Can a comprehensive transition plan to barefoot running be the solution to the injury epidemic in American endurance runners?

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Can a comprehensive transition plan to barefoot running be the solution to the injury epidemic in American endurance runners?

A Thesis Presented
by

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To the Keck Science Department
Of Claremont McKenna, Pitzer, and Scripps Colleges
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1. Abstract

Fossils belonging to the genus *Homo*, dating as far back as two million years ago, exhibit uniquely efficient features suggesting that early humans had evolved to become exceptional endurance runners. Although they did not have the cushion or stability-control features provided in our modern day running shoes, our early human ancestors experienced far less of the running-related injuries we experience today. The injury rate has been estimated as high as 90% annually for Americans training for a marathon and as high as 79% annually for all American endurance runners. There is an injury epidemic in conventionally shod populations that does not exist in the habitually unshod or minimally shod populations around the world. This has led many to conclude that the recent advent of highly technological shoes might be the problem.

Although current literature has been inconclusive, there are two main limitations in virtually all of the studies: 1) transition phases of less than three months and 2) transition phases without rehabilitation exercises. These two aspects are key to the treatment of the structural consequences on the muscles and tendons of the foot and calf that habitually shod individuals have faced. This study includes a discussion of the cumulative consequences that lifelong shoe usage has on the development of the feet and lower legs. I propose a 78-week study that addresses the limitations of past studies by implementing a gradual, 32-week, multi-shoe transition complemented by an evidence-based rehabilitation program. I believe that this approach will restore strength and elasticity to muscles and tendons that have been inhibited by lifelong usage of overconstructed shoes and adequately prepare runners for the
increased demand brought on by a changing running mechanic. This comprehensive, multifaceted transition plan to a fully minimalist shoe will provide novel insight into the ongoing barefoot debate. Can this approach finally demonstrate the proposed benefits of losing the shoes?

2. Introduction

Humans aren’t the fastest, strongest, or most physically powerful creatures in the world. However, Bramble and Lieberman (2004) suggested that our ancestors were still successful hunters due to a superior capacity for endurance running. According to fossil evidence from the genus *Homo* dating back two million years ago, our ancestors developed characteristics that added little in terms of walking ability or sprinting speed yet exhibited a unique evolutionary advantage when it came to endurance running. There are over 25 different functional characteristics developed in these early fossils including: short toes for stability during plantarflexion, long Achilles tendon and stabilized arch for energy storage and shock absorption, large gluteus maximus for trunk stabilization, the

![Image of nuchal ligament](image.png)

**Figure 2.1** The nuchal ligament, a structure that stabilizes the head and body during endurance running, was first found on the early *Homo habilis* species. Dogs and horses are some of the only other animals that have a nuchal ligament.
nuchal ligament that works with other structures in the head to keep our head upright (Figure 2.1), and a variety of other features that allow for greater elasticity, impact-control, stabilization, balance, and energy storage. These traits allowed our ancestors to run for long distances essentially barefoot without injury.²

Recently there has been a resurgence of endurance running in the world, especially in America. Unlike our hunting ancestors, modern American endurance runners take on endurance feats like running marathons (Figure 2.2), recreationally. However, this return to endurance running is not without its consequences. As many as 79% of total runners⁴ and 90% of those training for a marathon in America report injury annually.⁵¹ The injury epidemic of endurance runners in America has many looking more closely at our footwear.

Figure 2.2: The modern fad of running marathons demonstrates the innate human desire to run. These 26.2-mile races are done recreationally but require extensive training.

¹ More conservative estimates claim that roughly half of endurance runners experience injury annually. Even with the lowest estimates, there remains an epidemic of running-related injuries that is unique to modern American runners.
The modern runner wears cushioned shoes with an elevated heel. These types of shoes were introduced in the late 1960s with the resurgence of distance running, claiming they absorb shock and even add spring to the stride.\(^6\) Despite the continued addition of new technologies in running shoes, the rates of injury of endurance runners in America has been unaffected or even slightly increased for the last several decades.\(^7\)\(^8\) Many Americans search for other ways to experience the benefits of running without the risks. Running has become viewed as inherently dangerous.

In the book *Born to Run: A Hidden Tribe, Superathletes, and the Greatest Race the World has Never Seen* (2009), Christopher McDougall presents an alternative narrative. He follows a native Mexican tribe, the Tarahumara, that runs ultra-distances (150+ miles) injury-free in nothing but an ultra-minimal sandal (Figure 2.3\(^9\)) on rocky surfaces not much softer than the American city street.\(^10\) A look at other minimally shod or habitually unshod populations around the world also speaks to the absence of the injury epidemic that plagues Americans.\(^11\)\(^2\)

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\(^2\) Specific numbers are hard to come by because of the lack of technology and data collection in these countries. However, there are several reports that the rate of running-related injuries are significantly lower.
Fascinated by these reports, researchers have tried to address this question by testing American runners in a variety of footwear conditions. They have found that our cushioned running shoes have increased vertical reaction force and loading rates by influencing a heel strike in our running gait as opposed a more natural forefoot strike. Barefoot runners exhibit a lower loading rate by striking the ground with the forefoot before the heel in a more elastic running gait. It has been suggested that higher loading rates are often associated with higher rates of injury, specifically in instances in which the drastic increase of force cannot be absorbed properly. Considering the proposed danger of these findings, some distance runners have been jumping on a growing movement of barefoot and minimalist running, cutting out the unnecessary and potentially harmful technologies between them and the ground.

The barefoot movement started in the early 2000s and boomed after McDougall’s book in 2009, despite the lack of consensus on the accuracy of the claims of injury-reduction. Although many of the studies have suggested similar rates of injuries in Americans running with and without conventional running shoes, they have pointed to a different nature of injuries. Those in conventional shoes experience more impact-related injuries (likely due to the higher loading rate at an unnatural position) while those without them experience more strain-related injuries (likely due to the higher elastic demand on the muscles). In order to test Americans in both conditions, researchers establish a

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3 Although less common, a midfoot strike is also observed by some barefoot runners. A heel strike is the least common in this population of runners.
transition period for their respective experiment which is the period of time it takes a runner to transition from a conventional running shoe to a fully minimal or barefoot running experience. Although there is no agreed upon transition period for researchers to use, Warne and Gruber (2017) give a deeper look at the available literature, revealing two commonalities among virtually all of the larger-scaled studies: 1) transition plans of less than three months and 2) transition plans lacking comprehensive rehabilitation components. Further, no known study has designed an experiment which combined both of these elements, demonstrating that the currently tested transition plans have not adequately considered the mechanical and structural effects that consistently wearing overconstructed shoes has on the human body over the decades (e.g. shortened, stiffened, weakened muscles and tendons). The few that have addressed the need for rehabilitation exercises in a transition plan have either been too small in scale to draw larger conclusions or contained too short of a transition period.

Perhaps research that includes a more comprehensive, multifaceted transition plan that restores strength and elasticity to the muscles and tendons, can demonstrate drastic reductions in the strain-related injuries that are occurring in barefoot runners. Such findings would not only showcase the overall injury reduction benefits of barefoot running but also upend the assumptions that the multi-billion-dollar shoe industry has relied on for the past half century.

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4 The study that came the closest to having both a longer transition plan and comprehensive rehabilitation was Cheung, Sze, Davis, and Cheung (2016) who tested a 6-month transition plan coupled with some basic exercises and stretches. The outcome of the study was focused more on intrinsic foot muscle size than the implications for injury rates.
3. A History of the Running Shoe

Davis (2014) explains that although the first known pair of shoes was discovered 10,000 years ago, the modern day cushioned running shoe is only about 50 years old. In the 1960s, Oregon track coach Bill Bowerman co-founded Blue Ribbon Sports (with one of his runners named Phil Knight) as an American based distributor of Onitsuka Tiger shoes. Bowerman combined two of the earliest models from the parent company to create a “hybrid” shoe. Although the shoe was initially branded by Onitsuka Tiger, Bowerman sold a rebranded version of the shoe under the name Nike. With the growing popularity of the shoe, Bowerman and Knight split off from Onitsuka Tiger and rebranded Blue Ribbon Sports as Nike in 1971. Eventually both Onitsuka Tiger and Nike enjoyed widespread success as one of the first “modern” running shoes, selling the same model shoe under the names Cortez and Corsair (Figure 3.1), respectively. Others quickly followed suit into a booming market of cushioned running shoes. The 1971 release of Runners’ World showcased 66 different models from 32 brands.

The next evolution in the running shoe, pronation control, was based on characterizing a runner’s foot motion as neutral, overpronated (excessive inward roll), or...
underpronation (excessive outward roll). This technology took off with the introduction of the Brooks Vantage in 1977 (Figure 3.2), which discouraged the excessive inward pronation of the foot by slanting the sole outward. Although there was minimal research suggesting its benefits in injury prevention, the shoe’s success influenced the market to tailor their efforts more to stabilization as people began to link pronation to injury.

While the 1980s were dominated by stabilizing technologies, Beverly (2016) in Runners’ World magazine describes how the advent of the first Nike Air Max (Figure 3.3) in the late 80s led to a new focus through the 90s, visibly supportive outsoles. Companies experimented with flashy options (gels, grid, air pockets) that added little in terms of practical...
new technologies. With these new cushioning styles and the previous decade's advances in stability, *Runners' World* began to break up shoes into different categories: “Motion Controlled,” “Stability,” “Neutral-Cushioned,” and “Lightweight” for its ratings. Customers began to tailor their purchases to what they believed their running style needed.

The turn of the millennia brought forth some shocking discoveries. Nigg (2001) introduced the idea of a “preferred movement path” of joints and muscles which discredited the idea that pronation was directly related to injury. He instead argued that there is a natural pathway that a runner’s foot and leg will follow to be most economical, often times including a degree of pronation. Footwear that inhibits the “preferred joint movement path” should be avoided. Evolutionary biologists Dennis Bramble and Daniel Lieberman co-authored a hit article “Endurance running and the evolution of *Homo*” (2004), featured in *Nature*, which explained that two million-year-old fossils of the genus *Homo* demonstrate unique traits that made our ancestors exceptional endurance runners. They argued that throughout the long history of human evolution, the unique features created a balance of shock absorption, energy storage, stabilization, and elasticity that allowed humans to run long distances essentially barefoot in order to exhaust otherwise faster prey. Brüggemann, Potthast, Braunstein, and Niehoff (2005) expanded the discussion by outlining the effect of shoes on mechanical stimuli, finding that shoes serve as...
a medium of interference in the biological response of the body. The study concluded that shod participants experienced a decrease in muscle strength capacity from the reduced stimuli on the muscle tendon units.  

At the turn of the 21st century, Beverly (2016) describes how the running shoe industry had been dominated by just a few companies. After the findings of new research were released, the shift in public interest led to a breakthrough in the market—people were questioning what was on their feet. Although Nike is credited first modern minimalist shoe, the Free, it eventually got lost in the plethora of other shoes in Nike’s lineup. However, the ultra-minimal Vibram FiveFingers (2005) would soon become the symbol of the minimalist movement revived by Christopher McDougall’s book *Born to Run: A Hidden Tribe, Superathletes, and the Greatest Race the World has Never Seen* (2009). In the book, McDougall reiterated the thesis proposed in Bramble and Lieberman (2004) that humans by nature are “born to run.” He follows an indigenous tribe in Mexico, the Tarahumara, who consistently run over 150 miles at a time with virtually no injuries and nothing but ultra-minimal ‘huarache’ sandals on their feet. When looking at the astonishingly high rate of injuries in American runners, McDougall concluded that not only was the modern running shoe unnecessary but potentially harmful. 

![Figure 3.4: One of the first Vibram FiveFinger models, The Classic, showcases simplicity. The individual inlets for each of the toes allows for dexterity of the individual toes not afforded in most shoes. Studies have suggested that the forefoot-encouraged mechanic of minimalist shoes may reduce the risk of impact-related injuries.](image-url)
FiveFingers (Figure 3-4) \textsuperscript{40} boomed after the release of this book \textsuperscript{41} and the minimalist movement became the newfound religion of running. People were excited to move beyond their nagging injuries and experience the feeling of how they were “born to run.”

Since the minimalist running mechanics differed from shod running mechanics, companies like Vibram laid out a 10-week transition plan for customers new to minimalist running to avoid injuries. \textsuperscript{42} Especially with many ignoring recommendations of gradual transition, a new wave of strain-related injuries grew with the minimalist movement. \textsuperscript{43} The fervor of the minimalist movement was soon met with a reality check: it was not the panacea for running injuries.

As Tucker (2014) described, a class-action lawsuit was filed in 2012 against Vibram for the claims they were making about their FiveFinger shoes: 1) strengthen muscles in the feet and lower legs, 2) improve range of motion in the ankles, feet, and toes, 3) stimulate neural function important to balance and agility, 4) eliminate heel lift to align the spine and improve posture, 5) allow the foot and body to move naturally. The release of two studies, Ridge et al. (2013) and Ryan, Elashi, Newsham-West, and Taunton (2014), outlined injury risks while transitioning to the FiveFinger shoe. \textsuperscript{44} \textsuperscript{45} These findings were timely enough to push the lawsuit to a $3.75 million settlement in 2014, with the company offering a refund to anyone who purchased the shoes during the period they had made the claims. \textsuperscript{46} Interestingly, Vibram still stood by the claims and did not accept any fault. \textsuperscript{47} Although they continued to produce the shoes, sales dropped and minimalist shoes moved away from the immediate spotlight. It
did not help that Adidas was dealt with a similar lawsuit around this time for their minimalist shoe claims.\(^{48}\)

Although controversy around the minimalist shoe movement gave fuel to a growing maximalist movement led by the Hoka One Ones, the minimalist movement was far from extinguished.\(^{49}\) Proponents of minimalist shoes continued to point to the fact that there was no evidence to support the prescription of a cushioned heel or pronation control in distance running shoes for injury prevention purposes.\(^{50}\) Additionally, Lieberman et al. (2010) demonstrated that habitually barefoot individuals exhibit a forefoot strike mechanic when running which eliminates the impact transient present in shod heel strike runners. This decrease in impact force puts less of a stress on the joints of the lower leg.\(^{51}\) Many minimalist enthusiasts believed that it was only a matter of time before the growing body of scientific research would support their claims. Six years after the lawsuit, have we come to any more conclusions?

4. The Footstrike Phenomenon

A year after Christopher McDougall’s book *Born to Run: A Hidden Tribe, Superathletes, and the Greatest Race the World has Never Seen* (2009), Lieberman et al. (2010) introduced the first biomechanical analysis of habitually barefoot endurance runners. The study demonstrated that while habitually shod runners mostly favor a heel strike landing, habitually
barefoot runners mostly favor a forefoot strike landing. The forefoot strike of the barefoot runners was associated with reduced impact compared to the heel strike of the shod runners. The trend remained true regardless of the hardness of the running surface. In Figure 4.1, two separate spikes are shown with heel strike runners demonstrating an impact transient at the strike of the heel followed by a subsequent forefoot impact. Barefoot runners have a more fluid force trajectory, with no impact transient upon foot strike. The maximum vertical ground reaction force attained by the forefoot strike is significantly less than the

![Figure 4.1](image-url): The graph depicts the force generated during three types of impacts at 3.5 m s⁻¹ in the same runner: barefoot heel strike (top), shod heel strike (middle), and barefoot forefoot strike (bottom). The sharp spike of the heel strike in contrast to the more fluid curve of the forefoot strike was a major finding of this study. It suggested that the leg was put under a greater deal of stress during a heel strike. The heel strike has been called unnatural, especially when looking at an even higher increase of impact force in the barefoot heel strike graph.

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5 Habitually barefoot runners also exhibited a less common midfoot strike where both the ball of the foot and heel hit at the same time. For the case of this paper we will focus on the distinction between forefoot and heel strikers because those are the most prominent striking methods in barefoot and shod running style, respectively.
maximum ground reaction force attained by the shod heel strike. The initial peak is a product of the stiff leg knee-lockout strike that occurs with heel-to-ground contact. This phenomenon, compared to the flexed knee strike with forefoot strikers, is demonstrated in Figure 4.2.

Only with the introduction of the cushioned heel in running shoes has the heel strike become a viable mechanic for many runners. The forefoot strike encourages ankle compliance with increased plantar flexion of the foot and ankle at landing, increased knee flexion at impact, decreased stride length, increased stride frequency, and decreased ground impact time. Lieberman et al (2010) found that the effective mass that is impacting the ground in heel striking shod runners is 6.8% while 1.7% in forefoot striking barefoot runners. Although Lieberman et al. (2010) found similar loading rates in barefoot forefoot strikers and shod heel strikers, studies have shown that the mechanics of the barefoot forefoot strike reduces joint impact and decreases joint torques, reducing the effective loading rate compared to the shod heel strike.
Shih, Lin, and Shiang (2013) added more numbers to the discussion, finding that in testing different strike patterns in 12 habitually shod male runners, the rearfoot strike had nearly double the loading rate than a forefoot strike (shown in Figure 4.3). Studies have suggested that loading rate is a more significant factor than vertical ground reaction force on injuries. Van der Worp et al. (2016) reported that loading rates were higher in runners who had a history of stress fractures. Other studies have supported the notion that higher loading rates impact stress fractures as well as soft tissue dysfunction and plantar fasciitis. Nigg (2001) has been one of the only studies to imply that higher loading rates might be associated with reduced injury. Although this could simply be an anomaly it’s also possible that there are certain movements in which increased loading rates would be beneficial. Athletes in sports with higher loading rates (e.g. gymnasts) have shown to have greater bone mass density that...
continues even after they stop competing than do athletes in sports with lower loading rates (e.g. swimmers).\textsuperscript{66} However, higher loading rates might only be beneficial when they are applied in a physiologically sustainable manner.

Shih, Lin, and Shiang (2013) demonstrated that landing phase angle, stance phase angle, and range of motion were different in both the foot and the knee for forefoot strike versus heel strike. The angles for forefoot strike, especially the increased angle of the knee at landing, are believed to disseminate the force of initial impact and decrease the loading rate by spreading the force out over more time. The knee-lockout position of a heel strike is not a natural shock absorbing position and inflicts a greater demand and stress on the knee, hips, and back,\textsuperscript{67} increasing the potential for musculoskeletal injuries over strain-related injuries.\textsuperscript{68}

\textsuperscript{69}Milner, Hamill, and Davis (2007) demonstrated that sagittal plane (front to back) knee stiffness was higher in groups with significantly more tibial stress fractures, suggesting that how the loading rate is applied may be the underlying factor of injuries during high-loading situations. Certain positions, like stiff-knee heel strike, might put the body in a more vulnerable position, less capable of properly absorbing impact.\textsuperscript{70, 71}

Although Shih, Lin, and Shiang (2013) found a slight difference between forefoot striking in barefoot and shod conditions that wasn’t significant (according to Figure 6), Rice, Jamison, Davis (2016) brought in figures that were significant. Their finding was that forefoot striking in minimalist shoes produced a significantly lower peak instantaneous loading rate (ILR), as demonstrated in Figure 4.4\textsuperscript{72}. Further, the full minimalist forefoot strike was the only mechanic that didn’t demonstrate an impact transient peak. This implies that a partial
minimalist shoe doesn’t have the fluid dispersion of impact that was demonstrated in Lieberman et al.’s (2010) experiment results in Figure 4.1. This is an important finding suggesting that the introduction of technology in footwear affects mechanics, increasing the risks of impact-related injury associated with higher loading rate.\(^{73, 74, 75}\)

When studying elite runners at the 15-kilometer point of a half-marathon, Hasegawa, Yamauchi, and Kraemer (2007) found that a significantly lower number of runners exhibited a rearfoot strike when compared to all endurance runners in America. The study suggests that forefoot striking has a benefit for faster, more competitive runners.\(^{76}\)

5. Running Economy

Although the risk of injury is vital to how we develop our mechanics, runners also aim for a running mechanic that allows them to run as fast and as long as possible with the least
amount of effort. Given that there is a difference in striking patterns and overall running mechanics between barefoot and shod runners, which is more efficient?

There have been a handful of studies suggesting that barefoot running may be more metabolically efficient than shod running, suggesting that perceived exertion, heart rate, and oxygen uptake all increase in conventionally shod runners.  

Hanson, Berg, Deka, Meendering, and Ryan (2011) demonstrated that running shod was associated with a 5.7% higher VO\textsubscript{2} level at the same pace, indicating that being shod has a negative effect on the maximum level of oxygen the body can use (VO\textsubscript{2 max}). Divert et al. (2008) suggested that VO\textsubscript{2} consumption was affected with regard to the weight of the shoe but not necessarily with regard to the mechanical properties of the shoe. However, the net efficiency (which controls for the weight of the shoe) was still higher in the barefoot group. This suggests that the damping effect of shoes or mechanical change of the runner’s stride decreases the elastic energy restitution of the runner, thereby making the runner less efficient.

Franz, Wierzbinski, and Kram (2012) wanted to show that when controlling for running experience and foot strike, the advantage of barefoot running would be solely due to the weight of footwear. They controlled the running experience by testing experienced barefoot runners and the strike pattern by having them run shod and unshod using a midfoot strike. Metabolic power was calculated by measuring oxygen consumption and carbon dioxide production. Although they did not find a significant metabolic advantage when testing a barefoot condition against the lightweight shoe (130g), it must be noted that midfoot strike was used for both shod and barefoot conditions which is relatively uncommon in shod or
barefoot runners. The conclusions may suggest that the increase in efficiency in barefoot runners is absent when controlling for mechanics. However, it is hard to separate the shoe from its mechanical implications on the runner.

Catlin and Dressendorfer (1979) and Frederick (1984) have provided sound evidence that having additional weight on the feet decreases metabolic efficiency. They demonstrated that adding 100g in weight to each shoe at a 7:00/mile pace required 1.2% more metabolic energy and 175g of weight on each shoe required 3.3% more metabolic energy. Although there may be a point (ultra-lightweight shoe) at which weight does not affect efficiency, there is clear evidence in of increased efficiency due to decreased weight. There is also, overall, convincing evidence of increased metabolic efficiency in the barefoot condition either due to damping properties of the shoe or mechanical effects on the runner.

6. Anatomy of the Foot

To examine the more structural impacts of different foot striking patterns, an understanding of the foot’s anatomy is essential. This section is adapted from Houston Methodist (2001), Kelikian and Sarrafian (2001), and Swierzewski (2015). The foot contains 26 bones (one-quarter of the body’s bones), 33 joints, over 100 muscles, tendons, and ligaments, over 200,000 nerve endings, over 250,000 sweat glands, and a network of blood vessels. The foot is connected to three major muscles: gastrocnemius (large calf muscle), soleus (lower calf muscle) and quadratus plantae (sole muscles). The foot
is split into three regions: forefoot, midfoot, and rearfoot. The forefoot is composed of five phalanges (commonly referred to as toes) and their connecting bones (metatarsals). The midfoot contains five irregularly shaped tarsal bones (forming the foot’s arch which acts as a shock absorber) that are connected to the forefoot and rearfoot by muscles and the plantar fascia ligament. The rearfoot contains three joints and the largest bone in the foot, the calcaneus (heel bone), which is protected at the bottom by a cushioning layer of fat.

The five main muscles of the foot are the anterior tibial (allows for upward motion), the posterior tibial (supports the arch), the peroneal tibial (controlling movement of the outer ankle), the extensors (allow for toe raise for forward step), and flexors (stabilize toes to ground). Muscles are connected to bones and joints by tendons. The largest tendon, the Achilles tendon, connects the calf muscle to the heel and facilitates our ability to walk, run, and jump. Ligaments hold the tendons in place and stabilize the joints. Medial ligaments (inside of foot) and lateral ligaments (outside of foot) provide stability to the foot enabling it to move up and down. The largest ligament, plantar fascia, serves to give support, structure, and strength to the arch to initiate movement.

It is safe to say that our feet are essential to how our body functions. The amount of structures in our foot speak not only to the complexity of our movements but to our ability to perform the foot’s two most important functions: 1) absorbing shock and 2) propulsion. The way we treat our feet has major implications on our bones, muscles, tendons, and ligaments—which are ultimately the driving force behind these two functions. When one part is injured, it can affect every other part. Considering that up to 80% of people will experience
complications in the foot during their lives, understanding how to keep the foot healthy is vital.

7. The Arch

The arch of the foot is vital for support of the body and the ability to absorb shock upon impact. It is made up of three parts: medial longitudinal, lateral longitudinal, and transverse as shown in the Figure 7.1. This section outlines the influence of shod and unshod conditions on the development of the arch, the dangers of a weak arch, and recommendations for strengthening the arch, which is vital in creating a proper transition program for our experiment.

*Figure 7.1:* The arch is made up of three parts: the medial longitudinal, lateral longitudinal, and transverse. Habitually barefoot populations have thicker, stiffer muscles comprising the longitudinal arch increasing the arch’s ability to absorb shock, maximize efficiency, and retain elastic energy during running.
7.1. Shoes and Arch Strength

It is known that muscles grow when exercised and atrophy when not. Campitelli, Spencer, Bernhard, Heard, Kidon (2016) compared the effects of minimalist conditions on foot strength in endurance runners. The use of a full minimalist shoe, Vibram FiveFinger Bikila, was associated with an increase in strength of the abductor hallucis (a key component of the longitudinal arch) at both 12 and 24 weeks in runners going through a transition period with the 10% philosophy of increasing mileage each week. The control group experienced no significant differences in foot strength over the same periods. Johnson, Myrer, Mitchell, Hunter, Ridge (2016) confirmed these results finding a 10.6% increase in the abductor hallucis in runners in transitioning to Vibram FiveFinger shoes.

Holowka, Wallace, Lieberman (2018) studied a population of minimally shod men in northwestern Mexico against American men wearing conventional shoes with features like arch support, heel elevation, and toe boxes to compare how the strength of the foot muscles differed. The results were that minimally shod individuals had larger abductor hallucis and digiti minimi muscles as well as higher and stiffer longitudinal arches compared to the conventionally shod individuals. While walking, the abductor hallucis size was positively associated with the stiffness of the longitudinal arch. The study suggests that shoes with stability features may predispose an individual to reduced foot stiffness and pes planus (i.e. flat feet). Their findings on intrinsic foot muscle difference is found in Figure 7.2. This study reinforced previous research suggesting that running barefoot or in minimalist shoes
increases the strength and stiffness of the longitudinal arch which encourages stability and balance and discourages flat-feet.\textsuperscript{93, 94}

**Figure 7.2:** The graphs demonstrate the increased intrinsic foot strength of minimally shod populations compared to conventionally shod populations through the measurement of the following: a) Static measurements of the arch height index (AHI) and arch stiffness index (ASI) show an increased arch height and stiffness in the minimally shod population. b) Cross-sectional area (CSA) of the abductor hallucis (AH) and abductor digiti minimi (ADM) are significantly larger in the minimally shod population (values scaled by body mass [BM])\textsuperscript{2/3}. c) Dynamic measurements of maximum arch deformation angle (\(\theta_{\text{max}}\)) and arch stiffness are lower and higher, respectively, in the minimally shod populations (\(k_{\text{mid}}\) scaled by (body mass))\textsuperscript{2/3}).

* denotes statistically significant difference between groups

### 7.2. What’s So Bad about a Weak Arch?

Between 10-30% of the American population have flat feet, with even more possessing weak arches.\textsuperscript{95–96} Kaufman, Brodine, Shaffer, Johnson, Cullison (1999) concluded that weak arches, specifically dynamic pes planus, were associated with higher risk of overuse injuries in a study of 449 Naval Special Warfare Training Center trainees.\textsuperscript{97} Queen, Mall, Nunley, Chuckpaiwong (2009) suggested that flat footed individuals may have a greater risk of medial and lateral midfoot injuries such as metatarsal stress fractures when performing athletic movements, looking at how 12 normal-footed and 10 flat-footed individuals
responded to four sport specific tasks (cross-cut, side-cut, shuttle run, and landing from a simulated lay-up). Additionally, Menz, Dufour, Riskowski, Hillstrom, Hannan (2013) added that the pronated foot posture exhibited in flat feet was associated with higher levels of lower back pain in a study of 1930 people. Although not all people experience further pain or injury, evidence supports a higher risk of symptoms in people with weak arches. Additional symptoms include: Achilles tendonitis, arthritis in the ankles, arthritis in the feet, bunions, hammertoes, plantar fasciitis, posterior tibial tendonitis, shin splints, and knee, hip, and back pain.

De Villiers, Venter (2014) compared a shod group of ten female athletes against a barefoot group of ten female athletes through an eight-week training program. In addition to improvements in speed and agility, the study found significant improvements, exclusively for the barefoot group, in overall stability of the leg, anterior-posterior stability of the leg, and the medial-lateral stability of the leg in barefoot training, suggesting that barefoot training increases stability and balance. These results confirm those found by Dabholkar, Shah, Yardi (2012), suggesting that dynamic balance is negatively affected in flat-footed individuals by using the Star Excursion Balance Test (SEBT), a widely accepted test of dynamic balance. McGuine, Keene (2006) demonstrated in a study of 765 high school athletes that balance training significantly lowered the risk of ankle sprain injuries. Thus, the increased balance and stability in those with strong arches, specifically habitually barefoot populations, has implications for injury reduction.
The treatment for weak arches is often to put more support on the arch. However, a meta-analysis of the existing literature suggests very limited long-term benefits to the use of arch supports. Rather, the more effective solution is in strengthening the longitudinal arch through exercises. The studies above suggest that barefoot training and running is a suitable complement to strengthening arches.

7.3. Early Development

Studying children allows us to approach many problems while they are being developed. Vittore et al (2008) studied the cause of flexible flat feet in children, a common developmental condition in children in which the arch collapses while bearing weight. They concluded that although the problem can sometimes be in the bony structures of the foot, it is most often in the deficiency of the support of the plantar arch. Active support (tibialis anterior and posterior tibialis muscles) and passive support (flexor hallucis longus and flexor digitorum longus muscles) of the longitudinal arch are deficient in children who display flexible flat feet. Although in many cases the condition goes away, without proper strengthening of the components of the longitudinal arch the condition can progress into flat feet in adulthood. In a survey of 2300 children, Rao and Joseph (1992) demonstrated that children who were habitually shod exhibited flat feet at a rate three times as high as their unshod counterparts. The study suggests that use of shoes from a young age limits the full development of the longitudinal arch as children mature. Thus, there are benefits to children going barefoot, aiding in the long-term development of a strong, stable arch.
next section will explore some of the other conditions that shoes can influence from a young age.

8. Shoe Technologies: The Origin of Dysfunction

Why does the country with the most “advanced” shoe technology experience so many foot and ankle problems? Over the course of their lives up to 95% of Americans will experience foot and ankle problems, a figure that is unique to this country.\textsuperscript{109} The development of a variety of technologies in our shoes has been embraced by runners and non-runners alike. Although many of these technologies claim to protect the foot from injury, there is virtually no evidence to support the claims.\textsuperscript{110} On the other hand, there is good evidence that some of the developments in shoes have encouraged our feet to exhibit otherwise unnatural behaviors. Although many of the conditions discussed in this section are developed when we aren’t running, they can have major consequences for when we are.

8.1. Tight Toe Box

Most of the shoes on the market do not have sufficiently wide toe boxes and subsequently force our toes into unnatural positions. The following conditions, which impede proper foot function and cause a host of further complications, can be developed due to a tight toe box.
**8.1.1. Squished toes:** As Hughes (2018) explains, the toes’ natural position is to form a wide, stable base for the body with space in between each toe. As shown in Figure 8.1, a tight toe box prevents the natural splaying of our toes to bear weight properly and forces our ankles, knees, and hips to pick up the slack. Without the load bearing properties provided by splayed toes, we experience a reduction in overall balance and foot function.

![Figure 8.1: A tight toe box prevents the natural splaying of our toes.](image)

**8.1.2. Bunions:** Fischer and Haddad (2012) explain that although this condition can sometimes be attributed to genetic factors, a tight toe box puts you at a much higher risk to develop these bony protrusions of the first or fifth metatarsal. As shown in Figure 8.2, the big toe will point inward to create hallux valgus, the protrusion of the first metatarsal. The Tailor’s Bunion can also develop on the fifth metatarsal with the fifth toe pointing inward (as shown in Figure 8.2).
8.1.3. Corn: As shown in Figure 8.3, tight toe boxes cause consistent pressing together of the toes. Corns are calluses, often between and on top of the toes, that are developed as a response to the irritation to the skin due to consistent pressure on the toes.

8.1.4. Hammer Toe: As shown in Figure 8.4, the toe will begin to curl up instead of lying flat at its natural position. This is often accompanied by a corn developing at the top of the middle toe joint.
8.1.5. Overlapping Toe: As shown in Figure 8.5\textsuperscript{120}, this condition occurs when one of the auxiliary toes moves on top of the adjacent toe.\textsuperscript{121}
8.1.6. Adductovarus Toe: As shown in Figure 8.6\textsuperscript{122}, this condition is experienced when one of the toes has been pushed under another toe.\textsuperscript{123}

8.1.7. Mallet Toe: As shown in Figure 8.7\textsuperscript{124}, this happens when a toe has abnormal bending at only the last joint.\textsuperscript{125}
8.1.8. Claw Toe: As shown in Figure 8.8\textsuperscript{126}, this abnormal bending of the second and third joints of the toe can often cause rough calluses to develop from digging into the sole of shoes. Without treatment, this condition can become irreversible.\textsuperscript{127}

![Figure 8.8: Claw toes, although they are often caused by nerve damage outside of a shoe’s influence, can still be developed through the effects of a tight toe box.](image)

All of these conditions can severely limit the rest of the foot’s ability to perform its proper functions. Want to test whether or not your shoe has a tight toe box? Take out the sole of your shoe and stand on it with your bare foot, allowing your toes to naturally spread. If your toes are wider than the width of the sole, the toe box is too tight.

8.2. Toe Spring

As shown in Figure 8.9\textsuperscript{128}, the upward curvature of the sole puts the toes at an unnatural elevated position. Having our toes locked in this position can inflict a host of issues.
8.2.1. Increased Pressure on Ball of Foot: As will be discussed further below in Rossi (2001), we are already at a disadvantage compared to other creatures with regards to stability. Toe springs (especially when combined with heel lifts) put an extraordinary amount of pressure on the ball of foot by preventing the toes from gripping the ground.129

8.2.2. Decreased Mobility of the Toes: Hughes (2016) explains that the toe spring decreases the mobility of the toes and makes it hard to engage them to push off the ground during running. The upward position of the toes creates an imbalance of the tendons on the bottom and top of your foot and can encourage many of the toe deformities discussed previously.130

8.2.3. Increased Likelihood to Heel Strike: Robillard (2011) explains that the toe spring encourages a heel-to-toe “rocker” effect with constant dorsiflexion of the toes. This encourages the foot to rely heavily on the sole of the shoe for momentum instead of actively

Figure 8.9: Excessive toe springs limit the toe’s natural gripping of the ground and encourage unnatural running mechanics.
engaging the feet with consistent feedback from the ground, resulting in higher impact forces and less proprioception.\textsuperscript{131} 132

\textbf{8.2.4. Plantar Fasciitis:} Bolga and Malone (2004) discuss the windlass mechanism, the tightening of the plantar fascia due to dorsiflexion of the big toe. This mechanism is associated with plantar fasciitis, the inflammation of the plantar fascia ligament. Since the toe spring keeps the big toe in this dorsiflexed position (windlass mechanism), it may cause increased plantar fascia tightness as well as the development of plantar fasciitis.\textsuperscript{133}

\textbf{8.2.5. Limitations on Shock Absorption:} Cucuzzella, Katovsky, and Pang (2017) explain that an overbuilt toe spring often comes with an excessively curved toe box. The curvature of the edge of the outsole cuts off the functionality of the fifth metatarsal, an important structure for weight bearing and impact control. Since many runners rely on the more flexible fifth metatarsal to bear the initial load when running, limiting its mobility can lead to injury or loss of proper mechanics.\textsuperscript{134}

Curious if this affects you? Take off your shoe and lay it on the ground. If the front most part of the sole is not touching the ground, your shoe has a toe spring. To observe the natural position of your toes with load bearing, stand barefoot on the ground and notice how your toes grip the floor for stability, something that is prohibited with the toe spring feature.
8.3. Arch Support

![Arch Support Image]

**Figure 8.10**: Apart from the medical treatment of excessive ankle internal rotation with custom orthotics, there is virtually no evidence to back the widespread implementation of arch support in shoes. The claim of reduced injury by using arch supports has been discounted continually.

According to a 2016 National Runner Survey: motion control, cushion, stability, and injury prevention were at the forefoot of the consumers’ purchases. Arch support, as shown in Figure 8.10, outside of specific medical conditions diagnosed by a podiatrist, are virtually useless in injury risk or running economy.

**8.3.1. Weaker Intrinsic Arch Relative to Unshod Groups**: Studies have shown that there are no injury prevention implications to wearing arch supports. In fact, Holowka, Wallace, and Lieberman (2018) suggest that too much support of the arch may lead to reduced strength in the arch, whereas increased intrinsic foot muscles usage in habitually barefoot populations subsequently leads to a stronger arch.
8.3.2. Minimal Improvements of Mechanics: A meta-study of the literature by RunRepeat (2018) found that a minimal 2% difference in foot pronation has been observed in motion control shoes. However, continued research has not linked pronation to injury or found an association between arch support and posture, strength, or stability.\textsuperscript{142}

8.3.3. Increased Knee Varus Torque: Arch support has been linked to higher knee varus torque (inward displacement of the knee) which ultimately has been linked to knee osteoarthritis.\textsuperscript{143}

8.3.4. Reduced Functionality of the Arch: Two primary features of the arch are to absorb shock upon impact and provide elastic response to propel us forward. Rigid arch supports can limit the natural pronation and flattening of the arch on impact (shock absorbing mechanism) and can reduce running efficiency characteristics of the arch.\textsuperscript{144}

8.4. Thick Sole

\textbf{Figure 8.11:} The Hoka One One is a maximalist shoe that implements a thick sole for increased cushioning. Although not to the degree of maximalist shoes, most conventional running shoes have a significant amount of cushioning that makes up the sole of the shoe.
The introduction of the thick, cushioned sole in the running shoe (as shown in Figure 8.11) is only 50 years old. In addition to virtually no evidence supporting its widespread implementation, many of the natural functions of the foot have been limited by this feature.

8.4.1. Decreased Sensory Adaptation: As Professor of Biology Daniel Howell explains, the hundreds of thousands of receptors on the sole of the foot comprise the highest density of neuroreceptors in the body. The two other highly nerve-dense areas of the body, the mouth and hands, are constantly receiving feedback from the environment. With a thick sole, the receptors cannot adequately receive feedback, inhibiting the body from adequately firing the intrinsic foot muscles to absorb impact forces.

8.4.2. Weakening of the Metatarsal Bones: Zipfel and Berger (2007) discuss some other important factors when comparing shod and barefoot conditions. When studying the feet of three modern human groups (Sotho, Zulu, European) against those of a pre-pastoral hunter gatherer group (Holocene), they found that feet had the least pathologies of the metatarsal bones in the unshod Holocene and minimally shod Zulu groups. The habitually shod European group had the highest level of pathologies in the metatarsal bones. These findings suggest that footwear has a negative effect on the development of the metatarsus and the overall health of the foot.

8.4.3. Increased Risk of Ankle Sprain: Ramanathan, Parish, Arnold, Drew, Wan, Abboud (2011) demonstrated that a thicker sole came with an increased risk of ankle sprain, due to the lack of feedback from the ground to the foot.
8.4.4. Decreased Proprioception: There is decreased spatial awareness and fluidity of movements as a result of the decreased sensory feedback to the foot and the added weight of shoes.\textsuperscript{150} 151 152

8.4.5. False Sense of Protection: Our bodies develop improper mechanics due to decreased feedback and proprioception. We are more susceptible to learn improper mechanics that make us less able to absorb the shock we are creating.\textsuperscript{153}

8.5. Heel Elevation

Figure 8.12: An elevated heel can cause a variety of consequences up the entire chain of the body by encouraging an unnatural posture.

The use of heel elevation, as shown in Figure 8.12,\textsuperscript{154} is ubiquitous in the shoe industry. Although many use it as a way to look fashionable (i.e. high heel), it is also used in most running shoes for purposes of adding more cushion under the heel. Whether for fashion or for performance purposes, the habitual use of an elevated heel has some serious
consequences. The consequences of heel elevation are the most significant in consideration of endurance running. Rossi (2001) describes the many factors below.\textsuperscript{155}

**8.5.1. Improper Load Bearing:** Humans are already at a disadvantage in load bearing compared to other four-legged creatures. Figure 8.13\textsuperscript{156} demonstrates that any elevation of the heel will shift the natural 50/50 load bearing balance between the forefoot and heel and subsequently result in the shifting of the center of mass and reduction in length of the Achilles tendon.

Further, D’Août, Patak, Clercq, and Aerts (2009) studied a group of 70 habitually barefoot walkers in India, comparing them with 137 habitually shod Indians and 48 habitually shod Westerners. The findings demonstrated that the habitually barefoot group had a load carrying surface that acted much more uniformly than did the shod individuals. Those who were shod demonstrated higher peak pressures on the hallux, metatarsals, and the heel of the foot. This lack of uniform loading distribution in shod populations affects the morphology of the foot and the effectiveness of its output.\textsuperscript{157}
8.5.2. Dangerous Posture Adjustments: Because of the change of the load bearing vertical plane (as shown in the figure), adjustments have to be made at various levels of the body, putting an abnormal strain on the muscles, joints, and tendons that are bearing excessive loads. These adjustments are unnatural to the structure of the body and can cause a variety of problems and injuries not just limited to the foot and ankle. Kerrigan, Todd, and Riley (1998) demonstrated that in 2-inch heels, the weight borne on the center of the knee increased by 23% and was no longer shared equally between the lateral and medial surfaces as seen in neutral loading positions. The increased load on the medial portion of the knee may contribute to the development of knee osteoarthritis in women.\textsuperscript{158} \textsuperscript{159}

8.5.3. Reduced Ankle Mobility: The more plantarflexed position of the foot reduces the mobility of the ankle joint. Reduced ankle mobility results in mechanical compensations elsewhere in the body.

8.5.4. Shortening and Stiffening of the Achilles Tendon, Plantar Fascia, and Calf: The shortening of the Achilles tendon starts at an early age when toddlers commonly wear shoes that have a heel \( \frac{3}{8}-\frac{1}{2} \)-inch in height (concept demonstrated in young boy’s shoe in Figure 8.14\textsuperscript{160}).\textsuperscript{161} Relative to their height, this elevation of heel is comparable to a 2-inch heel in adults. On a medium to higher heel, the continual bowing of the longitudinal arch effectively shortens the plantar fascia as the forefoot and heel are brought closer together. According to
Csapo, Maganaris, Seynnes, Narici (2010), a study of 11 women against a control group who consistently wore heeled shoes suggested that in addition to Achilles tendon stiffening, the women experienced a reduction in length of the gastrocnemius medialis muscle and the surrounding fascicles due to consistent contracting of the muscles. When returning to neutral shoes or barefoot conditions, shortened and stiffened muscles and tendons, especially those in the foot, ankle, and calf, are at higher risk for injury. We will consider these implications when designing a proper transition program in our experiment.

8.5.5. Weakened Arch: With the tightening of surrounding tendons and reduced ankle mobility, the arch can loosen to make up for lack of mobility. A weakened arch can lead to the development of flat feet.

8.6. Application

Improper mechanics, deformities in the foot and toes, and the change in length, stiffness, and strength of the muscles and tendons of the foot, ankle, and calf, won’t go away on their own. In fact, the majority of injuries experienced by barefoot runners are involving these same structures. When we increase the load too quickly on muscles, tendons,
ligaments, and bones that are underdeveloped or lack support from surrounding structures, injury will result. As will be discussed in the next section, the current studies on transition plans haven’t adequately addressed these deeply-ingrained imbalances and subsequently fall to a continued pattern of strain-related injuries. Thus, our experiment will work to reintroduce strength, mobility, and elasticity to these structures through the use of a comprehensive rehabilitation plan.

9. The Injury Debate

It is estimated that up to 79% of American endurance runners and up to 90% of runners training for a marathon will get injured each year.\textsuperscript{165, 166} Despite the additions of new technologies in shoes, the injury rate has only increased since it began to be reported in the 1970s.\textsuperscript{167} Before the 1970s, there were no official reports of injuries, potentially signifying their lower occurrence.\textsuperscript{168} What has changed since then?

9.1. Is the Shoe the Problem?

Many point to the creation of the cushioned running shoe as a potential culprit. It encourages an unnatural heel strike mechanic that introduces a higher loading rate upon impact, putting a larger demand on the major joints of the leg.\textsuperscript{169} As more runners began to adopt this mechanic, the rate of knee injuries became more prevalent—more than doubling from the 1970s until today.\textsuperscript{170} As people became frustrated by continued knee and impact-
related injuries, the minimalist movement was born, seeking to return to the natural, barefoot mechanics that we were born to have. Those in support of this movement will point to the lower incidence of injuries in unshod populations around the world.\textsuperscript{171} Although reports of lower injury rates in unshod populations likely have some merit, these injury reports are more anecdotal than numbers-based. Studies have been unable to consistently demonstrate this trend in literature, often resulting in similar rates of injury between shod and unshod runners who are tested. Since the mechanics of shod runners and barefoot runners are different, there will be drastic effects on the muscles used, impact created, parts of the body that absorb shock, and how bones, tendons, ligaments, and muscles ultimately react.

Although the key debate is whether there is a difference in the rate of running injuries between shod and barefoot runners, there is good evidence that the type of injury experienced is distinct in these two groups. Shod runners report higher rates of patellofemoral pain, iliotibial band syndrome, plantar fasciitis, musculoskeletal injuries, and ankle sprains while unshod runners have reported higher rates of metatarsal pain (including stress fractures), Achilles tendonitis, and calf strains.\textsuperscript{172} \textsuperscript{173} \textsuperscript{174} Many of the following studies have been carried out by comparing injury rates between shod and transitioning minimalist groups. Although the conclusions of the injury comparisons have been inconclusive overall, they give insight as to how different transition to minimalist shoes worked and how it can be improved in future study. It additionally points to specific shortcomings in the current literature that will be addressed in our experiment.
9.2. Transition Period

Vibram initially suggested a 10-week gradual (10% a week) transition period for its FiveFinger minimalist shoes.\textsuperscript{175} When the transition plan was tested by Ridge et al. (2013) it was found that bone marrow edema was significantly more prominent in transitioning minimalist runners (10 out of 19) than in traditionally shod runners (1 out of 17).\textsuperscript{176} The study was soon followed by Ryan, Elashi, Newsham-West, Taunton (2014) who studied a total of 99 runners with mild to neutral pronation, randomly assigning them to one of three types of footwear to follow a 12-week training program for a 10 kilometer race: neutral (Nike Pegasus 28), partial minimalist (Nike Free 3.0 V2), or full minimalist shoe (Vibram 5-Finger Bikila). They found that the partial minimalist group displayed the most injuries (12) while the neutral shoe group displayed the lowest amount of injuries (4). The full minimalist group experienced greater shin and calf pain.\textsuperscript{177}

With these results, we might be quick to conclude that barefoot running comes with a higher risk of injury. However, these studies more realistically suggest that transition periods of 10-12 weeks, by themselves, may progress too quickly or are too narrow in scope of what is being addressed. Intrigued by these results, Johnson, Myrer, Mitchell, Hunter, and Ridge (2016) looked more deeply at a 10-week transition period to Vibram FiveFingers, discovering that those who developed bone marrow edema had weaker intrinsic foot muscles, specifically the abductor hallucis, than those who did not (as shown in Figure 9.1). Out of the 8 runners who developed bone marrow edema, 7 were female, highlighting a trend observed by Ridge et al. (2013) in which 8 out of the 11 of the runners who developed bone
marrow edema were female. They suggested that in developing a more effective transition plan, we should consider exercises to strengthen the muscles of the intrinsic foot as well as encourage additional transition time for female runners.

Mechanically, a transition period likely involves a change in foot strike. Although the extra movement of forefoot strikers from plantar flexion at impact to dorsiflexion at midstance has actually been shown to provide cushion for runners, the muscles, tendons, and bones responsible for controlling impact are often underdeveloped from underuse with shod mechanics, fatiguing quickly. Hashish, Rami et al. (2016) have confirmed this notion by studying rearfoot striking individuals who are habitually shod in their initial transition to either forefoot or midfoot barefoot striking patterns. After runs of 20% of their shod running distances, these novice forefoot and midfoot strikers demonstrated a reduction in ankle energy absorption and an increase in loading rate due to fatigue in the triceps surae (the gastrocnemius and soleus muscle pair), putting them and the surrounding structures at a higher risk of injury.
Figure 9.2: The dark gray denotes pre-exertion and light gray denotes post-exertion in the top two graphs. Novice barefoot runners exhibited fatigue in their soleus and gastrocnemii during light running (top two) that decreased their ability to absorb energy (bottom). The authors of the study suggest incorporating eccentric exercises in transition to prevent fatigue of the muscles in the calf and foot.
A proposed study by Fuller, Thewlis, Tsiros, Brown, Buckley (2015) approaches the transition period concept more deeply by implementing a 26-week transition period and testing running economy, biomechanics, foot strength, and bone density at several points in the process. The authors outline the variety of transition periods that have been tested in previous literature in Figure 9.3, none of which break the 12-week mark in study. Although there have been a few studies that have implemented a transition period of greater than 12

<table>
<thead>
<tr>
<th>Author</th>
<th>Date</th>
<th>Minimalist shoe</th>
<th>Week 1</th>
<th>Method for transitioning to minimalist footwear*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Giancolini et al</td>
<td>2013</td>
<td>Salomon Sense S-Lab</td>
<td>33%</td>
<td>Increase by 3–17% each week until reaching 100% in week 4</td>
</tr>
<tr>
<td>Ridge et al</td>
<td>2013</td>
<td>Vibram FiveFingers</td>
<td>3–13%</td>
<td>Increase by 3–13% each week until week 3</td>
</tr>
<tr>
<td>Ryan et al</td>
<td>2013</td>
<td>Vibram FiveFingers</td>
<td>19%</td>
<td>Gradual increases were made from week 1–12</td>
</tr>
<tr>
<td>Miller et al</td>
<td>2014</td>
<td>New Balance Road Minimus</td>
<td>7%</td>
<td>Increase by &lt;10% each week from week 1–12</td>
</tr>
<tr>
<td>Warne and Warrington</td>
<td>2014</td>
<td>Vibram FiveFingers</td>
<td>10%</td>
<td>Gradual increases were made from week 1–4</td>
</tr>
<tr>
<td>Moore et al</td>
<td>2015</td>
<td>Vibram FiveFingers</td>
<td>3–10 miles</td>
<td>Increase by no more than 20% each week</td>
</tr>
</tbody>
</table>

*Values indicate percentage of weekly running performed in the minimalist shoe condition.

**Figure 9.3:** This table documents a variety of different transition periods used in literature. A range of methods are illustrated demonstrating a lack of consensus on the issue. It is interesting to note that none of the studies exceed 12 weeks in transition period.
weeks, none were able to draw extensive conclusions on injury rates due to the focus or size of the experiment. This demonstrates the lack of prospective research on a longer transition period.

9.3. Transition Aside

Although the studies of shorter transition periods have been inconclusive with regards to injury prevention in minimalist running, several studies have suggested that, absent of the testing of transition period, the mechanics underlying minimalist running result in lower injury rates. One such study conducted by Hryvniak, Dicharry, and Wilder (2014), collected data via a 10-question survey posted on running blogs and Facebook pages. The study concluded that, upon taking up barefoot running, 68% of runners had no new injuries and 69% of runners experienced significant improvement of previous injuries (e.g. knee, foot, ankle, hip, and low back).

Daoud et al. (2012) conducted a retrospective study of the injuries of Harvard’s cross country team over a four year period. This study examined 52 runners, 36 (69%) were identified as heel strikers and 16 (31%) were identified as forefoot strikers. The findings of the study were that although a majority of the runners experienced injury each year (74%), the rearfoot striking runners were approximately twice as likely to experience repetitive stress injuries as forefoot striking individuals. This study was one of the first studies to conclude that a forefoot strike was associated with significantly less overall injuries than a rearfoot strike. Since the mechanics of barefoot and shod running generally take on these
striking patterns, it doesn’t seem too much of a stretch to consider these conclusions in the barefoot versus shod debate.

Altman, Davis (2016), in one of the most comprehensive studies of barefoot running to date, found that barefoot runners experienced fewer impact-related musculoskeletal injuries (i.e. patellofemoral pain syndrome and iliotibial band syndrome (ITBS)) as well as a reduced occurrence of plantar fasciitis while experiencing higher rates of injuries to the calf and plantar surface of the foot (i.e. Achilles, calf, and posterior tibialis strains). These findings supported past notions on a different nature of injuries between the two conditions.\textsuperscript{191,192} The study looked at 201 participants (107 barefoot, 94 shod) over the course of a year and had them log their miles and report injuries. The average barefoot runner had been experimenting with barefoot running for 1.65 years, one of the longest controls with respect to transition in current literature. Although the barefoot running group reported fewer overall injuries, they also ran fewer miles than the shod running group on average. The injury rates between the two groups were fairly similar when considering injuries per mile run. The authors offer that the difference in miles logged might be due to an overall demographic trend; barefoot runners tend to be older, less competitive runners.\textsuperscript{196}

This study controlled well for a longer transition period (by recruiting already transitioned minimally shod runners) and took a prospective (as opposed to retrospective) approach, two things that aren’t common in existing literature. However, there were limitations in the methods that prevent the conclusions from being the end of discussion on the topic: 1) it used a self-reporting survey method to collect data, 2) it did not account for
more exhaustive data on past injuries, 3) it had a demographic distinction (i.e. age, running
distance) in the two experimental groups,\textsuperscript{6} 4) it did not account for how strength of intrinsic
foot muscles varied,\textsuperscript{7} 5) it did not monitor the runners’ mechanics,\textsuperscript{8} and 6) it did not
document how the runners had transitioned to minimalist shoes (perhaps the biggest
shortcoming).\textsuperscript{197} Without monitoring the transition period, we don’t know whether or not
the transitioned runners had adequately addressed the deeper structural limitations (e.g.
stiffened, weakened, or shortened tendons and muscles in the feet, ankle, and calf) before
full transition to barefoot running. As we will talk about in the next section, it is vital to restore
strength, mobility, and elasticity to these muscle-tendon units during transition through the
use of rehabilitation exercises. Without proper attention, runners are likely to still experience
the lingering effects of these structural limitations even years after transitioning, which may
have been an explanation for the higher rate of injuries in barefoot runners in the experiment.

\textbf{9.4. Impact of Running Surface}

When trying to explain the injury epidemic in American runners, many people are
often quicker to point to our running surfaces rather than our running shoes. They claim that

\textsuperscript{6} Ridge et al. (2013) and Johnson et al. (2016) suggested that demographic differences play an important
role when determining injury rates.

\textsuperscript{7} The findings of Johnson, Myrer, Mitchell, Hunter, and Ridge (2016) suggested that the strength of intrinsic
foot muscles has important implications for who does or does not experience injuries.

\textsuperscript{8} The findings of Daoud et al. (2012) suggest that running mechanics might have important implications
for running injury. The survey style experiment cannot look more deeply at individual runners and their
mechanics.
although we may have been “born to run” on softer ground, we were not born to run on concrete. Is this notion supported in literature?

Marti, Vader, Mider, and Abelin (1988) explored this topic by surveying the nature of jogging injuries among all participants of a popular 16-kilometer race. A response rate of 83.6% yielded 4,358 male participants. The study found no significance in the relationship between training surface and incidence of injuries. Taunton et al (2003) studied a group of 844 recreational runners over 12 weeks and found no relationship between running surface and incidence of injuries. There is no known large-scale study that has concluded a harder surface results in more injuries.

The concept of leg stiffness was studied by Ferris, Liang, and Farley (1999), in examination of how runners adapted to their first step on an abrupt change in running surface. They found that runners anticipated the stiffness of the running surface and adjusted the stiffness of their leg before impact to maintain a consistent ground contact time, stride frequency, and overall center of mass, despite a big change in surface compression from 6 cm to 0.25 cm. Vertical ground reaction force was fairly similar on both the hard and soft surface and was only different when the change in surface was unanticipated.198

The implications of this study may be counterintuitive to some. Runners operate with an increased leg stiffness on softer surfaces than on harder surfaces. Although there is no conclusive evidence that leg stiffness causes higher incidences of injuries, some studies suggest that there may be a different nature of injuries. Butler, Crowell, and Davis (2003) suggested that increased stiffness may be associated with higher risk of injuries to bones
while decreased stiffness may be associated with higher risk of injuries to soft tissues. Some experts have suggested that it may be beneficial to change up the running surfaces to work through a range of leg stiffnesses and work different muscles.

When runners want to change their mechanics, they usually start out on a softer surface to experience a more forgiving impact. However, a study by Gruber et al. (2013) found that if habitual rearfoot strikers ran barefoot on a hard surface, 65% ran with a forefoot or midfoot strike while only 20% ran with a forefoot or midfoot strike on the soft surface. This suggests that although a runner may want to start out on a softer surface, they should progress to harder surfaces to receive the better ground-foot feedback to train the desired change in mechanic. For our experiment, we will progress to harder surfaces from softer surfaces after two weeks of training a forefoot strike in transitioning runners.

9.5. Rehabilitation: The Missing Link

As we talked about previously, there are a variety of conditions that are developed in habitually shod populations that may severely inhibit a transition to barefoot running. These conditions target muscles, tendons, and bones in the foot, ankles, and lower calf, reducing the ability of a transitioning runner to adequately absorb shock during a forefoot strike. As Hashish et al. (2016) demonstrated, runners with underdeveloped structures in the feet, ankles, and calves will experience fatigue of these same structures, reducing their ability to absorb impact and putting them at a higher risk of injury. Additionally, Johnson et al. (2016) found an association between weak intrinsic foot muscles, specifically the abductor hallucis,
and the occurrence of bone marrow edema in transitioning runners. They suggested that a proper transition plan might involve improving strength of the intrinsic foot muscles. Others have also prescribed that strengthening exercises be used in transition programs to correct for these underdeveloped structures. As Thomas and Burns (2016) described, the benefits associated with strength training aspect of rehabilitation are: 1) increase in lean body mass; 2) increase in metabolic rate; 3) increase in bone density; 4) decrease risk of injury; and 5) building back lost muscle tissue that occurs with aging or underuse. Strengthening exercises during the transition period should be targeted at the longitudinal arch, ankle, and calf, which experience greater load during a transition to a forefoot strike.

In motion-oriented strength training movements there are two phases: concentric and eccentric. Concentric movement involves a shortening of the muscles during contraction (e.g. the push of a bench press or curl of a bicep curl) while eccentric movement focus on the lengthening of the muscles during contraction (e.g. negative portion of bench press or bicep curl). Concentric training is known to increase strength by loading the muscles in the contraction phase. Concentric-focused training is used the majority of time in strength training. Eccentric training, however, has a key place in complementing concentric training. Since the body can handle more weight in the eccentric phase compared to the concentric phase, it allows for greater load of the muscles and potential for greater muscle hypertrophy. Further, it can optimize muscle length for maximum tension development at a greater degree of extension. The program we will use in our experiment has a combination of both concentric and eccentric movement.
The benefits of stretching have been known for some time. Wilson et al (1992) studied the effects of flexibility training on bench press performance. While the control group exhibited no improvements, the group partaking in flexibility training improved the rebound bench-press performance likely by increasing the utilization of elastic energy during the rebound bench-press through a reduction in stiffness of muscle–tendon units. The study supported other research of the benefits of stretching on the performance of stretch-shortening cycle exercises and compliance of muscles. Mahieu et al. (2007) emphasized that although all stretching is beneficial in the rehabilitation process, ballistic stretching might play a more important role in addressing tendon stiffness while static stretching might play a more important role for passive resistance torque. Since athletes who engage in sports with higher stretch-shortening cycles are more likely to experience tendon injuries, Witvrouw, Mahieu, Roosen, McNair (2007) argue that elasticity-focused stretching should be incorporated in the training and rehabilitation programs of athletes in high stretch-shortening cycle sports. Harrison, Keane, Coglan (2004) recognize that although stretch-shortening cycles are a more prevalent movement for sprinters and jump-dominated sports, they still play a crucial role in endurance runners. Since barefoot forefoot striking runners go through higher rates of stretch-shortening cycles than shod heel-striking runners, a transition period from shod to barefoot running should include stretching that focuses on the elasticity of specific tendons and muscles in addition to static stretching. Since professionals still warn of the potential risk in ballistic stretching, we will stick to the use of static, dynamic, and Proprioceptive Neuromuscular Facilitation (defined in the paragraph below) stretching in our program. These stretches together are still effective at improving overall elasticity in the
muscles-tendon unit and can likely negate the effects of a stiffened tendon and muscles due to being habitually shod.

Toft et al. (1989) studied Proprioceptive Neuromuscular Facilitation (PNF), a stretch technique combining passive and isometric techniques. They found that the contract-relax variation of PNF stretching performed twice a day for three weeks reduced the passive tension in the plantar flexors by up to 36%, demonstrating improvement in ankle mobility in both the short-term and long-term.\textsuperscript{224} Because of its short-term effects on range of motion, the stretch should be done following exercise as opposed to before. Recent literature states that the use of PNF stretching is the fastest and most effective way to increase static-passive flexibility\textsuperscript{225} and can significantly increase range of motion and performance.\textsuperscript{226,227} We will target the muscles of the calf through PNF stretching.

Implementing an evidence-based rehabilitation program to the transition period might have drastic effects on the effectiveness of a safe transition to minimalist footwear.

\textbf{10. Minimalist Shoes}

So far, we have generalized barefoot experience to include both unshod and minimalist shoes. What makes a shoe “minimalist?” How well do minimalist shoes mimic the barefoot experience?
10.1. Minimalist Index

Esculier, Dubois, Dionne, Leblond, Roy (2015) were determined to reach a consensus scale on what makes a shoe “minimal,” using the Delphi method with 42 experts from 11 different countries. This panel of experts decided on five categories: weight, motion control/stability devices (as shown in Figure 10.1\textsuperscript{228}), flexibility (as shown in Figure 10.2\textsuperscript{229}), heel to toe drop, and stack height. These equally weighted categories formed what is now called the Minimalist Index, a scale system from 0 to 100% outlining how minimal a shoe is in practice. A 100% minimalist shoe most sufficiently mimics the barefoot experience. The scores from the Minimalist Index were highly correlated with the visual analog scale, confirming this as a reliable method to identify the degree of minimalism in a shoe.\textsuperscript{230}

Many studies have emphasized the efficacy of the Minimalist Index in how a shoe relates to the barefoot experience. Squadrone, Gallozzi (2009) demonstrated that the Vibram FiveFinger, a shoe that is close to 100% on the Minimalist Index, was not only effective in

Figure 10.1: These various technologies account for the motion control/stability devices score.

Top Row (left to right): flare of medial tip of midsole, elevated (instead of flat) medial midsole under arch, rigid heel counter

Bottom Row (left to right): supportive tensioned medial upper, multi-density midsole, thermoplastic medial portion of midsole
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mimicking the barefoot running mechanic but also provided a small amount of protection from the ground. Hein and Grau (2014) conducted a similar study but with regards to the Nike Free 3.0, a shoe listed at roughly 65% on the Minimalist Index. Although there were many similarities to barefoot mechanic, there were also some distinctions. When compared to the runners in the Nike Free 3.0, barefoot runners revealed a flatter foot placement, a more plantar flexed ankle joint, and a less inverted rearfoot when striking. A similar study done by Bonacci et al. (2016) demonstrated the same conclusions when using both the Nike Free 3.0 and the racing flat Nike LunaRacer2, showcasing the importance of the level of minimalism of a shoe in mimicking a barefoot running experience.

Our experiment will transition from a conventional shoe to a halfway shoe before transitioning to a full minimalist shoe. The time frames will follow the conservative guideline suggested by The Running Clinic, the sponsor of the Minimalist Index study. The guideline
suggests taking roughly a month for transition of every 10% jump (up or down) in the Minimalist index (as demonstrated in Figure 10.3\textsuperscript{235}).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{diagram}
\caption{The Running Clinic prescribes roughly a month of transition for each jump of 10% in the Minimalist Index. Accordingly, runners should take 8 to 9 months to transition from a conventional shoe (~10-20%) to a fully minimalist shoe (~100%). In the literature, there has been few studies with transition plans longer than 12 weeks and no studies with transition plans of more than 6 months.}
\end{figure}

11. Methods

11.1. Subjects

This experiment involves 300 total runners from the Greater Los Angeles Area who run at least four days per week, have been running in a conventional running shoe (Minimalist Index <30%), run primarily on harder surfaces, and have not been injured in the last month. These runners will be split into 3 groups of 100 runners (300 total) trying to control for
demographics of the following (from most important): similar average of miles run in a week, similar distribution of striking mechanics (i.e. heel versus forefoot strike), and similar age.

11.2. Transition Program

In the literature reviewed, there has not been an agreed upon transition period for runners who are switching to a minimalist running shoe. In one of the more conservative estimates, The Running Clinic, sponsors of the Minimalist Index study, suggest that runners should aim for roughly one month of transition period for every 10% change in Minimalist Index score. Thus, they recommend anywhere from 5 to 9 months as a transition period for a runner switching from a conventional shoe to a full minimalist shoe (as shown in Figure 10.3). The experiment will utilize a 32-week transition period from a conventional shoe (roughly 20% Minimalist Index rating) to a near 100% Minimalist Index shoe, the Vibram FiveFinger KSO EVO. During the first 12 weeks, participants will transition to an intermediate shoe, the Under Armour Speed Swift (Minimalist Index value of roughly 50%). The final 20 weeks will be spent transitioning from the Speed Swift to the KSO EVO. The chart below details the progression. The experiment utilizes a plan that implements “jump weeks” that add an additional day of running in the transition shoe every few weeks. Although the transition plan is based on the number of days run in the shoe, participants are encouraged to begin a “jump week” by using the additional day of transition shoe running for one of their shorter runs. This will allow for gradual progression of transition.
Figure 11.1: Runners in this experiment run at least 4 days per week. Depending on the amount of days run during the week, runners will slowly add days over the course of the 32-week plan. Notice that the transition to the fully minimalist shoe doesn’t begin until week 13. The first 12 weeks, the participants will transition to a mid-way shoe at about 50% Minimalist Index.
11.3. Rehabilitation Program

<table>
<thead>
<tr>
<th>Category</th>
<th>Exercise</th>
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<tbody>
<tr>
<td>Introductory Activity</td>
<td>Barefoot Walking Progression</td>
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<tr>
<td>Running Form</td>
<td>Strike and Frequency Progression</td>
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<tr>
<td>Proprioception</td>
<td>Single-leg Balance Progression</td>
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<td>Flexibility</td>
<td>Single-leg Wall Calf Stretch</td>
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<td>Single-leg Stair Calf Stretch</td>
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<td></td>
<td>PNF Calf Stretch</td>
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<td></td>
<td>Golf Ball Arch Roll</td>
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<tr>
<td>Strengthening</td>
<td>Towel Curls</td>
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<td></td>
<td>Standing Short Foot</td>
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<td>Toe Spreads</td>
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<td>Eccentric Stiff-leg Calf Drop Progression</td>
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<td></td>
<td>Eccentric Bent-knee Calf Drop Progression</td>
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<tr>
<td>Plyometric</td>
<td>Vertical Ankle Jump Progression</td>
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<td>Lateral Quick Jump Progression</td>
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<td>Bounding</td>
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<td>Split Scissor Jump</td>
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<td></td>
<td>Depth Jump</td>
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Figure 11.2: The rehabilitation program is split into six categories that focus on a multifaceted approach to preparing the body for minimalist running.

In one of the transitioning groups, we will add a rehabilitation program. The overarching categories, adopted from Rothschild (2012), will include introductory barefoot activity, running form, proprioceptive exercises, flexibility exercises, strengthening exercises, and plyometric exercises. In addition to the description given below, the participants will be required to watch explanatory videos on the exercises to educate them on proper mechanics.
The participants will keep a weekly log of their exercises in an online database, ensuring that they have completed the designated number of sets and reps for each exercise. Participants should expect to be sore for the first few weeks and also the week a new exercise is introduced. Although the program builds gradually, if a participant feels the program is progressing too quickly, they should adjust sets and reps to suit their needs. All changes in sets and reps must be logged in the online database and the participant will receive follow-up about how to progress forward.

Further explanation of each exercise is given in the following section. Note that all exercises are done barefoot except the plyometric exercises, which are done in the transition shoe. The program is done Monday through Friday, giving specific days for different exercise to be completed.
Figure 11.3: The rehabilitation program is the core of our experiment. Each exercise is evidence-based to restore muscle-tendon units to perform at their potential.
11.3.1 Introductory Activity: This will focus on beginning to restore the sensory feedback to the foot.

11.3.1.1 Barefoot Walking Progression: This exercise is simply walking for the allotted time and surface given in Figure 11.3. This allows for participants to begin to feel the benefits of the sensory feedback of their feet and begin to get a feel for the ground. It will also encourage the natural splaying of the toes that is often limited by wearing shoes, something that will further develop over the course of the transition to running in fully minimal shoes.  

11.3.2 Running Form: Since the mechanics of barefoot running are much different than conventionally shod mechanics, we must consider retraining the running gait. The desired striking pattern for minimalist runners is forefoot strike to reduce vertical ground reaction force as well as loading rate, accompanied by a decrease in stride frequency. Since runners don’t automatically retrain their gait, instruction has proven important to influence the development of proper mechanics. Warne (2014) and Wilson et al (2014)
demonstrated that many runners still kept shod running mechanics even when running unshod, suggesting a benefit for gait retraining exercises.\textsuperscript{243, 244}

11.3.2.1 Strike and Frequency Progression: This progression exercise focuses on two things: forefoot striking\textsuperscript{9} and stride frequency. A shod heel strike and forefoot strike are shown above in Figure 11.4\textsuperscript{245}. Mechanics of barefoot running demonstrate that the forefoot strike is more natural,\textsuperscript{246} aiming to strike the ground with the ball of the foot between the fourth and fifth metatarsals and allow the subsequent rolling of the foot inward (pronation)

\textsuperscript{9}It is important for the participants to note that this forefoot strike (toe-heel-toe) is distinct from the forefoot strike used by sprinters in which their heel never hits the ground.
to absorb shock as the heel hits the ground.\textsuperscript{10} While training the strike, runners should focus on taking short, quick steps as opposed to longer, slower strides. A cadence of 180 steps per minute will be sent to each participant to listen through headphones or speakers in order to develop optimal stride frequency,\textsuperscript{247} which will aid in the effectiveness of the forefoot strike. The progression follows from soft surfaces to hard surfaces. Although not a perfect indicator, a general gauge for the hardness of a surface is to bounce a ball on it—the higher the bounce the harder the surface.

Figure 11.5: This side-by-side comparison of a shod heel strike with a barefoot forefoot strike highlights two key distinctions: 1) locked knee vs. bent knee 2) foot strike out in front vs. foot strike within center of mass.

Participants are instructed to strike with the forefoot and take shorter strides.

\textsuperscript{10} Other exercises will strengthen the arch and intrinsic foot muscles to control for excessive pronation of the feet.
11.3.3.1. Proprioception: As mentioned earlier, a thick sole can limit the proprioceptive development in runners. Training proprioceptive feedback is crucial to restoring overall balance and stability.

11.3.3.2. Single-leg Balance Progression: Ankle disc balance exercises have been shown to be one of the best ways to develop increased proprioception. This progression focuses on increasing ankle stability and lower limb proprioception in order to better control impact forces. The progression (ground → balance disc → ground with eyes closed → balance disc with eyes closed) is done in increments of 4 weeks and should allow the participant to more effectively adopt a forefoot strike.

Figure 11.6: Single-leg balance will build increased stability and proprioception to aid in effective rehabilitation. Participants are encouraged to engage different parts of the foot, especially the toes, while balancing.
11.3.4. **Flexibility**: Flexibility is a crucial component in transitioning to forefoot striking mechanics. Without proper flexibility in the ankles, Achilles tendon, calves, and surrounding tissues, a runner will experience injuries due to a lack of elastic capacity in the muscles.\textsuperscript{250} These series of exercises are crucial in restoring proper range of motion to safely transition the forefoot running mechanic.

11.3.4.1. **Single-leg Wall Calf Stretch**: This stretch is done by placing the front foot flat on the ground and the back foot behind it with two hands on the wall. From this position the heel of the back foot should be pushed towards the ground. The participant should move the foot back until a stretch is felt through the calf while the heel is still on the floor.

![Figure 11.7](image)

*Figure 11.7*: Single-leg wall calf stretch is performed by pressing the heel back until a stretch is felt in the calf. Avoid knee movements that are not directly over the toes.
11.3.4.2. Single-leg Stair Calf Stretch: This exercise involves the participant standing on a stair or step with the ball of one foot and dropping the heel off the edge until the participant feels a stretch through the Achilles tendon and calf. It is recommended to have a railing or chair to hold on for balance assistance.

Figure 11.8: Single-leg stair calf stretch is a great exercise to loosen the muscles and tendons of the lower leg. Simply press the forefoot into a raised surface and drop the heel until a stretch is felt.

11.3.4.3. PNF Calf Stretch: This exercise is a unique target for calf and ankle mobility. This variation, adapted from Bodybuilding.com (2015), is performed by wrapping a towel or band around the forefoot while sitting flat on the ground with feet extended. The participant starts by pulling the toes towards the body in dorsiflexion for 10 seconds. Then, the participant pulls with force on the band towards the body while simultaneously pushing against the force of the band. After 6 seconds, the toes point again towards the body bringing the foot to dorsiflexion for 30 seconds. This completes one rep. Because of the effectiveness
of these stretches, it is recommended that they are performed after a running workout to avoid being too loose.\textsuperscript{251}

11.3.4.4. The Golf Ball Arch Roll: This exercise involves rolling out the muscles and tissues that make up the arch of the foot. Either standing up or sitting down, the participant will roll the golf ball across the longitudinal arch, pausing on spots that are tender. It is important to utilize different angles as the participant rolls through the arch. Although this

\textbf{Figure 11.9:} PNF stretching is one of the best ways to achieve flexibility returns. Participants are strongly encouraged to do this stretch after a run rather than before to avoid potential injury.
exercise is primarily designed for the release of the arch, the participant is encouraged to roll through the heel, forefoot and toes to release tension in other parts of the foot.

![Figure 11.10: The golf ball arch roll is a great way to reduce tension and pain in the foot. Simply roll the ball along the arch utilizing different patterns to target sensitive areas.](image)

11.3.5. **Strengthening:** Conventionally shod runners absorb a lot of their impact with their joints during a heel strike mechanic. When transitioning to a forefoot strike, runners need to focus on developing the strength to absorb forces effectively in the arch, calf, and surrounding muscles and tendons. These exercises specifically target the muscles that will take on greater loads in a forefoot striking mechanic.

**11.3.5.1. Towel Curls:** This exercise is great for strengthening the arches and toes as well as building better structural support of the foot, specifically targeting the flexor
digitorum longus and brevis, lumbricals, and flexor hallucis longus.\textsuperscript{254} The exercise is carried out by placing the entire foot and toes facing straight forward on the edge of a small towel, with the rest of the towel in front of your foot. The towel starts flat on the ground and is scrunched continually with the curling of the toes until the other end of the towel is reached or the towel cannot be scrunched anymore. This counts as one rep. If the towel does not scrunch until the other end, consider 12 curlings of the toes to be one rep.

![Image](image.png)

\textbf{Figure 11.11}: The towel curl is a great way to increase strength in the arch and increase dexterity of the toes. Even if the towel doesn’t scrunch as desired, the continued curling of the toes is the primary focus.

\textbf{11.3.5.2. Standing Short Foot}: This exercise targets many of the same muscles as the towel curls, with specific emphasis on activating the abductor hallucis, the largest of the intrinsic foot muscles.\textsuperscript{255} Strengthening of the abductor hallucis and surrounding muscles will help prevent overpronation in participants. The exercise is performed by standing with the feet and toes flat on the floor. The participant starts by pushing through the arch to lengthen the foot, resulting in a flatter arch. From this position, the participant pushes through the heel, forefoot, and toes while subsequently trying to lift the arch, holding this short foot
position for 5 seconds. A return to the initial, flatter position completes one rep. A tip to successfully reaching the short foot position is to think of it as flexing the arch. The research suggests that this is one of the best exercises for restoring arch strength and structure.\textsuperscript{256 257}

![Figure 11.12: The short foot exercise may be the best way to restore the arch to its proper shape and function. Move from a flattened (low) arch to a contracted (high) arch to complete the exercise.](image)

**11.3.5.3. Toe Spreads:** The natural load bearing position of our feet is the spreading of our toes. This exercise is great for restoring dexterity and strength in the toes and intrinsic foot muscles brought upon by years of tight toe boxes, which will improve overall posture and stability.\textsuperscript{258} Kim et al. (2015) found that this exercise was beneficial for both strengthening the abductor hallucis as well as reducing the hallux valgus angle, suggesting its effectiveness in treating bunions. The exercise, adapted from Correct Toes (2018), is performed by placing the big toe on the ground, rotating the elevated heel inward, pressing the pinky toe on the ground to fan out the rest of the toes, and then dropping the heel to the ground to complete one rep. The exercise might be challenging at first (especially for those


with bunions), but participants are encouraged to perform it to the best of their ability, knowing they will show improvement with more practice.\textsuperscript{259}

![Image](image.png)

**Figure 11.13:** Starting with the big toe on the ground, move the lifted heel internally planting the pinky toe on the ground and subsequently spreading the toes as the heel comes to the ground. Dexterity and strength in the toes is vital for a proper transition to minimalist running.

### 11.3.5.4. Eccentric Stiff-leg Calf Drop Progression:

Eccentric training has shown to not only improve the strength of the muscles but increase the flexibility, coordination, and elasticity of muscles, especially during stretch-shortening cycles important in endurance running.\textsuperscript{260 \ 261} The eccentric calf drop in particular has been supported as one of the most effective non-surgical treatment and prevention options for Achilles tendinopathy.\textsuperscript{262}

Additionally, this exercise doubles up as a dynamic stretch for the calf. Needless to say, it is an essential part of this program. The eccentric calf drop begins with two legs on a stair or step, with something nearby to hold on to for balance (e.g. railing, chair). With only the ball of the foot and toes on the stair, perform a calf raise by pushing up to a heel-elevated ankle-locked position (this can be assisted by the railing as we are focusing on the negative part of
the exercise). From here, control the negative (eccentric) movement for three seconds until you reach a heel-drop position with the heel below the level of the stair and forefoot. Pause at the bottom for a second before raising back up into a heel-elevated ankle-locked position. A cycle of raise and control down to a heel-drop position is one rep. For the progression, the participant will switch from two-leg to one-leg. Participants are also encouraged to add weight in a backpack and/or increase the time of the eccentric portion if the exercise gets too easy.

Figure 11.14: Starting on your toes, drop down slowly to a heel drop position to complete one rep. This is one of the best exercises for reducing fatigue in the calf in elastic movements.
11.3.5.4. Eccentric Bent-knee Calf Drop Progression: The exercise follows the same mechanics and progression as the previous exercise while introducing a consistent knee bend throughout the exercise. This will allow for more direct targeting of the lower calf, ankle, and Achilles tendon. Participants are encouraged to add weight in a backpack and/or increase the time of the eccentric portion if the exercise get too easy.

![Figure 11.15](image): Bending the knee on the eccentric calf drop allows for different parts of the calf to be isolated.

11.3.6. Plyometric Exercises: Plyometric exercises play an important role in developing elasticity in the muscles and tendons. Each of the following exercises has been tested to improve distance running performance. 

11.3.6.1. Vertical Ankle Jump Progression: This exercise is great for training the elasticity of the tendons and muscles in the feet and calves. Start with both feet on the floor facing forward about shoulder width apart. Jump up with only a slight bend of the knee. Upon landing, bend the knees only slightly and jump back up as quickly as possible. The focus of
this exercise is not to jump as high you can but to spend as little time as possible on the ground. One jump is one rep.

**Figure 11.16**: These jumps are meant to be quick and not at max height. Utilizing a minimal arm swing will encourage decreased ground contact time.

### 11.3.6.2. Lateral Quick Jump Progression:

This exercise is also great for training elasticity in the foot and calves. However, the movement is unique and targets muscles and tendons that support lateral movement which are important for stability while running. This exercise is best performed with a cone, object, or line to jump over. Start on one side of the cone with feet about hip distance apart. While toes and body face forward, jump laterally
over the cone. Upon landing, spring back up and over the cone to where you started with your first jump. A cycle of there-and-back jumps is one rep.

\textbf{Figure 11.17}: The lateral jump is a great way to increase the stability of elastic response. Focus should be put on minimalizing ground contact time.

\textbf{11.3.6.3. Split Scissor Jump}: This exercise encourages single leg isolation, power development, and dynamic flexibility of the chain of muscles from the foot to hips. It is performed by assuming a split squat position with the back knee roughly 6-12 inches off the ground. Swing the arms up to propel the body into a jump, switching the legs at the top and
landing in a split-squat position with the other leg forward. Spending minimal time on the ground, swing the arms up to propel the body in the air, landing with the starting leg forward once more. A cycle of two jumps equals one rep. The focus of this exercise is minimal ground contact time.

11.3.6.5. **Depth Jump**: This exercise is one of the best ways to train the elastic response of the feet and legs. Start by standing on top of a platform 6 to 24 inches of the ground. It is recommended that the participant starts at a height on the lower end of this range before progressing to higher levels in order to prevent injuries. With both feet on the step facing forward, the participant will step off the box, contact the ground with the forefoot

![Figure 11.18: The split scissor jump is a more complex movement but great for single leg isolation and training elastic response from different angles.](image)
of both feet, and propel back up vertically as quickly as possible. It is important to note that the feet should be facing forward at impact and the knees should be directly above toes (avoid knee valgus). Since stepping off the box requires a horizontal element, the subsequent jump should be roughly the equivalent angle that the participant impacted the ground, and not strictly vertical.

**Figure 11.19**: The depth jump is one of the best exercises for training the retention of elastic energy. Upon hitting the ground, spring up as quickly and highly as possible, making sure the knees don’t roll inwards.

**11.3.6.5. Bounding**: This exercise improves coordination in addition to elasticity. It is nearly identical to a running stride except with an exaggerated push-off component. The goal of the exercise is to spend as little time on the ground as possible while covering as much
horizontal ground with each bound. A bound on both legs (i.e. two ground contacts) counts as one rep.

**Figure 11.20:** Bounding is a practical exercise that increases elastic efficiency in the stride. Start by pushing off one leg as far as you can, landing on your forefoot, and then pushing again. The goal is to cover as much ground with each bound.

### 12. Expected Results

Neither the proposed 32-week transition plan nor the rehabilitation program have ever been tested in the literature before. In fact, virtually all of the studies have studied transition periods of 12 weeks or less and had no testing of rehabilitation components. Thus, the results of this study are designed to bring to light blind spots in our knowledge about transition periods.
With the gradual 32-week transition period alone, the muscles and tendons will have the chance to naturally develop the elasticity to withstand some of the strain-related injuries exhibited in past studies. However, the transition plan sans rehabilitation program will not solve the structural deficiencies as effectively. Group C will exhibit the highest rate of injuries, with the majority of them being impact-related musculoskeletal injuries. Group B will exhibit a higher rate of strain-related injuries than Group C, but a lower overall injury rate. Group A will experience impact-and-strain-related injuries at rates lower than both of the groups due to effective preparation of muscles and tendons to increased demand. The difference in injury rates for Group A and Group B compared to Group C will be especially noticeable after the completion of the transition period in week 32. Differences due to demographic differences should be accounted with the gradual multi-faceted transition program (e.g. higher rates of bone marrow edema experienced in women during transition periods).

One potential factor for different results would be the response of participants to the rehabilitation program. Impact-heavy plyometrics pose a risk of additional injuries. The addition of non-running-related injuries would inhibit the effectiveness of the study by introducing a hidden variable. However, the introduction of plyometrics in this experiment is gradual and done at a maximum twice per week. The plyometric exercises are evidence-based in their benefits for endurance runners.

Another concern in the experiment is the accountability of the participants. It is virtually impossible to monitor each of the 300 participants for accuracy of what they report. If a large enough portion of participants in Group A are dishonest about their completion of
the rehabilitation exercises, the results would be misleading. Additionally, participants in Group A and Group B could be dishonest about the speed of transition over 32-weeks. Although the second transition shoe is not sent to the participant until week 11, participants may still be tempted to rush through the final 20 weeks of transition. The primary point of accountability will be in having participants sign a waiver of honest reporting, pledging that the weekly logged information regarding completion of the strength and exercise program and miles run in transition shoes is accurate. False information will result in loss of all payments from the experiment and the possibility of legal charges.

A final concern is that the two transition shoes used uniformly by the 200 participants in Group A and Group B will not adequately fit the feet of each individual. With a variety of widths, toe lengths, and deformities of the feet, there will surely be a few complaints. However, with assistance from the two companies who will provide shoes, we can address some of the concerns the participants share, finding the correct size and addressing discomfort. In specific cases, we can allow the use of alternative shoes with roughly the same Minimalist Index value. We will also issue replacements if there are defects in the shoes.

13. Future Research

Although this study will establish strong evidence for the effectiveness or ineffectiveness of barefoot running in injury prevention, further studies can bring further light to the topic. Six areas for future research are suggested. First, future studies can focus on the
longer transition period by using a different transition style. While this study does not have runners change their weekly mileage, future studies can implement a transition that starts with minimal miles. Second, additional intermediate transition shoes can be introduced to increase the degree of minimalism more gradually. Third, future studies can test the effectiveness of different exercises on successful transition, subtracting and adding exercises from this experiment. Depending on the results, the use of various levels of plyometrics will be an important area of studying. Fourth, although this program did not implement ballistic stretching due to safety reasons, there is evidence of its benefit in reducing tendon stiffness. Future studies could find a way to implement this method of stretching, particularly targeting the Achilles tendon, to reduce the excessive stiffness and shortening of Achilles tendon due to lifelong heel elevation in shoes. Fifth, future studies can address the limits of the survey method used in this experiment by using more in-person tracking of participants. This would also allow for the reliable testing of factors like loading rate, intrinsic muscle size, running economy, and running mechanics. Sixth, future studies could add a fourth group of lifelong habitually unshod runners to test the true effectiveness of the transition period.

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