Barefoot Running: Biomechanics and Implications for Running Injuries

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Abstract
Despite the technological developments in modern running footwear, up to 79% of runners today get injured in a given year. As we evolved barefoot, examining this mode of running is insightful. Barefoot running encourages a forefoot strike pattern that is associated with a reduction in impact loading and stride length. Studies have shown a reduction in injuries to shod forefoot strikers as compared with rearfoot strikers. In addition to a forefoot strike pattern, barefoot running also affords the runner increased sensory feedback from the foot-ground contact, as well as increased energy storage in the arch. Minimal footwear is being used to mimic barefoot running, but it is not clear whether it truly does. The purpose of this article is to review current and past research on shod and barefoot/minimal footwear running and their implications for running injuries. Clearly more research is needed, and areas for future study are suggested.

Introduction

According to the authors of a 2004 article published in *Nature*, humans were born to run (5). Bramble and Lieberman (5) have suggested that our body structure was significantly influenced by the fact that we needed to run for survival. These changes came about at a time when our brains were getting bigger and there was a greater demand for fats and proteins. Carrier *et al.* (6) has suggested that, prior to the invention of spears, bows, and arrows, *Homo* had to run his prey into heat exhaustion. Therefore, many believe that running is in our genes. Despite inferences that running may have been necessary for survival, there are clearly no data reflecting running injuries in these early *Homo* populations. Regardless of why we began to run, we clearly began running without shoes. The earliest example of footwear was discovered near Fort Rock, OR, and dated back over 10,000 years. These shoes were constructed of a flat surface of woven sagebrush with strapping to keep them on the feet. Their function simply was to protect the bottom surface of the foot.

Running footwear has evolved significantly from the early prototypes. Up until the running boom of the 1970s, shoes were constructed of a flexible upper attached to a thin outersole (19). However modern running shoes now have a significant amount of cushioning and stabilization incorporated in them, marketed for comfort, injury protection, and correcting movement patterns. This brings us to an important question. If we indeed have evolved to run and now have shoes that cushion and control our feet, why do we get injured doing it? Clearly many factors have changed since the evolution of our species, including but not limited to our environment, diet, and daily workout routines, but it has been suggested that our running footwear may have played an important role. It has been suggested that the cushioning features of modern footwear alter the way that we run and that the controlling features may decondition our feet. Proponents of modern shoes believe that these cushioning and motion control features are needed in order to protect us from injury. However no changes in injury occurrence are observed when appropriately matching runners to shoe type, based on foot structure (24–26,34).

There is a growing contingency that believes we were designed with all we need in our feet to be able to run sans shoes or with minimal shoes that mimic the running footwear of the 1960s. In fact, there has been a suggestion that running without the assistance of modern running shoes might lead to a reduction in the incidence of running injuries (28). However there have been many claims made on both sides of this issue. This footwear debate has led to healthy discussions but with many unanswered questions remaining. The purpose of this article is to review the current state of the evidence regarding differences in mechanics between shod and barefoot running and how this might be related to injury. The article concludes with areas for future research.

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Shod Running Mechanics

Before discussing what happens when running barefoot, it is important to understand how the modern running shoe has evolved and what it has afforded us. The earliest running shoe was developed in the 1890s by J.W. Foster and Sons (Reebok, Canton, MA) (19). The Foster Running Pump was a basic leather shoe with spikes added to the forefoot. The first sneakers, the Keds Champions (Keds, Richmond, IN), appeared in 1917 with the advent of vulcanized rubber. The running shoe progressed further in 1925, when Adi-Dasler (Adidas, Herzogenaurach, Germany) produced the first spiked running shoe that was customized for different types of feet. Generally up until the 1960s, running shoes were composed of a flat outsole, with an attached leather upper. They were lacking elevated heels, arch supports, cushioned midsoles, and stiff, supportive heel counters. These were the shoes that runners of those times, such as Frank Shorter, Bill Rodgers, Amby Burfoot, and Ron Hill (Fig. 1), donned for the Boston Marathon (19).

Running footwear began to change when Phil Knight imported the Asics Onitsuka Tiger, the first shoe with a cushioned heel, to the United States in 1963 (30). The trend continued when Knight left Asics to form Nike in 1972, where he developed their own brand of cushioned shoe, the Nike Cortez. As time has passed, the running shoe has continued to evolve with characteristics of movement control and stability. The modern shoe often has a dual-density midsole, elevated, cushioned heel, arch support, stiff heel counter, and an array of other features purported to assist in foot function and reduce injury. The benefits of these technological advances on injury prevention have not been documented.

It is well accepted that when running in modern running shoes, at least 75% of distance runners land on their heel, which is referred to as a rearfoot strike (RFS) (17), potentially due to the elevated, cushioned shoe heel. Twenty-four percent of runners land with a flat foot or a midfoot strike (MFS), and 1% land on the ball of their foot, referred to as a forefoot strike. In a more recent report, Larson *et al.* (27) observed 88.9% of runners as rearfoot, 3.4% as midfoot, and 1.8% as forefoot strikers at the 10-km point of a half-marathon and marathon road race. The authors attribute this increase to the amateur nature of this sample, compared with the more elite runners in the Hasewaga *et al.* (17,27) study. Footstrike patterns are adapted for many different reasons, including running environment, coaching, footwear, and body structure. Differences in mechanics between landing patterns are also well documented (1,7,28,48). Landing with an RFS results in a very defined impact peak in the vertical ground reaction force during contact, which precedes the propulsion peak (Fig. 2). This results in high loading rates in early stance. However, forefoot strikers are able to eliminate this impact transient through the eccentric loading of the posterior calf musculature, significantly reducing this loading. Midfoot striking results in more variable loading, but load rates typically fall between the rearfoot and forefoot strike pattern (1).

Landing with a forefoot strike also results in a shorter stride length (1,11), with the foot landing closer to the center of mass of the body. This reduces the moment arm of the ground reaction force to the hip and knee joints, likely reducing the joint moments that are generated. In fact, a study by Heiderscheit *et al.* (18) demonstrated that just a 10% decrease in stride length, while still rearfoot striking, results in a significant reduction in hip and knee energy absorption, thereby decreasing the loading to these joints. Similarly, small reductions in stride length have been shown to reduce the impact peak and loading rates (20). A reduced stride length appears to benefit bone as well. In a finite element modeling study, Edwards *et al.* (13) reported that reducing stride length by 10% (while maintaining speed) reduces the probability of developing a tibial stress fracture, despite the greater number of contacts one has with a higher cadence.

Forefoot striking does result in increased loads to the posterior calf musculature (8,16,48) as indicated by an increased moment and increased eccentric work of the plantar flexors. Additionally forefoot striking is associated with increased dorsiflexion velocities during the eccentric phase of gait (48). This may result in greater strain and strain rate to the Achilles tendon. Finally landing on the ball of the foot, especially if pronounced, will likely increase the stress to the metatarsal heads.

Shod Running Injuries

van Gent *et al.* (46) conducted a fairly recent, systematic review of the running injury literature. Based upon their review criteria, 17 articles, dating from 1982 to 2006, were included. These authors concluded that between 19% and

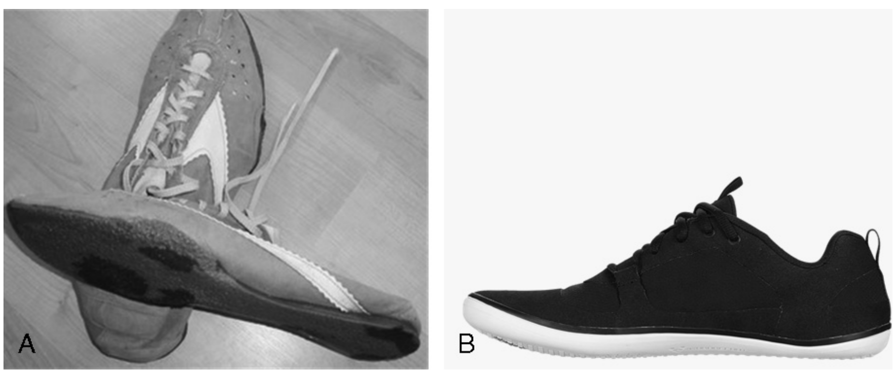

Figure 1: Shoes of Ron Hill, winner of the 1970 Boston Marathon (A). These shoes look very much like the minimal footwear of today with the thin sole and soft, flexible upper (B).

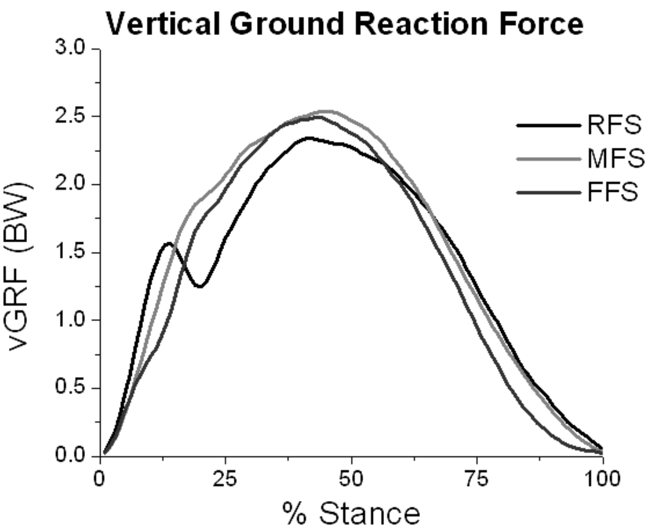

Figure 2: Vertical ground reaction force of a shod RFS, MFS, and FFS. Note the distinct impact peak of the RFS that is missing in the MFS and FFS patterns. RFS, rearfoot strikers; MFS, midfoot strikers; FFS, forefoot strikers.

79% of runners get injured within a given year. The knee is the most common site of running injuries, followed by the lower leg, foot, and upper leg. Patellofemoral pain, iliotibial band syndrome, tibial stress syndrome/fractures, plantar fasciitis, and Achilles tendinitis are typically among the most common injuries reported (45).

If running was important for our survival, an obvious question might be why we frequently are injured doing it. The etiology of running injuries is multifactorial in nature. Clearly overuse and previous injury play important roles (46). However abnormal mechanics also are believed to contribute to injury risk. While abnormal running alignment (foot pronation, genu valgus, and so on) has received much attention in the running injury literature, recent attention has been focused on the impact transient, with its high rate of loading, that is associated with an RFS pattern. Conversely the modern runner often participates in infrequent high-speed and high-intensity bouts of running for exercise or competition. This may place the modern runner at a higher risk for injury than our persistence hunting ancestors, utilizing regular bouts of longer, low-intensity running to catch their prey.

High rates of loading have been associated with the development of microfractures in rabbit tibia (40). These findings motivated our investigation of the vertical ground reaction loading rates in runners with a history of tibial stress fractures. We found increased vertical impact peaks and load rates as well as tibial shock in those runners with a history of tibial stress fractures (29,33). These results were supported further in a systematic review indicating high vertical load rates often were related to lower extremity stress fractures (50). We have since expanded our studies to include other types of injuries. We found high impact loading variables in RFS runners with a history of plantar fasciitis (32) and patellofemoral pain (3), two of the most common injuries runners sustain.

Rearfoot striking is associated also with an increased load to the muscles of the anterior compartment of the lower leg, due to the dorsiflexed ankle positioning at footstrike. This can result in hypertrophy of these muscles and increased pressures in the anterior compartment (23) and lead to chronic exertional compartment syndrome. This often is treated surgically with a fasciotomy to relieve the compartment pressure. In a very recent study, Diebal *et al.* (11) recruited 10 military cadets who were RFS runners with chronic exertional compartment syndrome and were indicated for a fasciotomy. They underwent a 6-wk program aimed at transitioning their running gait to a shod forefoot strike pattern. Following the intervention, pain was reduced to below 10/100 on a visual analog scale, anterior compartment pressures were reduced to normal, and subjects were able to increase significantly their running distance. Improvements further continued at the 1-year follow-up, and most importantly, all patients were able to avoid surgery — simply by transitioning off their heels (11).

Shod forefoot striking has received further support in a recent publication by Daoud *et al.* (8). In this retrospective study of mid and long distance runners, the injury records from 2006 to 2011 of 36 rearfoot strikers and 16 forefoot strikers on a collegiate cross-country and track team were analyzed. The study showed that mild and moderate running-related injuries occurred 2.5 times more frequently in rearfoot strikers than in forefoot strikers. The authors also determined that hip pain, knee pain, low back pain, tibial stress injuries, plantar fasciitis, and stress fractures (excluding metatarsal bones) were 2.7 times more likely to occur in rearfoot strikers (8).

Barefoot Running Mechanics

There is a rapidly growing body of evidence regarding mechanics during barefoot running. It is undeniably clear that running without shoes encourages a forefoot strike pattern (Fig. 3) (2,10,12,28). Landing on one's heel barefoot results in very high vertical ground reaction load rates that exceed those of shod heelstriking (28,10) and is typically very uncomfortable. The shock attenuating fat pad under

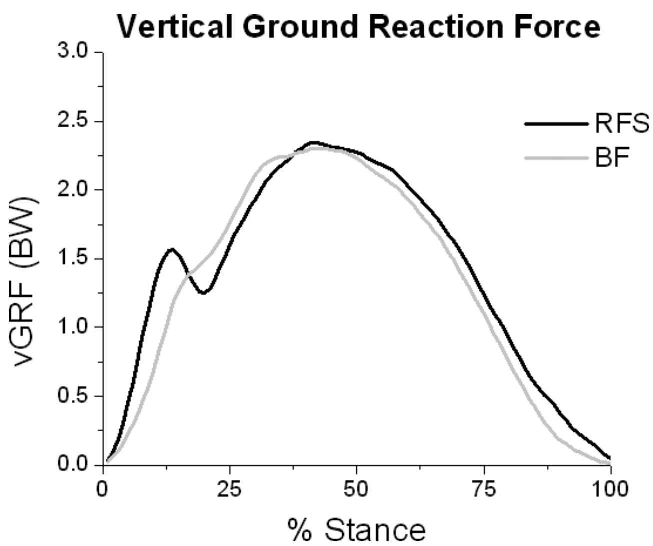

Figure 3: Vertical ground reaction force of a shod rearfoot striker (RFS) and a barefoot runner (BF). Note the similarity between the forefoot (Fig. 2) and barefoot curves.

the calcaneus deforms 169% more during a bare rearfoot strikers than in shoes (9). It has been suggested that the anatomy and small surface area of the heel is suited for the loads of walking, but not for attenuating the repeated impacts associated with running (36).

Barefoot running is associated with a shorter stride length and higher cadence than in typical shod running with an rearfoot strikers pattern (10,12,16). As suggested previously, this reduced stride length results in lower loads experienced by the body and may protect the runner from impact-related injuries (13,18,20). The ankle is plantarflexed slightly at landing when barefoot compared with slight dorsiflexion noted in the shod condition (43). Despite the plantarflexed position of the bare foot at contact, metatarsal pressures were similar to the shod conditions. As metatarsal contact area is likely to be lower in bare feet, contact forces during barefoot landings had to have been lower than in shod running in order for pressures to be similar. This suggests runners landed softer when running barefoot.

Barefoot running alters the mechanics of all of the joints of the lower extremity. At the rearfoot, the moment arms of the vertical and mediolateral ground reaction force are reduced, thereby reducing the external eversion moment (Fig. 4) and decreasing the tendency to evert. In support of this, De Wit *et al.* (10) reported that runners exhibited significantly lower rearfoot eversion in early stance during novel barefoot running compared with their shod condition. Forefoot striking while barefoot takes greater advantage of the energy-storing capacity of the arch, which is observed by the increased vertical arch motion during load acceptance (31). Arch elongation is reduced likely when running in shoes with supportive arches. There is some concern that running barefoot might result in fallen arches due to the repetitive loading of an unsupported foot. To the contrary, Robbins and Hanna (36) demonstrated a shortening of the medial longitudinal arch following 4 months of barefoot walking and running. Knee and hip mechanics are altered also when running barefoot. At the more proximal joints, Kerrigan *et al.* (22) reported that knee flexion, knee adduction, and hip external rotation moments were reduced when running without shoes. These authors explained these reductions were a result of reduced moment arms of forces acting at these joints.

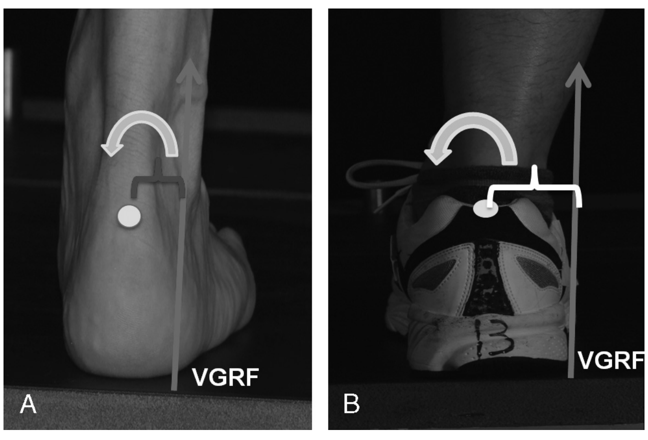

Figure 4: Eversion (pronation) moment (curved arrow) during barefoot (A) and shod (B) running, created from the vertical ground reaction force at landing. The eversion moment is higher in the shod condition (B) due to the larger moment arm resulting from the increased width of the shoe and heel flare.

Being barefoot appears to allow for more sensory input to the neuromuscular system. Shinohara and Gribble (41) reported greater static balance when standing in bare feet compared with socks. Similar to wearing gloves on our hands, socks likely filter out some of the important sensory input coming from the mechanoreceptors in our feet. Interestingly ankle position sense may be improved also when barefoot. A study by Squadrone and Gallozzi (44) found that static standing ankle joint proprioception was improved also when barefoot compared with being shod. In a more dynamic study, Rose *et al.* (38) found that dynamic stability during a single-leg landing using the Dynamic Postural Stability Index (47) was better in bare feet than in standard running shoes. This is despite the fact that the shoes had a larger base, and larger floor-shoe contact area, than the bare foot.

"Barefoot" Shoes

There has been an explosion of new barefoot running shoes on the market. Nearly every major shoe company now markets a "barefoot" or minimal shoe. The most commonly used minimal shoes recently reported were the Vibram Five Finger (Vibram, Albizzate, Italy), Nike Free (Nike, Inc., Beaverton, Oregon), Saucony Kinvara (Saucony, Inc, Lexington, MA), and New Balance Minimus (New Balance, Boston, MA) (39). However new minimal shoe companies are emerging also. While these new shoes are vastly different from the heavily cushioned, heavily controlling, modern running shoes, it is still unclear as to whether they truly mimic barefoot running.

There only have been few studies of running mechanics associated with minimal footwear running. It is assumed that, with the lack of cushioning in these shoes, runners will land more softly and less on their heels. Willy and Davis (49) conducted a pilot study of five recreational runners who were novice minimal footwear users. They reported that when running in the Nike Free 3.0 (Nike, Beaverton, OR) footwear, subjects actually landed in greater dorsiflexion and exhibited greater vertical load rates and tibial shock compared with a standard neutral running shoe (Nike Air Pegasus). However the Nike Free 3.0 does have a midsole and therefore allows for comfortable rearfoot striking.

In contrast, the Vibram Five Finger shoes are constructed of a thin rubber sole and mesh upper and offer very little in the way of cushioning. In the supplemental data of the *Nature* article by Lieberman *et al.* (28), the authors report on a training study using Vibram Five Finger shoes. Of the 14 runners, 10 of them began the training program landing with an RFS pattern. After 6 wk of training, all runners landed less dorsiflexed, but surprisingly, five of them still remained as rearfoot strikers. Without the sensory feedback between the sole of the foot and the surface of the ground, as originally proposed by Robbins and Hanna (36), the runner may not have the complete neural cueing to convert to a forefoot strike pattern. These results also suggest that even the thin rubber outer sole offered some protection to the heel to allow them to land on it. Additionally it is possible that runners were able to adjust their mechanics to land more softly, thereby significantly reducing the load on the heel at contact. This notion is supported by the fact that runners have been shown to soften their footstrikes when landing on hard surfaces (14).

Minimal footwear, like barefoot running, offers no support to foot, thereby increasing the demand on the foot and ankle musculature. Brugemann *et al.* (4) followed two groups of 25 runners for 5 months. One group warmed up for 20 min in the Nike Free 3.0 shoe (considered minimal at the time) and ran in their normal running shoes. The other group warmed up and ran in their normal running shoes. After 5 months, the group that warmed up in the Nike Free 3.0 shoes demonstrated a significant increase in the cross-sectional area of some of the intrinsic and extrinsic muscles of the foot and ankle, an indication of strengthening. In a related study, Shroyer *et al.* (42) studied the effect of wearing articulated toe shoes on the medial arch height. The authors reported no significant change in arch height and concluded that these preliminary data suggest that arches do not fail in the absence of support. This finding may be due to strengthening of the arch musculature, as was noted in the Brugemann *et al.* (4) study.

Barefoot/Minimal Footwear Running Injuries

The top reason that runners choose to switch to barefoot/minimal footwear running is to avoid future injury (39). However while 75% of all runners surveyed indicated an interest in barefoot/minimal footwear running, only 36% had attempted it. The most prevalent barrier to barefoot/minimal footwear running reported was fear of possible injury. Injury risk is, in fact, the aspect of barefoot and minimal footwear running with the least amount of evidence. The internet is full of testimonials of runners cured of their chronic running injuries by shedding their shoes. In contrast, there are also many stories about how barefoot running was the cause of being sidelined. However controlled injury studies are required. A recent article by Giuliani *et al.* (15) reported on two cases of minimal footwear users who developed metatarsal stress fractures associated with running. However without any data on mechanics, training patterns, and the like, most of this report was speculative regarding the cause of these injuries.

Based on what we know about barefoot running mechanics, it is possible to begin to generate some hypotheses about injuries in barefoot runners. These runners are generally forefoot strikers and as such have reduced rates of loading compared with the majority of their shod counterparts who are rearfoot strikers. While potentially related to the forefoot strike pattern, barefoot running is associated also with a reduced stride length, which also has a load-reducing effect. This combination may reduce their injury rate, as high load rates have been associated with numerous running-related injuries (3,29,32,33). However a forefoot landing will increase the load to the posterior calf musculature and thereby increase the risk of calf strains and Achilles tendinitis (16,48). In addition, a forefoot strike landing can increase the load to the metatarsal heads. However a natural barefoot landing is described typically as a very mild forefoot strike with the foot landing slightly plantarflexed and the heel slightly off the floor before lowering (12,28,36) (see video, supplemental digital content 1, at http://links.lww.com/CSMR/A3). Running with this type of mild forefoot landing may be ideal, as it has been shown that running without a heelstrike eliminates or significantly attenuates the impact transient (48). Running with a forefoot strike (FFS) pattern that also minimizes plantarflexion should reduce also the load to the posterior calf. Also, in theory, a low inclination of the foot at footstrike may reduce the load to the metatarsal heads by increasing the surface area of the foot at contact.

A concern often voiced is that running barefoot on hard surfaces will increase loading to the lower extremity and increase the chance of injuries. However it has been shown in numerous studies that runners will immediately reduce their leg stiffness in response to landing on harder surfaces (14). With gradual practice running on hard surfaces, it is possible that one can train the leg to be more compliant and adapt to these surfaces.

Running barefoot clearly exposes the plantar surface to injury. However the plantar surface is well suited for barefoot locomotion. It can tolerate 600% more abrading loads than hairy skin on the thigh (35). When loading becomes unexpectedly high, such as landing on a rough surface, the plantar surface of the foot provides sensory input that elicits an avoidance response, indicated by rapid hip flexion (37). This results in a quick unloading response, which is protective when stepping onto something such as a small pebble. However it is unarguable that the foot is more exposed and thus vulnerable to cuts, bruises, and abrasions when barefoot.

One of the biggest theoretical risk factors in barefoot running is doing too much, too quick, too soon. The body must have time to adapt to the new loading that it is experiencing. Habitual rearfoot strikers wearing modern running shoes with 10 to 14 mm elevated, cushioned heels should not abruptly change their footwear to zero drop, unsupportive, uncushioned shoes while maintaining their current mileage. It is imperative that a program that transitions runners slowly to the use of minimal footwear and the adoption of a mild forefoot strike pattern is followed. It takes time to develop the foot and lower leg musculature, as well as to acclimate to the plantar sensations during barefoot running (21,36). The most common problem associated with transition is soreness in the lower leg and foot (39). As sports medicine experts, we have a responsibility to educate runners about transitioning slowly to this new style of running in order to safely guide runners through an injury-free transition.

A few words of caution should be mentioned also. First of all, while it appears that runners plagued with injury may benefit from switching to a barefoot strike, at this time, there is less justification for changing running mechanics in injury-free runners. It is also unknown how barefoot running may affect those with special foot conditions, such as bunions, severe diabetes, or neuromas. In addition, caution should be taken when examining the evolutionary argument for barefoot running. In the era when persistence hunting may have been common, many environmental and societal factors also were different. For example, our ancestors were mostly located in warm, flat lands and were mostly animalistic in nature. Our current technologies allow us to live in subfreezing temperatures and spend much of our time sedentary. It should be noted that it is unknown what effect these factors have on current running injuries or on barefoot running in our modern environment. It is possible that the use of minimal footwear during cold months and unfriendly terrain may help to protect the feet while maintaining the mechanics achieved during barefoot running.

Future Research

At this moment, there is significantly more that we do not know about barefoot running than what we do know. Articles addressing biomechanical and physiological aspects of barefoot running are beginning to permeate the literature. There is suggestion in the literature that, along with reducing the impact transient, being barefoot provides increased sensory input (37,38,41) that results in greater static and dynamic stability. In addition, there is evidence that removing support from the arch results in improved strength of the foot and ankle musculature (4). However there is a paucity of studies describing injury patterns in this population. There are many questions yet to be answered before medical professionals can make informed decisions about what to recommend to their running patients. The following are six very basic areas to be addressed:

1. What are the differences between shod forefoot striking and barefoot running? Is there added benefit to the increased proprioception of barefoot running and potential strengthening of foot and ankle musculature, or are all potential benefits of barefoot running due to the mild forefoot strike pattern?
2. Who is appropriate for barefoot or minimal footwear running? Are there certain preexisting injuries or structural deviations that should preclude someone from barefoot running? Can runners using orthotics eventually adapt to running barefoot without injury?
3. What are the best ways to transition from shod to barefoot running to minimize injury? Are there specific strength prerequisites of certain muscles for transitioning to minimize injury? Is it best to start exclusively running barefoot in a slow, controlled progression, or slowly introduce barefoot running into an existing shod running program without altering mileage?
4. Are barefoot runners injured less often than shod runners? Are the injury patterns different between barefoot, minimal footwear and heavily shod rearfoot strikers runners?
5. What are the long-term effects of running barefoot on foot structure and muscle physiology, and how might these changes be related to injury?
6. What are the effects of running barefoot on long-term bone and joint health?

Conclusions

Running is likely the most natural form of exercise we have. There is some evidence that we were designed to run, and did so as part of our survival. However we spent most of our evolutionary history barefoot, with modern running shoes only appearing in the past 50 years. Therefore, one could argue that running with heavily cushioned and controlling shoes is actually unnatural and may contribute to the high rate of injuries that modern runners experience today. Clearly there are biomechanical differences between barefoot and shod rearfoot strikers running, and these have been documented well in the literature. However the injury risk associated with barefoot running is largely unknown. A paradigm shift in the way we think about footstrikes, footwear, and even treatment of the foot may be emerging. Well-controlled, large-scale, prospective injury studies are needed to determine whether shedding our shoes while we run is truly good for our health.

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