Review Article

Orthopaedic Perspective on Barefoot and Minimalist Running

Jonathan Roth, MD
Julie Neumann, MD
Matthew Tao, MD

Abstract

In recent years, there has been a movement toward barefoot and minimalist running. Advocates assert that a lack of cushion and support promotes a forefoot or midfoot strike rather than a rearfoot strike, decreasing the impact transient and stress on the hip and knee. Although the change in gait is theorized to decrease injury risk, this concept has not yet been fully elucidated. However, research has shown diminished symptoms of chronic exertional compartment syndrome and anterior knee pain after a transition to minimalist running. Skeptics are concerned that, because of the effects of the natural environment and the lack of a standardized transition program, barefoot running could lead to additional, unforeseen injuries. Studies have shown that, with the transition to minimalist running, there is increased stress on the foot and ankle and risk of repetitive stress injuries. Nonetheless, despite the large gap of evidence-based knowledge on minimalist running, the potential benefits warrant further research and consideration.

From the Department of Orthopaedics and Rehabilitation, Fort Belvoir Community Hospital, Fort Belvoir, VA (Dr. Roth), and the Department of Orthopaedic Surgery, Duke University, Durham, NC (Dr. Neumann and Dr. Tao).

None of the following authors or any immediate family member has received anything of value from or has stock or stock options held in a commercial company or institution related directly or indirectly to the subject of this article: Dr. Roth, Dr. Neumann, and Dr. Tao.

J Am Acad Orthop Surg 2016;24: 180-187

http://dx.doi.org/10.5435/JAAOS-D-14-00343

According to evolutionary biologists, efficient endurance running played a crucial role in the survival and expansion of *Homo sapiens*.[1,2] Researchers have identified numerous physical and physiologic adaptations of prehuman ancestors and early humans that specifically promoted bipedal endurance running.[1] These modifications originated >2 million years ago, allowing early hominids to safely and effectively hunt animals. Their larger brains also required a diet higher in protein and fat. Although initially fundamental for hunting and speed, running has recently become an important component of recreational exercise and competition. In 1972, American marathoner Frank Shorter won an Olympic gold medal—an accomplishment generally esteemed as the precipitating event that led to the running boom in the United States. In 2012, >25 million Americans reported running at least 50 days per year.[3]

Concurrent with the beginning of the running boom, the modern running shoe was first launched in the United States in the early 1970s.[4] Since then, advances in shoe design, including an elevated cushioned heel, arch support, and a stiff heel counter, have been introduced to make running easier and more comfortable. Despite 40 years of supposed improvements, however, the incidence of lower-extremity running injuries has remained essentially unchanged. Annually, up to 75% of runners sustain injuries, mostly about the knee and lower leg.[5-9]

Touted as the natural way to run and the key to injury-free endurance running, minimalist running (MR) rapidly gained popularity after Christopher McDougall published the book *Born to Run* in 2009.[10]

Proponents stress that, with minimal footwear, a runner naturally transitions to a forefoot or midfoot strike to reduce the impact force on the bare heel. They argue that improved sensation and proprioception, along with this lighter gait, could reduce injury risk and improve efficiency. However, critics have reported a trend in foot and ankle injuries specific to runners who have transitioned to MR and caution against foregoing shoes. Because this discussion was recently initiated, definitive results have not yet been shown.

MR can include running without shoes (ie, barefoot running [BR]) or wearing minimalist shoes. Because differences have been noted between running barefoot and running with minimalist shoes,[11] we will define MR as running with minimalist shoes and BR as a separate entity. Minimalist shoes are now produced by most shoe manufacturers and cover a spectrum that varies with regard to sole thickness, flexibility, and cushioning. The common factors include a heel-toe offset (ie, the height differential of the sole between the hindfoot and forefoot) that is typically <4 mm, increased flexibility, and a less cushioned sole. Shoes that have no heel-toe offset, or zero-drop shoes, widely vary in the amount of overall cushioning. Modern running shoes, or shod shoes, have a large heel-toe offset (typically >8 mm), stiffer heel counters, a supported arch, and extra cushioning in the heel.

Review of Gait

The running gait cycle consists of the stance, swing, and aerial phases.[12] The cycle consists of controlled and repetitive jumping and landing, as opposed to the passive inverted pendulum gait observed in walking. The greatest distinction between barefoot and shod running is recognized in the first portion of the stance phase, known as the foot strike pattern.[13] The strike pattern is classified as a forefoot strike (FFS), midfoot strike (MFS), or rearfoot strike (RFS).[13] Runners that use the FFS pattern initially make contact with the ground over the fourth and fifth metatarsal heads, followed by ankle dorsiflexion. This action is attenuated by eccentric gastrocnemius-soleus complex–soleus muscle contraction to avoid heel strike. Intrinsic foot muscles fire isometrically to absorb force through the toes. Concentric gastrocnemius-soleus complex–soleus contraction actively plantar flexes the foot into toe-off and swing phases of the running cycle. The MFS pattern is characterized by landing the entire foot on the ground simultaneously.[13] The RFS pattern entails landing with the heel and rolling to the forefoot in a heel-to-toe pattern.[13] In general, habitually barefoot or minimalist runners tend to run with a FFS pattern, whereas habitually shod runners tend to use a RFS pattern.[13-16] RFS is uncommon in MR.[15,16] The RFS pattern accommodates greater heel impact secondary to increased heel padding and shock attenuation.[13,14,17] Approximately 75% to 89% of all distance runners use a RFS pattern, which may be the result of elevated, cushioned heels in modern running shoes.[15] In comparison, MFS and FFS are used less frequently—3.4% to 24.0% and 1.0% to 1.8%, respectively.[15]

Each strike pattern has implications for force transmission. Because BR does not ensure heel support, impact pressure dissipates through a flatter foot placement. The placement primarily mimics a FFS pattern, or less frequently, a MFS pattern.[18] This increases the total surface contact area and decreases the focal pressure on the heel during BR. Thus, load decreases on more proximal joints and select surrounding ligaments.[13] In addition, the gastrocnemius-soleus complex muscle contraction has a shock-absorbing effect because it attenuates the axial load of body weight (BW) on the bone and articular cartilage. Because of the aforementioned reasons, strike pattern may affect performance.

Biomechanics

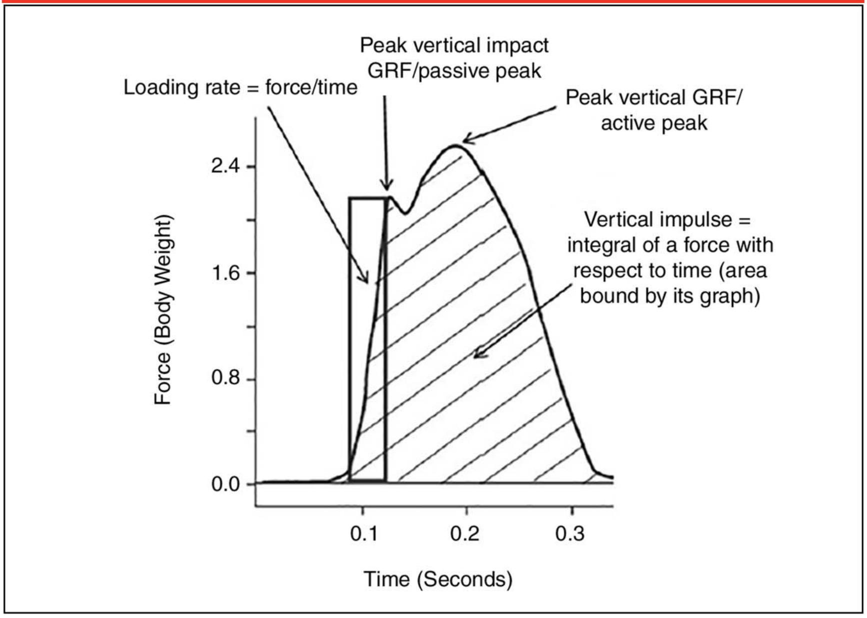
Many hypothesized benefits of BR exist, including lower collision force, reduction in running cost, increased muscle strength and movement perception, improved performance, and decreased injury rates.[13,14] However, cushioned shoes may decondition the feet[15] by depriving the glabrous skin of repeated stimuli. The cushions may diminish loading across the static structures within the foot and ankle, which will weaken over time.

Shih et al[14] suggest that strike pattern is more important than barefoot or shod conditions in preventing running injuries. Among kinetic parameters, runners with a FFS pattern had a substantial reduction in the loading rate, which is considered an important factor for running injuries. The loading rates did not substantially change in barefoot and shod conditions. Accordingly, most of the biomechanical literature today focuses on the difference in kinematics between FFS and MFS patterns compared with a RFS pattern. The focus is not on BR versus shod running. FFS and MFS biomechanics are similar and will be regarded as interchangeable for the remaining discussion.[15]

Kinetics and Kinematics

An understanding of both kinetics (ie, forces) and kinematics (ie, motions) is important in addressing the biomechanics of running. Motion analysis is important because increased cadence, shortened stride length, reduced ankle dorsiflexion, and increased knee flexion at contact are hallmarks of FFS running. A primary focus in the literature,

Figure 1



Graph demonstrating a typical ground reaction force (GRF) curve of one rearfoot strike (RFS) running stride. (Reproduced with permission from: Hall JPL, Barton C, Jones PR, Morrissey D: The biomechanical differences between barefoot and shod distance running: A systematic review and preliminary meta-analysis. *Sports Med* 2013;43[12]:1335-1353.)

however, is the inherent force differences between gait patterns because these are likely contributors to injury rates. The impact transient is the force transmitted at initial ground contact during the first 50 ms of stance phase,[13] whereas peak vertical ground reaction force (GRF) is the greatest amount of force seen through a given strike cycle. The loading rate is the force of the impact transient divided by the amount of time taken to achieve the peak (Figure 1).

Barefoot Running

As noted earlier, BR, by nature, encourages a FFS pattern; thus, BR and FFS will be used interchangeably.[15] There are several biomechanical differences between FFS and RFS. First, FFS results in a shorter stride length,[11] which means that the foot lands closer to the body's center of mass. This landing reduces the vertical displacement of the center of mass.[15,19,20] A systematic review of current literature on FFS showed consistent reduction in the moment arms of the vertical and mediolateral GRF of the knee and hip joints.[20] FFS also reduces the external eversion moment and decreases the tendency of the foot to evert with BR.[15] Second, several studies have shown that BR promotes a higher stride frequency (ie, cadence).[11,21] A higher cadence reduces loading, which may protect against impact-related injuries.[22,23] With a FFS pattern, impact force equals 58% BW compared with 189% BW with RFS.[18] In addition, with RFS, the knee and hip experience collision forces that are approximately two to three times the runner's BW, despite the cushioning of a modern running shoe.[13] Stride frequency and cadence may impact running performance.

One of the key differences in FFS running is that the impact transient is eliminated or considerably attenuated because of the lack of heel strike[11,13,15,17,19] (Figure 2). This decrease is achieved through eccentric loading of the posterior calf musculature. Based on electromyography signals, the gastrocnemius muscle demonstrated considerably higher activity in runners using FFS than in those using RFS in both the preactivation and stance phases.[14] This activity implies that there may be greater muscle load placed on the posterior calf musculature when using FFS.[14] Over time, this can lead to training the Achilles tendon and posterior tibialis muscle to take on an increased load—a potential cause of increased injuries to this area associated with MR.[14,15] However, there is a theoretical reduction in tibia stress reaction and wear of articular cartilage in the lower extremity.

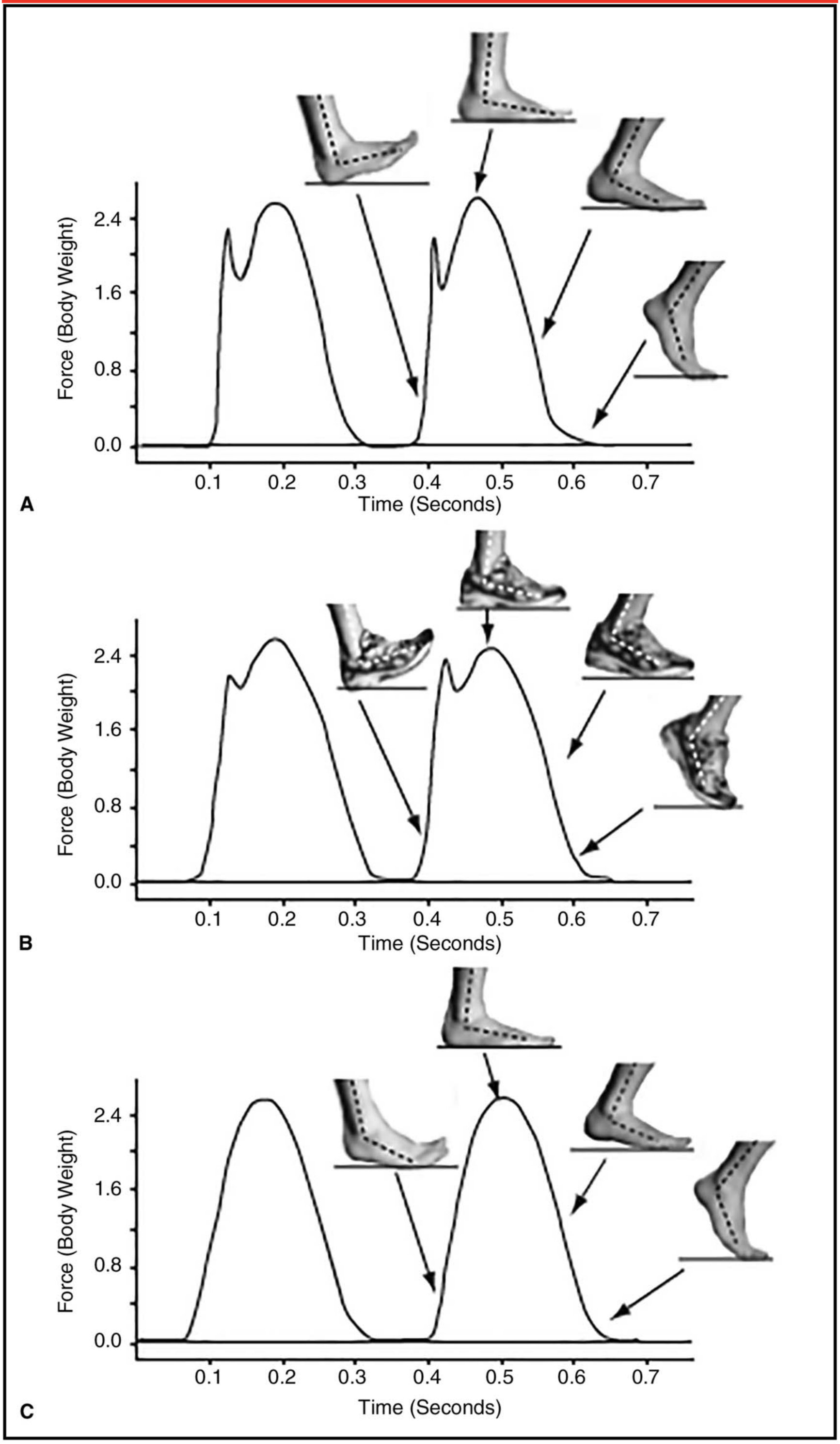
With the FFS pattern, the ankle is slightly plantarflexed during landing, as opposed to being dorsiflexed in shod conditions. Compared with RFS, ankle stiffness with the FFS pattern is decreased because the metatarsal heads are the first contact point with the ground.[13] This contact is associated with increased stress on the metatarsal heads and, thus, an elevated risk of stress injuries.[13,15,17]

Kerrigan et al[24] reported that knee flexion, knee adduction, and hip external rotation moments are all reduced with the FFS pattern secondary to reduced moment arms on these joints. Bonacci et al[11] reported that BR had a decreased peak knee extension moment (9%) that was significantly less than that previously reported with shod running (36%).[24] BR resulted in increased knee flexion at touchdown, which indicates that muscle activity is likely greater in the thigh during BR.[17] The larger knee flexion angle achieved upon landing provides a greater cushioning effect and increases the compliance of the lower extremities.[14] Therefore, the lower extremity has more shock absorption when running with a FFS pattern.[14] BR showed a calculated 12% reduction in peak joint reactive force, which led to a 12% reduction in patellofemoral joint (PFJ) stress (standardized mean difference, 0.5).[11]

Although biomechanics and injury rates are associated with running styles, strike pattern may also affect performance. Shih et al[14] considered FFS and MFS patterns to be less efficient because the center of trajectory moves posteriorly prior to the center's moving forward again. In contrast, Warne and Warrington[25] and Franz et al[26] have suggested that BR represents a more natural and efficient movement pattern. The concept of running economy (ie, the oxygen cost [VO_2 sub-max] of running at a fixed intensity) is often used as a marker of performance. Weight appears to be an important factor because metabolic efficiency decreases approximately 1% for every 100 g added to the foot.[26] This alone can account for the improved performance seen with BR; however, the aforementioned differences in kinetic and potential energy transfer may provide additional advantages.[13] Warne and Warrington[25] compared running economy in 15 highly trained male runners who wore traditional shod footwear and then minimalist shoes after a 4-week transition period. The authors noted a markedly reduced oxygen cost with MR. Despite a slight 250-g difference in weight, there was a 6.9% improvement in overall running economy. Perl et al[4] also noted improved running economy in runners wearing minimalist footwear even after controlling for shoe mass and stride frequency. However, this was independent of strike pattern because both FFS and RFS were notably more efficient with the minimalist shoes. Still, no statistical difference was found between the two patterns.

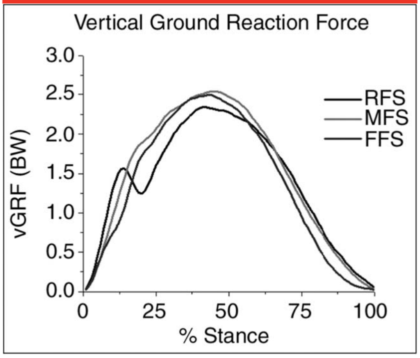
The FFS pattern takes better advantage of the energy-storing

Figure 2



Graphs demonstrating vertical ground reaction force curves for three foot strike patterns in the same runner. **A,** Rearfoot strike during barefoot running. **B**, Rearfoot strike during shod running. **C**, Forefoot strike during barefoot running. (Reproduced with permission from: Lieberman DE, Venkadesan M, Werbel WA, et al: Foot strike patterns and collision forces in habitually barefoot versus shod runners. *Nature* 2010;463[7280]:531-535.)

Figure 3



Graph demonstrating the vertical ground reaction force (vGRF) curves associated with a shod rearfoot strike (RFS), midfoot strike (MFS), and forefoot strike (FFS). Note the distinct impact peak of the RFS that is missing in the MFS and FFS patterns. BW = body weight (Reproduced with permission from Altman AR, Davis IS: Barefoot running: Biomechanics and implications for running injuries. *Curr Sports Med Rep* 2012;11 [5]:244-250.)

capacity of the arch.[15] This is depicted by an increased vertical arch motion during load acceptance. Removal of the arch support in footwear results in increased strength of the foot and ankle.[15] Some sources suggest that the arch may fall without cushioned shoes,[15] but this has not been definitively proven. In addition, BR leads to increased sensory input to the neuromuscular system resulting from increased feedback from foot-ground contact.[15] This response leads to improved static and dynamic stability of the lower extremity compared with shod running.[15]

Shod Running

The main function of heel cushioning in modern shoes is for comfort during RFS, which becomes increasingly intolerable if barefoot. Although cushioning helps to reduce peak GRF and improve leg compliance, the benefit is actually quite minimal.[16] Thus, although there is a perceptible difference in comfort, the true benefit of cushioning from a kinetic standpoint is most likely far less substantial.

The cushioned sole of a traditional shoe can also decrease RFS loading rates, although to a lesser degree than a FFS pattern.[16] In general, loading rates with RFS are up to three times higher than loading rates with FFS.[13,15] A defined impact peak in vertical GFR precedes the propulsion peak[13,15] (Figure 3). Higher impact transients related to increased vertical loading rates and tibial shock, as seen in RFS, are associated with bone and soft-tissue injuries, such as tibial stress fractures and plantar fasciitis.[15,17] To date, no proven correlation exists between increased GRF and tibial stress fractures in runners.[13] Still, high-impact loading variables have been seen in runners who use the RFS pattern and have a history of plantar fasciitis and patellofemoral pain.[15]

Patellofemoral pain and plantar fasciitis are common injuries in runners and may be a result of excessive eversion at heel strike. This motion stretches the plantar fascia and deltoid ligaments and could cause injury.[13] Excessive ankle eversion or forefoot pronation may be a result of excessive cushioning. In addition to excessive eversion, use of cushioned shoes may require greater angular work at the knee, resulting in higher patellofemoral and tibiofemoral compressive forces and possibly greater risk of injury to the knee.[19] A recent study shows that, compared with shoes with a low heel height, shoes with a medium or high heel height increase PFJ stress even during walking.[11] One benefit of modern running shoes is that the wider heel stabilizes the hindfoot at impact, preventing excessive inversion or eversion.

Injury Prevention

Much of the interest surrounding the MR phenomenon centers on injuries. Daoud et al,[9] among others, have suggested that “running injury rates are unacceptably high, with no substantial decline during the last 30 years, despite considerable efforts to reduce them.” van Gent et al[7] have also reported annual injury rates of up to 75% in runners although the underlying purpose of running is to improve overall health. A review of >2,000 running-related injuries revealed that patellofemoral pain syndrome (PFPS), iliotibial band syndrome, plantar fasciitis, Achilles and patellar tendinitis, and various stress fractures are the most common.[27] As with many orthopaedic issues, running injuries are multifactorial by nature and involve both intrinsic and extrinsic factors.[9] Shoes and gait pattern are only small pieces of the puzzle; thus, BR and MR have been met with understandable skepticism. Nevertheless, the perpetually high injury rate in runners warrants consideration of new avenues for improvement.

Despite the fact that running has been a popular form of exercise during the past 40 years, associated injury patterns are still not fully understood. Acute, traumatic events aside, most believe that injuries are an overuse phenomenon resulting from repetitive impact forces over time. Hreljac[28] discusses the concept of an injury threshold, which is a theoretical curve relating stress level and running frequency. Although this threshold differs among people, it helps to conceptualize the effect of recurring microtrauma. However, the concept of overuse is not universally accepted and may be considered a means of classifying injuries as opposed to being a true explanation of the mechanism of injury. With regard to BR and MR, the proposed injury reduction is a result of decreased impact peak and loading rate with FFS running.[16,29] Intuitively, altering these forces would lead to a reduction in injuries; however, this has yet to be substantiated in the literature.

Zadpoor and Nikooyan[30] examined the effect of vertical GRF and loading rates on lower extremity stress fractures. No difference was found between stress fracture and control groups with regard to forces, but the average and instantaneous rate of loading was considerably increased in those who sustained metatarsal and tibial stress fractures. Heiderscheit et al[31] demonstrated that, in the setting of an RFS running pattern, a 10% decrease in stride length decreased the risk of developing a tibial stress fracture, despite a higher cadence. In a study of female runners with plantar fasciitis, Pohl et al[32] observed an increased loading rate compared with the rate in the control group. Although there was a trend for higher impact peak among women with plantar fasciitis, this evidence was not substantial. However, the correlation between impact forces and injury is not universally accepted. Nigg and Wakeling[33] proposed that "repetitive impact forces during physical activities are not important from an injury perspective but are the reason for changes in myoelectric activity (muscle tuning) to minimize soft tissue vibrations."

The question whether FFS running will truly reduce injury rates longitudinally remains unanswered. Most of the data, as previously discussed, hinge on inferences and small sample sizes. The most compelling literature today involves a retrospective cohort study that analyzed a Division I collegiate cross-country team (52 athletes) over a 4.5-year period.[9] These athletes had a 75% injury rate per year, which agrees with previously reported data.[5-8] Injuries were categorized as either traumatic or repetitive. Strike type was also characterized for each athlete, with 31% of athletes demonstrating an FFS pattern and 69% demonstrating a RFS pattern. Although there was no difference in the traumatic injury rate, FFS runners were 1.7 times less likely to sustain repetitive injuries. However, these results should be interpreted cautiously because of potential limited generalizability based on the retrospective nature of the study and its small, homogenous cohort. In addition, a recent class action lawsuit was settled against the shoe manufacturer Vibram for unfounded claims about the positive effects their FiveFingers shoes have on the body.[34]

Moreover, FFS running seems to create a new injury profile, with potentially high risks of metatarsal stress fractures, plantar fasciitis, and puncture wounds (with true BR).[13] Salzler et al[35] reported on a case series of 10 consecutive injuries in a cohort of experienced runners who became injured an average of 2.8 months (range, 1 to 10 months) after transitioning to minimalist footwear. Notably, half of the runners converted slowly over a period of up to 2 months and half underwent no transition period. The injuries included eight metatarsal stress fractures, one plantar fascia rupture, and one calcaneal stress fracture, which was noted as uncharacteristic by the authors, given the presumably decreased force across the calcaneus with FFS.

Several authors have reported injuries during the switch to minimalist footwear, particularly when there was no transition period.[36,37] Ridge et al[38] found that, even in the absence of a clinically evident foot injury, patients frequently displayed increased bone marrow edema on MRI. Caution should be used when transitioning to MR because it does not ensure injury-free activity. A summary of injuries based on running technique is outlined in Table 1.

Injury Treatment

Although much of the focus of MR is on the prevention of injury, the treatment component cannot be overlooked. The prevalence of PFPS has been discussed,[27] and clinically, it remains a difficult and persistent problem for both patients and healthcare providers. The proposed hypothesis behind PFPS is increased PJF stress, likely related to maltracking secondary to either anatomic malalignment or an imbalance of the vastus medialis obliquus.[39] Traditionally, treatment is centered on a physical therapy (PT) regimen involving static soft-tissue stretching and bracing as well as dynamic strengthening of the vastus medialis obliquus, hip abductors, and core musculature.

Bonacci et al[40] performed a video motion analysis of 22 highly trained runners (without prior BR training) while measuring lower extremity kinematics and GRF. Compared with shod running, BR showed a 12% decrease in stress and PFJ reaction forces. Scant prospective data exist at this point; however, Cheung and Davis[41] analyzed three female runners with PFPS who were treated exclusively with landing pattern retraining. Each runner underwent eight PT sessions with the purpose of transitioning away from a RFS pattern. Posttraining, all three runners converted to FFS/MFS for >90% of their landings. These results remained stable at a 3-month assessment. GRF showed the predictable loss of impact peak for each runner, as discussed earlier. More pertinent to PFPS, each runner had durable improvement in symptoms (as measured by the Kujala scale and the visual analog scale for patellofemoral pain) and functional limitations.

Chronic exertional compartment syndrome (CECS) is another diagnosis that represents challenging symptomatology for runners and sometimes unrewarding treatment options from a surgeon's perspective. Runners make up nearly 70% of CECS patients and are often initially treated nonsurgically with activity limitations and PT, with limited success reported.[42,43]

Table 1

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	Lower risk
Metatarsal stress fractures	Higher risk	Lower risk
Puncture wounds/temperature extreme foot injuries	Higher risk	Lower risk

FFS = forefoot strike, RFS = rearfoot strike
Reproduced with permission from Murphy K, Curry EJ, Matzkin EG: Barefoot running: Does it prevent injuries? *Sports Med* 2013;43[11]:1131-1138.

Although fasciotomies provide a seemingly definitive solution, success is not guaranteed and complications still exist. Diebal et al[44] conducted a prospective case series involving 10 active duty service members with CECS for >10 months. Each service member underwent baseline compartment measurements after a 6-week training regimen and at 1-year follow-up. The training consisted of regular PT sessions focused on transition to FFS using drills, running cues, cadence measurement, and video analysis. The authors reported substantial increases in running tolerance, increased scores on the Single Assessment Numeric Evaluation and Lower Leg Outcome Survey, and decreased scores on the visual analog scale. Objectively, they also noted a decrease in mean anterior compartment pressures (78 mm Hg to 38 mm Hg) following the conclusion of the training regimen. Although PFPS and CECS are multifactorial issues whose pathophysiology is not well understood, early data suggest potential improvement when runners move to a FFS landing pattern.

Knowledge Gaps

In many ways, the social trends and public curiosity about BR and MR have outpaced evidence-based data. Despite its popularity, minimalist footwear lacks industry standards, which further contributes to the scarcity of objective research. Evidence indicates that the importance lies not so heavily in the shoe as in the foot strike itself. Although many advocates recommend stretching, strengthening, and stabilizing the foot and ankle, no consensus has been reached regarding an appropriate transition program.

The best biomechanical literature available to date is of moderate quality at best, with much of the content based on small studies. The effect of FFS mechanics on injury rates is even more difficult to determine. Additional prospective, longitudinal data are required to determine the benefits and drawbacks associated with BR and MR.

Summary

Although the popularity of MR has increased in recent years after it was presented as the natural way to run, critical analysis of the available data is crucial. Much of the public interest centers on shoe selection; however, the key issue seems to be gait pattern, specifically RFS versus FFS patterns. The literature has demonstrated that, with less cushioned footwear, runners spontaneously transition to a FFS pattern. Biomechanically, compared with RFS, FFS translates to reduced impact forces proximally, in exchange for elevated stress across the foot and ankle. In addition, although footwear is often a marker of strike pattern, runners can transition to FFS in any type of shoe, with the appropriate training. Many believe that decreasing the associated impact transient and loading rates with FFS will correlate with lower injury rates; however, this has yet to be firmly substantiated. Recent literature has shown that patients with patellofemoral pain and chronic exertional compartment syndrome benefit from converting to a FFS pattern. However, there is still concern for increased foot and ankle injuries in these patients, particularly when they do not have an appropriate transition period. Regardless, MR is an emerging phenomenon that warrants continued interest and exploration from an orthopaedic perspective to help identify the true long-term risks and benefits.

References

Evidence-based Medicine: Levels of evidence are described in the table of contents. In this article, references 4, 11, 14, 17, 18, 22-26, 31, 38, and 40 are level II studies. References 7, 9, 16, 19-21, 27, 30, and 32 are level III studies. References 6, 35-37, 41, 42, and 44 are level IV studies. References 29 and 33 are level V expert opinion.

References printed in **bold type** are those published within the past 5 years.

1. Bramble DM, Lieberman DE: Endurance running and the evolution of Homo. *Nature* 2004;432(7015):345-352.

2. Lieberman DE, Bramble DM, Raichlen DA, Shea JJ: Brains, brawn, and the evolution of human endurance running capabilities, in Grine FE, Fleagle JG, Leakey RE, eds: *The First Humans: Origin and Early Evolution of the Genus Homo*. New York NY, Springer, 2006, pp 77-92.

3. Running USA: 2013 State of the Sport: Part II. Running industry report. http://www.runningusa.org/state-of-sport-2013-part-II?returnTo=annual-reports. Accessed November 16, 2015.

4. **Perl DP, Daoud AI, Lieberman DE: Effects of footwear and strike type on running economy. *Med Sci Sports Exerc* 2012;44(7):1335-1343.**

5. Fields KB, Sykes JC, Walker KM, Jackson JC: Prevention of running injuries. *Curr Sports Med Rep* 2010;9(3):176-182.

6. van Mechelen W: Running injuries: A review of the epidemiological literature. *Sports Med* 1992;14(5):320-335.

7. van Gent RN, Siem D, van Middelkoop M, van Os AG, Bierma-Zeinstra SM, Koes BW: Incidence and determinants of lower extremity running injuries in long distance runners: A systematic review. *Br J Sports Med* 2007;41(8):469-480.

8. **Rixe JA, Gallo RA, Silvis ML: The barefoot debate: Can minimalist shoes reduce running-related injuries? *Curr Sports Med Rep* 2012;11(3):160-165.**

9. **Daoud AI, Geissler GJ, Wang F, Saretsky J, Daoud YA, Lieberman DE: Foot strike and injury rates in endurance runners: A retrospective study. *Med Sci Sports Exerc* 2012;44(7):1325-1334.**

10. McDougall C: *Born to Run: A Hidden Tribe, Superathletes, and the Greatest Race the World Has Never Seen*. New York, NY, Alfred A. Knopf, 2009.

11. **Bonacci J, Saunders PU, Hicks A, Rantalainen T, Vicenzino BG, Spratford W: Running in a minimalist and lightweight shoe is not the same as running barefoot: A biomechanical study. *Br J Sports Med* 2013;47(6):387-392.**

12. Standring S: *Gray's Anatomy: The Anatomical Basis of Clinical Practice, Expert Consult*, ed 40. London, UK, Churchill Livingstone, 2008.

13. **Murphy K, Curry EJ, Matzkin EG: Barefoot running: Does it prevent injuries? *Sports Med* 2013;43(11):1131-1138.**

14. **Shih Y, Lin KL, Shiang TY: Is the foot striking pattern more important than barefoot or shod conditions in running? *Gait Posture* 2013;38(3):490-494.**

15. **Altman AR, Davis IS: Barefoot running: Biomechanics and implications for running injuries. *Curr Sports Med Rep* 2012;11(5):244-250.**

16. Lieberman DE, Venkadesan M, Werbel WA, et al: Foot strike patterns and collision forces in habitually barefoot versus shod runners. *Nature* 2010;463(7280):531-535.

17. **Olin ED, Gutierrez GM: EMG and tibial shock upon the first attempt at barefoot running. *Hum Mov Sci* 2013;32(2):343-352.**

18. **Mullen S, Toby EB: Adolescent runners: The effect of training shoes on running kinematics. *J Pediatr Orthop* 2013;33(4):453-457.**

19. **Goss DL, Gross MT: A review of mechanics and injury trends among various running styles. *Army Med Dep J* 2012;Jul-Sep:62-71.**

20. **Schubert AG, Kempf J, Heiderscheit BC: Influence of stride frequency and length on running mechanics: A systematic review. *Sports Health* 2014;6(3):210-217.**

21. **Hall JP, Barton C, Jones PR, Morrissey D: The biomechanical differences between barefoot and shod distance running: A systematic review and preliminary meta-analysis. *Sports Med* 2013;43(12):1335-1353.**

22. **Hobara H, Sato T, Sakaguchi M, Sato T, Nakazawa K: Step frequency and lower extremity loading during running. *Int J Sports Med* 2012;33(4):310-313.**

23. Edwards WB, Taylor D, Rudolphi TJ, Gillette JC, Derrick TR: Effects of stride length and running mileage on a probabilistic stress fracture model. *Med Sci Sports Exerc* 2009;41(12):2177-2184.

24. Kerrigan DC, Franz JR, Keenan GS, Dicharry J, Della Croce U, Wilder RP: The effect of running shoes on lower extremity joint torques. *PM R* 2009;1(12):1058-1063.

25. **Warne JP, Warrington GD: Four-week habituation to simulated barefoot running improves running economy when compared with shod running. *Scand J Med Sci Sports* 2014;24(3):563-568.**

26. **Franz JR, Wierzbinski CM, Kram R: Metabolic cost of running barefoot versus shod: Is lighter better? *Med Sci Sports Exerc* 2012;44(8):1519-1525.**

27. Taunton JE, Ryan MB, Clement DB, McKenzie DC, Lloyd-Smith DR, Zumbo BD: A retrospective case-control analysis of 2002 running injuries. *Br J Sports Med* 2002;36(2):95-101.

28. Hreljac A: Impact and overuse injuries in runners. *Med Sci Sports Exerc* 2004;36(5):845-849.

29. **Lieberman DE: What we can learn about running from barefoot running: An evolutionary medical perspective. *Exerc Sport Sci Rev* 2012;40(2):63-72.**

30. Zadpoor AA, Nikooyan AA: The relationship between lower-extremity stress fractures and the ground reaction force: A systematic review. *Clin Biomech (Bristol, Avon)* 2011;26(1):23-28.

31. Heiderscheit BC, Chumanov ES, Michalski MP, Wille CM, Ryan MB: Effects of step rate manipulation on joint mechanics during running. *Med Sci Sports Exerc* 2011;43(2):296-302.

32. Pohl MB, Mullineaux DR, Milner CE, Hamill J, Davis IS: Biomechanical predictors of retrospective tibial stress fractures in runners. *J Biomech* 2008;41(6):1160-1165.

33. Nigg BM, Wakeling JM: Impact forces and muscle tuning: A new paradigm. *Exerc Sport Sci Rev* 2001;29(1):37-41.

34. Thomas E: Vibram: "Barefoot Running Shoe" Company, Settles Multi-Million Dollar Lawsuit. *Huffington Post*. May 10, 2014. http://www.huffingtonpost.com/2014/05/10/_n_5302213.html. Accessed November 19, 2015.

35. **Salzler MJ, Bluman EM, Noonan S, Chiodo CP, de Asla RJ: Injuries observed in minimalist runners. *Foot Ankle Int* 2012;33(4):262-266.**

36. **Cauthon DJ, Langer P, Coniglione TC: Minimalist shoe injuries: Three case reports. *Foot (Edinb)* 2013;23(2-3):100-103.**

37. Giuliani J, Masini B, Alitz C, Owens BD: Barefoot-simulating footwear associated with metatarsal stress injury in 2 runners. *Orthopedics* 2011;34(7):e320-e323.

38. **Ridge ST, Johnson AW, Mitchell UH, et al: Foot bone marrow edema after a 10-wk transition to minimalist running shoes. *Med Sci Sports Exerc* 2013;45(7):1363-1368.**

39. Collado H, Fredericson M: Patellofemoral pain syndrome. *Clin Sports Med* 2010;29(3):379-398.

40. **Bonacci J, Vicenzino B, Spratford W, Collins P: Take your shoes off to reduce patellofemoral joint stress during running. *Br J Sports Med* 2014;48(6):425-428.**

41. Cheung RT, Davis IS: Landing pattern modification to improve patellofemoral pain in runners: A case series. *J Orthop Sports Phys Ther* 2011;41(12):914-919.

42. Detmer DE, Sharpe K, Sufit RL, Girdley FM: Chronic compartment syndrome: Diagnosis, management, and outcomes. *Am J Sports Med* 1985;13(3):162-170.

43. Shah SN, Miller BS, Kuhn JE: Chronic exertional compartment syndrome. *Am J Orthop (Belle Mead NJ)* 2004;33(7):335-341.

44. **Diebal AR, Gregory R, Alitz C, Gerber JP: Forefoot running improves pain and disability associated with chronic exertional compartment syndrome. *Am J Sports Med* 2012;40(5):1060-1067.**