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REVIEW ARTICLE

Barefoot Running: Does It Prevent Injuries?

Kelly Murphy · Emily J. Curry · Elizabeth G. Matzkin

Abstract Endurance running has evolved over the course of millions of years and it is now one of the most popular sports today. However, the risk of stress injury in distance runners is high because of the repetitive ground impact forces exerted. These injuries are not only detrimental to the runner, but also place a burden on the medical community. Preventative measures are essential to decrease the risk of injury within the sport. Common running injuries include patellofemoral pain syndrome, tibial stress fractures, plantar fasciitis, and Achilles tendonitis. Barefoot running, as opposed to shod running (with shoes), has recently received significant attention in both the media and the market place for the potential to promote the healing process, increase performance, and decrease injury rates. However, there is controversy over the use of barefoot running to decrease the overall risk of injury secondary to individual differences in lower extremity alignment, gait patterns, and running biomechanics. While barefoot running may benefit certain types of individuals, differences in running stance and individual biomechanics may actually increase injury risk when transitioning to barefoot running. The purpose of this article is to review the currently available clinical evidence on barefoot running and its effectiveness for preventing injury in the runner. Based on a review of current literature, barefoot running is not a substantiated preventative running measure to reduce injury rates in runners. However, barefoot running utility should be assessed on an athlete-specific basis to determine whether barefoot running will be beneficial.

1 Introduction

Over the course of millions of years, the *Homo* genus evolved to run long distances as a means of survival. Endurance running required long-term thermoregulation capabilities in response to high temperatures and enabled hunters to pursue prey for miles [1–4]. Mechanical adaptations to store and release elastic energy also emerged to aid in endurance running, such as the Achilles tendon and foot arch. For many years, *Homo sapiens*' ability to run was not considered evolutionarily useful or necessary. When compared with other mammalian sprinters, such as greyhounds, horses, and cheetahs, even the most elite human sprinter pales in comparison [3]. Humans evolved into endurance runners rather than sprinters and this allowed hunters to pursue prey for long distances. Although humans have been running for millions of years, the earliest records of footwear date back as recently as 40,000 years ago [5, 6]. Prior to the invention of primitive shoes, humans were running barefoot [5].

The number of runners and miles run per week in the United States has increased tremendously in the past 35 years [7]. Similarly, the fields of sports medicine, orthopedics, and podiatry have also grown exponentially. Increased running injury occurrence led to a concomitant increase in treatment modalities; however, injury rates remain virtually unchanged over the past 30 years [8, 9]. Sneakers were developed in the early 1900s and running shoes only came into widespread use in the 1970s [1, 5]. In the past 10 years, shoe companies have attempted to

K. Murphy
Tufts University Medical Center, Tufts University, 800
Washington St, Boston, MA 02111, USA

E. J. Curry (✉) · E. G. Matzkin
Division of Sports Medicine, Department of Orthopaedic
Surgery, Brigham and Women's Hospital, 75 Francis St,
Boston, MA 02115, USA
e-mail: ecurry1@partners.org

enhance running performance and decrease injury by adding shoe modifications, such as gels, cushions, air pockets, and arch supports; however, there has been no associated injury reduction [10]. Conversely, many athletes have recently returned to barefoot running as a result of the popularization of the book, *Born to Run: A Hidden Tribe, Superathletes and the Greatest Race in the World* by Christopher MacDougall. As an alternative to barefoot running, minimalist shoes have also gained popularity. Minimalist shoes provide a protective foot covering for rough terrain and mimic the feeling of barefoot running, but lack any kind of cushion or support.

Controversy exists as to whether barefoot/minimalist running promotes healing, increases performance and decreases injury rates. This review will discuss biomechanical and kinematic differences in the barefoot (or minimalist) runner as compared with the shod runner. It will also examine the potential correlation of injury development and prevention in both types of runners.

2 The Gait Cycle

Understanding running gait biomechanics is necessary to understand the effects of barefoot running (Table 1). The running gait cycle begins and ends when the foot makes contact with the ground. The entire cycle for one leg is divided into four phases: stance phase, early float, mid swing, and late float [11]. The greatest distinction between shod and barefoot running occurs during the stance phase, which is classified by forefoot, midfoot, and rearfoot strike patterns (Fig. 1) [5]. In the rearfoot strike (RFS) pattern, the runner lands heel first and then places the metatarsal area down in a heel–toe fashion. In the forefoot strike (FFS) pattern the runner makes initial contact with the metatarsal heads and then continues with a toe–heel gait pattern until the heel is on the ground. The midfoot strike (MFS) pattern lands with the entire foot contacting the ground at approximately the same time [5, 11].

Despite recent controversy, studies have indicated that habitually barefoot runners tend to adopt in most cases the FFS or MFS patterns [5, 12–14]. However, it is clear that habitually shod runners use the RFS pattern [15, 16]. The RFS pattern is thought to be adopted by shod runners because the additional running shoe support and cushioning allows for greater heel impact [5]. Delgado et al. [17] also found that runners perceive RFS to be a more comfortable landing pattern, despite having a greater shock attenuation than FFS. However, since barefoot runners lack heel support, impact pressure is dissipated by a flatter foot placement. This increases total surface area contact and reduces focal pressure on the heel, causing decreased load on specific joints and surrounding ligaments [18].

3 Kinematic Variables in Different Strike Patterns

When analyzing human locomotion, ground reaction force (GRF) is commonly evaluated. GRF magnitude is a function of many different variables, including stride length, running speed, shoe characteristics, inclination, and stiffness of the ground surface [11]. In a typical runner, the GRF plotted against time forms a bell-shaped curve with the thrust peak occurring when the sole of the foot is in ground contact [5].

There is a significant difference in the observed GRF between barefoot and shod running. A barefoot (or ultra minimalist) runner tends to FFS, which creates smaller collision forces and therefore generates a smaller GRF than the shod runner [5, 12]. The barefoot runner also has a diminished stance phase, and therefore, less contact time with the ground which generates smaller peak forces compared with the shod runner [11, 19].

The impact transient is another collision force used to compare shod runners with barefoot runners. The impact transient is a peak observed during the GRF and occurs in the first 50 ms of the stance phase [5]. The impact transient is absent in the GRF curve generated by the habitually barefoot runner with a FFS pattern. However, the impact transient for the habitually shod runner with a RFS pattern is displayed as a peak within the GRF curve and is a collision exerted on the lower extremity of approximately two to three times the runner's body weight [20].

Another variable to consider is loading rate during the stance phase of the gait cycle. The loading rate is defined as the slope of the GRF versus time graph. Lieberman et al.

Table 1 Summary of barefoot-running versus shod-running biomechanics

Criteria	Barefoot running	Shod running
Typical strike pattern	Forefoot strike	Rearfoot strike
Impact transient of ground reaction force	Minimal	Significant
Average loading rate	3× less than shod	3× higher than barefoot
Ankle stiffness	Lower	Higher
Energy efficiency during ground collision	Higher	Lower
Leg stiffness	Lower	Higher

Fig. 1 Barefoot runners tend to adopt a forefoot strike pattern (**a**), while shod runners tend to adopt a midfoot strike (**b**) or rearfoot strike (**c**)

[5] observed a three-fold increase in the average loading rate in the habitually shod runner with a RFS pattern as compared with the habitually barefoot runner with a FFS pattern. Interestingly, this observation is seen even if the habitually shod runner is running barefoot if they continue using the same heel-to-toe gait pattern [5]. The reduced loading rates of MFS runners has been found to be in part a result of an increased pre-activation of the gastrocnemius lateralis, but the precise significance of this finding is unknown [21].

Another kinematic variable is leg stiffness, defined as the ratio between the maximum GRF and the maximum leg compression during ground contact [18]. Effective vertical stiffness is a ratio of the peak force generated and the net vertical displacement of the center of mass. When running on different surfaces, runners tend to adjust leg stiffness for maintenance of constant overall vertical stiffness. A runner on a compliant surface will increase leg stiffness, while a runner on a harder, less compliant surface will decrease leg stiffness [22]. An individual who experiences uneven terrain must constantly change leg stiffness to maintain stability [23]. Bishop et al. [24] studied the effects of shoes on lower limb stiffness, and found that leg stiffness significantly increases when using high-cost shoes as compared with barefoot running.

Ankle stiffness must also be considered and is a function of inertial mass, muscle fiber recruitment, and reflex responses. The heel is the initial contact point when the foot lands with the RFS pattern [5]. Translational kinetic energy is dissipated by the collision of the heel with the ground, thereby increasing the effective mass of the runner [5, 25]. This may be detrimental because collision forces incurred by the joint increase and may contribute to a higher injury incidence. However, when the runner lands with a FFS pattern, the metatarsals are the initial point of ground contact and ankle stiffness is considerably lower. Therefore, the GRF 'torques the foot around the ankle' and converts translational kinetic energy into rotational kinetic energy. This conversion to rotational kinetic energy allows for improved energy storage and recovery in the Achilles tendon and foot arch. In addition, conversion from kinetic to translational energy is more energy efficient in the barefoot (FFS) runner because less energy is lost during ground collision [5, 26].

4 Modern Running Shoes and Minimalist Running Shoes

Modern running shoes typically consist of three layers: insole, mid-sole, and outsole. The insole is typically made of synthetic material, such as nylon, and the outsole is typically made from hard rubber [27]. The mid-sole is typically where most variation occurs between different running shoes. This layer provides support for the sole, and provides cushioning under the heel. Cushioning is typically made of foam (or some other compliant material) and elevates the heel 8–16 mm [28].

Intuitively, the additional support or cushioning for the lower limbs should be beneficial. However, it is hypothesized that additional arch support and cushioning could be detrimental to overall foot and joint health. Extra support may result in decreased tissue tolerance to mechanical stress and secondarily predispose individuals to developing more injuries. This may also decrease intrinsic arch support [29]. In addition, excessive cushioning may cause excessive foot pronation (eversion), which stretches the fascia and deltoid ligaments in the medial aspect of the foot. This can cause injuries such as plantar fasciitis [5]. Some authors suggest a positive correlation between higher cost of the shoe and higher injury rates in the runner [30, 31]. This correlation may exist because of an increased sense of security by purchasing a more expensive shoe. Runners often have the misguided belief that higher impact running is possible without joint injury in expensive running shoes.

As a way to embrace barefoot running without foot exposure to the external environment, some runners use minimally cushioned running shoes, which contain a soft, ultra-flexible midsole with substantially less cushioning than conventional running shoes [32]. Recently, minimalist footwear has come into widespread use [11]. All of these shoes aim to maintain the freedom and essence of barefoot running without the cushioned midsole of standard running shoes. In a study by Perl et al. [33], they found that minimalist footwear was significantly more economical for runners compared with traditional running shoes regardless of strike type (RFS or FFS).

5 Running Injuries

There are many purported factors leading to running-related injuries, including joint and muscle overuse, pre-existing injuries, type of running surface, and improper footwear [34]. Common running injuries include patellofemoral pain syndrome, tibial stress fractures, plantar fasciitis, and Achilles tendonitis. Plantar fasciitis, tibial stress fractures, and Achilles tendinitis all result from repetitive wear and tear of the lower limbs, and are categorized as overuse injuries (Tables 2, 3) [35].

Runners commonly experience knee pain or injury [8]. Patellofemoral pain syndrome accounts for 20 % of all running-related injuries [11]. Patellofemoral pain syndrome presents with pain localized to the anterior aspect of the knee joint. Frequently there is no obvious pathology or mal-alignment seen. However, excessive eversion of the planted foot at heel strike could result for some runners in overall mal-alignment of the limb and increase of the risk of patellofemoral pain syndrome [36]. Shod runners tend to display excessive eversion of the heel at foot strike and this may lead to an increased rate of patellofemoral pain syndrome compared with barefoot runners.

Plantar fasciitis affects up to 25 % of all athletes and is the third most commonly encountered running injury [37]. Barefoot runners with FFS pattern decrease localized heel pressure because the vertical impact force is spread out over the larger surface area of the fore and mid-foot. The proposed benefit is that the peak GRF is smaller, thus reducing lower extremity stress during each stance phase [18]. Although a positive correlation exists between excessive pressure on the plantar fascia and the progression of plantar fasciitis, distributing pressure across the fascia does not correlate with plantar fasciitis prevention [37].

Tibial stress fractures are reported as one of the top five most encountered injuries in runners [38]. Intuitively one would posit that the increased tibial load due to increased GRF would contribute to the increased incidence of tibial stress fractures [38]. This theory remains unproven, and there currently is no definitive correlation between increased GRF and tibial stress fractures in runners [39]. A meta-analysis published in 2011 confirmed current available data does not support the hypothesis that there is a significant difference between the GRF of the stress fractures group and that of the control groups. However, differences were observed for the average and instantaneous vertical loading rates [40].

6 Collision Forces and Running Injuries

The collision sustained by a RFS dissipates much of the translational kinetic energy acquired during the previous push-off and swing phase, preventing its conversion to rotational kinetic energy and eventual storage into elastic potential energy [5, 41]. When this occurs there is an increase in effective mass of the runner, increasing the overall collision forces on the runner's lower extremity joints [5]. Several authors have postulated that increased collision forces may contribute to the development of running-related injuries [8, 38, 42]. However, increased lower extremity forces have not been definitively attributed to the increase in running-related injuries, and therefore lack of rotational energy is not confirmed as a significant factor in injury [43].

Leg stiffness is another variable to consider when discussing the prevalence of injuries in the runner. Shod runners exhibit greater leg stiffness than barefoot runners. Shoe wear and the resultant increased limb stiffness can lead to an injurious landing strategy [24]. Williams et al. [44]

Table 3 Possible injuries based on biomechanical properties

Criteria	Common injuries
High RFS collision forces	PPS, TSF, AT
Greater leg stiffness (and high arches)	TSF and lateral ankle sprains
Lower leg stiffness (and low arches)	PPS
High impact transient	PF, TSF
Higher loading rate magnitude	PF, TSF

AT Achilles tendinitis, *PF* plantar fasciitis, *PPS* patellofemoral pain syndrome, *RFS* rear foot strike, *TSF* tibial stress fractures

Table 2 Risks of common injuries associated with different running styles

Injury type	Barefoot running (FFS)	Shod running (RFS)
Patellofemoral pain syndrome	Lower risk	Higher risk
Tibial stress fractures	Inconclusive	Possible higher risk
Plantar fasciitis	Possible higher risk	Inconclusive
Metatarsal stress fractures	Higher risk	Lower risk
Puncture wounds/temperature extreme foot injuries	Higher risk	Lower risk

FFS forefoot strike, *RFS* rear foot strike supported this idea by showing that an individual with high arches, who also exhibits high leg stiffness, demonstrates a higher tendency to develop bony and ligamentous injuries. Injuries included pathologies such as tibial stress fractures and lateral ankle sprains. However, an individual with low arches who exhibits low leg stiffness has an increased tendency of developing soft tissue injuries, such as patellofemoral pain syndrome [24, 44, 45]. Therefore, although it may appear increased leg stiffness has a positive correlation with certain injuries; decreased leg stiffness also has a positive correlation with certain running-related injuries.

The impact transient is also thought to contribute to running injury incidence because high-rate and high-magnitude forces "travel up the lower kinetic chain" and possibly facilitate injury development including plantar fasciitis and tibial stress fractures [11]. In a study done by Milner et al. [38], a higher impact transient peak was observed in runners with tibial stress fractures when compared with uninjured runners. However, the current literature lacks definitive data to show a positive or negative correlation between the presence or magnitude of impact peak transient and increased injury rates [5].

Loading rate magnitude observed in the runner has also been considered a contributing factor when evaluating potential causes of running-related injuries [5]. Indeed, a higher loading rate is seen in individuals with plantar fasciitis and tibial stress fractures when compared with runners who report no injuries [38, 42, 43]. The negative consequences of increased loading rate are thought to be so detrimental that one study performed a gait re-training program on ten healthy individuals who demonstrated higher-than-normal peak tibial acceleration (and therefore a higher impact loading rate). The purpose of the program was to change the runners' gait style to reduce loading rates and reduce injury risk, such as tibial stress fractures [46]. However, no direct evidence exists to corroborate loading rate as an established cause of injury in the runner [1]. In a meta-analysis conducted by Zadpoor and Nikooyan, GRF was not significantly higher in the stress fracture group compared with the control group [40]. However, vertical loading rate was significantly higher in the stress fracture group as compared with the control group and it is possible that the injury itself causes the higher loading rate.

7 Orthotic Devices

Orthotic devices are thought to reduce the likelihood of developing an injury in the shod runner. They are usually molded to the shape of the individual runner's foot to help redistribute foot pressure or prevent excessive ankle eversion or inversion [34]. Orthotic intervention is intended to provide greater stability during the initial part of the stance phase by reducing rearfoot eversion. However, the effect of orthotic devices is highly variable from one runner to another [48]. A study published by MacLean et al. [49] confirmed that use of orthotic devices led to a decrease in observed rearfoot eversion. Runners utilizing orthoses to treat Achilles tendinitis have reported a reduction in perceived pain [50]. However, both studies used orthotic devices as a short-term solution.

Although there is evidence that orthotic devices may change the runner's gait to adopt a less dangerous running style or reduce pain, there is still debate about whether injury rates are reduced. In particular, rigid orthoses, which provide maximum strength and less flexibility, can increase pressure on the bony prominences and contribute to the development of lower-extremity injuries, including stress fractures [34]. For certain injuries such as PF, there is no definitive evidence that custom-made orthotic devices actually reduce pain, even if some studies show positive results [32, 51]. One study published in 2011 found that the use of stability shoes (intended for naturally mild pronators) reduced perceived pain level for neutral foot types (no pronation naturally). This study also found that the use of motion control shoes for heavy pronators actually increased pain in the same subject group. This suggests that some support can be beneficial, but too much may be detrimental [52]. Therefore, although orthoses might alter the runner's gait pattern, currently there is no definitive evidence that they reduce running-related injuries. Both running shoes and orthoses provide stability; however, if adding orthotic devices has the potential to do harm, then it is possible that shoe use may have the same effect.

8 Contraindications for Barefoot Running

If a runner decides to switch from shod to barefoot running, many factors must be taken into account. The most obvious is the potential for injurious debris on the bare foot, including stones, glass, nails, and thorns. Puncture injuries may predispose the runner to developing an infection and temperature extremes can cause burns or frostbite [1].

The barefoot running FFS pattern, which causes higher peak pressures on the forefoot, could also be an injurious running strategy. Increased peak pressures under the forefoot and toes are thought to increase the risk for metatarsal stress fractures, if the change is done too quickly [53]. Studies comparing barefoot versus shod running are done in controlled environments. Often treadmills are used as opposed to outdoor terrain, where most runners tend to exercise. No studies investigate barefoot running when running downhill or in the extremely fatigued state [1].

Adapting to barefoot running must be done slowly. Runners who typically wear shoes with a very thick midsole

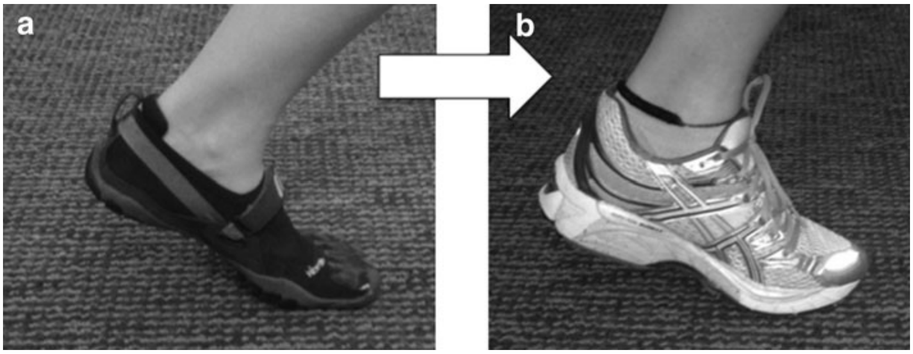

Fig. 2 The forefoot strike is most common in barefoot or 'minimalist' runners (**a**). The forefoot strike pattern while wearing a standard running shoe may be a conservative alternative for injury-prone shod runners (**b**)

will take longer to safely adapt to barefoot running than a runner who uses a shoe with less heel elevation. If the switch from shod directly to barefoot is done too quickly, this could induce soreness or injury [53]. In fact, if a habitually shod runner abruptly switches to barefoot running, it is likely that a RFS pattern will be maintained [5]. Sudden alterations in running routine have been associated with stress fractures and the drastic change from a cushioned supportive shoe to barefoot is unquestionably a significant change in running routine [34]. Mercer et al. [54] found that barefoot runners have reduced stride length compared with shod runners and this has been shown to be associated with reduced shock attenuation. Shod runners can also try to first reduce stride length and FFS to reduce shock attenuation.

9 Is the Shift to Barefoot Running Warranted?

Although barefoot running has grown in popularity since the publication of *Born to Run* by McDougall [55], one still must consider if the switch to barefoot running truly contributes to injury prevention. A substantial amount of information is still lacking about the difference between barefoot and shod running. In fact, there is no higher level evidence to support barefoot (or minimally supportive) running as a means of injury prevention, nor is there supporting evidence for shod running as a means of injury prevention either [11].

One of the biggest differences observed between barefoot runners and shod runners are the use of a RFS versus a FFS pattern. However, shod runners are capable of changing from a RFS pattern to a FFS pattern in the effort to reduce injuries (Fig. 2). Therefore, if the FFS pattern is associated with lower injury rates, clinicians can encourage gait retraining among shod runners to adopt a FFS pattern, without removing running shoes from the training routine. Mercer et al. [54] also found that shock attenuation is most associated with stride length, so adopting a reduced stride length may also decrease shock attenuation forces.

There are far more shod runners than barefoot runners. However, with increasing popularity of barefoot and minimalist running, FFS pattern-related injuries will become more prevalent in the orthopedic community [11]. Personal experiences on the use of minimalist or barefoot running have begun to appear on internet blogs. Anecdotal and published evidence suggest an increase in FFS-minimalist-associated injuries, such as metatarsal stress fracture, sesamoiditis, metatarsalgia, and fat pad syndrome, when the transition from traditional shoes is done to quickly [53, 56, 57].

The "deviation from normal movement" is thought to be a significant contributing factor in developing certain overuse injuries [58]. However, variable body structure and composition between individuals must be considered as a potential cause of injury development [59]. One study concluded that individuals with patellofemoral syndrome showed significantly decreased hip adductor muscle strength [60]. Another study concluded that predisposition to developing plantar fasciitis is more significant in individuals who naturally have a decreased range of motion for ankle dorsiflexion [47]. Both examples support the idea that intrinsic variability may predispose certain individuals to injury development. Therefore, adopting a certain strike pattern will not necessarily decrease injury rates for every runner because many variables contribute to injury development, not just shoe wear.

10 Conclusions

There are conflicting opinions about barefoot running as a means to injury prevention. There are still many aspects to consider when comparing the injury tendencies between barefoot and shod runners. One consideration is the effect of a sudden switch from shod to barefoot running. A controlled study investigating progression of habitually shod runners to barefoot running with immediate or gradual decrease in heel support should be conducted to investigate whether a sudden or gradual change to barefoot running alters injury rates. In addition, only one retrospective study directly compares injury rates of collegiate athletes with FFS patterns versus RFS patterns [9]. A prospective study should be done with a larger patient population to compare injury prevalence between shod runners' foot patterns (FFS vs. RFS).

Kinematics and gait patterns adopted by shod runners and barefoot runners are significantly different; however, there is no evidence to date concluding that these differences actually impact injury rates in the runner [11]. Therefore, it is necessary in the future to determine whether injury rates are significantly smaller in the barefoot as compared with the shod running population.

Although there is evidence to support differences between barefoot running and shod running for many kinematic variables, there is little conclusive evidence that barefoot running significantly reduces injury rates. If an injured runner is considering the switch to barefoot running to reduce pain or injury recurrence, it should be a decision concluded by both the runner and clinician. Gait pattern and training regimen must be considered because adopting a FFS pattern (as the barefoot runner does) may accentuate certain injuries.

In addition, there are many risks associated with barefoot running, such as injury and infection to the foot due to contact with sharp objects. If the runner decides to make the switch to barefoot running, the change should be done by gradually decreasing the amount of support underneath his heels while simultaneously increasing the amount of time spent running barefoot or with minimalist shoe wear. If at any point an injury begins to develop, the runner should increase the transition time or cease the new program and return to using running shoes as part of their regular training regimen.

Injuries are often multi-factorial, and it is unlikely that running shoes will decide whether a runner will develop an injury. For a previously injured runner, a switch to barefoot running has the potential to reduce loading rates and reduce pain, but may also further exacerbate the injury. In this case, it may be beneficial for the runner to gradually switch to barefoot running. However, if a runner is injury-free then a switch to barefoot running is likely not warranted, and the sudden change has the potential to do harm to the runner. There is no conclusive evidence for barefoot running preventing injury, so if the shod runner is not presently injured, the old colloquial phrase, "if it ain't broke, don't fix it" should be followed.

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