, using the percentage of each muscle's RMS value in relation to its highest elicited contaction.

Table 4. RMS EMG values for five trials in all conditions. This shows variation once again in each type of footwear.

	Abductor hallucis	Abductor digiti minimi	First dorsal interossei	Third dorsal interossei
Traditional	187.405	31.201	99.987	112.440
Minimalist	163.223	29.558	172.225	173.356
Barefoot	41.235	30.123	548.893	147.552
Highest contraction	343.431	79.785	783.677	311.212

RMS muscle activation
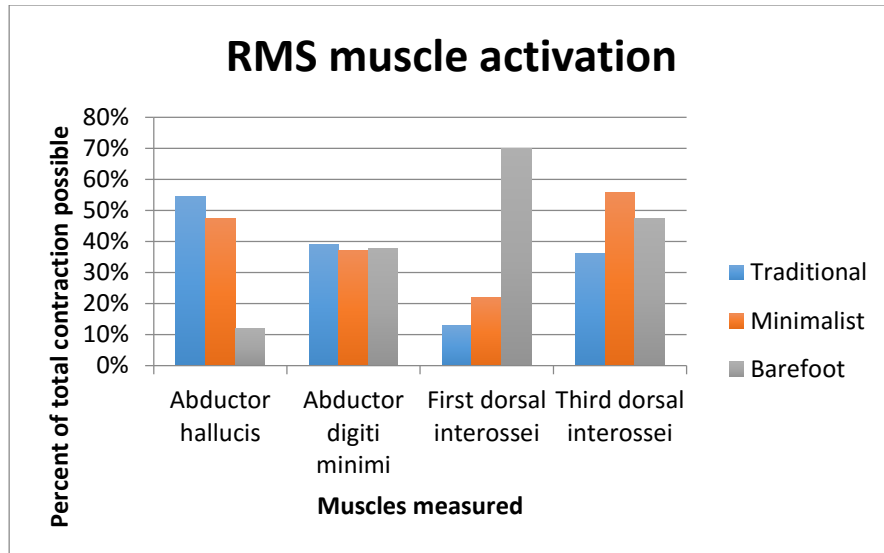
Figure 23. An illustration of RMS muscle activation as a percentage of its highest elicited contraction. While the abductor digiti minimi values were low, they were similar to the other muscles when normalized based on the contractions. More effective MVC tests should be used in future studies.

Figures 24, 25, 26, and 27 each show two cycles (steps) from a treadmill trial in traditional shoes for each of the muscles being studied. This aids in visualization of the muscular activation (again, measured in microvolts) over time. In this case, time was based on a scale that Matlab created while processing the signal. An interval of 0.25 on the graphs below is equivalent to approximately 1 second of running.
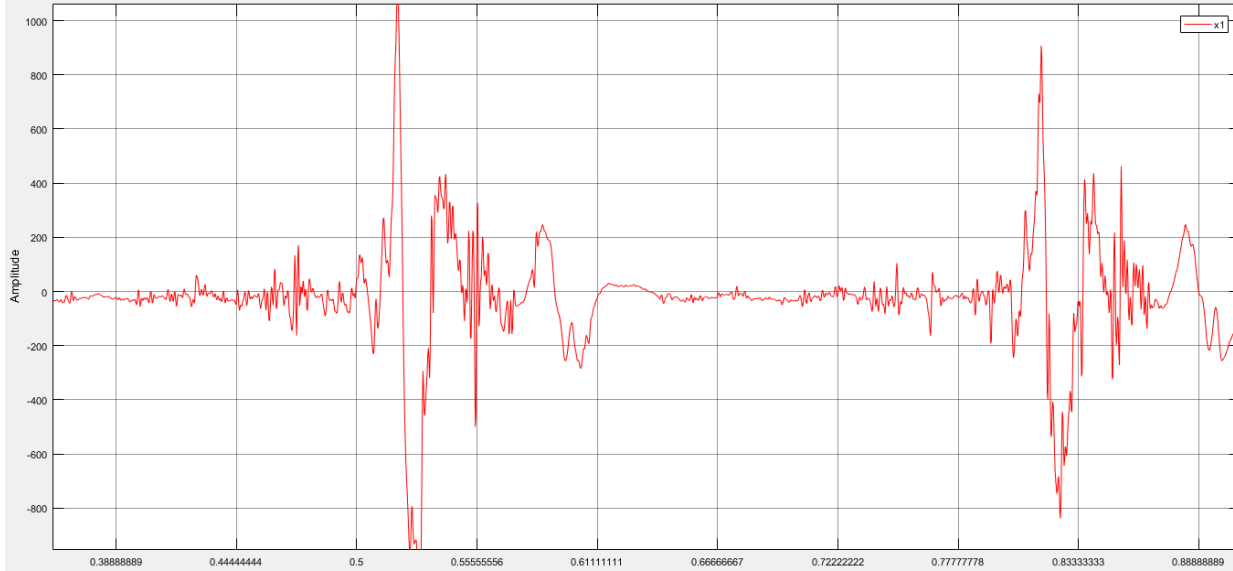
Figure 24. Abductor hallucis activity from a traditional shoe trial versus time. Two cycles (steps are shown, indicating distinct periods of strenuous activity and rest.
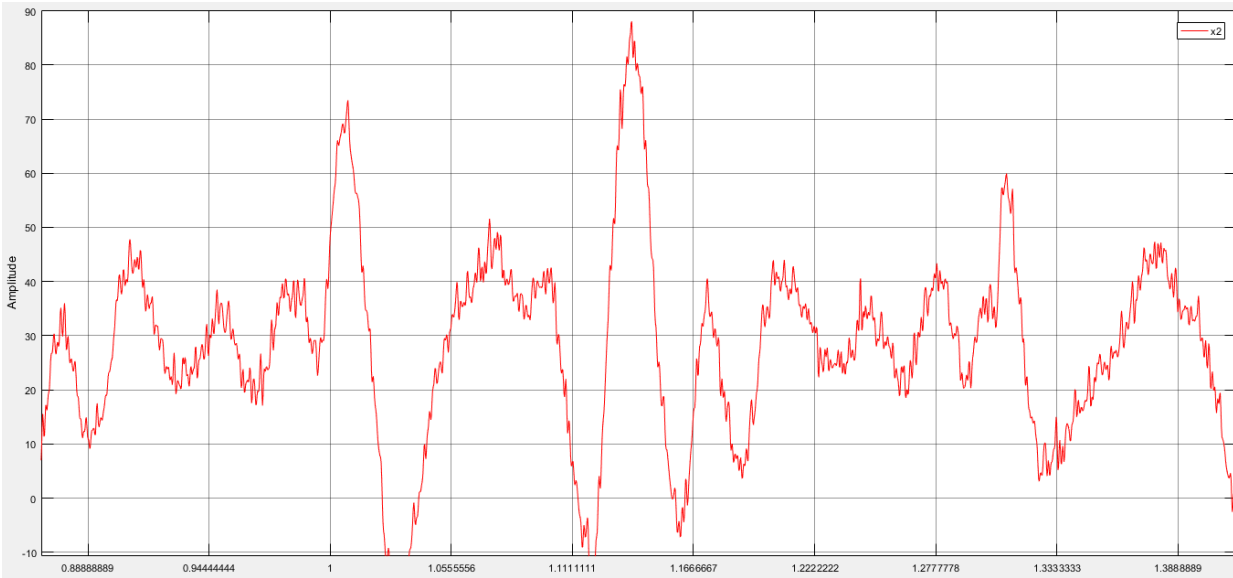
Figure 25. Abductor digiti minimi activity from traditional shoe trial versus time. Max values can be seen, the muscle receives little rest amongst steps.
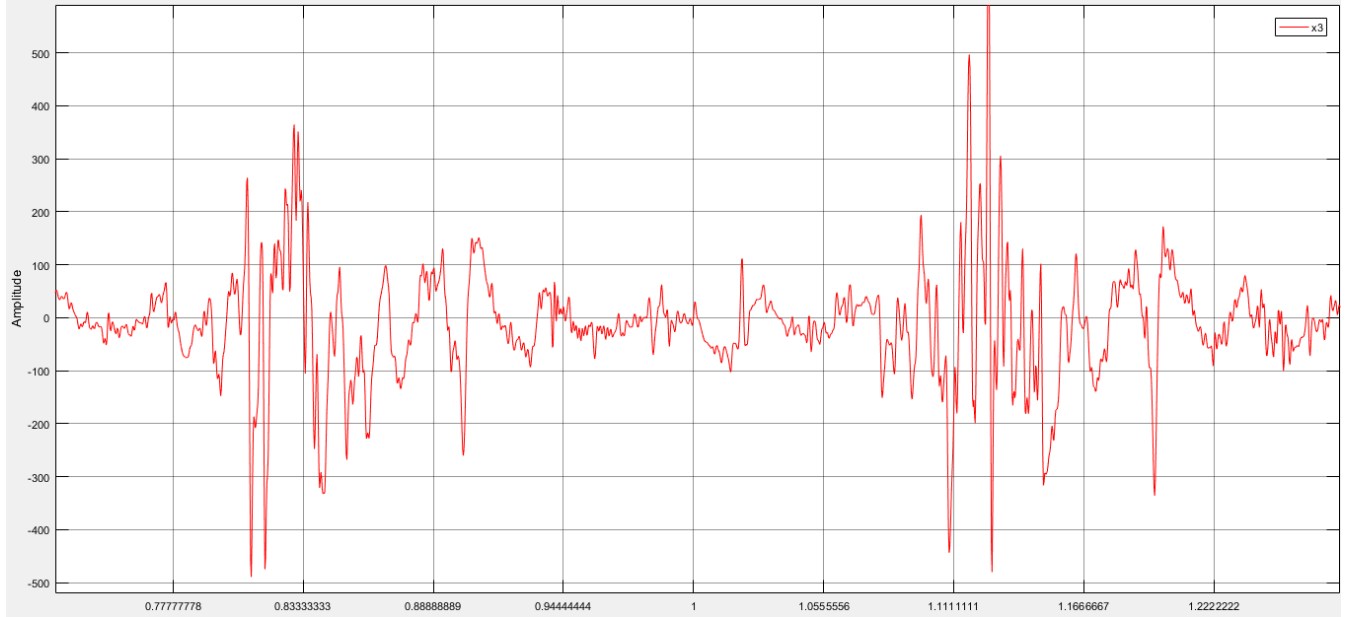
Figure 26. First dorsal interossei activity from traditional shoe trial versus time. Periods of high activity are short and easily distinguished.
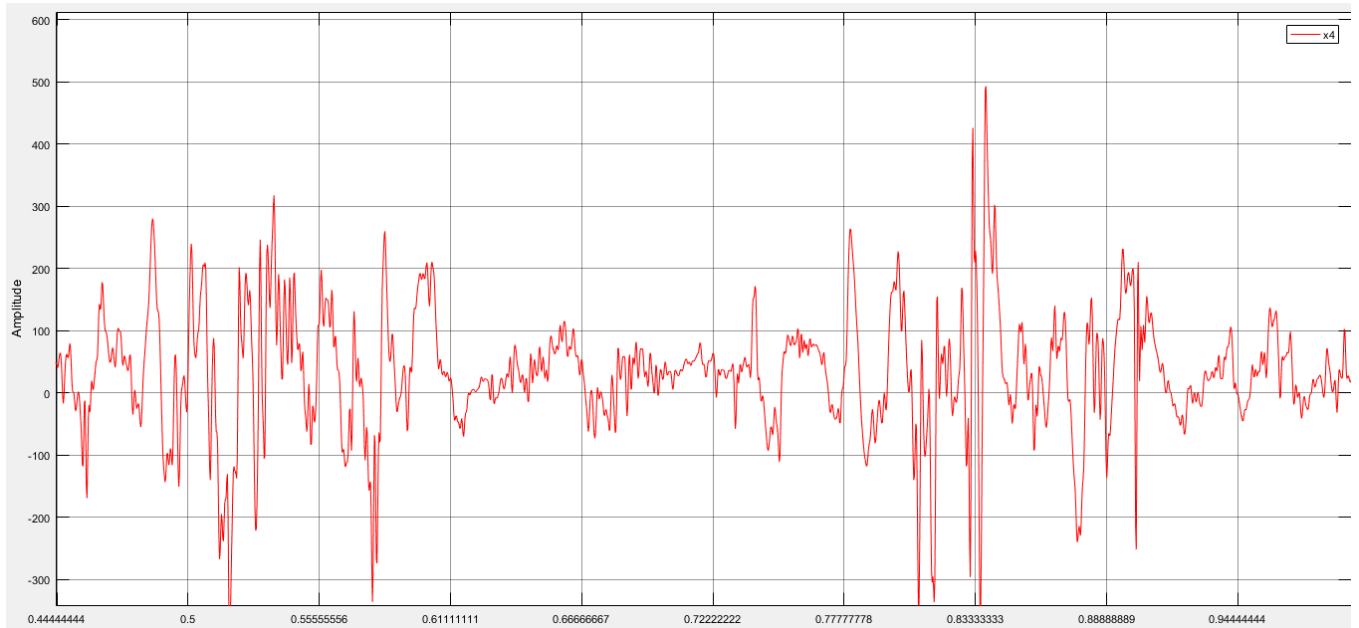
Figure 27. Third dorsal interossei activity from traditional shoe trial versus time. Similar results relative to the first dorsal inteossei with slightly more consistent activity.

The treadmill trials with traditional shoes showed high amounts of activity for the abductor hallucis and relatively mild activity for abductor digiti minimi, and the dorsal interossei muscles. The minimalist condition however showed nearly the same amount of abductor hallucis activity but almost double the activity for both dorsal interossei muscles. The barefoot treadmill trials were characterized by minimal activity from the abductor hallucis and abductor digiti minimi but very high activity from the first and third dorsal interossei muscles. The adbudctor digiti minimi never peaked above 100 microvolts.

Survey Data

The survey was meant to give a better understanding of the subject's background in running. Questions were asked regarding running experience, average pace and distance, preferred running shoe, etc. This was used to possibly indicate correlations between overuse and injuries, change in footwear and level of comfort, and so on. Again, the survey itself can be found in the appendix in full, Figure 28 shows how the information was recorded in excel.

The other purpose of the survey was to gather critical information that would have been unknown otherwise. This allowed for possible outliers to be explained. For example, if a subject produced much lower pressure values in minimalist shoes for example, then perhaps there could be a possible explanation in the given survey data. Perhaps they have had significant experience in minimalist shoes and use a unique running style that lowers pressure values more than expected. However, no such outliers could be identified in the collected data set.

	Question	Answer
SUBJECT 1		
	1	5+
	2	1-2x
	3	3
	4	5;7
	5	4
	6	Comfort
	7	n/a
	8	n/a
	9	Minimalist

Figure 28. Example of survey data with answers from subject one. This information helped

identify outliers in data collection but would be more useful in a larger study population.

Discussion

Traditional, minimalist, and barefoot running differed in many ways in the subject measured for this study. Because only one subject was analyzed, concrete conclusions regarding these differences cannot accurately be made. Rather, the information supports indications of what might happen within the general running population. While it was found that traditional shoes generally accomplish their goals to reduce pressure points on the foot and muscle activation, they do however, alter a runner's natural stride. The increased heel cushioning causes runners to land with a RFS when they tend to run with a FFS in both barefoot and minimalist running. The intrinsic muscles produce a lower amount of activation in traditional shoes, and this may result from a reduced need to resist foot dorsiflexion.

The intention of this study was to discover if there were changes in intrinsic muscle activation across footwear conditions. While the data suggests there are differences among them, the function being performed by each muscle is difficult to determine. What seems to be occurring is that the function remains the same but they have differing levels of exertion in the three running conditions. Some of the muscles are forced to compensate for the others due to changes in footwear resulting in new levels of activation, but the actual task being accomplished fundamentally remains the same.

The dorsal interossei muscles are primarily responsible for abducting (moving away from) toes 2-4 and the abductor hallucis takes care of the big toe. The abductor digiti minimi abducts and flexes the pinky toe. However, as a group, the primary action of the intrinsic muscles in the foot is to provide dynamic support of the longitudinal arch of the foot, resisting those forces that act momentarily to spread the arch during walking and running (33). It should be noted however that confirmation of this has not been supported by substantial research studies.

Progressive overload refers to continually increasing the demands on the musculoskeletal system in order to continually make gains in muscle size, strength and endurance. In simplest terms - in order to get bigger and stronger individuals must continually lift more and more and make their muscles work harder than they are used to (36). The intrinsic muscles have already been confirmed to work harder in the minimalist and barefoot conditions. The issue then becomes whether the muscles are being strengthened or if they are being overworked in those conditions. Miller et all (22) found that over the course of time, foot muscles tend to grow while running in minimalist shoes. Their hypothesis was that running in minimalist shoes would cause hypertrophy in these muscles and lead to higher, stronger, stiffer arches. It was found that the flexor digitorum brevis muscle became larger in the control and minimalist groups by 11% and 21%, respectively, but only the minimally shod runners had significant areal and volumetric increases of the abductor digiti minimi of 18% and 22%, respectively, along with significantly increased longitudinal arch stiffness (60%). If the muscles are able to strengthen properly then it is likely they could get better at doing their job and lead to reduction in overuse injuries, including plantar fasciitis.

This study was not without its limitations. The most notable of these issues was the small sample size. Expansion of the database for this study would drastically increase the ability to complete further analysis, increase diversity, and reduce uncertainty. The equipment was not without its faults either. Often there were error messages that had to be noted while recording data and not all of these errors could be successfully addressed during the completion of the experiment. This study managed to create a foundation for advancement of this body of knowledge (i.e. biomechanics, intrinsic foot muscles) but would need to be carried on in order for any substantial

claims to be made. Most importantly, it provided a way to test and observe the intrinsic muscles of the foot while laying it out in a way to make it easily repeatable.

Data analysis from the subject in consideration revealed that minimalist shoes cause increased activation of intrinsic foot muscles in comparison to traditional running shoes. Additionally, average and peak pressure values were higher in both minimalist and barefoot running than in traditional shoes. This supports the predictions of this study that there is increased muscle activation in minimalist and barefoot running which may lead to a reduction in running injuries, specifically plantar fasciitis. The reduction in injuries would be a result of training the intrinsic muscles, making them stronger over time. It is possible though that these results could change with a larger sample size.

A sample population for further study was calculated by completing a power analysis. In order to compute this value, several decisions had to be made regarding error and confidence levels; adjusting these to better suit specific experimental needs will alter the result accordingly. Using a 95 percent confidence interval, 0.5 standard deviation, and a margin of error of +/- 10 percent a sample size of 96 participants is recommended. The values used in this calculation were conservative, meaning this population size could likely be decreased and still produce statistically significant results.

Limitations

Throughout this study there were many problems encountered along the way. As mentioned previously, there were issues regarding the methods, equipment, participants, and amount of time needed to complete the study. These all played a role in the results and the outcomes of this paper so it is only fair to explain those here and discuss what impact they may have had on the study as a whole.

One of the major flaws encountered in the initial phases of testing were the specific set of procedures for the subjects to follow. For example, it was stated that the subjects were allowed to select a comfortable running pace for the duration of testing. The experiment began before a design of experiments analysis was completed on the interaction of variables. This analysis concluded there were in fact interactions between variables that had not previously been considered which could consequently affect the results. This meant that any data collected prior to the design of experiments analysis was not scientifically accurate and should not be used in the results section, which is part of the reason only one subject was analyzed.

Another problem encountered during initial testing was the inability to extract maximum voluntary contractions from subjects. Although there were two separate tests in place for this, neither one came close to the peaks experienced during the subject's running trials. While different methods were tested to try and combat this, a sufficient solution could not be found. As a result of this, MVC values had to be based on absolute maximum values recorded in any of the trials (for each condition). This managed to provide a way to normalize the data however, a test known to elicit the full strength of each of the muscles being tested would have provided a more accurate indication of how hard the muscle was truly working.

The equipment used throughout the study was generally very successful at accomplishing the tasks they were meant to perform. However, there were quite often issues that came up during testing that may have had an impact on the results. For example, the pressure insoles caused issues during calibration due to a faulty wire producing error codes during testing. This was fixed in subsequent experiments. The kinematic markers proved to be the most frequent issue, as they would fall off during testing as the subjects continued to sweat. These were reapplied and trials were repeated until they remained on the subject throughout five trials. However, this affected the runner's pace and consistency because they were forced to stop the treadmill each time a marker needed to be reapplied.

It was also difficult to find a large group of qualified participants for this study that fit all the necessary criteria. While a difficulty is certainly not a limitation, it led to a major limitation of this study (the small sample size). Not only did runners need to have experience with minimalist or barefoot running, but they needed to own a pair of minimalist shoes. Furthermore, in order to get proper readings from the pressure insoles, the minimalist shoes could not have toe slots as this would affect the readings. Finally, they also needed to have a shoe size between eight to ten (U.S. Men's) because these were the only sizes available in the laboratory for functioning pressure insoles. If the pool of qualified applicants had been larger, this would have enabled more tests to be completed. More data would have resulted in lower variability, increased diversity and more specific conclusions. This was the biggest drawback of the study.

Conclusion

This study helped to lay preliminary groundwork for understanding the testing and functionality of intrinsic foot muscles. Use of traditional and minimalist shoes was associated with changes in running styles, supporting extensive data that traditional shoes are associated with RFS in runners as opposed to a FFS experienced in minimalist and barefoot running. This produced much higher pressures on the ball of the runner's foot but significantly reduced midfoot and hindfoot pressure whereas traditional shoes had lower overall pressure distribution but was concentrated on both the forefoot and heel.

There were small differences between intrinsic muscle activation in minimalist and barefoot which emphasized dorsal interossei use but both of these styles contrasted markedly with traditional running shoes which had low intrinsic muscle activation all around with exception of the abductor hallucis which was found to be similar across the three conditions. This indicated that there was in fact increased intrinsic muscle activation in minimalist and barefoot running.

These data suggest that while there were noticeable changes between each of the running conditions, the fundamental functions of the intrinsic muscles were not tested. The intrinsic work differently in each type of footwear and are likely strengthened during running in minimalist shoes and barefoot. If these data are supported by further study, it would suggest that such strengthening may help reduce running injuries such as plantar fasciitis. While this study offered initial findings, more studies and greater in depth analysis needs to be completed on this topic for confirmation and further exploration of the results. A major limitation of this study was the small sample size.

Appendix

Procedure

Before subject arrives

1. Prepare reflective markers (for both legs, feet) and electrodes (for one foot). Attach transmitters to the electrodes.
2. Prepare insoles and the belt so it is ready for use.
3. Open, prepare the EMG and Qualisys software on double monitor. Calibrate the cameras (Be sure to do a static trial before the dynamic). Turn on force plates.
4. Turn on laptop and open, prepare the NOVEL database containing Pedar and Emed.
5. View emed (pressure mat) and pedar (insoles) files. Will open, record to that database.
6. Insert the pressure mat, plug usb into the laptop.
7. Turn the treadmill on, have it ready to go.

After the subject arrives

1. They must have traditional and minimalist shoes, allow them to change if needed.
2. Give them the speech, go over protocol for the experiment.
3. Sign consent forms, if they agree to participate.
4. Have them complete the survey.
5. Take their height and weight, record.
6. Attach EMG electrodes to abductor hallucis, abductor digiti minimi, 1st and 3rd dorsal interossei after applying rubbing alcohol and sandpaper to area; then reflective markers on 1st metatarsal, navicular tuberosity, posterior calcaneus, 5th metatarsal head and base, lateral and medial malleolus, lateral and medial tibia condyles.
7. Tape transmitters, any dangling wires.
8. Let subject have 10 minute warmup on the treadmill.
9. Place insoles in shoes, put belt on subject, turn transmitter on.
10. Have subject stand up on toes 3 times for muscle contraction to normalize data.
11. Complete treadmill test in 6 minute increments. Randomized order of traditional, barefoot, minimalist with break in between each.
12. Have subject prepare for the barefoot test once treadmill trials are complete.
13. Have them run across the pressure mat, complete 2 trials for each foot.
14. Close out, goodbye, thank participant, give any information needed to follow up.

Survey

In order to get a better understanding of your running background we ask that you answer the following questions honestly and to the best of your ability.

When did you start running recreationally?

5+ years ago | 4 years ago | 3 years ago | 2 years ago | 1 year ago | < 1 year ago

How often do you run?

1-2x per week | 3-4 x per week | >5x per week

How far/long do you typically run?

1 mile/<10 minutes | 2 miles/<20 minutes | 3 miles/<30 minutes | >4 miles/>40 minutes

What is your average pace to run one mile?

3-5 minutes | 5-7 minutes | 7-10 minutes | >10 minutes

When did you start running minimalist or barefoot?

5+ years ago | 4 years ago | 3 years ago | 2 years ago | 1 year ago | < 1 year ago

What changes have you noticed since the switch (select all that apply)?

Change in stamina | Change in performance | Change in comfort | Change in form

Do you typically notice any areas of discomfort while running (select all that apply)?

Leg | Foot | Hip

Have you had trouble with injuries from running (select all that apply)? If so, what type of injuries?

Leg | Foot | Hip

What type of running do you prefer; traditional, minimalist, or barefoot?

Traditional | Minimalist | Barefoot

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