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Invited review

Why forefoot striking in minimal shoes might positively change the course of running injuries

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Abstract

It is believed that human ancestors evolved the ability to run bipedally approximately 2 million years ago. This form of locomotion may have been important to our survival and likely has influenced the evolution of our body form. As our bodies have adapted to run, it seems unusual that up to 79% of modern day runners are injured annually. The etiology of these injuries is clearly multifactorial. However, one aspect of running that has significantly changed over the past 50 years is the footwear we use. Modern running shoes have become increasingly cushioned and supportive, and have changed the way we run. In particular, they have altered our footstrike pattern from a predominant forefoot strike (FFS) landing to a predominant rearfoot strike (RFS) landing. This alters the way in which the body is loaded and may be contributing to the high rate of injuries runners experience, engaging in an activity they were adapted for. In this paper, we will examine the benefits of barefoot running (typically an FFS pattern), and compare the lower extremity mechanics between FFS and RFS. The implications of these mechanical differences, in terms of injury will be discussed. We will then provide evidence to support that forefoot striking provides an optimal mechanical environment for specific foot and ankle structures, such as the heel pad, the plantar fascia and the Achilles tendon. The importance of footwear will then be addressed, highlighting its interaction with strike pattern on mechanics. This will underscore why footwear matters when assessing mechanics. Finally, proper preparation and safe transition to an FFs pattern in minimal shoes will be emphasized. Through the discussion of the current literature, we will develop a justification for returning to running in the way we were adapted for in order to reduce running-related injuries.

Keywords: Footstrike pattern; Minimal footwear; Running; Running injury; Running mechanics; Tissue mechanics.

1. Introduction

Some evolutionary biologists suggest that the modern human form reflects numerous adaptations that facilitate bipedal running[1]. To the best of our knowledge, and based on anthropological evidence, it has been suggested that humans began running approximately 2 million years ago[1]. Human ancestors were and modern humans are relatively slow runners compared to other scavengers. However, it is posited that our human ancestors evolved into effective endurance runners. This allowed them to run their prey into exhaustion, enabling them to get close enough to club them to death. Indeed, humans are the only primate capable of endurance running. Despite the derived capabilities of the modern human to engage regularly in running, up to 79% of modern endurance runners are injured in a given year, with 46% of injuries being recurrences[2]. These injury statistics seem inconsistent with the idea that humans have numerous morphological features that are specific to running.

One explanation for this high injury rate in runners may be based in the mismatch theory of evolution. This theory generally suggests that many of the health problems in society today are the result of the rapid change in environment and diet relative to the rate at which the human body has adapted [3,4]. This includes the processed food we eat, the polluted air we breathe and the relative lack of activity we now engage in. Whereas in the past, we often died of communicable diseases, we are now dying of preventable, non-communicable diseases such as those associated with obesity and cardiovascular conditions. The high rate of running injuries today may be another example of this mismatch theory. Runners may be adapting their mechanics to the modern environment in a way that is mismatched to the mechanics we evolved to run with.

There has been an ongoing debate about whether the way a runner strikes the ground plays a role in running injuries today. Up to 95% of traditionally shod runners land on their heel (rearfoot strike – RFS) when they run[5–7] on modern hard surfaces. According to De Almeida, et al.[5] approximately 5% land with a flat foot (midfoot strike – MFS) and 1% land on the ball of their foot (forefoot strike – FFS). Conversely, the majority of *habitual* barefoot runners land with an FFS, in slight plantarflexion[8,9]. Given that humans evolved the ability to run without the assistance of footwear, strike patterns during barefoot running likely represent our most natural form. Whereas primitive shoes have existed for some 10,000 years, cushioned running shoes have only existed for the past 50 years. As a softer surface encourages more of a heel strike landing[10], the cushioning in modern running shoes is likely responsible for the predominant RFS pattern in runners today. Therefore, it is plausible that footwear has changed the way the modern humans run, which is mismatched from the running style we evolved to use.

The purpose of this paper is to examine whether changes in strike pattern and footwear have contributed to the high rate of injury associated with running. We will provide evidence to support the argument that the strike pattern of our most natural state, in footwear that does not interfere with one's natural mechanics, may be the optimal way to reduce injury risk in runners. We will do this by examining the mechanics of barefoot running and reviewing the differences in lower extremity mechanics between RFS and FFS patterns and how these differences are related to injury. We will then examine the effect of strike pattern on mechanics at the tissue level including the heel pad, plantar fascia and Achilles tendon. Finally, we will elucidate the complex interactions between footwear, footstrike pattern, and mechanics. These interactions will, in turn, lend credence to the idea that running with an FFS in minimal shoes might positively change the trajectory of running injuries today. For the purpose of this paper, we will focus on the mechanics of running on relatively hard surfaces (ie. not sand, grass, trails) as this is where the majority of modern running occurs and where the majority of studies are conducted. We will also focus on habitual running mechanics as opposed to novice, unpracticed mechanics that may be temporary in nature.

2. What can we learn from barefoot running?

It has been suggest that our human ancestors began running over 2 million years ago[11], yet the earliest example of footwear is dated back over 10,000 years. Thus, modern humans and our ancestors ran barefoot for the vast majority of our evolutionary history. As humans evolved the ability to run in the absence of shoes, we consider barefoot running to be the baseline condition that is reflected in human morphology.

The most ecologically valid means of assessing barefoot running is to examine those who habitually run this way. Most studies have revealed that *habitual* barefoot runners do not typically land on their heels, unlike their shod counterparts[12,13]. These studies have been limited to running on hard surfaces which are where the majority of runners do their training volume. The primary reason for this is that loads associated with landing on the heel without cushioning during running exceeds those associated with the pain pressure threshold that occurs at fast walking.[14] It is logical that humans would run in a way that is least painful. It has been reported that habitual barefoot runners will use a RFS pattern when running on soft surfaces.[13] However, landing with an FFS is our most typical running style when running on hard surfaces.[8,12,13] One study has observed that habitually barefoot people from the Daasanach tribe in northern Kenya mostly run with a RFS. However, it has been noted that these individuals who live in a hot sandy desert, are traditional pastorists who walk long distances for herding purposes and do not run much.[8,9,15]

Barefoot running has a number of documented benefits. It has been shown that removing support (as provided by modern footwear) from the arch of the foot during running strengthens the foot. This is evidenced by an increase in the cross-sectional areas of both intrinsic and extrinsic foot muscles following a period of running in minimal shoes that mimic barefoot running[16]. It has been reported that Indian children who live in communities where they are habitually barefoot have significantly higher arches than their counterparts from communities where either open toed sandals or closed toed shoes are worn[17]. Being barefoot also allows the maximal sensory input to the lower extremity. This sensory input has been shown to be important for both static and dynamic stability[18,19]. Sensory input is also important in modulating the appropriate leg stiffness for the surface being encountered[20–22]. High leg stiffness is associated with greater loading rates and shock, which may increase the risk of injury to bone tissue[23–25]. On the other hand, excessively low stiffness has been associated with soft tissue injuries[26,27]. Furthermore. it has been shown that stiffness differs between RFS and FFS running patterns[28]. Achieving optimal stiffness is important as it is influences running economy and performance as well as shock attenuation and injury risk[29].The heightened sensory input available when barefoot running may facilitate the optimization of lower limb stiffness.[30]

3. Mechanics of rearfoot *vs*. forefoot striking

Foot strike pattern, which is defined by the part of the foot which first strikes the ground during running, plays a significant role in the lower extremity mechanics during early stance[31–33]. During a RFS, the ankle is dorsiflexed and the rearfoot is inverted at landing. The foot lands out in front of the center of mass with the knee slightly flexed (Fig. 1A). From this position, the foot dorsiflexes and everts and the knee continues to flex. At midstance, these motions reverse until toe-off. During an FFS, the ankle is plantarflexed at initial contact with greater rearfoot inversion than in a RFS. The knee lands in more flexion with the foot placed more directly below the center of mass (Fig. 1B). Due to the increased plantarflexion and inversion, the foot goes through greater dorsiflexion and eversion range of motion during stance in FFS running. This greater excursion occurs over a similar time frame as RFS, resulting in greater dorsiflexion velocities. This pattern is associated with greater plantarflexion muscle moments, as well as greater negative work required of the plantarflexors (Fig. 2). In contrast, the knee goes through a greater flexion excursion during RFS but over a similar time frame to FFS, resulting in higher knee flexion velocity. Greater demands are placed on the knee extensors as evidenced by the higher knee extension muscle moments and negative work. Therefore, an FFS pattern is associated with greater demands on the foot and ankle, and a RFS pattern is associated with greater demands on the knee.

Clear differences in ground reaction force time histories can also be seen between a RFS and a FFS pattern[13,34,35]. A RFS pattern often displays a distinct impact transient early in stance that is associated with high vertical loading rates (Fig. 2). An FFS pattern typically has no impact transient and is associated with vertical rates of loading that are approximately half those of a RFS. However the active peak vertical force that occurs near midstance is generally similar or slightly increased in an FFS pattern. Therefore, the majority of differences between a RFS and a FFS pattern occur in the early part of stance and are directly related to the manner in which the foot contacts the ground.

4. Strike pattern and injury

The high vertical loadrates associated with a RFS pattern have been linked both prospectively and retrospectively with injury[36–38]. Musculoskeletal structures are viscoelastic in nature and vulnerable to injury at high rates of loading. This has been underscored by animal studies demonstrating injuries to both bone and cartilage when imposing impulsive loads, rather than gradual ones[39,40]. This has also been demonstrated in human studies. A recent meta-analysis reported a significant relationship between vertical load rates and tibial stress fractures in RFS runners[41]. Interestingly, knee osteoarthritis with associated cartilage degradation has been linked with higher than normal vertical rates of loading during walking[42]. High vertical load rates may translate to abnormal loads in ligamentous structures as well. This was evidenced in a study demonstrating higher load rates in RFS runners with a history of plantar fasciitis compared to an uninjured group[38]. The majority of these studies have been retrospective in nature making inferences regarding cause and effect difficult. However, a recent prospective investigation revealed that runners who go on to sustain a medically diagnosed injury had significantly higher load rates at baseline than their never-injured counterparts[36]. These prospective, along with the retrospective, data provide compelling support for an association between ground reaction force load rates and musculoskeletal injuries in runners.

If humans are best adapted for FFS landings, then it follows that it should be associated with the lowest injury risk. Clearly, FFS running is associated with lower vertical load rates compared with RFS. Unfortunately, there are only a few studies to date that have examined the relationship between strike pattern and injury. Warr et al.[43] found no difference in injury histories of runners with differing strike patterns. However, these authors compared RFS runners to the combined group of MFS and FFS. Additionally, running injuries in this study were self-reported and relied on recall. A recent report suggests that MFS and FFS runners should not be combined due to the statistically higher loadrates during MFS landings.[44] In another retrospective investigation of a collegiate cross country team, Doaud et al.[45] reported that RFS runners sustained medically diagnosed repetitive stress injuries twice as often as FFS runners.

Future prospective studies examining footstrike patterns and injury are needed to further determine these relationships.

Transitioning from a RFS to an FFS pattern has been shown to have a beneficial effect on common running injuries. One study involved a group of U.S. military (West Point) cadets presenting with anterior compartment syndrome and high intracompartment pressures[46]. These cadets were scheduled for, but had not undergone, a surgical release of the fascia surrounding the anterior compartment. After completing a gradual 6-week transition to FFS running, all 10 subjects demonstrated significant reductions in their intracompartmental pressures (to within normal limits). Additionally, subjects reported large improvements in outcome questionnaires, and were able to complete a 5 km run without pain. All of the outcome variables were further significantly improved at the 1 year follow-up. Most importantly, surgical intervention was avoided in all cases. In a recent case series report, 3 runners with a longstanding history of patellofemoral pain (mean = 40 months) underwent a transition to an FFS pattern[47]. All had failed conventional physical therapy which had focused on hip and knee strengthening, along with electrical stimulation for the quadriceps. Participants underwent 8 sessions of landing pattern modification from a RFS to an FFS over 2 weeks, using real-time audio feedback from a force sensor placed within the shoe. Feedback was gradually faded as run time was increased to 30 min by the last session. All 3 runners were able to successfully transition to an FFS pattern and reduce their vertical average and instantaneous load rates by 19% and 24%, respectively. Additionally, pain was markedly reduced. All improvements in outcome variables persisted at the 3-month follow-up. These results are supported by a modelling study by Bonacci et al.[48] who demonstrated that patellofemoral contact stresses are reduced when running barefoot with an FFS pattern. These studies collectively underscore the efficacy of transitioning to an FFS pattern in treating runners with these common running injuries.

5. Strike pattern and tissue mechanics

In this section, we will consider how strike pattern influences key anatomical features of the foot including the heel pad, the plantar fascia, and the Achilles tendon.

5.1 Heel pad

The heel pad is thought to provide 3 useful functions during gait, namely: *shock reduction*; *energy dissipation*, and *protection against excessive plantar pressure.*[49] During the initial contact phase of heel–toe walking (10–20 ms after heel strike), deformation of the heel fat pad has been suggested to lower the peak force and/or the rate of loading of the lower limb[50]. The fat pad has been noted to undergo considerable vertical deformation, about 9 to 11 mm (~45%–60% strain), during barefoot walking[14,51]. However, the initial loading rate of the heel pad is extremely high (~1.2 MPa/s). Additionally, the energy required to compress the heel pad (1.5 J) is relatively low[51] compared to the total energy exchange during walking (~21 J in a 70 kg adult walking at 4.5 km/h)[52]. Hence, the heel pad offers minimal resistance to deformation during initial contact suggesting it has only a minor shock reduction capacity during walking, let alone running.

With every step, a proportion of the strain energy stored within the heel pad during loading is lost with unloading. This energy loss is believed to play an important role in damping high-frequency vibration within tissue[53]. Although the ratio of energy lost verses energy stored in the heel pad is in the order of 55% to 70%, only about a 1.0 J is dissipated by the heel pad in absolute terms during heel-toe walking[49,51]. This is considerably less than that of the Achilles tendon (~ 2.5 J)[54] and the ligamentous structures (~ 3.1−4.5 J) of the medial longitudinal arch of the foot[55,56], which have ”spring like” properties and are important for energy return. The overall *energy dissipated* by the heel pad, therefore, is relatively low and unlikely to substantially increase with speed, making it a less than ideal structure for dissipating the impacts associated with running[14](Fig. 3).

The heel pad does serve to reduce excessive pressures, and therefore pain, during ambulation[57]. The limit of pain tolerance for impacts involving the heel pad corresponds to a predicted heel pad deformation of 10.7 mm, which is marginally greater than that observed during walking (10.3 ± 1.9 mm). Thus, even at preferred walking speeds, deformation of the heel fat pad approaches the limits of pain tolerance (Fig. 4). Therefore, an FFS pattern adopted during barefoot running may reflect a pain–avoidance strategy[10]. Interestingly, cadaveric studies have shown the fibroadipose tissues of the forefoot have a higher material stiffness and higher energy dissipation than the heel pad[58]. This suggests that the forefoot may be more suited to attenuate the loads experienced during early stance in running.

5.2 Plantar fascia

The longitudinal arch provides significant passive elastic storage and return. With deflection of the longitudinal arch, the plantar fascia and associated deep ligaments are strained and store energy then subsequently return around 6% to 17% of the total mechanical work of running[55,59]. As with tendon, however, the elastic-return mechanism of the passive components of the longitudinal arch is largely strain-dependent[55]. An FFS pattern has been shown to induce greater deflection of the arch than RFS[60]. As such, an FFS pattern has greater potential to store and return elastic strain energy and contribute to overall metabolic energy savings compared to a RFS pattern. FFS runners have also been shown to have a greater volume and strength of the intrinsic foot muscles, which assist in the function of the plantar fascia, when compared to habitual RFS runners[61,62]. In addition, the plantar fascia is also well innervated with both free nerve endings and mechanoreceptors[63]. These mechanoreceptors contribute significantly to proprioception in the arch.[63] The greater plantar fascial elongation of an FFS pattern[60] may facilitate these mechanoreceptors, and thus proprioception, to a greater degree than in a RFS pattern.

5.3 Achilles tendon

The Achilles tendon is the largest and the most elastic tendon in the human body, reportedly returning around 95% of the elastic-strain energy stored with the loads typically encountered during running (Fig. 5)[64]. During RFS running, Achilles tendon loading is typically characterized by 2 maxima and minima. Peak loads coincide with peak eccentric muscle action during late midstance propulsion and terminal swing, and minimum loads occur with concentric muscle action during early stance and pre-swing[65]. There is a rapid reduction in Achilles tendon force that occurs during initial contact in a RFS pattern, that is absent in FFS running[65]. This results in greater activation of the triceps surae[66] along with an earlier[67,68] and higher rate [65,67,68] and magnitude (8%–24%)[67,68] of Achilles tendon loading during FFS running (Fig. 5).

Greater triceps surae activation in the eccentric phase of movement[67], combined with high stretch velocity[65] induces greater stiffness within the muscle-tendon unit. This mechanism is known to be beneficial to storage of elastic strain energy[69]. Based on cadaveric studies, a 24% increase in Achilles tendon load with an FFS pattern would result in an additional 6J energy returned by the tendon[54,55]. This favors the FFS pattern when it comes to leveraging the Achilles tendon for energy return. Moreover, such high-magnitude strains, often thought detrimental to tendon health, have also been shown to be critical for Achilles tendon adaptation and homoeostasis[70]. In support of this, a recent study investigated the Achilles tendons of jumping athletes that are chronically exposed to elevated mechanical loading[71]. The authors noted that the Achilles tendons of the jump leg in these athletes exhibited greater mechanical (stiffness) and material (Young's modulus) properties. These findings suggest a clear benefit from the stimulus of jumping. Therefore, running with an FFS pattern which increases the loading of the Achilles tendon, is likely beneficial to the mechanical and material properties of the tendon.

Over the last decade, ultrasonography has been used to investigate the effects of loading on the elastic properties of human tendons in vivo. High peak loads have been found to be most beneficial for homeostasis and improvement of human tendon properties[70]. The Achilles tendon and triceps surae muscles experience higher loads in an FFS as they assist in dissipating much of the impact energy associated with eccentrically controlling the ankle dorsiflexion moment[72]. Indeed, habitual FFS runners exhibit greater ankle plantarflexion strength than habitual RFS runners[73], exposing the Achilles tendon to higher stress stimulus in FFS running. Both sprinting and minimalist footwear are known to promote an FFS pattern[15,74]. Sprinters have been reported to have stiffer Achilles tendons than distance runners[75]. Additionally, it has been recently reported that minimalist footwear runners exhibit greater stiffness and cross-sectional area of the Achilles tendon compared with their traditionally shod counterparts[74]. These studies collectively suggest that a *habituated* FFS pattern may invoke the necessary stimulus required for tendon adaptation and homeostasis, leading to stronger calf muscles and Achilles tendons. There is a 52% lifetime incidence of Achilles tendinopathy in runners[76] with over 90% of runners being RFS[5]. Additional studies are needed to determine if adaptations associated with an FFS pattern will result in fewer injuries to these structures.

6. Interaction of footwear and footstrike

There is clearly an interaction of footwear and footstrike on running mechanics. This is most evident when assessing the strike patterns and resultant ground reaction forces. Most studies investigating the impact of footstrike pattern on ground reaction forces have focused on the vertical component only. Specifically, they have examined the average and instantaneous loadrates associated with early stance because of their reported links with injury. These studies have all reported lower vertical loadrates when running with an FFS compared with those with a RFS [13,34]. However, during running, the body actually experiences a resultant force comprised of the vertical, anteroposterior and mediolateral forces. In a recent study, Boyer et al[34] compared the vertical as well as the resultant loadrates between habitual RFS and habitual MFS/FFS runners. In support of previous studies, they found that the FFS group had significantly lower peak vertical loadrates compared to their RFS counterparts. However, when assessing the peak *resultant* loadrate, there was no difference between groups. This was due to the higher loadrates in the anteroposterior and mediolateral directions in the FFS group. However, their runners wore neutral cushioned shoes.

Preliminary data in our lab has suggested that forefoot striking in neutral cushioned shoes results in greater plantarflexion and inversion at footstrike than when barefoot. This may be due to the elevated heel and lateral flare that is characteristic of a modern running shoe which may alter the footstrike position. Greater plantarflexion and inversion may result in greater anteroposterior and mediolateral forces that were noted in the Boyer et al.[34] study. Therefore, we conducted a similar study, but with the addition of a minimal footwear group[77]. Minimal footwear was defined as having little to no cushioning. This resulted in 3 groups: RFS who habitually run in neutral cushioned shoes, FFS who habitually run in neutral cushioned shoes and FFS who habitually run in minimal shoes. In support of Boyer et al.[34], we found that those who FFS in neutral cushioned shoes exhibited similar *resultant* loadrates than those who RFS in these same shoes. However, we found that those runners who FFS in minimal shoes exhibited significantly lower loadrates than either of the traditionally shod groups (Fig. 6A). This was due to lower loadrates in all components of the GRF in the minimally shod group. Interestingly, the minimally shod group was made up of some runners who were habituated to full minimal shoes (no midsole, simply an outersole) and others to partial minimal shoes (minimal midsole). A subanalysis of this group revealed that those FFS runners who habitually wear *full* minimal shoes exhibited resultant loadrates that were approximately 17% lower than those FFS runners who habitually wear *partial* minimal shoes. These results highlight an important interaction between footwear and footstrike and suggest that any cushioning in footwear influences mechanics. It appears that running with an FFS in full minimal shoes without cushioning results in the lowest vertical loadrates at landing (Fig. 6B). Future studies investigating the relationship between strike pattern and injuries should therefore include runners habituated to minimal footwear as well.

7. A word about transitioning

There have been reports of injuries associated with abrupt transitions to minimal footwear.[78,79] This is not surprising as the musculoskeletal system needs time to adapt to changes in load so that injury does not occur. If humans began running barefoot or in full minimal shoes at an early age, there would be no need for transitioning as the body would naturally adapt to the associated loads. However, when we have habituated to heelstriking in supportive, cushioned shoes, transitioning to an FFS pattern, in minimal shoes without proper preparation involves risk[78,80]. FFS pattern increases the load on the plantarflexors as they control the heel descent in early stance. An FFS pattern also increases the load to the plantar foot musculature which is important for controlling the deformation of the arch with each step. When this motion is not well controlled, additional strain to the plantar fascia and/or metatarsals may result. Therefore, a strengthening program that includes exercises to address the calf muscles, as well as intrinsic and extrinsic foot muscles should precede an FFS transition. Studies that have incorporated foot and lower leg strengthening, along with a slow increase in training volume have demonstrated that an instructed transition to an FFS pattern in minimal footwear can be made safely without injury[81,82].

8. Summary

In summary, barefoot running, our most natural state, is most often associated with an FFS pattern. However, most runners today wear footwear to protect their feet. It is well-recognized that modern footwear changes our natural pattern to a predominant RFS landing that results in significantly different mechanics from an FFS pattern. Some of these RFS mechanics, such as increased load to the knee and increased vertical loading rates, have been significantly associated with running injuries. Running with an FFS is associated with a loading stimulus of the plantar fascia and Achilles tendon, that benefits their “spring-like” function and may stimulate their adaptation or maintain their homeostasis. Running in full minimal footwear is associated with increases in both intrinsic and extrinsic foot muscular strength, as well as being associated with the most soft landings. Converting to an FFS pattern in minimal shoes should be done slowly and be accompanied by foot and lower leg strengthening to minimize injuries during the transition. With proper transition, an FFS pattern in true minimal footwear that most closely mimics our natural, barefoot state, may positively change the trajectory of running injuries in the modern day runner.

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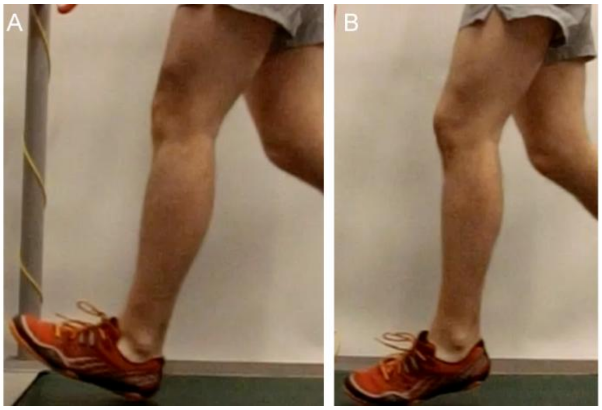

Fig. 1. Lower extremity alignment at footstrike of: (A) Rearfoot strike. Note the ankle dorsiflexion, angulated tibia, and extended knee. (B) Forefoot Strike. Note the ankle plantarflexion, knee flexion, and vertical tibia.

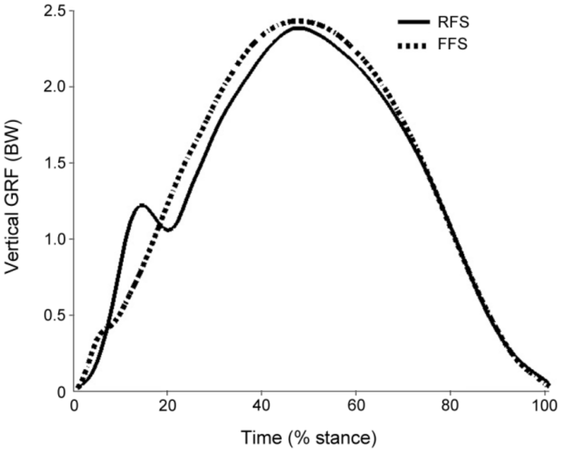

Fig. 2. Vertical ground reaction force of a rearfoot strike (RFS) and forefoot strike (FFS) runner. Note the vertical impact peak of the RFS that is not present in the FFS pattern. BW=body weight ; GRF = ground reaction force.

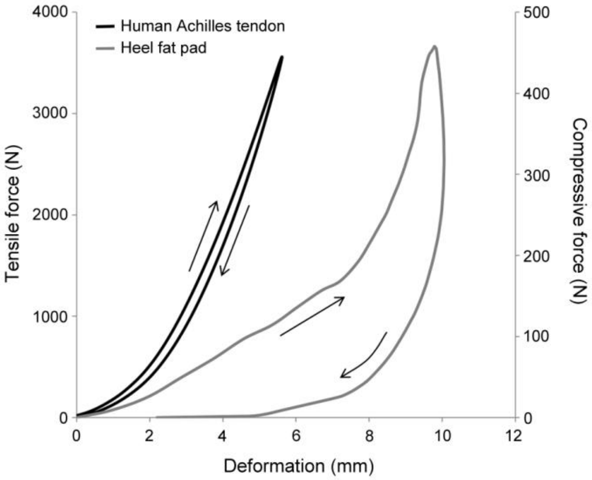

Fig. 3. Typical force deformation curve for the Human Achilles tendon and heel fat pad. Arrows indicate direction of loading and unloading. While the deformation lag of the heel pad on unloading (i.e., hysteresis) suggests there is a substantial loss of energy within the tissue, only 1.0 J is dissipated by the heel pad during walking, which is considerably less than that for the Achilles tendon (~ 2.5 J), as peak physiological loads in the Achilles tendon are around 10 times higher.

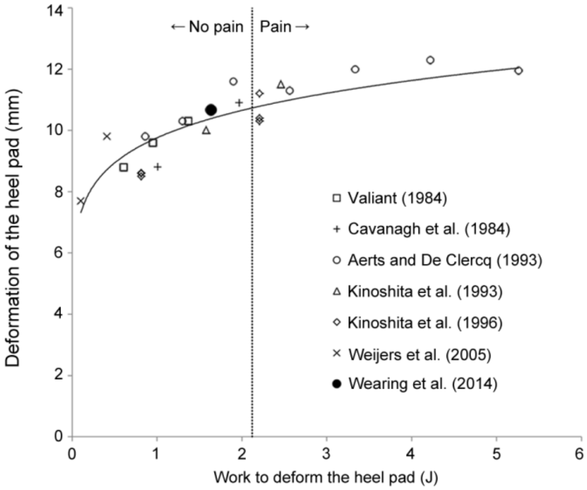

Fig. 4. Maximum deformation of the heel pad as a function of the work required to deform the heel fat pad *in vivo*. Note the limit of pain tolerance for impacts of the heel pad (dotted line) corresponds to a predicted heel pad deformation of 10.7 mm, which is similar to the average deformation during walking at preferred speed (10.3 ± 1.9 mm). Adapted with permission.[14]

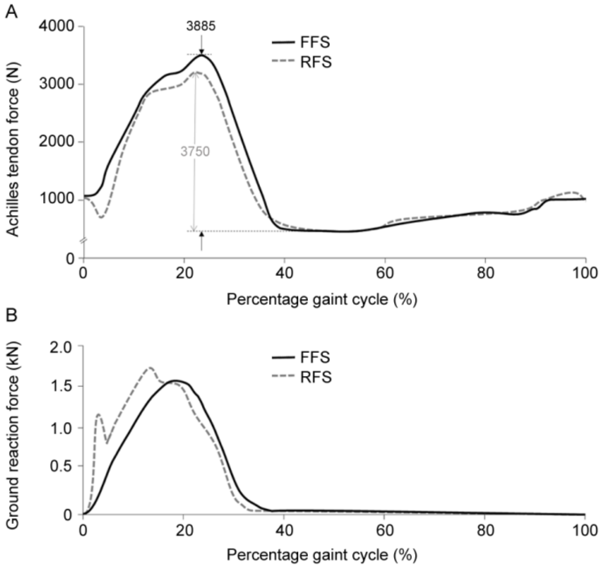

Fig. 5. (A) *In vivo* Achilles tendon force and (B) Vertical ground reaction force during barefoot running with an FFS and RFS pattern at approximately ≈14 kph. Achilles tendon force was measured directly via a surgically implanted buckle transducer. Note the greater Achilles force in the FFS pattern. FFS = forefoot strike; RFS = rearfoot strike. Adapted with permission.[65]

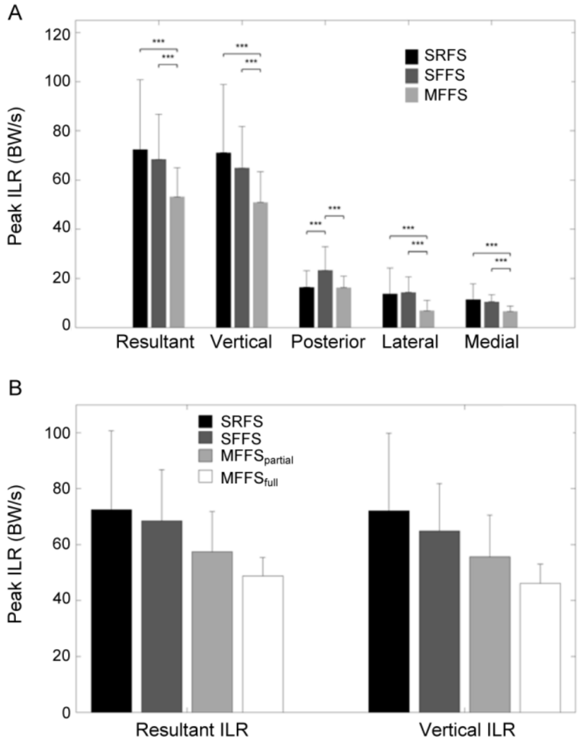

Fig. 6. (A) Loadrates between habitual RFS in standard shoes (SRFS), FFS in standard shoes (SFFS), and FFS in minimal shoes (MFFS). Note the statistically significant reduction (***$p < 0.001$) in loadrates in the MFFS compared with the SRFS and SFFS. (B) Subanalysis of loadrates between MFFS partial and MFFS full. Note that loadrates are the lowest when running with an FFS pattern in full minimal shoes. ILR = Instantaneous Load Rate. Adapted with permission.[77]