THE EFFECT OF MINIMALISTIC RUNNING ON RUNNING RELATED INJURIES IN HABITUALLY SHOD INDIVIDUALS: A REVIEW

by

Katie Lynn Bond

Honors Thesis

Appalachian State University

Submitted to
The Honors College
in partial fulfillment of the requirements for the degree of

Bachelor of Science in Business Administration

August, 2017

Approved by:

____
Abigail Stickford, Ph.D., Thesis Director

____
Pennie Bagley, Ph.D., Second Reader

____
Ted Zerucha, Ph.D., Interim Director, The Honors College

Abstract

THE EFFECT OF MINIMALISTIC FOOTWEAR ON RUNNING-RELATED INJURIES IN HABITUALLY SHOD INDIVIDUALS: A REVIEW

Katie Bond

B.S.B.A Appalachian State University

Running as a form of locomotion has existed for thousands of years – historically the activity has been predominantly barefoot in nature with a more recent gradual transition to shod conditions. As the popularity of the exercise increased and turned into sport, running shoe manufacturers began to invest heavily in athletic footwear. Substantial evidence from various scientific fields suggests that the human body may have evolved to run extensive distances; however, the rate at which running-related injuries are sustained remains alarmingly high, despite innovations in footwear. Consequently, there has been renewed interest in minimalist and barefoot running as a means of injury prevention. The purpose of this paper was to examine previous research on the effects of barefoot and minimalist running compared to modern cushioned footwear, and present the findings in a summarized report. Research indicates barefoot and minimalist footwear have effects on running form, peak impact force, and a number of common running injuries. Subsequently, these footwear styles may increase the risk of certain injuries. Because running-related injuries are multifactorial in nature, there has not been a decisive conclusion regarding potential benefits of barefoot and minimalist running for injury prevention. The opportunities for further research are plentiful as minimalistic running becomes more popular and additional data can be gathered and tested.

Introduction

The human body is a complex and fascinating machine. When it comes to athletic performance, and specifically running, the human body is capable of performances that continue to push past previously held barriers, going further and faster than once believed to be possible. Before 1954, the world believed that achieving a sub four-minute time while running a mile was an impossible feat. Numerous runners attempted it and they all failed, leading the running community to believe that it was unattainable. However, on May 6, 1954, Roger Bannister was the first recorded individual to break that barrier with a time of 3 minutes, 59.4 seconds (“First-Four Minute Mile”, 2016). Thousands of runners have followed in his footsteps since that race, continuing to complete the mile distance in increasingly faster times, with the current world record holder running a time of 3 minutes, 43.13 seconds in 1999 (“IAAF: World records,” 2016). Similar record breaking feats are ubiquitous across the world, addressing not only speed, but also endurance. As technology advances, researchers are able to delve into the numerous factors that affect performance, including running form, and, of particular importance to the current review, how current footwear may play a role in either promoting or inhibiting that performance.

Running-Related Injuries

As the popularity of running increases, both as a professional sport and a recreational activity, it becomes necessary to address injuries commonly associated with running. The rate at which runners are sustaining injuries has increased within the last decade to a relatively high percentage. According to review of published articles performed by Gent et al. (2007), up to approximately 79 percent of runners today sustain lower extremity injuries in a given year, leading the running community to question the reason behind this elevated rate of injury.

Repeated impact from activities such as running, have been associated with increased risk of overuse injuries. The most common overuse injuries from running shown in Table 1 typically affect the bones and tendons of the lower limb and include injuries such as patellofemoral pain syndrome, tibial stress fractures, plantar fasciitis, and Achilles tendinitis (Murphy, Curry & Matzkin, 2013, Abstract). Acute patellofemoral pain syndrome is the irritation on the underside of the patella (i.e., kneecap) and is the predominant site of lower extremity injuries. Achilles tendonitis is the inflammation of the Achilles tendon. Plantar fasciitis consists of small tears or inflammation of the tendon that runs from the calcaneus to the metatarsals. Tibial stress fractures typically begin as shin splints and progress into a splintering of the tibia (Aschwanden, 2016). The contributing factors to this upward trend in injuries, is not fully elucidated; however, the role of footwear is increasingly considered in this discussion, for example, there has been a relatively recent surge in research regarding the trend of *minimalistic running*, i.e., wearing a minimalistic shoe, or even going barefoot, while running. The idea of minimalistic running is not a new idea; however, it has rapidly gained popularity in the discussion of whether running barefoot versus shod is more beneficial in reducing injuries most commonly associated with running. Compared to shod running, minimalistic/barefoot running changes both the way in which the foot strikes the ground, and the corresponding forces exerted upon the lower extremities. According to a study performed by Fredericks et al. (2015), foot strike style does not change with speed, but does change with shod condition, with minimalist shoes exhibiting a forefoot strike pattern in between that of shod and barefoot runners. Foot strike patterns will be discussed in more depth in subsequent sections.

Barefoot runners and runners using a minimalistic form of footwear may endure a lower impact force from the ground, as well as shorter stride lengths and higher stride frequency. A shorter and more frequent stride rate is typically correlated to decreased ground contact time, flight time, and stride duration when compared to shod runners. Footwear decreases the available sensory input the foot is able to process from the ground, which can lead to an increased risk of injury from the inability to engage the intrinsic foot musculature (Rothschild, 2012). The adapted table below from Bent et al. (2007), provides a comparison of injury rates and locations compiled from different studies.

TABLE 1

Running-Related Injury Incidence and Common Injury Locations.

Author, year of publication	**Injury Incidence Rate**	**Location Specific Injury Rate**				
	Overall (%)	**Knee(%)**	**Foot(%)**	**Ankle (%)**	**Lower Leg (%)**	**Hip/Pelvis (%)**
Bovens *et al, 1989*	84.9%(174 injuries by 62/73 runners)	24.7	5.7	12.1	32.2	11.5
Jakobsen *et al,* 1989	19.4%(193 injuries by 161/831 runners)	26.9	6.9	10.8	16.6	
Lun *et al, 2004*	79.3% (69 injuries by 69/87 runners)	7.2	15.0	3.9	9.0	5.0
Maughan & Miller, 1983	27.2%(122 injuries by 122/449 runners)	32.0	39.3	4.9	13.1	3.3
Taunton *et al, 2003*	28%(236 injuries by 236/840 runners)	35.2	14.0	11.0	26.7	9.7
Wen *et al,* 1998	32.9%(84 injuries by 84/255 runners)	31.0	16.7	10.7	32.1	5.9

Human Foot Evolution

In order to discuss running-related injuries, it is necessary to have an understanding of the foot and the physiology behind running as well as how humans have evolved throughout time to allow for locomotion. The foot is one of the most specialized and unique anatomical structures of the body. It is comprised of 26 bones with a complex structure of ligaments and tendons that form the joints and allow for movement. The plantar (i.e., bottom) surface is deeply covered with soft tissue, which aids in providing sensory input from the ground while in motion (Wang, Abboud, Günther, & Crompton, 2014). The four primary groups of muscles and ligaments within the foot are the triceps surae, the tibialis anterior, the intrinsic dorsal muscles and ligaments, and the plantar intrinsic muscles and ligaments. The triceps surae and tibialis anterior work to support the body's center of gravity, while the plantar muscles and ligaments in the foot bear relatively small tension, allowing for extended standing without exhausting the muscles and ligaments (Wang & Crompton, (2004). Based upon these factors and a number of other physiological characteristics, humans are in fact more suited to bipedal walking.

Over the course of thousands of years, the human foot has morphed from that of the ape to one with a myriad of characteristics that favor bipedal activity. These changes likely originated soon after the lineages of the chimpanzee and human diverged. During bipedal locomotion, the foot is the only structure that has direct contact with the ground, therefore, it has to have the capability to handle the significant pressures exerted upon it, in addition to maintaining balance and providing propulsion in an efficient manner (Smith & Aiello, 2004). According to Wang and Crompton (2004), the ratio of the power arm (the distance from the heel to the talocrural, i.e., ankle, joint) to the load arm (from the talocrural to the distal head of the metatarsals, i.e., the end of the bones of the midfoot) is markedly different between the human and the ape foot. The ratio is approximately 40 percent in humans, 46 percent in gorillas, 28.2 percent in chimpanzees, and 19.6 percent in orangutans. A ratio of the power arm to the load arm of 40 percent (as in the case of the human foot) minimizes the required muscle force at the talocrural joint. By using less force, it is believed the runner is able to consume less aerobic energy, which ultimately could increase the capability to travel further distances without fatigue. Dudley Morton produced one of the most widely known models of the evolution of the foot in 1935. He suggested that a hypothetical early hominid foot linearly evolved from that of a gorilla. The foot was still a flexible and grasping organ, similar to the ape, with a relatively lengthened opposable hallux (i.e., big toe), however, it had an enlarged heel for greater weight bearing, shorter toes and no longitudinal arch (Smith & Aiello, 2004). An important fact to consider is Morton did not have fossils to work with, only comparative material that was modern at the time. According to Susman (1983), adaptations in the human foot skeleton included

> The presence of a longitudinal arch: the shift of support from lateral to medial with concomitant pronation of the forepart of the foot; hypertrophy, and stabilization of the hallux; the plantarflexed orientation of the forepart of the foot and the stabilization of the caneocuboid joint; the widening of the calcaneal tuberosity; the elongation of the midfoot; the pronation of the foes; and the shortening of the phalangeal segments (p. 368).

There is a lot of research in existence about the origins of the human foot and its evolution to the modern day skeleton; however, there is not a clear consensus. Figure 1 below depicts the skeletal structure of the foot (Encylopedia Britanica, 2007).

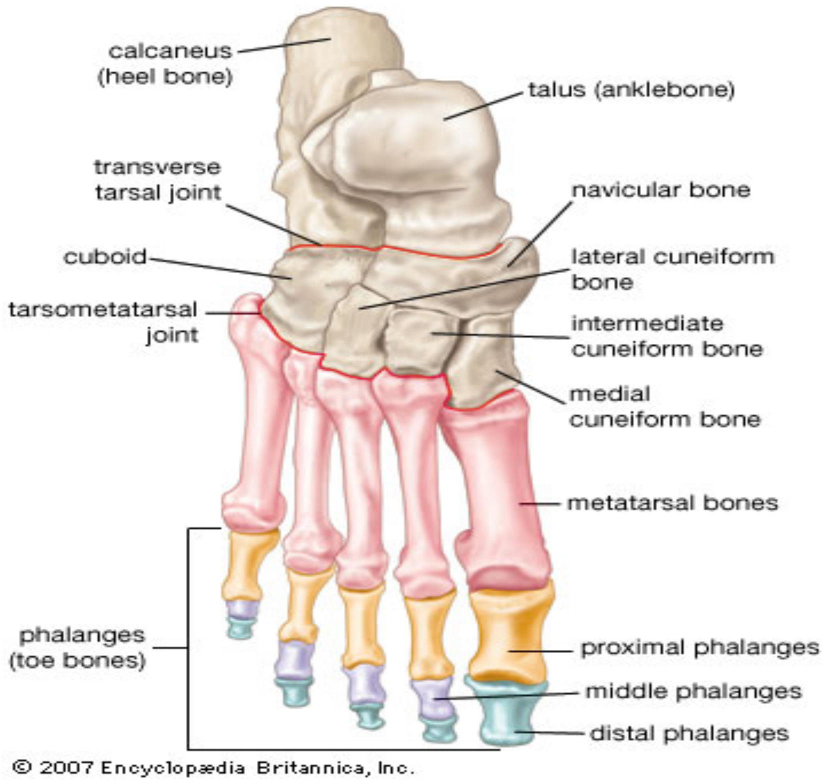


FIGURE 1

Top-down diagram of the skeletal structure of the foot.

Running History

"Human bipedal running has been predominantly barefoot or in minimalistic footwear for millions of years" (McCallion, Donne, Fleming, & Blanksby, 2014). Some research has indicated that humans have certain adaptations that are conducive to endurance running, in particular, defined as running many kilometers over extended time periods using aerobic metabolism. Some of the reasons, historically, for why running was popular included survival, travel and communication, and recreation.

Running was integral to the survival of the early hominin. Research suggests that the increased size of the human brain relative to other primates, may have played an important role in the endurance running evolution. In a study that compared brain size and maximum metabolic rate in a range of mammals across a range of species, a positive correlation between brain size and maximum metabolic rate (i.e., aerobic capacity) was observed. There are also strong associations between exercise and neurogenesis in individual subjects (Raichlen and Gordon, 2011). It is possible that the growth of early hominin cognitive processes and running extensive distances were mutually beneficial in the development of important nervous tissue. Distance running in early humans was likely purposeful in nature (i.e., not for recreational purposes), as the search for resources and food was a powerful motivator. This required complex cognitive processes due to the need for retention and recollection of details such as topography, water sources, and potential food sources over a large area of land in a timely manner. Individuals who possessed a superior cognitive ability would likely have an advantage over individuals with lesser processing ability. Early humans might have needed endurance running in order to effectively scavenge for food and compete with other scavengers. This theory is difficult to test however, because modern hunter-gatherers tend to be more opportunistic in their scavenging, rather than investing time in a lengthy hunt (Bramble and Lieberman, 2004).

Humans have some advantages over most quadrupedal mammals when it comes to distance running. Quadrupedal mammals typically must pant to release heat as they exercise. Panting forces air across evaporative surfaces in the nose and mouth, which works to dissipate the stored heat produced during locomotion, but at the cost of additional energy requirements. An integral key to human efficiency at long distance running compared to quadrupedal animals, is the ability to dispel heat through sweat. Sweating is responsible for about 95 percent of the cooling process. Humans have approximately two to five million sweat glands, substantially more than that of any other mammal (Bramble and Lieberman, 2004). Sweating allows humans to use the body's entire skin surface area to get rid of heat, but in order to sweat efficiently, early hominids had to lose the majority of their body hair. There is still no consensus, however, about the timeline of evolutionary hair loss and whether it occurred pre or post-bipedalism. Research by Ruxton and Wilkinson (2011) suggests that "while early hominins remained hair-covered they would have struggled with overheating if active in hot, sunny, open environments." They predict that once hair loss and sweating ability evolved to near-modern levels, thermoregulation was possible, even under hot, sunny conditions. Because bipedal hominins are relatively poor sprinters compared to other animals (elite human sprinters are capable of maintaining speeds of only 10.2 m s^{-1} for less than 15 seconds), they most likely benefitted from these improved abilities to handle overheating during extended endurance exercise, especially while foraging in the hottest parts of the day in order to avoid predators (Bramble & Lieberman, 2004).

In addition to thermoregulation, humans have a respiratory cycle that is less restricted by locomotion. Research has indicated that quadrupedal mammals can take only one breath per stride at higher speeds, and still maintain a ratio in synch with the stride cycle at slower speeds. This is a result of the load bearing activities on the thoracic complex (i.e., ribs, sternum, and associated musculature) during locomotion as the forelimbs alternatively strike the ground. Each time the forelegs of quadrupedal animals touch the ground, their body cavities, including their lungs, are compressed so strongly that they must breath out. Conversely, as they push off from the ground, their body cavities rapidly expand, thereby forcing them to take a breath (Bramble and Carrier, 1983). The lungs and diaphragm of humans are not subject to the same thoracic load bearing forces upon the foot striking the ground, meaning humans do not need to take a one-to-one breath ratio in relation to gait. They have the ability to use variable strides per breath, thus allowing the freedom to choose any breath ratio, regardless of speed. Figure 2 depicts stride breaths per stride between humans and horses.

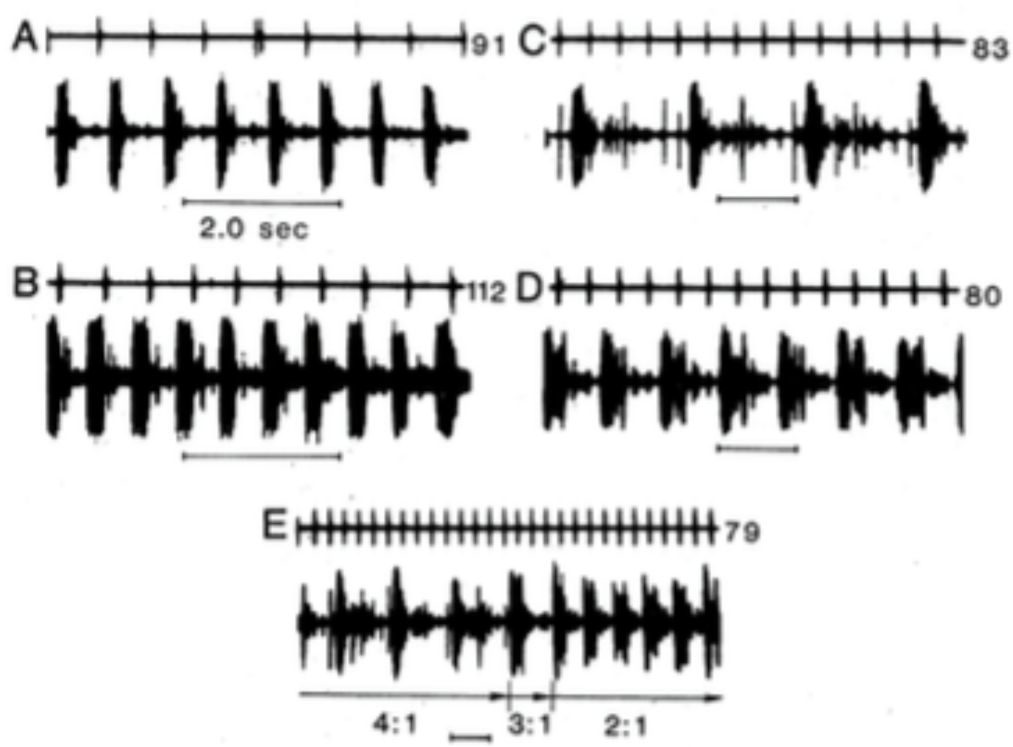


Figure 2

Adapted from Bramble and Carrier (1984). Oscilloscope records of gait and breathing in free-running mammals. The upper trace is footfall and the lower trace is breathing pattern. (a) Horse at trot; (b) horse at gallop; (c) human at 4:1 coupling ratio; (d) human at 2:1; (e) human during shift from 4:1 to 2:1. Number following upper trace is stride rate per minute.

Interestingly, despite this freedom, experienced runners tend to tightly couple their breath and step frequencies, similar to quadrupeds. In the most experienced (marathon) runners, coupled breathing occurred within the first four or five strides of a run. Lesser experienced runners usually required somewhat of a longer distance before breathing and gait coupled, and sometimes even showed little to no tendency to synchronize breath and gait (Bramble & Carrier, 1984). The ability to regulate heat, along with the freedom to take more than one stride per breath, provides an advantage over most four-legged animals when it comes to running for extended durations. While the precise role of running in the evolution of early humans is still unclear, there is certainly agreement that running did have an impact.

Many researchers have proposed that meat eating was also critical to the evolutionary success of the human lineage. Individuals may have thrown sticks or rocks at prey, but sharpened wooden spears do not appear until about 400,000 years ago and stone projectiles only about 40,000 years ago (Pickering and Bunn, 2007). If meat eating was so critical to the evolutionary process, how did early hominins acquire it? A likely answer is *persistence hunting*, which is the act of running an animal to death. Four-legged animals require varying levels of energy in response to changes in speed, therefore, when allowed to choose their own speeds, the majority of four-legged animals will select speeds that require the least amount of energy within that gait. The energy that humans require to run increases almost linearly with speed, which means that the energy used for a human to run a certain distance is nearly constant, regardless of the choice in speed, as shown in Figure 3. Because humans do not have an optimal running speed, it is likely that they could have forced four-legged animals to maintain a speed that was not optimal (Bramble and Carrier, 1983). It typically takes a persistence hunter anywhere from two to five hours, sometimes even more than a day, to run down an animal. By catching one medium-sized animal a week however, a family of four could be supplied (Sears, 2015, pg.12). Persistence hunting reinforces the theory that humans are efficient endurance runners, with the capability of covering extensive distances.

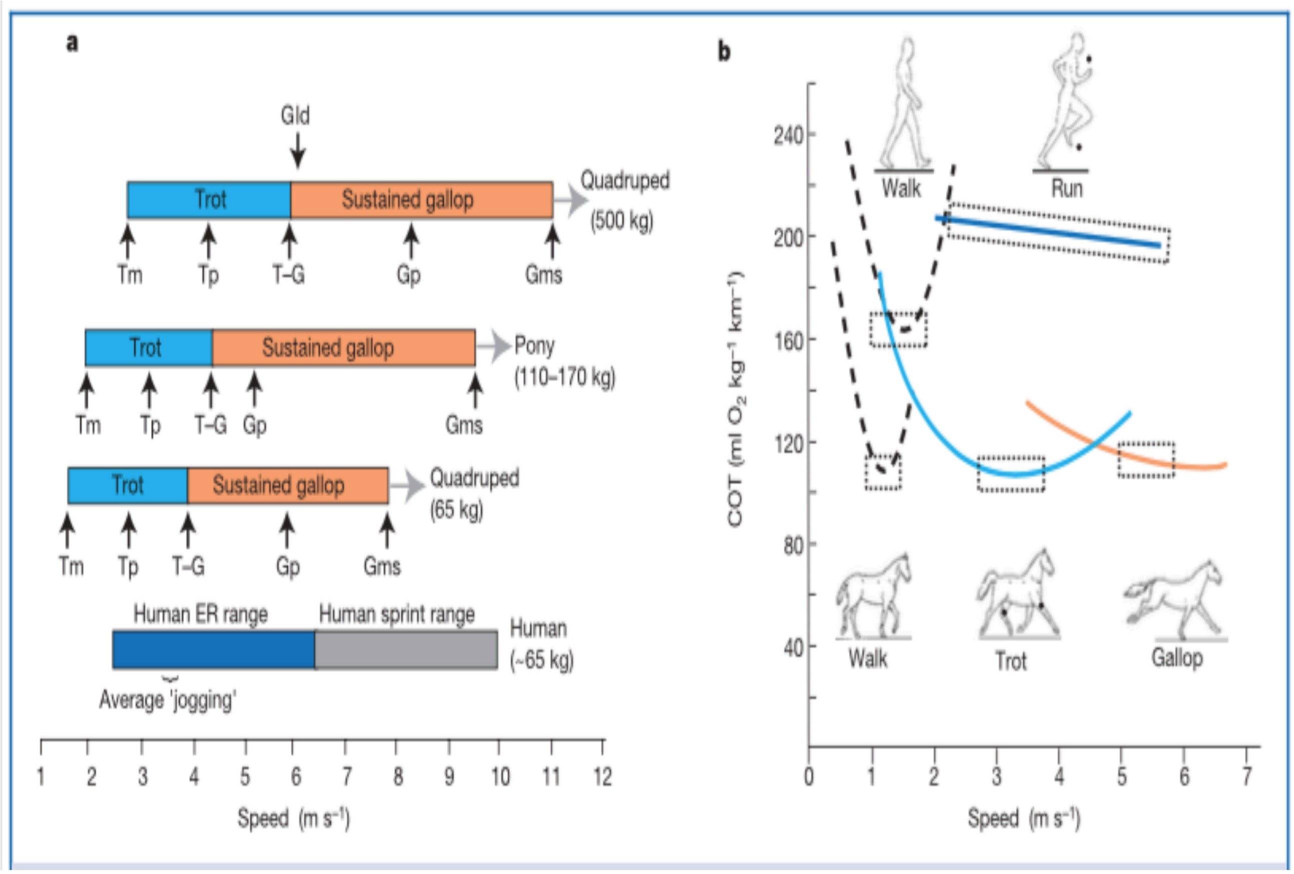


Figure 3

Adapted from Bramble and Lieberman (2004). Comparative endurance running (ER) performance in humans and quadrupeds. ***(a)*** *Range of speeds for human ER and sprinting and minimum trot (Tm), preferred trot (Tp), trot-gallop transition (T-G), and maximum sustained gallop (Gms) for quadrupeds of 65 and 500 kg.* ***(b)*** *Comparison of the metabolic cost of transport (COT) in humans and ponies. Both species have U-shaped COT curves for walking, but the human COT is essentially flat at ER speeds. Preferred speeds are the dotted rectangles.*

The first recorded history of human locomotion occurred well-before most roads and paved pathways were constructed. Because there was not a quick and reliable method for travel and communication, most individuals relied on human locomotion. In the mid-fifteenth century, it was common for wealthy individuals to hire footmen, who were known for their skill in distance running, to escort their coaches and deliver their messages. As road conditions improved, coaches and carriages were able to maintain consistent higher speeds, which caused footmen to run increasingly faster and further in order to remain relevant in their jobs. The dress between messengers of different regions varied. Some wore footwear, while others covered the distances barefoot (Sears, 2015, pg. 41-42).

With the improvement of roads and travel conditions, running became less of a necessity for survival and more a tool for game, sport, and power. Egyptian kings were required to take part in the Sed-Festival to prove their physical ability to rule. The king would run a circuit, and if he completed the run, he stayed in power. He would be required to perform this ritual every three years to prove he is still fit for the throne (Uphill, 1965). According to Sears (2015), kings would also use running to display military strength. Armies would sometimes engage in “prostitute” races, where prostitutes, mounted soldiers, and looters of the attacking army would take turns competing in races outside of the city they planned to siege in order to display their symbolic victory. Even in Greek mythology, running played a major role. Foot races were performed to mark significant events, such as an important person’s death or in honor of a god. They would also be held to find worthy suitors. The ancient Greek Olympic Games, which first emerged in 776 B.C., were so popular that warring states would declare a truce in order to allow athletes and spectators to travel to them unharmed (Sears, 2015, Pg. 22). Much like current Olympic Games, top winners would be rewarded for their athletic superiority, and winning countries would earn the honor of producing the best athletes. Running became used as a symbol of power. As running continued to increase as a recreational sport throughout history, the type of footwear available to runners also experienced a rapid increase in variety and design.

Running Biomechanics

Running consists of a rising and falling motion through a series of small leaps; therefore, it is not a smooth, gliding motion. It involves the conversion of muscular forces through complex movement patterns that incorporate nearly all of the major muscles and joints in the body. Immediately after a foot is placed upon the ground, the body loses kinetic energy and gravitational potential energy, because it begins slowing down and losing height. That energy is regained later in the cycle of the step as it begins to accumulate speed and rise up to exert a propulsive force. This suggests that the human body undergoes a process similar to a bouncy ball, upon impact it is deformed and loses kinetic energy; however, the deformation stores up elastic strain energy, which it expels as the elastic recoil restores the ball to its original shape and propelling it off the ground (Alexander, 1987). The entire process of running consumes energy that has an effect on running performance. Taylor (1973) states that humans use approximately twice as much energy to run at a given speed as most four-legged animals of relative weight. It provokes the question of whether this is a result of engaging two, rather than four, legs. However, the energy consumed by chimpanzees is about the same whether they run on two legs or four. Alexander (1987), found that a 154 pound (70kg) runner at a middle-distance speed uses about 100 joules (kinetic plus gravitational energy) in each step. Approximately 50 joules of this energy becomes heat, which the body will need to dispel. Another 35 joules go toward stretching the Achilles tendon and the approximate remaining joules are stored in the arch of the foot. Both the arch of the foot and the Achilles tendon act as springs, and together, they return about 50 percent of the energy used in running. While running does require a large amount of energy, the Achilles tendon and the foot work to create an efficient process of utilizing and returning that energy.

This cycle of small leaps applies a significant level of pressure on the lower limbs, particularly the tendons and ligaments, which increases the risk of sustaining the common running injuries shown in TABLE 1 above. An efficient distance runner typically utilizes an optimal form, which helps with performance as well as leading to good running economy. Consequently, individuals with good running economy usually tend to sustain less injuries. According to Anderson (1996), running economy is a critical element of overall distance running performance. The running economy of an individual is influenced by a number of significant biomechanical, physiological, and environmental factors such as height, percent of body fat, leg morphology, stride length, knee angle during the swing, and pelvis width. The running surface and the choice of footwear can also both have an effect on running economy. According to a recent review performed by Moore (2016), if shoe mass is not adjusted for in the calculations of maximal oxygen consumption (VO_2 Max: e.g., a criterion measure of aerobic fitness), then running barefoot, or in light minimalistic shoes, improves running economy compared with traditional running shoes. Moore also suggests that there is an "optimal" level of surface conditioning for running economy. A firmer surface that will return the energy it absorbs (i.e., due to the elasticity of the surface) will benefit a runner's economy. As with the elasticity of the running surface, researchers have also found that the elasticity of tendons and ligaments have an effect on running economy.

Footwear (or lack thereof) can affect running biomechanics through factors such as the way in which the foot typically tends to strike the ground, stride length, vertical oscillation of the center of gravity, and knee flexion, among countless others. Because these factors are often associated with a runner's economy, footwear that alters a runner's biomechanical parameters may have an effect on the rate of injury occurrence. The choice of footwear entails consideration of numerous factors that create significant differences between choices. "While offering more protection than barefoot, minimalist footwear has a lighter mass, greater sole flexibility, lower profile, and smaller heel elevation compared to traditional shoes" (Lussiana, Losier, & Mourot, 2015). Depending on the dangers of the running surface, a minimalistic choice in footwear may be more feasible than going barefoot for some runners. According to Lussiana et al., the biomechanics of running in minimalistic footwear differ from traditional footwear to a smaller extent than that of the difference between minimalistic and barefoot running, leading to a wider shift to minimalist footwear. Runners are often categorized by their foot strike pattern, which is typically a rearfoot, midfoot, or forefoot strike. Rearfoot strikers land with their heel making contact with the ground first, forefoot strikers make ground contact with the balls of their feet, and midfoot strikers land with both their heel and ball making contact almost simultaneously. Figure 4 displays the distribution of pressure between a rear and midfoot strike.

Figure 4a

Mean Center of Pressure. Adapted from Cavanagh & Lafortune (1980). Shoe divided into three equal regions. A) Display of rearfoot strikers and dispersion of pressure. Initial contact made in rear one third of shoe.

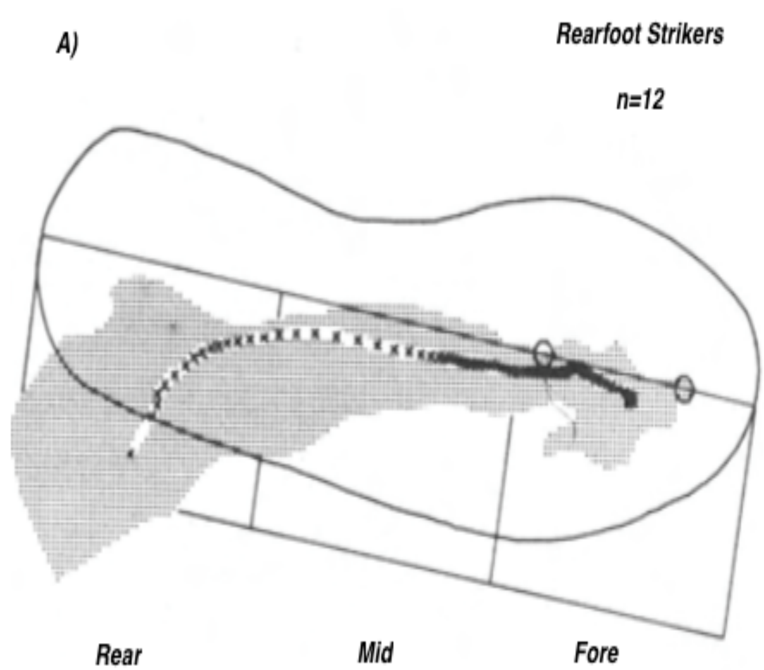
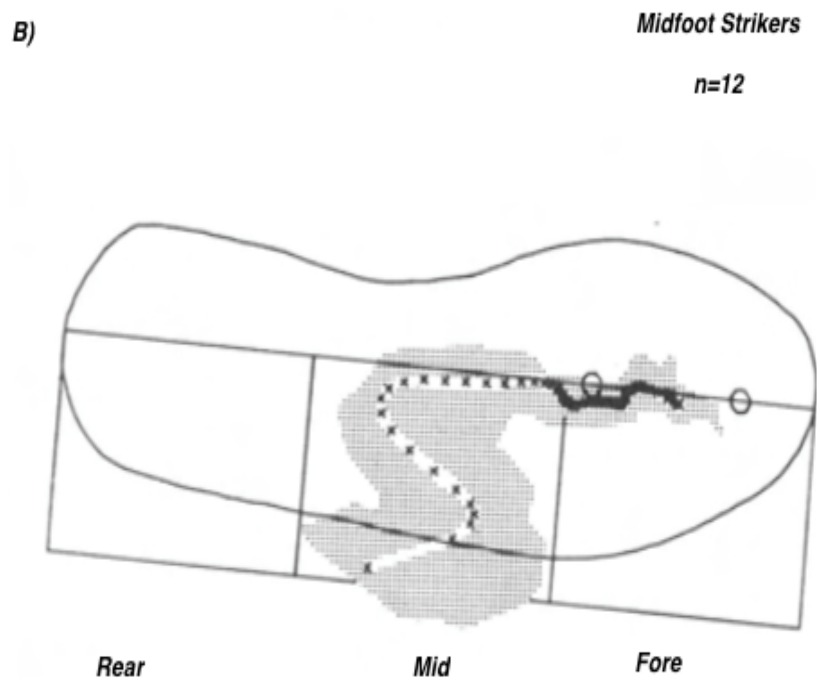


Figure 4b

Adapted from Cavanagh & Lafortune (1980). Shoe divided into three equal regions. B) Display of Midfoot strikers and dispersion of pressure. Initial contact made in middle third of shoe.



Approximately 85 percent of habitually shod individuals have been found to land in a rearfoot strike pattern, while most barefoot runners have been found to land with either a midfoot or forefoot striking pattern (Lieberman, Castillo, Otarola, Sang, & Sigei, 2015). However, habitually shod individuals have also been observed to forefoot strike, and, conversely, barefoot runners may rearfoot strike when they run. Even though runners are typically categorized by foot strike, they actually tend to switch between striking patterns (Lieberman et al., 2015). For example, runners typically adopt a forefoot strike while running up a steep incline and, conversely, adopt a rearfoot strike on the descent

Foot strike patterns are important because it has been suggested that higher rates of change and magnitude of vertical impact forces transmitted to the lower limbs during running may contribute to running-related injuries. Modifying certain striking patterns can assist in changing the level of the impact force from the ground. Increased vertical loading risks may be associated with increased risk of tibial stress fractures (Almeida, M.O., Davis, I.S., Lopes, A.D., 2015). Barefoot running is associated with reduced peak ground reaction force, increased foot and ankle plantarflexion, and increased knee flexion at contact with the ground compared to running in a modern running shoe. A forefoot strike pattern may also increase the strength of the gastrocnemius-soleus (i.e. calf muscle). Reduced peak ground reaction force may decrease the risk of tibial stress fractures and patellofemoral pain syndrome (Divert, Mornieux, Baur, Mayer, & Belli, 2005). A drawback to barefoot running and a forefoot strike pattern however, is that it causes increased stress on the plantarflexors and the Achilles tendon. If the runner does not slowly adapt to the new load areas and different foot strike pattern, injuries to such areas may result, including stress fractures to the metatarsals. A rear foot strike increases tibialis anterior activity, due to the need to control plantar flexion at the ankle while running. This increases the risk for tibialis stress fractures from the higher load impact, but conversely, has a lower stress load on the Achilles tendon and gastrocnemius-soleus muscle (Hall, Barton, Jones, & Dylan, 2013). Decreasing the impact force generated during running is a significant factor in reducing running-related injuries, and the foot strike pattern that runners adopt influences that force. Figure 5 below adapted from Almeida, Saragiotto, Yamato, & Lopes (2015), displays different foot strike patterns.

a b c

Figure 5

Foot strike patterns during running. a) Rearfoot pattern, b) midfoot pattern, and c) forefoot pattern.

Introduction of the Running Shoe

Historically, running was a necessary form of locomotion, but it has evolved into a recreational pursuit. As this transition emerged, early barefoot runners developed footwear, which, through modifications over the following centuries, has transformed into the modern running shoe. The shoe is the primary interface between the body and the road; therefore, it has a potentially important role in the management of repetitive impact loads. Although there were many modifications in shoe design, shoe manufacturers largely neglected the running shoe movement until around the early to mid twentieth century. According to Fields, Sykes, Walker and Jackson (2010), a series of events occurred which skyrocketed the popularity of running. For example, in 1972, Frank Shorter won the Olympic marathon in Munich, which sparked a rapid growth in marathon participation. Another significant event was the publication of *The Complete Book of Running* by Jim Fixx in1977. It became the how-to guide for an individual who wished to become a runner, and it remains a bestselling book to this day. With the rapid "boom" in running, shoe manufacturers recognized a prosperous opportunity to expand into that market, which is now a multibillion dollar industry. Fields et al. (2010), suggests that approximately 10-20 percent of Americans run regularly. One of the biggest risks with running is the high prevalence of injury. A primary focus of running shoe manufacturers is on decreasing the risk of injury to the wearer, which has brought about several modifications throughout its evolution to what is now the current trend in footwear.

Early Running Shoes

The first sports-specific shoe was developed around 1861, and was initially intended to be worn by cricket players. It was constructed from leather and had three spikes under the forefoot and one under the heel, which promoted greater traction. The idea of a spiked shoe became widely adopted when the sport of track flourished from 1864 to 1896. To this day, most track athletes use a spiked shoe while competing. As athletes began to move beyond the circular track into distance running, the need for durable outsoles and more flexible materials, rather than leather, sparked another advancement in shoe models. Shoe companies rapidly grew in number and models available. In 1895, Joseph William Foster opened up a family-owned shoe business in Bolton, UK. They also made thin shoes constructed of rigid leather, like many other shoe companies during their time, but they began to stitch a leather strip around the top of the shoe. Foster's grandsons left the family business in 1958 and conceived Reebok. In Germany in 1920, a man named Adolf Dassler began making shoes, and was soon joined by his brother. Due to a family feud in 1948, they split up and Adolf formed Adidas, while his brother developed Puma. Onitsuka Co. Ltd. was a Japanese shoe company that started constructing shoes in 1949. One of their first shoes, the Tiger shoe, which had a separate compartment for the big toe, was worn by the winner of the 1951 Boston Marathon. Eventually that shoe company became known as ASICS (Werd & Subotnik, 2014).

The first modern running shoe, Trackster, was introduced by New Balance in 1960. The owner, Paul Kidd incorporated his experience from making orthopedic shoes to create the New Balance Trackster. It created a virtual monopoly of the running shoe market, at least in England. The shoe had a leather upper and rubber ripple-sole. A significant difference from previous shoes was that New Balance added a wedge of rubber under the back part of the heel, which added cushioning to the wearer. According to the editor and writer of *Runner's World,* the shoe had a "palpable amount of cushioning or springiness that the others did not have. The minute that somebody offered us a shoe with a little bit of cushioning from the road shock, we all went in that direction, because it felt good" (Beverly, 2016). The Trackster was the beginning of the heavily cushioned shoe. In 1964 University of Oregon track coach Bill Bowerman teamed up with Phil Knight, a former athlete of his, and began a small shoe company called Blue Ribbon Sports that imported the Tiger shoes from Japan. They quickly dominated the market and became the most popular running shoes in 1967. The Tiger had a light rubber outsole with a separate forepart and heel, including a reverse leather upper, and eventually began to offer all-nylon uppers. In 1972, Blue Ribbon Sports and Tiger separated and Blue Ribbon Sports was renamed Nike, after the winged Greek goddess of victory. A significant differentiating factor that separated Nike from all of its competitors occurred when Bowerman and a colleague used methane and a waffle iron to construct extremely light running shoes. The 1970s saw the introduction of a running shoe that revolutionized the sport just as long-distance running and racing shifted from a competition commonly among the elite, to a popular exercise for the general masses. In 1974, Nike employed a chemical engineer who introduced ethylene vinyl acetate, a light, shock absorbing material, which introduced a groundbreaking new shoe in the way of cushioning (Beverly, 2016).

Cushioned Shoes

In the early 1970's, Bill Bowerman developed a shoe named the Cortez, the first shoe designed for American runners, which later became the front runner shoe for Nike. It had a sponge-rubber midsole with a wedge-shaped second layer of cushioning under the heel to absorb impact. The Cortez spiked a surge in demand for cushioned running shoes, and shortly after its debut, other shoe companies soon developed their own brand of cushioned running shoes. Soon leather uppers were replaced with nylon uppers and mesh to make a shoe that was more comfortable all-around (Beverly, 2016). As mentioned previously, the most common foot strike runners adopt while wearing shoes is the rear foot strike, where upon landing the foot's center of pressure is initially located in the heel and subsequently moves toward the toes. The initial impact force is generated when the heel makes contact with the ground, and is rapidly absorbed by the cushioning system in the heel of the shoe. However, with a lack of cushioning, much of the mechanical strain is transmitted by the skeletal tissue and articular surfaces in the foot, which do not function as effective shock absorbers. Consequently, runners landing on their heels are often more susceptible to running injuries such as the tibial stress syndrome or stress fracture of the tibia (Szulc et al., 2016). According to Wright, Neptune, Bogert, & Nigg (1997), the impact force can be as much as one to three times body weight in heel-to-toe landing. Their study found that *peak* vertical impact forces have no significant correlation with shoe hardness, while vertical loading *rates* were found to be positively correlated with increasing shoe hardness. This suggests that there might be a mechanism by which the body regulates the magnitude of external impact force during running. Although peak impact forces were not found to vary with shoe hardness, internal forces, such as muscle groups, were affected, which in turn resulted in changes in tendon and joint forces. In this way, the cushioning vs. hardness of a shoe can certainly alter these internal physiological forces. Since one of the goals in running shoe design and evaluation is to reduce the risk of overloading, it is important to understand how internal forces, and not just external ground reaction forces, are affected with varying stiffness (Wright et al., 1977).

The alignment of the talo-calcaneal joint upon impact is also a risk factor in running injuries. Varus (i.e., inner) alignment and other anatomical factors predispose an athlete to overuse injuries by amplifying the internal stress placed upon bone and soft tissue during impact. To facilitate balance during normal running, the foot typically makes contact with the ground beneath the body's center of mass; therefore, the foot naturally makes contact with the ground in a slightly supinated (i.e., facing outward and upward) position depicted in figure 6a. Pronation (i.e., facing inward and downward) combines eversion and abduction of the foot by rotation about the talo-calcaneal joint and dorsiflexion of the ankle, shown in figure 6b. The subtalar joint performs a complex motion during ground contact in running. The joint is oriented in a manner that links pronation with internal tibial rotation and may play a role in running injuries. Excessive pronation and the associated internal tibial rotation can cause patella femoral pain syndrome and, in extreme cases, the high pressures cause degradation of the cartilage and underlying bone (Pedoe, 2000).

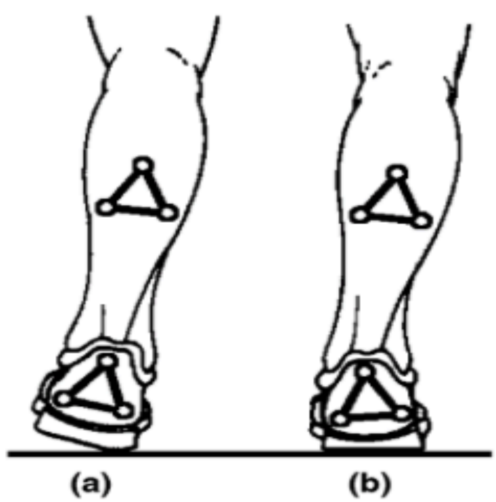


FIGURE 6

Rear view of the right foot and lower leg during ground contact adapted from Pedoe (2000), showing (a) supination of the talo-calcaneal joint at heel contact and (b) pronation of the talo-calcaneal joint at mid-stance.

Excessive pronation is also associated with some types of tibial stress syndrome, an increased risk of Achilles tendinitis, as well as implications toward plantar fasciitis Consequently, most running shoe manufacturers include anti-pronation features in order to address the aforementioned risks of excessive pronation, including stiffer cushioning, insole boards, stiff heel counters, and varus wedges. Shoes manufactured with "rearfoot control" are designed to limit the amount or rate of pronation immediately following foot strike (Nigg & Morlock, 1987). In a study of 10 rearfoot striking runners, shoes with a soft midsole and no heel flare allowed for the greatest amount of maximum pronation, while the shoes with a hard midsole and 30-degree flare tended to give more rearfoot control and allowed for the least pronation. Figure 7 displays where the heel flare is measured on a shoe. Control of the amount of pronation has been cited as an important consideration for runners during shoe selection (Clarke, Frederick, & Hamill, 1983).

Figure 7

Adapted from Nigg & Morlock (1987). Rear illustration of running shoes displaying different flare values on the lateral (L) side. Shoe A has a flare of 16°, shoe B has no flare, and shoe C has a negative flare.

The degree of cushioning in the shoe also has an influence on the energy cost. When a shoe provides inadequate cushioning, the runner typically produces greater muscular effort to provide the necessary shock absorption upon impact in order to reduce the risk of injury and jolt (Anderson, 1996). The soles act as a type of spring; they compress during each footfall and recover as the foot leaves the ground. In a study by Alexander (1987), soles designed to go under the ball of the foot were removed from shoes and tested for their elastic properties by mechanically squeezing them to the same peak value seen during the impact phase of running. Only 60 percent of this work was returned in the elastic recoil. Additionally, similar testing performed on high-quality running shoes resulted in a return of only 40 to 50 percent of the work done on them. The elastic property of shoes is important for shoe manufacturers to consider, because if they only treated soles as shock absorbers, a rigid foot would get a sharp jolt when it hit the ground. The foot would decelerate swiftly and large forces would act upon it, potentially increasing the risk of damage and injury, especially on artificial surfaces such as the road; however, the energy return would be greater. A foot with elastic compliance, whether in the foot or in the sole of a shoe, would utilize the elastic cushions upon impact, leading to a gentler deceleration, but presumably less elastic recoil. Figure 8 below, adapted from Pedoe (2000), displays the difference in cushioning on force. It is also important to consider the natural cushion of the foot when discussing the effects of supplemental cushioning in footwear. The heel itself, without the support of a shoe, behaves elastically, returning 68 percent of the work done on it. Similar tests on the heels of a sample of running shoes provided a comparable elastic recoil of 65 percent of the work done on them. Runners who make initial contact with the heel before moving forward onto the ball of the foot might benefit more from shoes with a shock-absorbing heel, but an elastic sole that returned most of the work done on it (Alexander, 1987). Because the foot inherently contains natural elastic properties, it might benefit shoe designers to utilize the natural bounce of the foot when creating shoes.

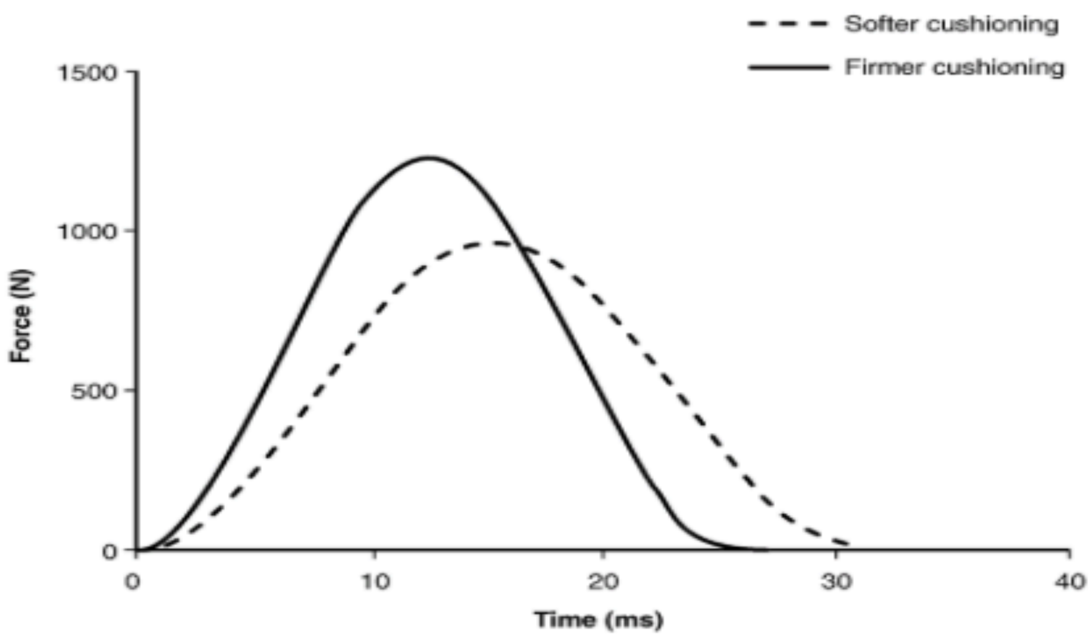


Figure 8

Effect of cushioning on force-time during impact.

Barefoot Resurgence

Cushioned running shoes rapidly gained attention and popularity among both elite and recreational runners because they were believed to decrease the risk of running injury and alleviate chronic issues in form, such as over or under pronation. However, cushioned shoes did not seem to have a significant effect on lowering injury rates. According to Van Gent et al. (2007), approximately 30 to 70 percent of runners were still sustaining injuries annually. The lack of any apparent decline in injuries since the introduction of early running shoes, despite substantial investments in research, and evolving shoe designs, suggests that there might be additional influences to consider when evaluating correlations between common running injuries and footwear. In the search for an answer, a recent resurgence in the idea of barefoot running has emerged, fueled by a hypothesis that many running injuries are caused by poor running form, and unencumbered running may result in better running mechanics/form. From an evolutionary perspective, wearing big, cushioned shoes is "abnormal", therefore, runners may be maladapted to wearing shoes in ways that predispose them to injury (Van Gent, et al., 2007). There has been renewed mainstream media interest regarding barefoot running as elite and recreational runners explore new training methods to increase endurance and strength. A recent survey, including 380 competitive, 364 recreational, and 41 elite runners participating in running races ranging from 5 kilometers to a full marathon, reported that greater than 50 percent of runners had switched from shod running to running with minimalistic or barefoot running (Cheung & Ngai, 2016). However, the impact of barefoot running on injury and performance is still not entirely clear, despite a large shift in attention to it. Certainly though, the increased interest in barefoot running lead to an increased demand in a new type of shoe- minimalistic. Shoe manufacturers began producing a variety of barefoot simulating footwear to provide the flexibility and feel of being barefoot, while still providing protection to the plantar surface from the environment.

Barefoot Versus Shod

An important factor to consider is that shoes limit proprioception, or the unconscious ability to perceive movement and spatial orientation, due to the thickened soles. Plantar proprioception activates reflexes and variable kinematic gait patterns to help avoid painful impacts, maintain stability, and modulate leg stiffness. The Spring Mass Model is widely used for the definition and measurement of leg and vertical stiffness. The Model states that during the stretching phase (spring compression), the spring-leg, loaded by the body's mass, stores elastic energy and this energy is then returned during the shortening phase (spring extension). Greater stiffness is associated with greater energy absorbed/produced for a given compression/extension and a faster stretch-shortening cycle (Pappas, Dallas, & Paradisis, 2016). Runners typically tend to adjust leg stiffness when running on different surfaces in order to maintain constant overall vertical stiffness and thus energy return. For example, a runner on a harder surface will decrease leg stiffness, while a runner on a more compliant surface will increase leg stiffness. A study performed on the effects of shoes on the lower limb found that leg stiffness significantly increases when using high-cost (deemed as a light-weight cushioned trainer shoe with a retail price of 65 dollars when compared to a low-cost shoe of 10 dollars) shoes compared with barefoot running (Bishop, Fiolkowski, Conrad, Brunt, & Horodyski, 2006). The plantar surface of the foot adapted to provide sensory feedback in early humans in order to relay information about the ground, including hardness, roughness, unevenness, and any potentially sharp objects. Barefoot runners typically adopt a running form that modulates leg stiffness to avoid jarring and painful impacts. A shoe that inhibits the ability of the foot to relay such information could cause the runner to land with greater force than what a barefoot form would produce. Natural selection adapted the human body to a forefoot strike, i.e., the foot strike most commonly seen with barefoot running. Theoretically, the greater incidence of injuries in rearfoot striking runners may be a result of a running form that imposes forces on the body for which it is poorly adapted (Lieberman, 2012). Plantar proprioception is also important in the prevention and management of lateral ligamentous complex injuries in the ankle. Ankle injuries are one of the most common running injuries, as shown in Table 1 above, and can be partially attributable to reduced proprioception that causes an inability to utilize certain intrinsic muscles in dynamic situations; barefoot running may improve the strength of these muscles. Barefoot runners exhibit increased lateral ankle stability compared to shod runners, even when compared with runners wearing shoes specifically modified to improve lateral stability (Divert et al., 2005). Ankle stiffness also appears to vary in barefoot versus shod runners. When a runner lands with a forefoot strike (as is most commonly seen in barefoot runners), the metatarsals are the initial point of ground contact and the ankle stiffness is usually much lower compared to a runner with a rearfoot strike. There are also other factors that could influence the difference in Ankle stiffness such as previous injury to the ankle, and arch height. The translational kinetic energy is converted into rotational kinetic energy, which allows for better energy storage and recovery in the Achilles tendon and foot arch. This energy conversion allows less energy to be lost during ground collision (Murphy, Curry, & Matzkin, 2013).

Additionally, shoes that contain features such as high arches and pronation control mechanisms may create inflexibility in the feet and prevent muscles and bones from developing and adapting to certain stresses, especially during the growing stage of adolescence. The American Academy of Pediatrics has stated that children should not wear footwear until the environment necessitates it due to impaired intrinsic muscular development (Staheli, 1991). The earlier a child begins to wear shoes, the higher the likelihood of developing flatfoot deformity. The incidence of flatfoot deformity is detrimental to the development of the strength of the plantar intrinsic muscles and the longitudinal arch. Significant differences in the foot musculature development between barefoot and shod individuals have also been seen in adult populations. Running with barefoot simulation footwear was found to significantly increase the cross-sectional size and strength of intrinsic foot muscles in adults. (Hsu, 2012). Stronger intrinsic muscles can elevate the arch of the foot thereby creating a more effective shock absorber by deflecting the medial arch upon landing. Barefoot running also has been shown to cause increased electromyographic activity in the pre-activation of the plantarflexion muscles, including the soleus and gastrocnemius. The activation of these muscles work to decrease the stresses placed upon the lower extremities (Divert et al., 2005).

Barefoot and Common Running Injuries

Patellofemoral pain syndrome is one of the most common running injuries. The anatomical source of the pain remains a highly debated issue, but one reason it could develop is due to overall mal-alignment of the limb from excessive eversion of the planted foot at heel strike, as shown in Figure 9. Shod runners tend to show excessive eversion of the heel at foot strike and this may lead to increased risk of patellofemoral pain syndrome compared with barefoot runners (Barton, Levinger, Menz, & Webster, 2009; Sinclair, 2014).

Figure 9

Diagram adapted from Petersen et al. (2013). The cause for functional or dynamic valgus, i.e. outward tuning, can be from internal rotation of the femur, the tibia, or both. Internal rotation of the femur may be a result of weakness of the hip abductors; internal rotation of the tibia may result from excessive rear-foot eversion.

Foot injuries, such as plantar fasciitis are also among the top three most common injuries developed by runners. Despite its high prevalence, its cause remains unclear, although many point to overload of stress from repetitive impact as the basic mechanism for its development. A positive correlation exists between excessive pressure on the plantar fascia and the progression of plantar fasciitis, therefore, it appears beneficial to limit the amount of pressure placed upon the foot at ground contact. (Ribeiro et al., 2011).

Barefoot runners exhibiting a forefoot strike pattern, decrease localized heel pressure because of the larger surface area of the fore and mid-foot in which the vertical impact force is able to be spread. This leads to a smaller peak ground reaction force, thus reducing lower extremity stress. Additionally, the reduction in arch support during barefoot running may increase the cross-sectional area of the musculature of the arch. By strengthening this musculature, the incidence of arch collapse is decreased and should help to reduce the risk of plantar fasciitis (Altman & Davis, 2016). Figure 10, adapted from Altman & Davis (2016) shows the body part distribution of musckuloskeletal injuries incurred from a study of 201 participants.

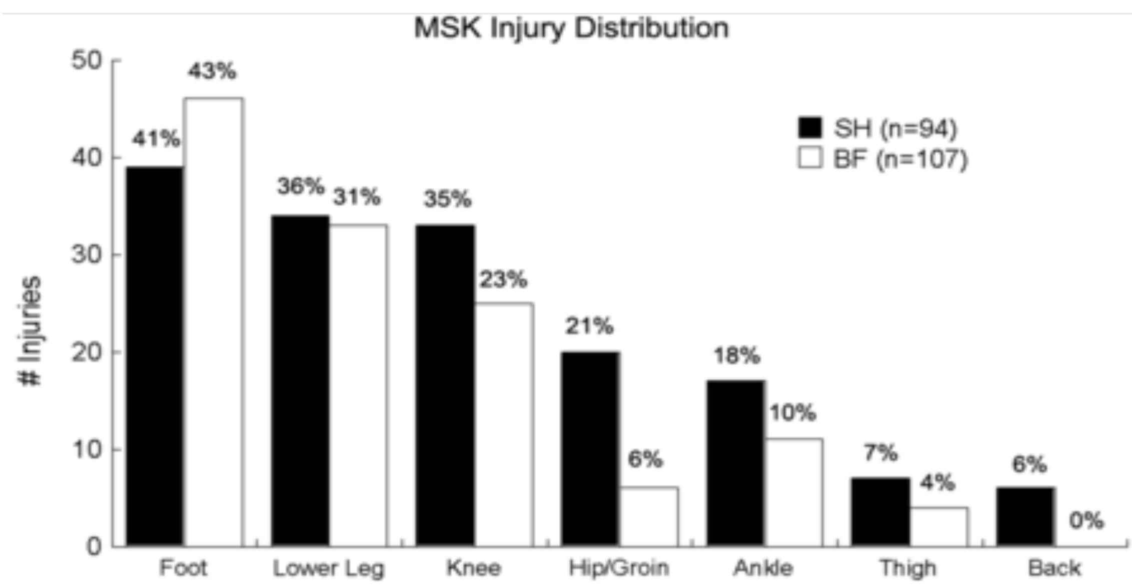


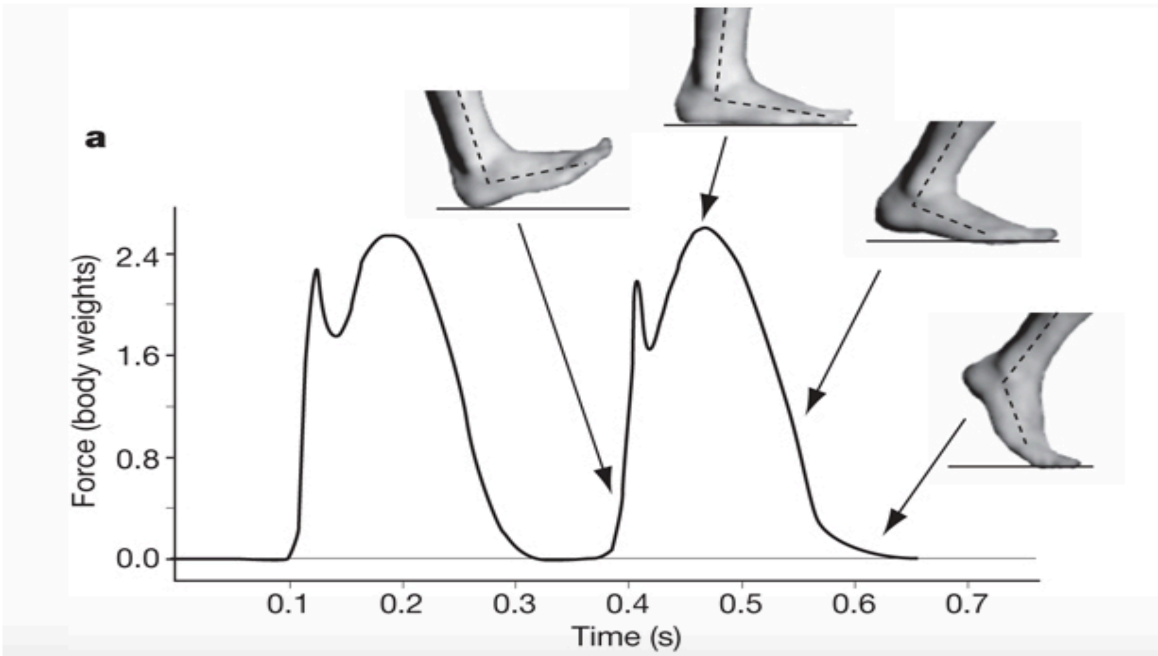
Figure 10

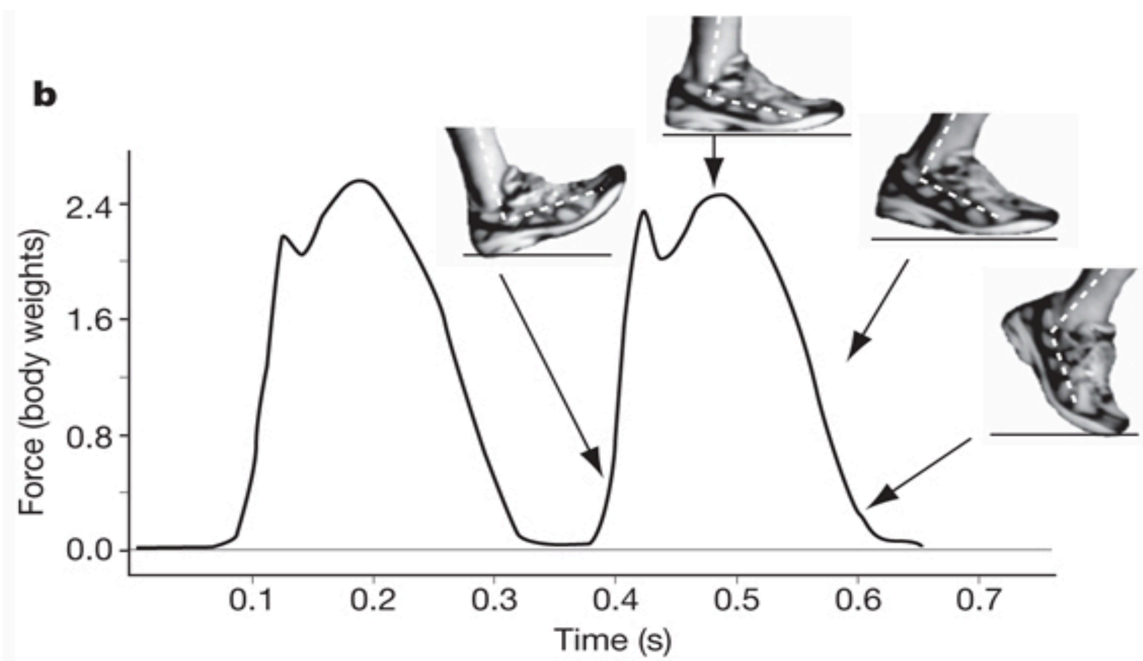
Distribution by body part of all musculoskeletal (MSK) injuries incurred (does not include plantar surface injuries to the foot). Due to the unequal number of runners between the shod and barefoot groups, the percentage above the bar denotes the number of injuries/number of runners for each group at each location.

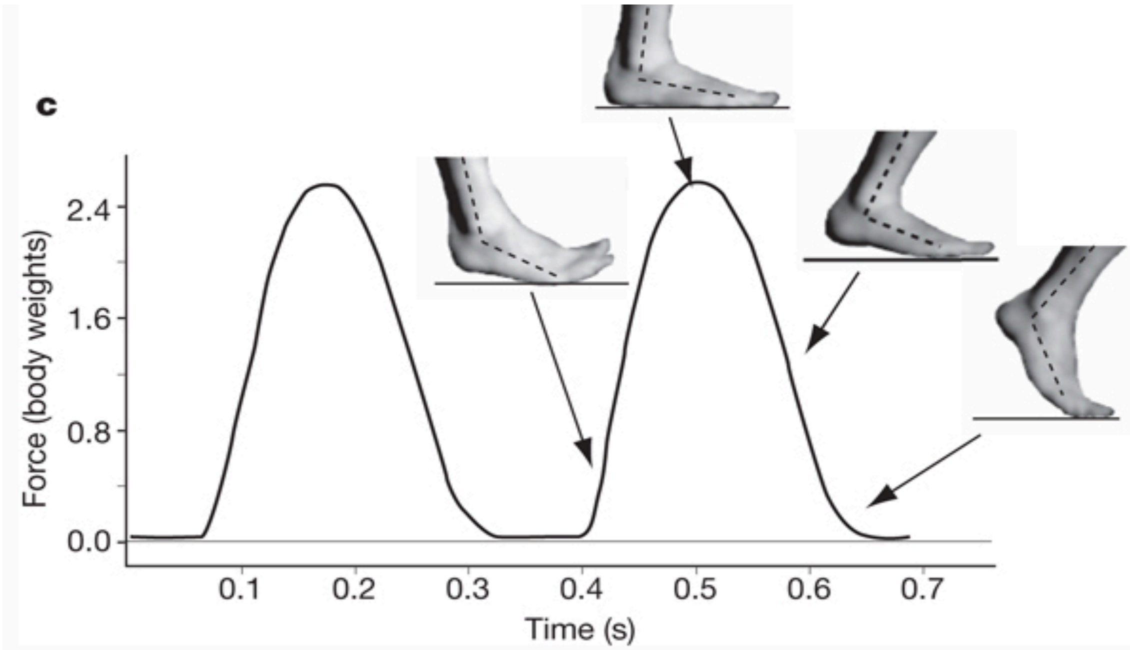
Typical rearfoot striking generates lower extremity forces up to 1.5 to 3 times body weight during each foot impact. In comparison, the mean rate of loading (i.e., body weights per second) of runners who adopt a forefoot strike are approximately seven times lower (Hsu, 2012). This is an important factor when considering running injuries because a higher loading rate produces greater stress on the musculature and tendons of the lower extremities. Furthermore, barefoot running is usually associated with a shorter stride length, and therefore, higher cadence (i.e., turnover rate). The shorter stride length may be a result of a more cautious gait due to higher proprioception, and the conscious or subconscious desire to decrease the impact force during landing (Hollander, Argubi-Wollesen, Reer, & Zech, 2015). Barefoot running is also associated with greater ankle and leg compliance, which combines to lower the body's center of mass relative to the force of impact and therefore, can reduce hip and knee loads. Lower hip loads can reduce hip adduction, which is linked to running injuries like stress fractures, iliotibial band syndrome, and patellofemoral pain syndrome (Hsu, 2012; Sinclair, 2014). Lieberman et al. (2010) found that the combination of higher cadence, shorter stride length and greater ankle and leg compliance resulted in a 3-fold decrease in overall peak ground forces as measured by impact force in body weights in shod versus barefoot running groups. Figure 11 adapted from Lieberman et al. (2010), compares the ground reaction forces between foot strikes.

Figure 11

Vertical ground reaction forces and foot kinematics for three foot strikes. a) Rearfoot strike during heel-toe running; b) Rearfoot strike during shod heel-toe running; c) Forefoot strike during barefoot toe-heel-toe







Potential Risks of Barefoot

There are a number of potential risks runners must take into account before transitioning to barefoot running. Without a protective sole, runners have an increased danger of sustaining a puncture injury from debris on the ground, such as stones, glass, nails, and thorns. Such an injury can lead to infection, and temperature extremes can have a greater impact on the feet through burns or frostbite (Murphy et al., 2013). In healthy individuals, the skin along the plantar surface of the foot, especially the heel, is quite resilient and requires a 6-fold higher abrading load in order to reach the same pain threshold compared with other skin surfaces. While the skin is more resilient, the risk of puncture still exists, and immunocompromised patients, along with individuals with a wound healing dysfunction are cautioned against barefoot running because of their elevated risk of infection (Hsu, 2012).

The transition from shod to barefoot should be made on a gradual basis by slowly decreasing the amount of support underneath the heel while simultaneously increasing the amount of time spent in minimalistic shoes or running barefoot (Murphy et al., 2013). The transition should happen over a period of weeks to months; however, there are no studies that have examined the most effective transition implementation training programs. Runners who typically wear shoes with a very thick midsole will typically require a longer transition period to safely adapt to barefoot running than a runner using a shoe with less heel elevation. Additionally, a six-week adaptation period for plantar skin and musculature along with brief periods of daily barefoot running has been suggested as a starting baseline (Hsu, 2012). There have been a small number of transition studies that have used barefoot-simulated shoes instead of the raw barefoot condition. In one such study, the shortest minimalist shoe transition of two weeks, which resulted in no significant injury rate differences in the majority of the participants. Another study utilized a ten-week, minimalist shoe intervention, and found that approximately half of the runners had signs of bone edema (a precursor to stress fractures) in the foot after the minimalistic running transition period. This particular study did not involve gait retraining, i.e., instruction on running form, and while other data pertaining to changes in running style and efficiency were not presented, the results do suggest caution regarding the switch to barefoot running (Tam, Tucker & Wilson, 2016). Another four-week, instructed, minimalist training study that incorporated specific lower limb exercises and gait retraining resulted in reductions in heel pressure with the minimalist footwear, as well as reduced maximum force upon impact. The study provided participants with running technique guidelines based on current findings in the literature, such as “Keep stride short and increase cadence” and “Keep hips forward and head up, running as tall and proud as possible.” Participants were also given a ten-minute lower extremity exercise program to follow and a detailed four-week training schedule (Warne et al., 2014). These studies suggest that runners who participate in a gradual, progressive training program that incorporates specific lower extremity exercises, as well as receiving instruction and guidance, are more likely to sustain fewer injuries than runners who rapidly switch.

While barefoot running may decrease the risk of certain running injuries, it also carries the risk of enduring different injuries. Oftentimes, without a proper barefoot gait implementation program, runners run barefoot, but still maintain a rearfoot strike, thus subjecting their feet to repetitive increased peak forces at the forefoot. The increased force on the metatarsals while barefoot running can potentially lead to stress fractures in the metatarsals (Murphy et al., 2013). Runners who maintained a rearfoot strike when barefoot exhibited loading rates that were more than double those of shod rearfoot striking runners. Similar results were found during rearfoot strike running in minimalist shoes. Forefoot striking runners were the only group to demonstrate a reduction in loading rate when barefoot (Hashish, Samarawickrame, Powers, & Salem, 2016).

The reduction in impact forces and load rates usually observed in runners utilizing a forefoot strike has a tradeoff that requires greater calf muscle strength than rearfoot striking. Thus, an inadequate transition from shod to barefoot running may also produce calf muscle strains and Achilles injury. The increased load to the calf and arch associated with a barefoot, forefoot strike pattern places additional stress to these areas (Altman & Davis, 2016; Hashish, Samarawickrame, Powers, & Salem, 2016).

Minimalist Shoes

The shoe industry has closely shadowed, if not largely influenced, the trends of the running industry. The heavily cushioned running shoes first seen towards the beginning of the running boom were popular because it was believed that the cushioning supported the foot and reduced injuries. Despite the lack of agreement regarding the beneficial effects of barefoot running on running related injuries, the popularity it has seen recently in the running community has influenced shoe manufacturers to design minimalistic footwear that simulates the idea of barefoot running, as a way to embrace barefoot running without the foot exposure to the external environment. Although a formal and specific definition for minimalistic footwear is lacking, there is general agreement that minimalistic shoes either ideally have less structure, heel-toe drop, and mass than a heavily cushioned and controlling shoe, or is more flexible and less restrictive for foot motion. The ambiguity of the term "minimalist" and the lack of standard guidelines have resulted in a myriad of models that are based on different approaches and conceptual ideas of what a minimalistic shoe should be. These models include heel-toe drop footwear (e.g. Vibram Five Fingers®, Merrell®, Barefoot™, and New Balance Minimus™); shoes that have a thicker sole and provide more cushioning (e.g. the NIKE Free™); and models that appear to be a compromise between barefoot and traditional racing flats (e.g. Saucony Kinvara® and Brooks Pure™ Series) (Squadrome, Rodano, Hamill, Preatoni, 2015). Running in a minimalist and lightweight shoe is not exactly the same as running barefoot, depending on the amount of cushioning the minimalist shoe provides. A study that compared Vibram Five Fingers® to barefoot running and a conventional cushioned shoe, found that the ankle contact angle was similar between the minimalist and barefoot, as well as both conditions exhibited a less dorsiflexed ankle at initial contact. On the other hand, a study that compared the NIKE Free™ to barefoot running and a conventional cushioned shoe found that barefoot running had a more substantial effect on the mechanics of the knee and ankle, whereas the minimalist shoe exhibited mechanics similar to that of the shod group. The difference in the findings between the two studies may result from the type of minimalist shoe used. The Vibram Five Fingers® has a 3.5mm rubber sole with limited cushioning, while the

NIKE Free™ has a soft heel of 17mm that still provides relatively considerable cushioning (Bonacci et al., 2013). While there is a large number of studies that investigate the difference in the mechanics between barefoot and shod running conditions, there is only a very limited number of studies that investigate the differences between minimalist and barefoot conditions. With a growing number of individuals choosing to switch to minimalist footwear, rather than barefoot, there is a great opportunity for further research in this area.

Orthotics

The trend towards minimalist and barefoot running also sparked an interest in running shoes that were more customized to the individual. Orthotic devices are usually molded to the shape of the individual runner's foot, and are thought to assist in reducing the likelihood of developing an injury in the shod runner by redistributing foot pressure or preventing excessive ankle inversion (i.e., turned inward) or eversion (i.e., turn outwards). The effect of orthotic devices is highly variable from runner to runner. The majority of orthotic studies have been performed primarily on runners with a rearfoot striking pattern and there are no studies that investigate the long-term effects of orthotics. The results of these studies vary greatly. Some have shown that the use of orthotics has no effect, others have reported a reduction in total rearfoot range of motion, rearfoot eversion velocity, and peak rearfoot eversion, and others have reported that it actually increased pain levels (Stackhouse, Davis, & Hamill, 2004).

Though there is evidence that orthotic devices may change the runner's gait to reduce pain, or adopt a less dangerous running style, there is no definitive evidence about whether pain or injury rates are reduced. Rigid orthotics, which provide maximum strength and less flexibility, may increase the pressure on bony prominences and actually contribute to the development of lower-extremity injuries. Both running shoes and orthotics aim to provide stability to the wearer; however, if adding orthotic devices has the potential to increase the risk of injury, then it is possible that shoes may also have the same effect. Current research is too limited to extrapolate the effects of orthotic implementation in running shoes (Murphy et al., 2013).

Limitations

Although there are studies that support the physiologic and biomechanical advantages of barefoot running, many are limited in methodology and statistical power. Because running injuries are multifactorial in nature, it is critical to control for strike type, shoe type, shoe weight, and the baseline strike patterns of subjects in investigations of barefoot running, because all of these factors can have a substantial influence on the results (Murphy et al., 2013). Studies comparing barefoot versus shod running are performed in controlled environments, meaning a treadmill or a runway is typically used as opposed to outdoor terrain, which oftentimes does not simulate a natural running environment. Correspondingly, the relative experience participants have had on treadmills or runways prior to the study may also have an effect on the results that are collected. Runway studies measuring kinetics are limited to data recorded from force plates imbedded in the runway. It is argued that this results in limited accuracy due to step variability and the requirement for participants to land on the force plate, thus, participants may either consciously or subconsciously alter their gait to land appropriately. There are also very few, if any, studies that investigate barefoot running when running downhill or in an extremely fatigued state (Hall et al., 2013).

A main limitation in barefoot running research is that no clinical studies are available to support or reject any injury prevention or performance benefits after habituation or on a long-term basis. Any controlled study investigating the progression of habitually shod runners to barefoot running with an immediate or gradual decrease in heel support would be beneficial in determining whether a sudden or gradual change to barefoot running alters running injury rates. Conversely, studies that transition traditionally barefoot runners to shod running would also be useful to gain a better comparison between the effects of footwear and foot strikes. Other potential future studies could involve further investigation of the relationship between kinematics, gait patterns, and biomechanics adopted by shod and barefoot runners on running injury rates to improve overall understanding of the underlying causes of running injuries. Additionally, studies investigating the effects of barefoot running on injured populations as a therapeutic tool should be an area of further research, since there is evidence suggesting that modifying running gait to a forefoot strike may be beneficial to patients with overuse injuries such as patellofemoral pain syndrome. The increase in popularity of minimalistic footwear over barefoot conditions also raises questions about the comparability between the two conditions. Varying levels of cushioned minimalistic footwear could be used to assist in determining how important of a role cushioning plays in the simulation of barefoot running (Murphy et al., 2013).

According to Hall et al. (2013), although most studies state past running experience and anthropometric data of participants, it is often difficult to determine whether that sample size is representative of the general running population in regards to volume of running, ability, and years of running. As mentioned previously, increased stride frequency is frequently associated with barefoot running, which is also associated with lower loading forces of the lower limb. However, a higher stride frequency will also cause an increase in the number of steps that are taken for a given distance. This may actually increase the *accumulated* loading force, which may be a secondary injury mechanism. The implications of this have not been investigated, although it could prove to be a confounding factor that should be considered in future studies investigating kinetics between differing footwear conditions.

Discussion

Proponents of barefoot running advocate that human feet are born to run bare on the ground, and that shoes are contributing to the high incidence of running injuries; however, the literature to date has not found decisive evidence supporting or contradicting these claims. There are far more shod runners than barefoot runners, however, with the growing popularity of barefoot and minimalist running, forefoot strike pattern-related injuries may become more prevalent. Oftentimes, it may not seem feasible to engage in barefoot running depending on environmental factors or the health of the individual, which is why minimalistic footwear has seen an increase in popularity among runners. The difference in foot strike patterns between barefoot and shod runners has been heavily discussed throughout this paper, and is certainly a critical factor regarding running injuries. Thus, would retraining the gait of shod runners result in beneficial adaptations that could reduce the risk of running related injuries, without some of the subsequent risks transitioning to barefoot running would have?

A recent study showed that runners have the ability to change their landing patterns rather easily in the short term, even habitual heel strike runners and habitual forefoot strike runners showed no difference in joint stiffness and joint work when performing the same landing pattern. The only difference found between a habitual forefoot striker and a converted, or novice, forefoot pattern was peak ankle plantar flexion moment and peak vertical ground reaction forces. Rear and forefoot striking runners could adapt to their non-preferred footfall pattern and there would be no significant difference in the re-organization of joint stiffness between groups performing the same footfall pattern. This study was over the short-term, therefore, further research should consider the change from one footfall pattern to another over an extended period of time (Hamill, Gruber, & Derrick, 2014). Another study investigated the difference between forefoot and rearfoot striking patterns in both shod and barefoot conditions. Kinetic data showed that the average loading rate and maximal loading rate were similar between barefoot and shod running conditions, and both were significantly higher in rearfoot strikes, with the barefoot condition actually resulting in a much higher loading rate than the shod condition. Lower extremities exhibited similar characteristics in the same striking pattern, whether barefoot or shod, but significant differences between striking patterns, including average and maximal loading rates; hip, knee, and ankle angles upon landing; and activities in the lower extremity muscles. The greatest challenge for habitually shod runners in adapting a forefoot strike may be the increased gastrocnemius (i.e., calf) activity. With appropriate intensity, forefoot strike running can be used as the training for the gastrocnemius. A well-trained gastrocnemius can provide an excellent cushion for runners; however, excessive training can lead to overload of stress and thus injury (Shih, Lin, & Shiang, 2013).

As mentioned previously, many habitually shod runners who use a rearfoot strike pattern will continue to use a rearfoot strike after transitioning to barefoot running, which may make them more susceptible to injury. From the kinematic and kinetic points of view, the striking pattern plays a more important role than the footwear condition in running (Shih et al., 2013). Habitually shod runners can gain more shock absorption by changing their striking pattern to forefoot strikes while running. Adapting a forefoot strike over a rearfoot strike may offer habitually shod runners an alternative approach to injury prevention that does not require a complete transition to barefoot or minimalist footwear. Some individuals have a predisposition to certain running injuries due to a variety of intrinsic factors and therefore, any runner considering transitioning to barefoot or minimalist footwear should consult with their clinician first.

References

1. Alexander, R.M., (1987). The spring in your step. *New Scientist.*
2. Almeida, M.O., Davis, I.S., & Lopes, A.D. (2015). Biomechanical Differences of Foot-Strike Patterns During Running: A Systematic Review With Meta-Analysis. *Journal of Orthopedic & Sports Physical Therapy, 45(10):*738-755. doi:10.2519/jospt.2015.6019.
3. Almeida, M.O., Saragiotoo, B.T., Yamato, T.P., & Lopes, A.D. (2015). Is the rearfoot patter the most frequently foot strikepattern among shod distance runners? *Physical Therapy in Sport, 16(1):* 29-33. doi: 10.1016/j.ptsp.2014.02.005
4. Altman, A.R., & Davis, I.S. (2016). Prospective comparison of running injuries between shod and barefoot runners. *British Journal of Sports Medicine, 50:*476-480. doi: 10.1136/bjsports-2014-094482
5. Aschwanden, C. (2016). The Big 7 Body Breakdowns. Retrieved September 03, 2016, from http://www.runnersworld.com/health/the-big-7-body-breakdowns
6. Barton, C.J., Levinger, P., Menz, H.B., & Webster, K.E. (2009). Kinematic gait characteristics associated with patellofemoral pain syndrome: A systematic review. *Gait & Posture, 30(4):*405-16. doi: 10.1016/j.gaitpost.2009.07.109
7. Beverly, J. (2016). BEST IN SHOE. *Runner's World, 51(10):*96-103.
8. Bishop, M., Fiolkowski, P., Conrad, B., Brunt, D., & Horodyski, M. (2006). *Journal of athletic training, 41(4):* 387-92.
9. Bramble, D.M., & Carrier, D.R. (1983). Running and breathing in mammals. *Science, 219(4582):*251-6

10. Bramble, D.M., & Lieberman, D.E. (2004). Endurance running and the evolution of Homo. *Nature, 432(7015):*345-52. doi:10.1038/nature03052

11. Bonacci, J., Saunders, P.U., Hicks, A., Rantalainen, T., Vincenzino, B.T., & Spratford, W. (2013). Running in a minimalist and lightweight shoe is not the same as running barefoot: a biomechanical study. *British Journal of Sports Medicine, 47(6):* 387-392. doi: 10.1136/bjsports-2012-091837

12. Cavanagh, P.R., & Lafortune, M.A. (1980). Ground Reaction Forces in Distance Running. *Journal of Biomechanics, 13(5):* 297-406. doi: 10.1016/0021-9290(80)90033-0

13. Cheung, R.T., & Ngai, S.P. (2016). Effects of footwear on running economy in distance runners: A meta-analytical review. *Journal of Science and Medicine in Sport, 19(3):* 260-266. doi: 10.1016/j.jsams.2015.03.002

14. Clarke, T.E., Frederick, E.C., & Hamill, C.L. (1983). The effects of shoe design parameters on rearfoot control in running. *Medicine and science in sports and exercise, 15(5):*376-81.

15. Divert, C., Mornieux, G., Baur, H., Mayer, F., & Belli, A. (2005). Mechanical Comparison of Barefoot and Shod Running. *International Journal of Sports Medicine, 26(7):* 593-598. doi: 10.1055/s-2004-821327

16. Fields, K.B., Sykes, J.C., Walker, K.M, Jackson, J.C. (2010). Prevention of Running Injuries. *Current Sports Medicine Reports, 9(3):*176-182. doi: 10.1249/JSR.0b013e3181de7ec5

17. First four-minute mile. (n.d.). Retrieved September 04, 2016, from http://www.history.com/this-day-in-history/first-four-minute-mile

18. Fredericks, W., Swank, S., Teisberg, M., Hampton, B., Ridpath, L., & Hanna, J. B. (2015). Lower Extremity Biomechanical Relationships with Different Speeds in Traditional, Minimalist, and Barefoot Footwear. *Journal of Sports Science & Medicine*, *14*(2), 276-283.

19. Gent, R.N., Siem, D., Middelkoop, M.V., Os, A.G., Bierma-Zeinstra, S.M., & Koes, B.W. (2007). Incidence and determinants of lower extremity running injuries in long distance runners: a systematic review. *British Journal of Sports Medicine, 41:*469-480. doi: 10.1136/bjsm.2006.033548.

20. Gillinoc, S.M., Laux, S., Kuivila, T., Hass, D., Joy, S.M. (2015). Effect of Minimalist Footwear on Running Efficiency: A Randomized Crossover Trial. *Sports Health, 7(3):*256-60. doi:10.1177/1941738115571093

21. Hall, J.P., Barton, C., Jones, P.R., & Morrissey, D. (2013). The Biomechanical Differences Between Barefoot and Shod Distance Running: A Systematic Review and Preliminary Meta-Analysis. *Sports Medicine, 43(12):*1335-53. doi: 10.1007/s40279-013-0084-3.

22. Hamill, J., Gruber, A.H., & Derrick, T.R. (2014). Lower extremity joint stiffness characteristics during running with different footfall patterns. *European Journal of Sports Science, 14(2):* 130-6. doi: 10.1080/17461391.2012.728249

23. Hashish, R., Samarawickrame, S.D., Powers, C.M., & Salem, G.J. (2016). Lower limb dynamics vary in shod runners who acutely transition to barefoot running. *Journal of Biomechanics, 49(2):*284-288. doi: 10.1016/j.jbiomech.2015.12.002

24. Hollander, K., Argubi-Wollesen, A., Reer, R., & Zech, A. (2015). Comparison of minimalist footwear strategies for simulating barefoot running: a randomized crossover study. *PLoS One, 10(5):* e0125880. doi: 10.1371/journal.pone.0125880

25. Hsu, A.R. (2012). Topical Review: Barefoot Running. *Foot and Ankle International, 33(9):* 787-94. doi: 10.3113/FAI.2012.0787

26. IAAF: World Records | iaaf.org. (n.d.). Retrieved September 08, 2016, from https://www.iaaf.org/records/by-category/world-records

27. Kerdok, A.E., Biewener, A.A., McMahon, T.A., Weyand, P.G., Herr, H.M. (1985). Energetics and mechanics of human running on surfaces of different stiffnesses. *Journal of Applied Physiology, 92(2):*469-78. doi:10.1152/japplphysiol.01164.2000

28. Lieberman, D.E. (2012). What We Can Learn About Running from Barefoot Running: An Evolutionary Medical Perspective. *Exercise and Sports Science Reviews, 40(2):*63-72. doi: 10.1097/JES.0b013e31824ab210

29. Lieberman, D. E., Castillo, E. R., Otarola-Castillo, E., Sang, M. K., Sigei, T. K., Ojiambo, R., . . . Pitsiladis, Y. (2015). Variation in foot strike patterns among habitually barefoot and shod runners in kenya. *PLoS One, 10*(7): e0131354. doi:http://0-dx.doi.org.wncln.wncln.org/10.1371/journal.pone.0131354

30. Lieberman, D.E., Venkadesan, M., Werbel, W.A., Daoud, A.L., D'Andrea, S., Davis, I.S., … Pitsiladis, Y. (2010). *Nature, 463(7280):* 531-5. doi: 10.1038/nature08723

31. McCallion, C., Donne, B., Fleming, N., Blanksby, B. (2014). Acute differences in foot strike and spatiotemporal variables for shod, barefoot or minimalist male runners. *Journal of Sports Science & Medicine, 13(2):*280-6.

32. Moore, I.S. (2016). Is There an Economical Running Technique? A Review of Modifiable Biomechanical Factors Affecting Running Economy. *Sports Medicine, 46(6):*793-807. doi: 10.1007/s40279-016-0474-4

33. Murphy, K., Curry, E.J., & Matzkin, E.G. (2013). Barefoot Running: Does It Prevent Injuries? *Sports Medicine, 43(11):* 1131-8. doi: 10.1007/s40279-013-0093-2

34. Nigg, B.M. & Morlock, M. (1987). The influence of lateral heel flare of running shoes on pronation and impact forces. *Medicine and Science in Sports Exercise, 19(3):*294-302.

35. Pappas, P., Dallas, G., & Paradisis, G. (2016). Reliability of Leg and Vertical Stiffness during High Speed Treadmill Running. *Journal of Applied Biomechanics,* 1-17. doi: 10.1123/jab.2016-0045

36. Pedoe, D.T. (2000). Marathon Medicine. *The Royal Society of Medicine Press Limited, 160-162.*

37. Petersen, W., Ellermann, A., Gösele-Koppenburg, A., Best, R., Rembitzki, I., Brüggemann, G., & Liebau, C. (2013). Patellofemoral Pain Syndrome. *Knee Surgery, Sports Traumatology, Arthroscopy, 22(10):* 2264-2274. doi:10.1007/s00167-013-2759-6

38. Pickering, T.R., & Bunn, H.T. (2007). The endurance running hypothesis and hunting and scavenging in savanna-woodlands. *Journal of Human Evolution, 53:*434-438. doi: 10.1016/j.jhevol.2007.01.012

39. Raichlen, D.A., Gordon, A.D. (2011). Relationship between Exercise Capacity and Brain Size in Mammals. *PLoS One, 6(6):* e20601. doi: 10.1371/journal.pone.0020601

40. Ribeiro, A.P., Trombini-Souza, F., Tessutti, V.D., Lima, F.R., João, S.M., & Sacco, I.C. (2011). The effects of plantar fasciitis and pain on plantar pressure distribution of

recreational runners. *Clinical Biomechanics, 26(2):* 194-9. doi: 10.1016/j.clinbiomech.2010.08.004

41. Rixe, J.A., Gallo, R.A, Silvis, M.L. (2012). The Barefoot Debate: Can Minimalistic Shoes Reduce Running-Related Injuries. *Current Sports Medicine Reports, 11(3):*160-165. doi: 10.1249/JSR.0b013e1825640a6
42. Rothschild, C.E. (2012). Primitive Running: A Survey Analysis of Runners' Interest, Participation, and Implementation. *Journal of Strength and Conditioning Research, 26(8):*2021-2026. doi:10.1519/JSC.0b013e31823a3c54
43. Ruxton, G.D., & Wilkinson, D.M. (2011). Avoidance of overheating and selection for both hair loss and bipedality in hominins. *Proceedings of the National Academy of Sciences of the United States of America, 108(52);*20965-9. doi:10.1073/pnas.1113915108
44. Sears, E.S. (2015). *Running Through The Ages* (2nd ed.). Jefferson, NC: McFarland & Company, Inc., Publishers
45. Shih, Y., Lin, K., Shiang, T. (2013). Is the foot striking pattern more important than barefoot or shod conditions in running? *Gait & Posture, 38(3):* 490-4. doi: 10.1016/j.gaitpost.2013.01.030
46. Sinclair, J. (2014). Effects of barefoot and barefoot inspired footwear on knee and ankle loading during running. *Clinical Biomechanics, 29(4):* 395-9. doi: 10.1016/j.clinbiomech.2014.02.004
47. Smith-Harcourt, W. E., & Aiello, L. C. (2004, May). Fossils, feet and the evolution of bipedal locomotion. *Journal of anatomy, 204(5):*403-16. doi:10.1111/j.0021-8782.2004.00296.x

48. Squadron, R., Rodano, R., Hamill, J., & Preatoni, E. (2015). Acute effects of different minimalist shoes on foot strike pattern and kinematics in rearfoot strikers during running. *Journal of sports sciences, 33(11):* 1196-204. doi: 10.1080/02640414.2014.989534

49. Stackhouse, C.L., Davis, I.M., & Hamill, J. (2004). Orthotic intervention in forefoot and rearfoot strike running patterns. *Clinical Biomechanics, 19(1):*64-70

50. Staheli, L.T. (1991). Shoes for children: a review. *Pediatrics, 88(2):* 371-5

51. Susman, RL. (1983). Evolution of the human foot: evidence from Plio-Pleistocene hominids. *Foot Ankle, 3(6):*365-76. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/6409715

52. Szulc, P., Waszak, M., Bartkowiak, M., Tomczak, M., Boch-Kmieciak, J., & Cieslik, K. (2016). Distribution of plantar pressure during jogging barefoot or in minimalistic shoes in persons who used to run in cushioned shoes. *The Journal of Sports Medicine and Physical Fitness.*

53. Tam, N., Tucker, R., & Wilson, J.L. (2016). Individual Responses to a Barefoot Running Program: Insight Into Risk Injury. *The American Journal of Sports Medicine, 44(3):* 777-84. doi:10.1177/0363546515620584

54. Uphill, Eric. (1965). The Egyptian Sed-Festival Rites. *Journal of Near Eastern Studies, 24(4):*365-383. http://www.jstor.org/stable/543647

55. Van Gent, R.N., Siem, D., Middlekoop, M.V., Van Os, A.G., Bierma-Zeinstra, S.M., Koes, B.W. Incidence and determinants of lower extremity running injuries in long distance runners: a systematic review. *British Journal of Sports Medicine, 41:*469-480. doi: 10.1136/bjsm.2006.033548

56. Wang, W.J., & Crompton, R.H. (2004). Analysis of the human and ape foot during bipedal standing with implications for the evolution of the foot. *Journal of biomechanics*, *37(12):*1831-6. doi: 10.1016/j.jbiomech.2004.02.036.

57. Warne, J.P., Kilduff, S.M., Gregan, B.C., Nevill, A.M., Moran, K.A., Warrington, G.D. (2014). A 4-week instructed minimalist running transition and gait-retraining changes plantar pressure and force. *Scandinavian journal of medicine & science in sports, 24(6):* 964-73. doi: 10.1111/sms.12121

58. Werd, M.B, Subotnick, S.L., (2014). The History of the Running Shoe-Part 1. *American Academy of Podiatric Sports Medicine, 33(4):* 169-171.

59. Wright, I.C., Neptune, R.R., Van Den Bogert, A.J., & Nigg, B.M. (1977). Passive regulation of impact forces in hell-toe running. *Clinical Biomechanics, 13(7):*521-531.