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What We Can Learn About Running from Barefoot Running: An Evolutionary Medical Perspective

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LIEBERMAN, D.E. What we can learn about running from barefoot running: an evolutionary medical perspective. *Exerc. Sport Sci. Rev.*, Vol. 40, No. 2, pp. 63–72, 2012. *Barefoot running, which was how people ran for millions of years, provides an opportunity to study how natural selection adapted the human body to run. Because humans evolved to run barefoot, a barefoot running style that minimizes impact peaks and provides increased proprioception and foot strength, is hypothesized to help avoid injury, regardless of whether one is wearing shoes.* **Key Words:** barefoot running, evolutionary medicine, injury, footstrike, proprioception, running biomechanics

INTRODUCTION

This review makes the argument that we can learn much about running in general from barefoot running. I first review the current debate about barefoot running, highlighting points of general agreement and disagreement, as well as some misconceptions. I then review the evolutionary medical hypothesis that the human body is adapted to a barefoot running style. I next consider what we do and do not know about the biomechanical differences between the ways many habitually barefoot and shod runners run and relate these contrasts to issues of injury, most of which are unresolved. I conclude with a series of questions and problems for future research.

Humans have been walking and running without shoes for millions of years, but there has been a recent surge of interest in barefoot running among runners, the media, and the sports medicine community. Although we know little scientifically about barefoot running, many diverse opinions have been expressed on the topic. As often is the case, extreme views tend to get the most attention. At one end of the spectrum, proponents of barefoot running argue that running without shoes is more natural and better for you and that shoes cause injury. At the other end of the continuum, skeptics argue that barefoot running is a dangerous "fad" to be avoided. Other frequently expressed opinions are that barefoot running is unhealthy because the foot needs cushioning, protection, support, and motion control; that barefoot running may be safe on a beach or a lawn but hazardous on hard surfaces such as asphalt and concrete; and that only individuals who are blessed biomechanically should run without shoes. One also hears a wide range of other passionate views but mostly confusion and many questions. Doesn't it hurt? Why are so many people interested in barefoot running? Is barefoot running better for you than shod running? How should people transition? What is the best way to run barefoot? What are the advantages and disadvantages of minimal shoes?

As an anthropologist who studies the evolution and biology of running, I find this cacophony of interest, opinion, and questions to be revealing. Dennis Bramble and I (1) have argued that humans have been running long distances for many millions of years, and, obviously, most of that running was done barefoot on hard, rough surfaces. Minimal shoes, such as sandals or moccasins, rarely survive in the archeological record, but they probably were invented in the Upper Paleolithic, which began only about 45,000 yr ago (21). Everyone including athletes ran barefoot or in minimal shoes until the 1970s when the modern running shoe with a cushioned heel, arch support, and stiffened sole was invented. It follows that the human body must be well adapted to running barefoot. From an evolutionary perspective, barefoot running is as natural as barefoot walking or, for that matter, doing anything else our hunter-gatherer ancestors did, such as nursing infants. Therefore, it is incorrect to consider barefoot running a fad or even intrinsically dangerous.

Another issue to consider is the conflation of running in minimal shoes with actual barefoot running. Many minimal shoes are advertised as barefoot shoes, but how can running in a shoe, no matter how minimal, be barefoot? The oxymoron "barefoot shoe" partly is marketing but also reflects a widely held opinion that there is a barefoot running style, for which minimal shoes are appropriate. If so, what is this style? In

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addition, are minimal or even standard running shoes appropriate for this kind of running?

Most fundamentally, the debate over barefoot running highlights concerns among runners, shoe manufacturers, and the sports medicine community about the high prevalence of running injuries. It is acknowledged widely that unacceptable numbers of runners — between 30% and 70% — incur running-related repetitive stress injuries per year (35–37), but there is no consensus on how to prevent these injuries. The lack of any apparent decline in running-related injuries over the last 30 yr (36), despite much attention, considerable research, and sophisticated shoe designs, suggests that current approaches are not working effectively. This lack of progress raises several widely held hypotheses. One is that running just intrinsically is injurious and that high rates of injury are normal and to be expected. Another common hypothesis is that many people today are maladapted to running long distances because of biomechanical abnormalities (*e.g.*, asymmetries), modern lifestyles that diminish flexibility or neuromuscular skill, or novel environmental conditions such as hard, flat paved running surfaces. A related, widespread hypothesis is that many injuries result from "training errors" when people run too far or too fast without properly adapting their musculoskeletal system or when they run too much on hard unvaried surfaces without appropriate protection from their shoes.

The barefoot and minimal shoe running movement primarily stems from a different hypothesis: that many running injuries derive from poor running form. Unlike swimmers, golfers, and tennis players, few runners today are taught running form in part because of a common assumption that running, like walking, is so natural that all humans develop a natural form appropriate to their anatomy and physiology. The evolutionary medical hypothesis discussed in the next section is that a barefoot style is, by definition, a more natural running style to which the human body must have been adapted over millions of years. If so, then a barefoot style might help runners avoid injury. Many barefoot runners also believe that the proprioceptive feedback one gets from being barefoot helps one learn this kind of form. However, it is important to stress that these hypotheses are so far untested. My impression is that most people who try barefoot or minimal running do so because they read or hear anecdotal claims, because they are curious about more natural ways to live, or because interventions such as orthotics or changing shoes have not cured their injuries. However, what is a barefoot running form, does taking off one's shoes encourage this kind of form, and is it really less injurious? Is actual barefoot running less injurious than running in minimal shoes? How will barefoot running or wearing minimal shoes affect performance such as speed or endurance?

The honest answer to these and other questions is that no one knows. My goal in this review is to first introduce why an evolutionary perspective on running is relevant to questions about the causes of running injuries. I then summarize what we do and do not know about barefoot running and how the study of barefoot running can be applied to the current epidemic of running injuries. The major hypothesis I propose is that the human body was adapted to running in a barefoot style whose kinematic characteristics generate less forceful impact peaks, which uses more proprioception, and which may strengthen the feet (6,20). I hypothesize that these factors may help runners avoid injury, regardless of whether they are wearing shoes. Put in simple terms: how one runs probably is more important than what is on one's feet, but what is on one's feet may affect how one runs. However, I stress that the data necessary to test this hypothesis conclusively are not yet available, so I conclude by highlighting key questions for future research that are of relevance to all runners, barefoot and shod.

WHY DOES EVOLUTION MATTER?

Sports medicine generally has not paid much attention to evolutionary biology, but this is a mistake. As the pioneering geneticist Theodosius Dobzhansky famously observed, nothing in biology makes sense except in the light of evolution (12b). All biological phenomena — from how DNA functions, to how humans run — are the consequence of millions of years of evolution, often through the action of natural selection. Therefore, considering phenomena, such as running through an evolutionary lens, helps one answer proximate "what" and "how" questions such as "What is the normal way to run?" and "How do people run without shoes?" as well as more ultimate "why" questions such as "Why do humans run?" and "Why do so many runners get injured?"

The burgeoning field of evolutionary medicine explicitly asks how evolutionary logic and information can help address why we get sick and injured (25). One key assumption behind evolutionary medicine is the mismatch hypothesis. The logic behind this important hypothesis is that the human body was molded over millions of generations to cope with conditions during the Stone Age. Because agriculture was invented less than 10,000 yr ago, and we ceased being hunter-gatherers, humans have changed their diet and physical environments so radically and so rapidly that natural selection has had little time to react. As a result, the Paleolithic bodies we inherited often are mismatched with modern environmental conditions. An uncontroversial example of this hypothesis is that humans were selected to crave formerly rare nutrients like fat and sugar. In the last few generations, our species has created superabundant and cheap sources of these nutrients, but most humans remain unable to control their inherited cravings effectively, leading to a propensity toward obesity. In other words, from an evolutionary perspective, it was "normal" to have limited access to fat and sugar, and it is "abnormal" to live in an environment where these foods are more abundant and less expensive than foods with complex carbohydrates and low percentages of saturated fat. This mismatch helps explain the obesity epidemic.

The mismatch hypothesis also may apply to shoes and running. It is human nature to assume the world around us is normal, but from an evolutionary perspective wearing big, cushioned shoes unquestionably is abnormal. Instead, it was normal for millions of years to walk and run barefoot. This does not mean, of course, that how our barefoot ancestors lived "normally" in the Paleolithic is better than how we live today. This obviously is a superficial and false kind of logic (would we be better off without antibiotics or aseptic surgical methods?). However, the mismatch theory does raise the reasonable hypothesis that humans are maladapted to wearing shoes in some ways that contribute to certain injuries. From an evolutional medical perspective, three novel consequences of wearing shoes may be relevant to injury.

First, shoes limit proprioception. Sensory feedback from the plantar surface of the foot evolved in early tetrapods as an adaptation for sensing characteristics of the ground including hardness, roughness, unevenness, and the presence of potentially dangerous objects such as sharp rocks. Plantar proprioception activates reflexes and helps the central nervous system make decisions that help increase stability and avoid injury. If so, then the way in which people run when barefoot likely is to reflect the effect of ancient evolved proprioceptive adaptations to maintain stability, to avoid painful impacts, and to modulate leg stiffness. In turn, these feedback mechanisms, which are curtailed in a shoe, may help avoid some traumatic and repetitive injuries (17).

Second, modern shoes with elevated heels, stiff soles, cushioning, and arch support may either facilitate or encourage a different running form than appears to be common among habitual barefoot runners (described in the next section). If natural selection adapted the human body to this general, barefoot style of running, then it is reasonable to hypothesize that this sort of running form may be less injurious because millions of years of natural selection would have promoted adaptations to cope with the stresses it generates. In other words, some runners today may be getting injured because the novel way they run imposes forces on the body for which it is adapted poorly.

Finally, there is reason to hypothesize that shoes can contribute to weak and inflexible feet, especially during childhood when the foot is growing. The musculoskeletal system is highly responsive to loading, most strongly during ontogeny, and the normal unshod mechanical environment in which human feet developed during most of human evolution surely was different from the more cushioned, supportive environment that is common today among shod people. Shoes with stiff soles, arch supports, and features that control pronation and other movements may prevent muscles and bones from adapting to stresses that used to be normal. Just as food processing leads to low chewing forces and weak jaw muscles that result in inadequate jaw growth and a high frequency of formerly rare malocclusions and impacted teeth (21), individuals who grow up wearing highly supportive shoes may develop abnormally weak feet, especially in the muscles of the longitudinal arch. Such weakness may limit the foot's ability to provide stability and other key functions. This hypothesis never has been tested rigorously (17), but unshod populations are reported to have less variation in arch form, including a lower percentage of *pes planus* (7), and a lower frequency of other foot abnormalities (30). In addition, there are some data that show using minimal shoes strengthens the foot (2,32). A strong foot may be more flexible and better able to control excess pronation and other movements that have been implicated in some running injuries (38,40).

Another basic prediction of evolutionary medicine is that many of the supposed symptoms of disease that we treat actually are evolved and beneficial adaptations. As an example, it is common to treat fevers with antipyretics such as aspirin, but an evolutionary perspective on the immune system encourages one to consider fevers as part of the body's immune response system that evolved to help fight infections. Suppressing fevers that are not life threatening may be counterproductive. Shoes with cushioned, elastic heels may be another example of a counterproductive way of treating symptoms, not causes, of injury because the heel counter lessens the pain caused by impact peaks, which occur from rearfoot striking on a hard surface (see later section on footstrike), but this kind of pain could be an adaptation to prevent the body from running in a way that generates repeated high impact peaks in the first place. Focusing on treating the causes rather than the symptoms of pain also may lead to different ways of thinking about common injuries such as plantar fasciitis and runner's knee. Plantar fasciitis, for example, is caused by too much tension on the plantar fascia and often is treated by prescribing orthotics or replacing one's shoes, which reduces loads on the plantar fascia (see (26,29)). An evolutionary medicine perspective suggests that these treatments only lessen the symptoms of plantar fasciitis rather than curing whatever biomechanical problem causes the plantar fascia to be overloaded in the first place. According to this approach, a useful preventative therapy may be to strengthen the muscles of the arch or alter a runner's kinematics to change the way the arch is loaded dynamically.

The more biologists study evolution, the more they appreciate the power of natural selection to arrive at solutions to problems that affect organisms' ability to survive and reproduce. No engineer possibly could come close to building artificial hands, arms, legs, and noses that function as well as a natural hand, arm, leg, or nose. As Leonardo da Vinci is reputed to have said, "the human foot is a masterpiece of engineering and a work of art." A reasonable hypothesis is that engineers are unlikely to build a shoe that functions as well as the natural human foot. So when we test questions like "Is barefoot running better?" or "Should people run barefoot?" we should determine what is the appropriate null hypothesis. From an evolutionary perspective, the correct null hypothesis is that running barefoot is less injurious than running in a shoe unless proven otherwise. Because of our skewed sense of what is normal, most scientists consider the alternative to be the correct null hypothesis, but I would contend that this logic is problematic.

WHAT DO WE KNOW ABOUT BAREFOOT RUNNING?

Until recently, most studies of barefoot running were conducted by asking habitually shod runners to take their shoes off in a laboratory (*e.g.*, (3,10,11,19,26)). Although such research has some utility, using only habitually shod runners to study barefoot running is problematic because one cannot expect such subjects to have developed the musculoskeletal adaptations and kinematic habits of habitual barefoot runners, and so they may run differently from people who either grew up barefoot or who have practiced barefoot running for a long time. It also is important to emphasize that all runners, barefoot and shod, vary in their form depending on a wide range of conditions such as speed, surface texture, surface hardness, and fatigue. Habitually shod runners when barefoot, for example, are more likely to rearfoot strike (RFS) on soft surfaces like grass and to forefoot strike (FFS) or midfoot strike (MFS) when running on hard surfaces (26). One hypothesis is that barefoot runners have even more variable kinematics than shod runners because they experience more proprioception from their feet. There is no such thing as a single barefoot running form but, instead, a highly variable range of kinematic styles.

With these caveats in mind, a number of studies on habitually shod and habitually unshod runners indicate that habitual barefoot runners often differ from habitually shod runners in several major elements of form (10,11,17,20,34). Whereas about 75% of shod runners RFS at moderate speeds on flat, hard surfaces (16), experienced barefoot runners are more likely to land toward the front of the foot, usually on the ball of the foot below the fourth and fifth metatarsal heads in either a MFS or FFS (see next section). That said, habitual barefoot runners sometimes RFS (20), and it is incorrect to assume that barefoot runners always FFS. Another common feature of habitual barefoot runners is a relatively short stride and a fast stride rate (>170 steps per minute), regardless of speed (11,15,19,28,34). A relatively shorter stride explains the observation that barefoot runners often land with the foot more vertically aligned with the knee and often the hip (less overstride).

To consider how these aspects of barefoot running form are relevant to the evolutionary medical hypothesis of injury, it is useful to review each of them in more detail to ask how they affect a runner's kinetics and performance.

Footstrike

The best-studied aspect of barefoot running is foot strike, which can be the most painful moment of stance when running unshod. Foot strike classification is confusing because of different definitions, but I define a RFS as a landing in which the heel lands before the ball of the foot (a heel-toe run), a FFS as a landing in which the ball of the foot lands before the heel (a toe-heel-toe run), a MFS as a simultaneous landing of the heel and ball of the foot, and a toe strike as when the ball of the foot first lands, but the heel never touches the ground. An alternative classification is the foot strike index, which uses the center of pressure at landing relative to maximum shoe length, with a RFS being less than 33%, a MFS between 34% and 66%, and a FFS as 67% or higher (4). However, this index is arbitrary with respect to the foot's anatomy. My observation is that the fourth and fifth metatarsal heads often are less than 67% of the foot's length, leading one to classify FFS and MFS landings in the same category.

Although a collision between any two masses causes an impact, it long has been recognized that the majority of RFS landings differ from FFS landings in causing a marked impact peak in the vertical ground reaction force (GRF_v): a high spike of force that is superimposed on the upslope of the GRF_v immediately after the foot's initial contact with the ground (Fig. 1). My colleagues and I have shown that during a barefoot RFS at 4 $m \cdot s^{-1}$ on a hard surface such as a steel force plate, the rate of loading of the GRF_v impact peak typically is 400–600 body weights per second and the magnitude of the peak is between 1.5 and 2.5 body weights (20). This impact then sends a shock wave up the body that can be measured in the tibia within a few milliseconds and in the head about 10 ms later (4,21). The elevated, elastic heel in modern running shoes dampens the magnitude of the impact peak caused by a RFS by approximately 10% but slows the rate of loading approximately sevenfold, usually to between 70 and 100 body weights per second (2,20,26). Rearfoot striking on a hard surface is thus comfortable in a modern running shoe, but the shoe does not eliminate the impact peak in the GRF.

Because a large and rapid impact peak is painful when barefoot, especially on hard or rough surfaces, it should be no surprise that habitual barefoot runners often use a MFS or FFS. These strike types, of course, do generate an impact with the ground, as evident from high-frequency vibrations (usually between 10 and 20 Hz) in the GRF_v, but many studies have shown that FFS and some MFS landings do not generate any discernable impact peak (*e.g.*, (4,26)). In vernacular

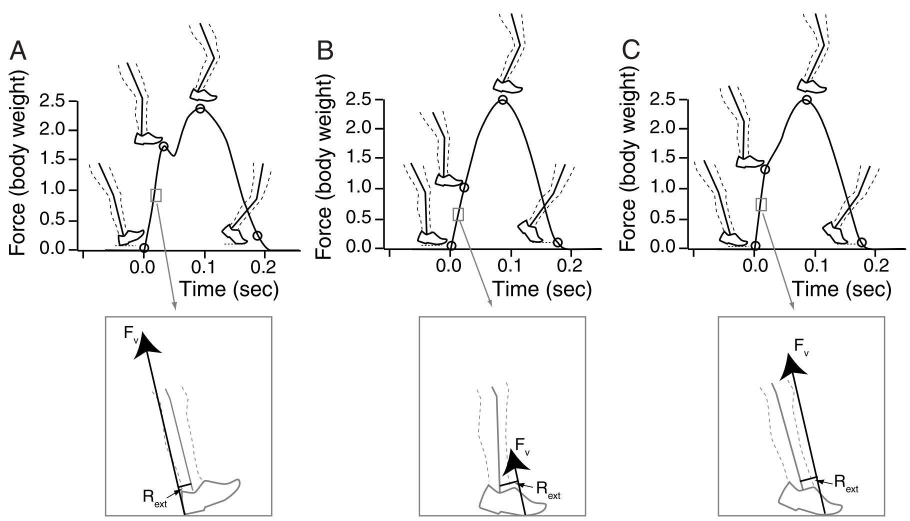

Figure 1. Kinematics and vertical ground reaction forces at 3.0 $m \cdot s^{-1}$ in a rearfoot strike (RFS) (A), forefoot strike (FFS) with a short stride (B), and FFS with a long stride (C). The RFS has marked impact peak, and the overstride FFS in (C) has a steeper rate of loading than the less extended FFS in (B). Below, schematic illustration of the external moment at peak rate of loading for each strike, the product of the vertical ground reaction force (F_v), and its moment arm (R_{ext}). The RFS produces a high dorsiflexing moment, and the overstriding FFS in (C) produces a much higher external plantarflexing moment than the less extended FFS in (B).

terms, runners who FFS land lightly and gently, in the same manner as other mammals who also do not generate impact peaks during running. Consequently, as pointed out by Nigg (26,27), FFS runners do not need any cushioning from a shoe to dampen the shock from impact, even on hard surfaces such as a steel plate, because they do not generate any impact peak in the first place. However, shoes do make FFS running more comfortable on rough surfaces in which abrasion or stress concentrations from pebbles can be painful. Note from Figure 1 that higher GRF_v forces are placed on the musculoskeletal system at midstance, when the body's center of mass is at its nadir, but these midstance forces rise more slowly than the impact peak, and they generally are similar in barefoot and shod running (10,11,19,20,26,34).

There are two major, related reasons for the variation in impact peaks between different strike types. The first is that during the period of impact in a FFS, the foot initially is plantarflexed and then undergoes controlled dorsiflexion at a compliant ankle, but in a RFS, the foot remains dorsiflexed, and the ankle is stiff during the same period. As a result, the percentage of mass that comes to a dead stop and thus exchanges momentum with the ground at the moment of impact (the effective mass, M_{eff}) is much greater in a RFS (9,26). My colleagues and I (20) measured M_{eff} in a sample of runners as 1.7 ± 0.4% body mass (bm) in FFS and 6.8% ± 3.0%bm in RFS running. As one predicts, these values roughly correspond to the percentage mass of the foot and the lower leg, respectively. The other reason FFS and some MFS generate no marked impact peak is compliance. A RFS runner usually lands with a more extended and stiffer knee and ankle than a FFS runner, whose ankle dorsiflexes and knee flexes more during the period of impact, allowing the lower extremity to dampen forces more effectively (20). This principle explains why most people land on the ball of the foot when they jump, and the same principle applies to barefoot running, which essentially is jumping from one leg to the other. MFS runners seem to generate a wide range of impact peaks and merit further study (10). Note also that toe strikes, which are uncommon in distance runners, can generate an impact peak because the runner's ankle can be relatively stiff at impact.

The influence of lower extremity compliance on the rate of loading in the GRF_v raises an important issue that merits further attention. Most studies measure compliance over the entire stance phase, but for studies of impact, the key period for measuring lower extremity compliance is just the period of the impact peak itself or the equivalent percentage of stance in landings without an impact peak (20). Figure 2 graphs the relationship between lower extremity compliance versus the rate of loading of the GRV_v during just impact for a sample of habitually barefoot and habitually shod runners in both FFS and RFS landings at approximately 4 $m{\cdot}s^{-1}$ in shod and unshod conditions (from (20)). Note that, as predicted, the slope of this relationship is much higher in RFS than FFS landings, but there are some very compliant RFS landings (in this case, all shod) whose rates of loading ranged between 60 and 100 $bm{\cdot}s^{-1}$, within the range of some barefoot FFS landings. However, no RFS landings in this sample had rates of loading as low as 30–40 $bm{\cdot}s^{-1}$, which was typical of many barefoot runners with a FFS. In addition, some runners who FFS had relatively stiff lower extremities and rates of loading that were higher than the most compliant shod landings. This variation raises the important point that a runner can alter lower extremity compliance in a number of related ways beyond using the elastic shoe heel, such as with shorter strides, more knee flexion, and less overstride (9). This point may explain why some barefoot runners sometimes RFS with no apparent discomfort (depending on surface conditions, speed, and other factors) and why some shod runners who RFS experience low impact forces (24).

Stride Rate and Length

Stride rates vary enormously among runners for many reasons, and few studies explicitly have quantified differences in stride rate between barefoot and shod runners. A number of studies (*e.g.*, (5)) have found that elite shod runners typically use a stride frequency between 170 and 180 steps per minute even at low speeds such as 2.75 $m{\cdot}s^{-1}$; in contrast, nonelite runners often adopt a lower average stride frequency of about 150–160 steps per minute at similar speeds (*e.g.*, (13)). A few studies of nonelite barefoot runners confirm that these runners tend to use a high frequency, ranging from 175 to 182 steps per minute at speeds of 3.0 $m{\cdot}s^{-1}$ (11,17,34); barefoot runners also tend to use slower stride rates and take longer strides when asked to run shod at the same speed (11,34).

Why stride lengths tend to be shorter in nonelite runners who are barefoot rather than shod is poorly studied. Several hypotheses that merit testing are as follows: first, shortening one's stride by flexing the knee more is an effective way to avoid a RFS and to increase compliance and decrease M_{eff} for a given ankle angle because a more flexed knee orients the foot's plantar surface more in plantarflexion (Fig. 1). Therefore, shorter strides will increase the tendency to FFS when barefoot

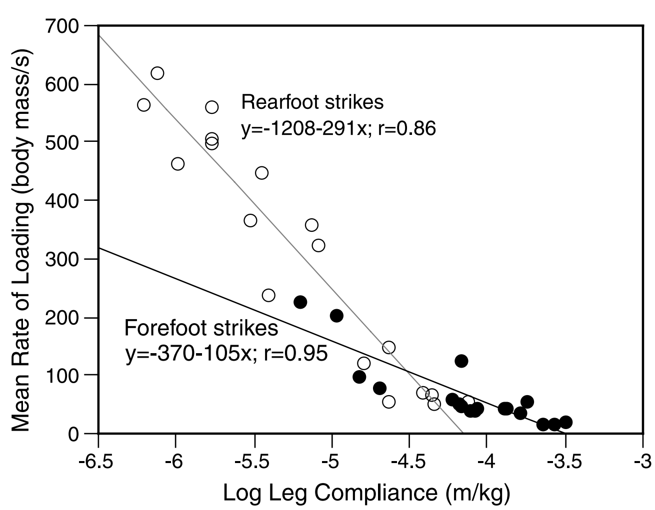

Figure 2. Compliance versus rate of loading of the impact peak. Rearfoot strikes (RFS; *open circles*) usually are less compliant and generate a higher rate of loading than forefoot strikes (FFS; *filled circles*), which usually are more compliant. Note that some FFS are relatively stiff with a high rate of loading, and some RFS are relatively compliant with a low rate of loading, but that none of the RFS measured have as low a rate of loading as the most compliant FFS. [Adapted from (20). Copyright © 2010 D.E. Lieberman. Used with permission.]

and to MFS when wearing a shoe with an elevated heel. Second, to FFS with a more extended knee, hence a longer stride, requires more plantarflexion. As Figure 1C shows, a more plantarflexed FFS increases the dorsiflexing external moment applied around the ankle in the sagittal plane, which needs to be countered by the plantarflexors. Therefore, a FFS runner with a shorter stride will have a less stiff ankle, a lower rate of loading, and will place less strain on the triceps surae muscles and Achilles tendon. There may be additional reasons to use a fast stride frequency related to economy and elastic recoil, but these are relevant to both shod and barefoot running.

Anatomical Adaptations (Calluses, Muscles, and Arch Shape)

Different stresses applied to the body often elicit varied physiological and anatomical responses. Barefoot running is no exception and may stimulate several adaptive mechanisms, but none have been studied in-depth. The first and most obvious response to running barefoot is that friction on the glabrous skin of the plantar surface of the foot stimulates keratinocytes to produce a callus. Calluses typically form on the ball of the foot above the metatarsal heads, on the heel pad, and on the toes. Calluses, which obviously are natural, apparently provide little in the way of cushioning, but they do protect the surface of the foot from injury and impact. How much they affect proprioception has not been studied.

A second, less well-documented change in need of further research is muscle hypertrophy or conditioning. Unlike RFS landings, FFS and MFS landings place eccentric loads on the plantarflexors during the initial part of stance (10,17,26,28). Because eccentric loads generate more muscle hypertrophy than concentric loads, it is reasonable to predict that runners who FFS or MFS or who transition to FFS or MFS gaits have stronger plantarflexor muscles. Because runners who habitually are barefoot or in minimal shoes without elevated heels undergo more controlled dorsiflexion during the initial phase of stance in a FFS (28), they place more stress and generate more muscle growth in the plantarflexors than RFS runners in shoes with elevated heels.

Similar principles likely apply to the muscles of the foot. It long has been known that the arch of the foot functions as a spring during running by stretching (collapsing) up to midstance and then recoiling during the second half of stance (18). As Figure 3 illustrates, the arch does not lengthen in a RFS until after the ball of the foot has landed (foot flat), but in a FFS, the longitudinal arch of the foot is loaded in three-point bending immediately at footstrike (28). A FFS therefore engages the extrinsic and intrinsic muscles of the arch differently than a RFS. In addition, shoes with arch supports presumably limit how much the arch collapses, lessening how much the arch elongates and thus how much negative (eccentric) work these muscles do. However, this effect has not yet been measured. If foot muscles respond to loading like other muscles in the body, then running barefoot or in minimal shoes will strengthen the arch's muscles more than running in shoes with arch supports; FFS running also may strengthen the foot more than RFS running. By the same logic, FFS and barefoot running likely also require more foot muscle strength to avoid injury. These hypotheses have yet to be tested thoroughly but are supported by one study, which showed that runners who trained for 5 months in minimal shoes (the Nike Free) had significantly larger and stronger extrinsic muscles (2). This study needs to be replicated and expanded. Research also is needed to quantify how variations in the stiffness of shoe soles affect how much work the foot muscles do.

Performance

There is no evidence that barefoot running has appreciable negative effects on performance (17). To be sure, most elite runners prefer to use shoes because they protect the foot and allow one to run on rough surfaces without worrying about foot placement, but barefoot runners such as Abebe Bikila and

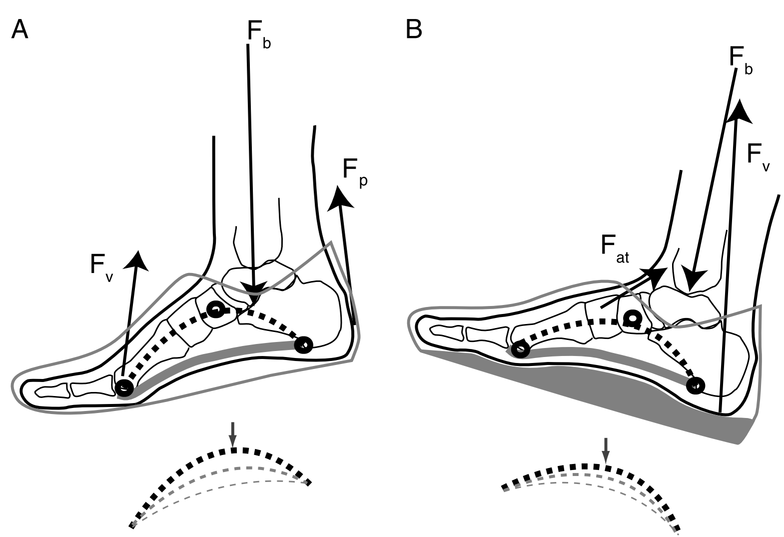

Figure 3. Schematic of (A) longitudinal arch function during a forefoot strike (FFS) in a minimal shoe without a stiff sole, arch support, and elevated heel and (B) a rearfoot strike (RFS) in a shoe with a cushioned heel and arch support (*shaded area*). F_v is vertical ground reaction force at impact, F_b is force from body mass, F_p is plantarflexor force (in the FFS), and F_{at} is anterior tibialis force (in the RFS). Because the FFS causes three-point bending from the moment of impact, it causes more tension on the arch; in addition, the shoe's arch support functions to limit how much the arch can tense (illustrated by schematic *dashed lines* below).

Zola Budd have set world records in the marathon and shorter distances. The world record holders for almost every long distance running event are FFS runners who race and sometimes train in racing flats or other kinds of minimal shoes. In addition, economy seems to be improved by being barefoot or in minimal shoes. Several studies have shown that barefoot or minimally shod runners are between 1.0% and 3.8% less costly per unit mass and distance (3,11,15,34), which is due in part to less shoe mass, which increases running cost by approximately 1% for every 100 g (26). A recent study from my laboratory (28) found that after correcting for shoe mass, stride frequency, and strike type, running in minimal shoes is 2.4%–3.3% more economical than running in standard running shoes. Such a difference could have substantial effects on performance over long distances by allowing runners to go faster for the same effort.

HOW MIGHT BAREFOOT RUNNING BE RELEVANT TO INJURY?

A major question on the minds of many runners, coaches, trainers, physical therapists, and physicians is whether running barefoot has any effect on injury rates. To many, the null hypothesis is that shod running is less injurious than barefoot running unless proven otherwise, but an evolutionary perspective challenges this assumption. Furthermore, as argued above, asking whether barefoot running is more or less injurious than shod running is a naive question given the complex, multifactorial bases for most kinds of injury. Simply comparing injury rates among runners who are barefoot, wearing minimal shoes, or wearing modern running shoes is likely to lead to confusing, probably conflicting results unless the studies control for aspects of running form and biomechanics that are the actual proximate causes of injury. Stated differently, putting a shoe on your foot (or taking it off) is no more a proximate cause of injury than training intensity. There are plenty of shod runners who do not get injured, even when they increase their training intensity, and there also are barefoot runners who do get injured. Therefore, the key question to ask is "What about the way that barefoot runners tend to run affects injury rates and patterns?" This question is relevant to all runners, barefoot and shod.

Answering this question requires testing a model of the factors that cause injuries, especially repetitive stress injuries, which are so prevalent among endurance runners (35–37). At a very proximate level, most repetitive stress injuries are caused by the accumulation of microdamage in tissues caused by the repeated application of forces that generate stress, which then cause strain. More specifically, microdamage accumulation occurs from interactions between the number, magnitude, direction, frequency, and velocity of the forces applied; and the size, shape, and material properties of the tissue experiencing the force. A major cause of microdamage is high strain with high rates, which cause bones to become more brittle and increase elastic hysteresis: the difference between the stress energy required to generate a given strain in a material and the elastic energy that is stored for a given cycle of loading (23). Repeated high levels of hysteresis potentially are injurious in both bones and more viscous tissues such as ligaments and tendons because some of the energy lost during unloading is converted to friction, generating heat, but the rest of the energy can be converted into structural damage. In most materials, higher rates of loading increase elastic hysteresis, and the bone is no exception.

Running generates a complex, dynamic set of forces, which are repeated with every step, hence millions of times a year for most runners. Given the proximate, mechanical causes of repetitive stress injuries outlined above, forces that cause repeatedly high rates and magnitudes of loading are likely to contribute to injuries. Of these forces, impact peaks stand out as the highest and most rapid loads the musculoskeletal system repeatedly experiences (Fig. 1). Some researchers have argued that impact peaks are not a cause of injury because injury rates are not affected by running on harder surfaces, shock absorbing insoles and heels consistently do not yield lower injury rates, and because one study found that injury rates were lower in RFS runners with higher impact peak rates (26,27). Nigg also has hypothesized that out-of-phase vibrations of the calf muscles are able to dampen impact peaks (27). In contrast, several recent studies have found that the rate and magnitude of the impact peak in runners is a significant predictor of injuries that one might expect to be impact-related: tibial stress fractures, patellofemoral pain syndrome (runner's knee), plantar fasciitis, and lower back pain (8,24,29). More research urgently is needed, but one limitation of all these studies is that they examined only habitually shod RFS runners. It is reasonable to predict that runners who FFS, regardless of whether they are barefoot or shod, incur fewer injuries caused by impact peaks for the simple reason that FFS landings do not generate an appreciable impact peak (6). That said, FFS running places higher loads on the Achilles tendon and plantarflexors, possibly causing a trade-off in injuries. In addition, as Figure 1C shows, some FFS runners, such as those who overstride, have higher rates of loading than others, within the range of rates of loading caused by shod RFS running. If high rates and magnitudes of loading cause some repetitive stress injuries, then these FFS runners may be at greater risk of impact injuries, highlighting my basic hypothesis that running form is a more important determinant of injury than footwear.

Two additional points regarding forces and injury merit brief mention. First, running generates many varied forces, and there is no question that internal forces in the lower extremity often are higher in magnitude than external forces generated by impact peaks (reviewed in (26)). However, not all forces are injurious, and more research is necessary to determine which repetitive forces the body is adapted to tolerate, which cause injury, and under what circumstances. The evolutionary medicine hypothesis is that the musculoskeletal system is better able to adapt to the forces generated by a barefoot running style. Second, different running forces cause covarying suites of different forces, making it difficult to separate cause and effect. For example, Davis and colleagues (8) found that individuals with higher impact peaks had higher rates of likely impact-related injuries such as tibial stress syndrome and higher rates of iliotibial band syndrome. The latter is unlikely to be caused by impact but could result from the same general RFS running form, which also applies higher external moments to the knee (19,39). In other words, certain aspects of running form likely lead to covarying suites of injury that do not have the same biomechanical bases.

Other points to consider are the effects of shoe cushioning and proprioception. Elevated, elastic heels are designed to cushion the impact peak of a RFS, slowing the rate of loading and slightly damping the magnitude. One might therefore expect cushioned heels to mitigate or prevent injury from impact loading. However, several studies have found that runners who RFS adjust leg stiffness to surface stiffness and, thus, run with stiffer legs on more compliant surfaces, keeping the overall degree of stiffness the same (12). This adjustment also occurs in barefoot or minimally shod runners who FFS (20). However, a major difference between barefoot and shod running is that the barefoot runner will have more sensory feedback from impact and, thus, should be better able to adjust leg stiffness (17). The blocking action of cushioned heels on proprioception likely explains the evidence that runners who wear more cushioned shoes are more likely to be injured than runners in less cushioned shoes (22). In other words, barefoot or minimally shod runners tend to avoid impact peaks, and they also are more likely to sense high rates and magnitudes of loading when they occur and thus adjust their gait or contract muscles appropriately.

Other possible but poorly studied contributors to injury are moments (torque forces) applied around joints. When external forces are applied to the skeleton, they generate external moments at joints that have to be counteracted by opposing internal moments generated by muscles, tendons, and ligaments. As with bone, high rapid rates of loading induce more hysteresis in connective tissues, which has the potential to lead to more tissue damage (23). In this regard, running form may be relevant because FFS and RFS gaits generate different moments. In terms of sagittal plane moments, FFS runners land with a more plantarflexed foot and, thus, undergo more ankle dorsiflexion during the first part of stance, causing higher external moments that must be controlled by the plantarflexors (26,39). In contrast, lower GRFs in combination with a less extended leg generate significantly lower sagittal moments in the knee in a FFS (39). Barefoot runners have been shown to generate lower sagittal plane moments in the knee and hip than shod runners (19), a difference that may be explained partly by aspects of shoe design that affect moments. Shoes with wide or elevated heels increase joint moments acting around the ankle, knee, and hip (26). One irony of shoes that control pronation is that these shoes also have a number of other features such as stiffened medial midsoles that correct for increased pronating moment forces generated by the heel.

We simply do not yet know if experienced habitually barefoot runners have fewer injuries than habitually shod runners, and this will be hard to test without correcting for confounding factors such as form as well as musculoskeletal strength and training intensity, which vary among both populations of runners. I hypothesize that if one holds other factors constant, what matters more for preventing injury is running form rather than footwear. Runners with a barefoot running "style," who tend to avoid or minimize impact peaks, overstride less, and use a high cadence, may be less likely to be injured than runners who generate high impact peaks, overstride more, and have a slow stride frequency, regardless of whether they are wearing shoes. This hypothesis requires prospective study, but we recently found in a retrospective study on a collegiate track team that the overall rate of repetitive stress injuries per distance run was more than twice as high in shod FFS versus RFS runners (6). In addition, more research is needed to test the effects of shoes on injury through mechanisms such as proprioception, rearfoot motion, pronation control, and other factors.

Another major and important category of injury to consider is the increased risk of injury from transitioning to either barefoot running or a barefoot style. FFS running requires more calf muscle strength than RFS running, and it also may require more foot muscle strength and foot control, especially if one is using minimal shoes. Runners who transition to barefoot or minimal shoe running frequently complain of calf muscle strains and Achilles tendinopathies, both of which reflect increased plantarflexor moments applied to the ankle during FFS gaits (26,39). In addition, although FFS landings do not generate high forces upon impact, runners who transition may not have strong enough extensor muscles or metatarsals to counter bending forces in the anterior foot (33), which could lead to increased risk of metatarsalgia or metatarsal stress fractures (14). Research urgently is needed to establish which runners might benefit from transitioning and what sorts of injuries runners who transition get and to devise effective transitioning strategies to avoid injury.

The final category of injuries to consider includes traumas caused by sudden accidents such as falls or landing on sharp objects. Because shoes protect the sole of the foot, one expects barefoot runners to have more traumatic injuries from lacerations, bruises, splinters, and punctures. However, because shoes limit proprioception, it is possible that barefoot runners may be less likely to fall and incur sprains. Muscle strains probably are common equally in barefoot and shod runners. Controlled prospective studies are needed to test all of these conjectures (see (17)).

In short, barefoot running raises more questions about injury than we have answers at the moment. Runners, both barefoot and shod, will get injured, and I hypothesize that barefoot running *per se* is neither more nor less injurious than shod running because what matters most is how one runs, not what is on one's feet. It is reasonable to expect that barefoot running with poor form can cause injury, and we already know that somewhere between 20% and 70% of shod runners do avoid injury (35–37), hypothetically because, among other factors, they have good running form. In this regard, minimal shoes may be problematic for some runners because they limit proprioception and provide no cushioning or support and, thus, may enable runners to run poorly without any of the protection afforded by a shoe. These runners may be at extra risk of injury. In addition, runners who transition from RFS to FFS gaits or who transition from shoes to barefoot running also risk injury, especially if they do so too rapidly without allowing the musculoskeletal system to adapt to the different forces this kind of running generates.

CONCLUSION

It is remarkable how little we know about something so basic and fundamental as barefoot running, and it should be evident that we need to roll up our shirt sleeves and take off our shoes to answer a wide range of questions about how the bare foot functions during running and the relevance of barefoot running to injury. A list of key questions to be addressed includes the following:

- How much do variations in running form, including those common in habitual barefoot and shod running, affect injury rates?
- How much does the lack of proprioception in a minimal shoe affect running form?
- What is the best way for a runner to transition to barefoot or minimal shoe running?
- How much does the body need to adapt to barefoot running anatomically if one previously has been running only in shoes?
- Do children adapt differently to barefoot running than adults?
- What are the effects of speed, substrate, and other environmental variables on barefoot and minimal shoe running form?
- How much does barefoot running affect foot strength and arch shape?
- How much do shoes affect foot strength and flexibility, and how relevant are these factors to injury?
- How much and when do barefoot runners use MFS and RFS landings, and if so, how do they modulate lower extremity compliance?
- Are there differences in injury rates among barefoot or minimally shod runners who use different strike types?
- Is actual barefoot running less injurious than running in minimal shoes?
- Can we identify which runners are most likely to benefit from or should avoid barefoot running (*e.g.*, runners with high or low arches, low flexibility, and other problems)?

We have much to learn. However, if there is any one lesson we can draw already from the barefoot running movement it is that we should be less afraid of how the human body functions naturally. The trend toward running without shoes also has provided a useful opportunity to question common assumptions about the relative benefits and risks of running with shoes or without them. There is nothing abnormal, faddish, unnatural, or even inherently dangerous about barefoot running, but taking off one's shoes to run is no panacea. People should and will run however they want and in whatever footwear they want. That said, I would encourage anyone who runs or studies running to try running barefoot on a hard, smooth surface like a road for 500 m to understand how it works and feels. Go ahead and try it!

In the long run, I suspect that the most important benefit from studying barefoot running is that, by incorporating either explicitly or implicitly an evolutionary perspective, it may help us evaluate ways to help runners avoid injury. Humans not only evolved to run but also to run barefoot. It is a reasonable assumption that our bodies bear the traces of millions of years of natural selection that favored adaptations to lessen a runner's chance of injury. Unfortunately, we lack data on injury rates from the 20th century before the modern shoe was created, let alone the Paleolithic. However, over the last few decades, injury rates have remained stubbornly high despite considerable investment in shoes as well as orthotics. Running injuries are highly multifactorial, and no single factor, such as shoe design, will explain more than a fraction of the injuries. In fact, several recent studies actually have found that motion control shoe prescriptions have no effect on reducing injury rates (31). These and other data, including the persistently high rate of running injury, suggest that many efforts to reduce injuries solely by tinkering with shoe designs are quixotic. I know of no evidence that points to a clear relationship between shoes and running injuries, and although there are millions of shod runners who are injured, there also are millions who are just fine. What about those different runners' form may predispose them to injury or not? My prediction — which I readily admit is nothing more than a hypothesis that could be incorrect — is that shod runners with lower injury rates have a more barefoot style form (after one controls for other confounding factors such as muscle strength). Likewise, I predict that injury rates are higher among barefoot runners who either lack enough musculoskeletal strength in their calves and feet (perhaps from insufficient time to adapt) or who still run as if they were shod with long strides and slow stride frequencies.

In short, the most useful insight we can gain from barefoot running is how the body was adapted to run in the first place, which means that we have much to gain by devoting our attention — as many studies are — to what aspects of running form generate injury and why. In this regard, the way in which experienced, habitual barefoot runners get more proprioceptive feedback, often shorten their strides and increase their stride frequency, avoid RFS and impact peaks on hard surfaces, keep joint moments low, and have strong feet, may be ancient adaptations for avoiding injury. The answers to questions about these and other aspects of barefoot running will benefit all runners, regardless of what is on their feet.

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