

From barefoot hunter gathering to shod pavement pounding. Where to from here? A narrative review

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ABSTRACT

Understanding the current prevalence and incidence of running injury from an evolutionary perspective has sparked great debate. Proponents of the evolutionary approach to understanding running injury suggest that humans ran using less injurious biomechanics prior to the invention of cushioned running shoes. Those who disagree with this view, point to the many runners, wearing cushioned running shoes, who do not get injured and suggest that the evolutionary approach is indulging in a 'natural fallacy'. This polarises the scientific debate into discrete categories such as 'shod' vs 'barefoot'. This review aims, first, to describe humans' innate impact moderating mechanisms which arise from our evolutionary legacy. Second, we discuss the impact of footwear on these mechanisms and the potential link to injury in some runners. Finally, we discuss the role of barefoot training in sports medicine and attempt to make some practical suggestions as to how it might be integrated in our modern urban environments.

INTRODUCTION

Humans have walked and run barefoot for millions of years.¹ Indirect evidence suggests that footwear emerged as recently as ~30 000 years ago.² The majority of time since then, humans have worn minimalist footwear designed to protect the sole of the foot.³ The first indication of fashionable footwear beginning to alter the shape of the foot emerged a little over 100 years ago⁴ and the invention of the mass market cushioned running shoe is as recent as ~1970.⁵ Therefore, large changes in footwear have occurred in a very short space of time relative to human evolutionary history. When rapid changes in physical or nutritional environments occur, it is described as a mismatch between biological evolution (occurring slowly over millions of years) and cultural evolution (occurring rapidly due to events such as the industrial or technological revolution). This mismatch has been proposed as a hypothesis, mainly by evolutionary biologists, to explain some of the current burden of chronic disease.⁶ To

What is already known on the topic?

- ▶ Plantar cutaneous input from the foot can influence whole body postural stability and kinematics during movement.
- ▶ Foot morphology differs between those who grow up habitually shod and barefoot.
- ▶ Differences in running kinematics exist between shod and barefoot runners.
- ▶ Differences in running kinematics exist when running on soft compared with firm surfaces.

What are the new findings?

- ▶ This narrative review synthesised information from the fields of evolutionary biology, anatomy, physiology and biomechanics to suggest how runners innately moderate impact.
- ▶ We make a number of suggestions on how these innate impact-moderating mechanisms may be influenced by footwear and subsequently increase the risk of running injuries.
- ▶ We offer practical suggestions as to how runners may integrate barefoot training in an urban environment.

provide an example, diseases which did not previously exist or were rare such as type 2 diabetes,⁷ osteoporosis⁸ and plantar fasciitis,⁹ are thought to be contributed to by rapid changes in energy availability, physical activity and modern footwear use.

Using an evolutionary lens to understand the current prevalence and incidence of running injuries has sparked great debate among scientists.^{10 11} Unlike other primates, the human foot has an arch capable of both stiffness and deformation¹² to varying degrees dependent on the terrain. It can store and release energy via springs (ligaments, aponeurosis, tendons) in order to make efficient use of muscle work during running.^{6 13 14} In fact, it is for this reason that the Achilles tendon is ~10 times longer in humans compared with other primates.⁶ Coordination between the spring system



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and the muscular system during running is thought to be optimised via using a mid to forefoot strike which allows the foot to stretch and recoil as the muscle moves from eccentric to concentric work.^{13 15} On this basis, it is suggested that humans likely ran with a mid to forefoot strike prior to the invention of running shoes.¹ An estimated ~75% of runners (recreational, >5 km) now use a rearfoot strike (RFS)¹⁶ and some researchers suggest that this increases the risk of certain types of stress pathology (ie, plantar fasciitis, medial tibial stress syndrome) in some runners.^{17–19} The loading rate or instantaneous loading impulse on ground contact may be greater during a RFS which does not allow for a gradual deceleration,¹⁹ as would be the case with a mid to forefoot strike.²⁰

Although, that is the essence of the debate, the aetiology of running injury is multifactorial.^{19 21} The incidence of running injury is high relative to many team sports²² and other aerobic exercises²³ but there are many runners who do not get injured, including those that use a RFS. In fact, most world championship marathon runners use a RFS.²⁴ Even habitually barefoot modern hunter-gatherers who farm more than hunt and therefore, do not require running as part of activities of daily living, predominately use a RFS up to speeds of ~5.0 m/s.²⁵ A tendency to RFS is also seen in habitually barefoot children,²⁶ perhaps due to lower body mass; women who do not run²⁷ and in runners running on soft surfaces.²⁸ It is clear that body mass, maturation, sex, running experience, speed and surface influence foot strike patterns in addition to footwear. That being said, we speculate that adult runners, regularly required to run at moderate speeds, without shoes and on firm surfaces would likely have used a mid to forefoot strike pattern prior to the invention of shoes.^{1 29} This strike pattern would allow runners to capitalise on innate impact moderating mechanisms (safety) and to maximise running speed for a given energy cost (efficiency).^{30 31}

The link between footwear, foot strike patterns and running injury may be better discussed in the context of certain types of runners and or certain types of injuries. For example, given that taller and heavier runners have a higher risk of injury²¹ and women with a history of plantar fasciitis¹⁹ experience greater loading rates, footwear and foot strike may become more important in certain groups of runners. The aim of this review is to discuss how footwear alters human innate impact moderating mechanisms and how that may contribute to running injury. Towards this aim, the paper is divided into three sections:

1. The innate capacity of humans to moderate impact during dynamic activities.
2. The impact of footwear on innate impact moderating behaviour and injury risk.
3. The use of barefoot training to reduce the incidence of running injury.

THE INNATE CAPACITY OF HUMANS TO MODERATE IMPACT DURING DYNAMIC ACTIVITIES

The spring-like function of the human foot

Biotensegrity is the term used to describe how human tissue (ie, skin, organs, muscles) repels sudden deformation through tensioning and stiffening elements.³² In the context of human movement, biotensegrity may be considered the property of tissue that underpins passive dynamics (tissue stretch and recoil during movement).³³ Movement of the foot into plantar flexion or dorsiflexion creates skin deformation sufficient to alter both skin thickness and hardness on the plantar and dorsal aspects of the foot.³⁴ Alterations in skin hardness and thickness even by non-weight-bearing movement have led Smith and colleagues to suggest that it is possible for skin movement to alter the threshold required to stimulate cutaneous mechanoreceptors.³⁴ These receptors play a key role in gait and postural stability.^{35 36} During running, subcutaneously, the plantar aponeurosis, plantar ligaments and spring ligament maintain integrity of the arch and provide a strain energy storing mechanism that is reduced by removing each structure in turn.^{14 37 38} These structures in conjunction with the Achilles tendon make a significant contribution to the total energy turnover during the stance phase of running.^{13 38} The contribution of these ‘springs’ is perhaps best illustrated by the fact that the caloric cost of running a 10 min or 7 min mile is the same.¹³ The ability of these structures to recoil is optimised by positioning the foot in a mid to forefoot position which allows the Achilles tendon and plantar arch to stretch during the early stance phase.^{13 15} The properties of these tissues are thought to be able to alter leg stiffness within ~40–60 ms (prior to any identifiable trace on Electromyography (EMG)). These responses are likely to overlap with sensory reflexes occurring 50–100 ms after landing, which are followed by EMG responses due to efferent motor activity 70–188 ms after landing.^{33 39 40} Biotensegrity is influenced by strain previously experienced by the tissue, foot position and muscle-tendon architecture.³² Positioning the foot and leg in a position whereby muscular and connective tissue components have mechanical advantage creates a more favourable limb position for the absorption of collision forces on ground contact.⁴¹

The sensory function of the foot

The sole of the foot contains the same class of mechanoreceptors (fast and slowly adapting type I and II) as the palm of the hand. Each of the four types of mechanoreceptors are uniquely sensitive to deformation and motion of the skin. Mechanoreceptors transmit tactile and proprioceptive feedback via sensory nerves to the central nervous system.⁴² Sensory feedback from the skin interacts with descending motor commands at the spinal cord which allows reflexive modulation of motor neuron excitability.⁴³ The density of mechanoreceptors on the plantar aspect of the foot appears to follow a proximal-distal and mediolateral gradient, that is, a higher density of mechanoreceptors towards the lateral edge of the foot, the metatarsals and digits.⁴³ An increase in the density of mechanoreceptors

improves tactile sensitivity to small changes in stimulus amplitude and spatial awareness. Control of balance and gait is dependent on the control of the centre of mass over a base of support. An increase in mechanoreceptors towards the lateral edge of the foot and the toes is thought to be important to subtly identify the outer limits of the base of the support.⁴³ This would be less important medially, first because the risk of falling or ankle sprain would be lower and second, because a well-developed arch is rarely in contact with the ground when barefoot. The lower density of mechanoreceptors and therefore, higher threshold required to stimulate the heel may be due to the heel's role in absorbing force during ground contact on walking and the fact that it cannot be independently manipulated.⁴³ Interestingly, noxious plantar stimulation of the heel or plantar surface near the metatarsal-phalangeal joints result in plantar and digit flexion.^{42,44} The result of this in a weight-bearing position is the redistribution of load towards the lateral edge of the foot and distal digits as the arch rises. Conversely, stimulation of the medial longitudinal arch, as would be in the case in arch-supported shoes, results in dorsiflexion of the ankle and digits.⁴⁵ Reducing cutaneous feedback to the plantar surface of the foot can alter whole body posture,⁴⁶ muscle activity and limb kinematics during walking.⁴⁷ Even manipulating sensory input to the dorsum of the skin is sufficient to alter joint (ankle and knee) kinematics during walking.⁴⁸ These findings combined suggest that cutaneous input from the foot in conjunction with the vestibular system,⁴⁹ neuromuscular system and vision play an integral role in the precise control of balance and gait.³⁵

Muscles in control of movement

The intrinsic (or local) muscles of the feet, in conjunction with the ligaments and plantar aponeurosis, act as a dynamic arch support in order to provide a platform for global muscles (hip, knee, ankle) to act on during dynamic activities.^{12, 50} These structures combined are intimately related to reflexive systems associated with stabilisation of the limb. The role of the intrinsic foot muscles may be considered akin to the local muscles of the neck.^{12, 51} The intrinsic foot muscles are subject to intrinsic, kinetic, mechanical, proprioceptive and reflex demands associated with postural stability.¹² A reduction in local or intrinsic muscle strength may allow external forces generated by global muscles to overload structures not designed for load absorption, for example, osteoligamentous structures in the cervical spine⁵² or non-contractile structures of the feet such as the plantar fascia.¹²

During running, muscles are continuously operating via both feedforward (in anticipation via vision) and feedback (in response via sensory physiology) mechanisms.³⁹ Passive (biotensegrity) and neural (reflex arc's) dynamics appear to be particularly dominant in the initial ground contact phase.³³ This may be especially true around the foot and ankle joints which make contact with the ground first and appear to have muscle-tendon architecture (short fibres and long tendons) designed for fast response.³⁹ The proximal muscles (long-fibred) may be seen to be

more dominant in initiating action (feedforward) and in absorbing energy subsequent to feedback from passive and reflex responses.³⁹ Indeed, it was the evolutionary transition to a sideways-facing pelvis and the proximal muscles of the hip (notably the gluteal muscles) that facilitated efficient bipedalism and eventually long distance walking and running. Running is a series of hopping actions from one leg to the other and our gluteal muscles essentially stop us from falling over.⁶ Muscle responses will perhaps be most evident via kinematic changes at the major joints and the extent of preactivation in anticipation of the expected ground contact. In many runners, acutely and at submaximal speeds, barefoot running results in a reduction in stride length and increased plantar and knee flexion.^{53–55} Runners (n=16; Kenyan runners) who are habitually barefoot demonstrate lower loading rates (force) compared with their shod counterparts.²⁰ This is thought to be due to the optimisation of the limb position for ground contact and the preactivation of muscles in anticipation.^{54–56} Previously shod runners who respond to a barefoot running intervention demonstrate greater plantar flexion, increased biceps femoris and gluteus medius preactivation, and decreased rectus femoris muscle activity between testing periods.⁵⁶ We speculate that the integration of the passive and sensory subsystems results in a motor response whereby joint positioning is optimised to provide muscles and tendons with mechanical advantage for the absorption of ground contact (figure 1).

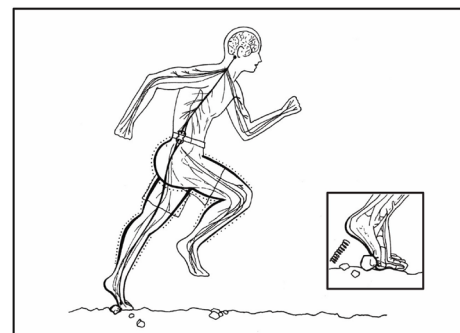


Figure 1 Humans' innate impact-moderating mechanisms on variable terrain. As the foot makes contact with the pebble (inset) it causes deformation of the skin and underlying tissues. This alters the position of the foot and the location and stimulation of the mechanoreceptors. Rapid and subtle adjustments are made via reflex arcs arising from stimulation of sensory nerves and modulation at the spinal cord. Based on this information (feedback) and visual input (feedforward) the brain directs motor output of the major muscles. Landing with a degree of flexion at the hip, knee and ankle provides mechanical advantage for muscles (gluteal, hamstrings, quadriceps, triceps surae) to absorb energy (eccentric control of deceleration) and generate propulsion during extension (concentric phase). Positioning the foot in the forefoot position (inset) on landing allows the Achilles tendon and the medial longitudinal arch (assisted by intrinsic foot muscles) to stretch as the heel comes towards the ground and rebound like a spring.

THE IMPACT OF FOOTWEAR ON INNATE IMPACT MODERATING BEHAVIOUR AND INJURY RISK

The human foot is composed of 26 bones and 33 joints, and is supported by a complex mesh of ligaments, aponeuroses and intrinsic foot muscles.¹² Its unique features give rise to a nimble structure capable of traversing the irregular surface it evolved to navigate. We suggest the regular interior of a shoe and the paved consistency of concrete may inhibit the recoil properties associated with the biotensegrity of human tissues. First, in a shoe, skin stretch and deformation may be less in response to subtle changes in the environment and second, a predominance of RFS in shod runners does not allow the plantar arch and Achilles tendon to stretch in the early stance phase. A cushioned shoe offers protection for the skin but reduces tactile sensitivity of the plantar aspect of the foot. Recent data suggest that this reduction in sensitivity during walking contributes to an impact impulse three times greater compared with when walking barefoot or in minimalist shoes.⁵⁷ These authors suggest we are likely adapted to cope with two to three times the loading rate and a third the loading impulse, suggesting that humans in modern footwear do not experience evolutionarily normal loading from walking. During treadmill running, the proportion of RFS increases as the amount of cushioning in shoes increases.⁵⁸ We suggest that this dampening of sensory input will impair subtle refinements in relation to the control of the centre of mass over a moving base of support. It is for this reason, the use of cushioned footwear is likely what contributes to concentrated pressure at specific locations such as the heel and metatarsals,^{59 60} thus negating the specialised role of the lateral aspect of the foot and the toes in the fine control of movement.^{43 61} In the context of a runner, a supportive shoe will provide a stimulus to the medial aspect of the foot, that is absent when running barefoot. We speculate, that stimulation of this region of the foot⁴⁴ may be one of the factors (in addition to a cushioned heel) that encourages a RFS in ~75% of runners.

Biotensegrity and tactile sensitivity are altered acutely by the use of footwear whether individuals are habitually shod or barefoot. Considering that motor output is governed, in part, by input from these systems, it is expected that shoes will alter whole body movement as a result of changes in muscle work. However, the long-term impact of footwear on muscle work is perhaps best observed from data comparing habitually shod and barefoot populations or changes occurring when either population alter their habitual footwear habits. Differences in foot morphology between those who have never worn shoes and those who are habitually shod have been described since 1905.⁴ The main developmental consequences of growing up shod compared with barefoot appear to be a reduction in arch height and a narrower foot.^{62 63} These developmental differences are thought to contribute to higher peak pressure

at the heel and metatarsals in shod populations.^{59 60} By contrast, habitually barefoot populations demonstrate wider feet, a lower prevalence of flat feet and more equally distributed peak pressures towards the lateral foot and distal phalanges.^{45 59 61 64} The differences in foot structure, particularly at the arch, are thought to be due to the function of the intrinsic foot muscles. A collapsed arch is associated with atrophy of the intrinsic foot muscles.¹² A similar reduction in arch height is also observed with fatigue of the intrinsic foot muscles.^{65 66} Increasing the amount of time spent barefoot, walking in minimalist shoes or doing foot strengthening exercises increases intrinsic muscle size and can increase arch height.^{67 68}

The consequences of wearing cushioned running shoes appear to be linked to the consequences of habitual footwear use such as a propensity towards pronation (reduced arch height) and more concentrated peak pressures (facilitated by RFS). These loading characteristics are associated with higher risk of stress pathology in runners.^{18 19 69–73} Indeed, the majority of running injuries in shod populations are repetitive strain injuries to non-contractile tissues.²³ We speculate, as McKeon and colleagues¹² have, that many of these injuries, particularly below the knee, will be contributed to by loading characteristics and intrinsic foot muscle dysfunction associated with the use of cushioned footwear. In the only prospective study to compare injuries between shod and barefoot runners, shod runners reported more plantar fasciitis (11 *vs* 3) and knee injuries (12 *vs* 5) than barefoot runners. Conversely, barefoot runners reported a greater number injuries to the calf-Achilles tendon complex (14 *vs* 5).⁷⁴ These findings may be expected due to the increased requirement for plantar flexor muscle work during barefoot running.^{54 55} We speculate that injury to the plantar flexor complex will be especially common in adults who were not habitually barefoot growing up and/or have progressed their barefoot training too quickly. However, muscles and tendons have the capacity to adapt in a way that structures like the plantar fascia cannot. These injuries among barefoot runners may indicate a transference of load towards structures designed for load absorption. That being said, greater knowledge on the optimal method of transition for runners who do wish to run barefoot is required. Otherwise, this form of training could increase rather than lower the incidence of running injury.

Patellofemoral pain syndrome is the most common running injury in adults and is particularly prevalent in women.²³ The mechanism of injury has commonality with that seen in more traumatic injuries of the knee (ACL), that is combined adduction and internal rotation of the femur.^{75 76} These mechanics are suggested to occur due to an inability to decelerate the hip and knee using eccentric muscle work from the posterior chain.⁷⁷ This leads to athletes adopting more upright postures and relying on the anterior musculature (quadricep dominance) for stability at the knee.⁷⁸ A longer stride

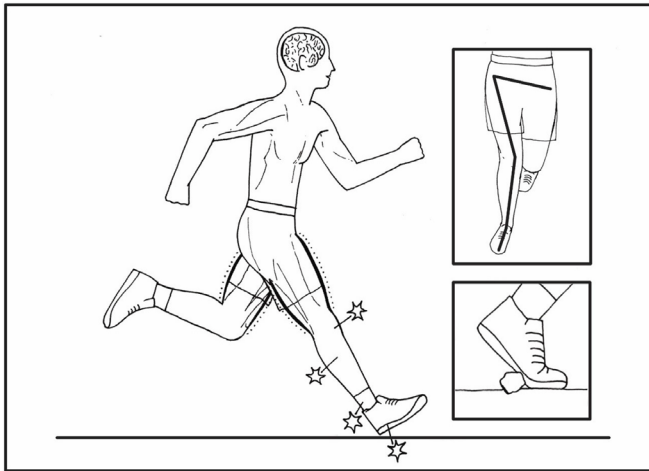


Figure 2 The proposed mechanism by which shoes may facilitate biomechanics which predispose some runners to certain types of injury. Cushioned footwear encourages a rearfoot strike which is associated with an extended lower limb and a more upright torso. This in turn encourages a longer stride length in which the base of support is located further away from the centre of mass. In this position, the limb does not have mechanical advantage during ground contact which may encourage excessive braking forces and increased repetitive tensile loading due to prolonged eccentric muscle contraction. One of the reasons these more ‘blunt’ running mechanics may occur is because the foot (inset) does not receive the same tissue deformation and sensory stimulation as it does in the barefoot condition. Over time this may lead to a reduced demand on posterior chain muscles and a collapsing of the hip inwards in the frontal plane (above). Running using these mechanics is perhaps also more injurious because intrinsic foot muscles may be weaker from habitual footwear use (encouraging pronation; above) and lower limb muscles (especially posterior chain) may be less conditioned from modern sedentary lifestyles.

(extended knee) during shod running means that the heel is located further away from the centre of mass. Combined, these mechanics (upright posture and more extended lower limbs on ground contact) may increase repetitive tensile loading due to tissue elongation and prolonged eccentric muscle contraction (figure 2).⁷⁹ Addressing the neuromuscular deficits (reduced proximal and posterior chain muscle activity) associated with these mechanics has been shown to reduce the incidence of ACL injury in women’s football.⁸¹ In the context of running, the earlier mentioned study by Tam and colleagues⁵⁶ suggests that those considered responders to barefoot running demonstrate an increase in posterior chain muscle preactivation and reduced loading rates associated with an increase in plantar flexion angle (towards a forefoot strike). These changes, occurring in some runners, lead us to suggest that footwear may have a negative impact on loading mechanics via reducing the contribution of eccentric muscle work required from the posterior chain. It is perhaps unsurprising that proximal muscles of the posterior chain, such as the gluteal muscles, are the

focus of many injury prevention and rehabilitation strategies across such a broad range of sports given their relevance in our evolutionary history.

RUNNING FROM INJURY: THE ROLE OF BAREFOOT TRAINING IN SPORTS MEDICINE

Proprioceptive training is recommended as an effective adjunct for the prevention and rehabilitation of musculoskeletal pathology in a range of sports.^{82–85} Equipment such as wobble boards, designed to create more unstable or less predictable conditions underfoot are used to challenge lower limb stability in particular around the foot and ankle.⁸⁶ Exercises to improve intrinsic foot muscle strength have been prescribed and advanced by the stimulation of foot muscles in more functional positions.⁸⁷ These approaches clearly have merit but we suggest that a highly task-specific form of proprioceptive training for runners would be to increase sensory input via the removal of shoes and to challenge it further by running (or walking initially) on less predictable surfaces such as firm grass or sand. In comparison to a control group (n=7), runners (n=10) encouraged to increase exposure to barefoot activity at home and when running for a period of 4 months, demonstrate a restoration in arch integrity as measured by a shortening of the medial arch and load redistribution towards the digits. Although, not controlled for, the authors suggest that the greatest adaptations were seen in those exposed to surfaces with greater variability.⁶⁷ More recent data from a study of 57 runners reported increases in foot strength and muscle size from walking in minimalist footwear for 8 weeks. The changes observed were equivalent to that seen with a strengthening programme undertaken for the same duration⁶⁸ and are sufficient to alter propulsive forces during running.⁵⁰ Therefore, it may be advisable for runners to engage in a foot strengthening programme in tandem with an increase in barefoot activities.

The kinematic changes (increased knee and plantar flexion) evident in some runners who transition to barefoot running seem to be similar to that experienced when running on an irregular surface. On an irregular surface, the knee and ankle appear to move in synchrony whereby the ankle stiffens and has a reduced rearfoot action. A spring-like ankle combined with an increase in knee flexion may increase impact attenuation.⁸⁸ The task (barefoot running) and environmental (irregular surface) constraints may enhance the coordinated action of the spring-like function of the foot and the energy absorbing capacity of more proximal muscles. This form of training whereby the ground deforms underfoot also satisfies the need for variability to avoid overuse injury from repetitive microtrauma. Subtle differences in ground deformation and subsequent foot placement will challenge the biotensegrity of foot structures and the plantar cutaneous nerve receptors to respond with variations of tensioning and stiffening. These variations facilitate a consistent outcome (running) using different patterns of joint relations, a concept known as dynamical

systems which has been described extensively in the literature.^{32 89 90} Lieberman and colleagues²⁸ reported 72% of barefoot runners use a varied foot strike pattern compared with just 32% of shod runners. All runners used a more varied foot strike pattern on a softer surface. This form of training may be particularly important in older runners or those with a history of injury who are known to adopt more rigid behaviours.^{19 91–93} In this case, the varied task and environmental constraints may assist in promoting variability in running action, subconsciously.

The challenge with this form of training is in the implementation. Gait retraining may be viewed as a more sensible alternative to barefoot training particularly in an urban environment and can address some of the kinematic changes needed to increase posterior chain muscle work.^{94 95} A gait retraining strategy, using less cushioned footwear, may be useful in conjunction with barefoot running in order to allow transfer of a barefoot running style to urban environments. We have most experience implementing barefoot running practices in the UK and Ireland which benefit from northern Europe's marine west coast climate and ensures a pliable grass surface for the majority of the year.^{17 53 96} Whether grass or sand is used, we suggest that a surface that is not too hard, that is, concrete and not too soft, that is, sand dunes, is important. A pliable surface allows the runner to maintain cadence while running with a freedom not afforded by running barefoot on concrete (at least initially). Conversely, a surface that is too soft makes the activity less like running and more like resistance exercise for the musculotendinous unit. We have used playing field surfaces to train 15 novice runners (9 female, 6 male) to run for up to 90 min barefoot in preparation for a half marathon, beginning with as little as 15 min.⁹⁶ The literature supports our view that barefoot running is well tolerated by most individuals when progressed in a careful manner, as is the case with any new exercise intervention.^{97–99} Although we recommend a cautious approach to integrating barefoot running and walking in previously shod adults, it should be noted that adolescents in New Zealand, classed as being habitually barefoot, are comfortable running distances of up to 3000 m barefoot on a tartan track.

The second challenge towards the implementation of barefoot running is part functional and part societal. Runners will no doubt be concerned about the exposure of the skin towards a roughened surface and the societal expectation to wear shoes in public. The skin of the plantar surface requires approximately 600% greater abrading loads to become painful by comparison to thigh region.⁴⁴ It has been shown to adapt to wear and to deform with pressure from objects to avoid perforation.^{44 45} Furthermore, the foot calluses that develop to protect the sole of the foot do so without any trade-off in tactile sensitivity.⁵⁷ The greater requirement for runners to look where they are going on such surfaces enhances the visual element of proprioceptive feedback and is usually sufficient to avoid perforation on surfaces such as playing fields which are well maintained. On surfaces

regularly interrupted by sharp objects, a covering of the foot may be advised in the form of a minimalist shoe. Although, this dampens the direct sensory input to the cutaneous receptors, the absence of heel or arch support appears to encourage kinematics similar to the barefoot condition in comparison to cushioned minimalist or standard running shoes.⁵⁸ During walking, impulse loading is still three times less in minimalist shoes relative to cushioned shoes.⁵⁷ Although, these data appear to suggest barefoot/minimalist activity has a positive effect on biomechanical variables associated with injury, there is an insufficient number of studies which have directly assessed the impact of increasing barefoot activities on injury risk.

CONCLUSION

The structure and function of the human body represents our evolutionary legacy. In other words, the body we have today was created over the course of ~6 million years since our ancestors stood upright. In this context, we have been barefoot for almost the entirety of our existence. It is clear that some runners have adapted to our relatively new urban environment and footwear practices better than others. In essence, this review suggests that some (injury prone) runners may need more assistance from their innate impact moderating systems (evolutionary legacy) than others. We presented these innate moderating systems sequentially before discussing the impact that footwear may have on them. Although there are no conclusive data to suggest a causal link between footwear use and injury risk, we believe there are a number of compelling arguments for the inclusion of barefoot or minimalist training in a runner's programme, towards the aim of injury prevention. First, an increase in sensory input to the sole of the foot improves postural stability and therefore, fine control of movement. Second, intrinsic foot muscle size and strength improve with barefoot or minimalist activities leading to a restoration of the foot arch.¹⁰⁰ Improving the integrity of the foot arch is one plausible strategy that could be used in an attempt to reduce the incidence of injuries associated with excessive deformation (pronation) of the arch. Third, individuals with extended lower limbs on ground contact demonstrate an increased reliance on passive tissues for shock absorption. The movement strategies used by such individuals, which underuse posterior muscles of the lower limb, are associated with both traumatic and overuse injuries of the knee. Many habitually barefoot runners do not use these mechanics and many runners who transition to barefoot running cease to use these mechanics. To reduce the load experienced by passive tissues during dynamic movement, greater hip, knee and ankle flexion are required. This requires greater eccentric muscle work by the posterior chain muscles. Whether this is achieved via neuromuscular training programmes, gait retraining or barefoot running, the evidence suggests that it has a positive impact on mechanics associated with injury and therefore, barefoot training also has potential in

this regard. The transition towards barefoot activities in daily life, especially barefoot running, needs to be managed carefully in adults who have spent most of their lives shod. Slowly increasing time spent barefoot and on variable surfaces may provide a suitable introduction to barefoot training for previously shod individuals. In this way, adults may be able to restore innate impact moderating mechanisms, associated with their evolutionary legacy, without muscle-tendon strain.

FUTURE RESEARCH DIRECTIONS

Many of the suggestions in this paper although based on a plausible logic and reason, are speculative and not evidence based. We propose the following research directions to advance understanding in this area:

- ▶ Prospective injury audits of barefoot and shod runners would add to the existing data published by Altman and Davis.⁷⁴ Understanding the prevalence and incidence of injury experienced by both populations is important to inform injury prevention and rehabilitation strategies and because it gives scientists some initial clues about the loading characteristics of both runners.
- ▶ Studies that seek to understand neuromuscular adaptation of previously shod runners to barefoot running on a variety of surfaces are required. Tam and colleagues⁵⁶ have performed some of the most informative work in this regard because they sought to group responders and non-responders in terms of kinematics, muscle work and loading rates. These studies are difficult to conduct due to the resources required but are badly needed to advance understanding in this field.
- ▶ A greater understanding of the characteristics of runners who do not get injured or are injured infrequently are required. This may shed light on beneficial running mechanics, training patterns or muscle-tendon unit function. This may serve to provide greater clarity on why barefoot training may be useful for some runners but not others.
- ▶ Available data suggest shod and barefoot runners both experience Achilles tendinopathy. Studies which can shed light on how a rearfoot or mid to forefoot strike contributes to Achilles tendon overload, are required.
- ▶ Follow-up data that can determine whether children-adolescents growing up habitually barefoot or shod have a different prevalence and incidence of running injury as adults.
- ▶ Studies into different methods for introducing barefoot or minimalist activities in urban environments, especially to determine the appropriate dose response that will maximise adaptation and minimise injury risk.
- ▶ We have begun to conduct research on the role of barefoot/minimalist activities in the treatment of patients with existing musculoskeletal conditions, namely plantar fasciitis.^{17 101} The role of such activities

for the treatment and rehabilitation of existing injuries requires further attention.

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