Stepping Back to Minimal Footwear: Applications Across the Lifespan

Irene S. Davis[1], *Karsten Hollander*[2], *Daniel E. Lieberman*[3], *Sarah T. Ridge*[4], *Isabel C.N. Sacco*[5], *and Scott C. Wearing*[6,7]

[1]Spaulding National Running Center, Department of Physical Medicine and Rehabilitation, Harvard Medical School, Boston, MA; [2]Faculty of Medicine, MSH Medical School Hamburg, Hamburg, Germany; [3]Department of Human Evolutionary Biology, Harvard University, Cambridge MA; [4]Department of Exercise Sciences, Brigham Young University, Salt Lake City, Utah; [5]Physical Therapy, Speech and Occupational Therapy, School of Medicine, University of São Paulo, São Paulo, Brazil; [6]Institute of Health and Biomedical Innovation, Queensland University of Technology, Brisbane, Australia; and [7]Faculty of Sports and Health Sciences, Technical University of Munich, Munich, Germany

DAVIS, I.S., K. HOLLANDER, D.E. LIEBERMAN, S.T. RIDGE, I.C.N. SACCO, and S.C. WEARING. Stepping back to minimal footwear: applications across the lifespan. *Exerc. Sport Sci. Rev.*, Vol. 49, No. 4, pp. 228–243, 2021. *Minimal footwear has existed for tens of thousands of years and was originally designed to protect the sole of the foot. Over the past 50 yr, most footwear has become increasingly more cushioned and supportive. Here, we review evidence that minimal shoes are a better match to our feet, which may result in a lower risk of musculoskeletal injury.* **Key Words:** minimal footwear, evolutionary mismatch, musculoskeletal health, gait mechanics, tissue properties, muscle strength

Key Points

- There is an evolutionary mismatch between modern footwear and the way our feet were adapted to function.
- Modern footwear is associated with the development of foot deformities such as hallux valgus and pes planus.
- Minimal footwear promotes strengthening of both the intrinsic and extrinsic foot muscles.
- Minimal footwear promotes walking and running gait patterns more similar to our natural barefoot gait.
- Minimal footwear is beneficial to healthy older adults and those with some pathologic conditions such as knee osteoarthritis.

INTRODUCTION

The barefoot condition is our most natural state, and the foot is well adapted for walking and running gaits without footwear. Although footwear originally was developed more than 10,000 yr ago to protect the sole of the foot, footwear over the past 50–60 yr has become both more cushioned and supportive (1). This type of footwear often is recommended for athletes, as well as elderly with musculoskeletal dysfunction. However, we will review how these shoes have been shown to interfere with natural foot and lower extremity mechanics in ways that may increase the risk for injury. The purpose of this article is to present the novel hypothesis that minimal footwear may lead to improved musculoskeletal health across the lifespan. To evaluate this hypothesis, we will review evidence regarding the relation between minimal footwear, foot strength, mechanics, and injuries in both athletic and nonathletic populations. Here, we define minimal shoes as those lacking any support or cushioning. We begin with an evolutionary perspective on foot development and footwear. We then address studies of minimal footwear in children. This is followed by a review of minimal footwear and lower extremity mechanics in adult runners. Next, we address minimal footwear and the foot musculoskeletal system. The relation between foot strike pattern and tissue properties (tendons and fat pads) is then reviewed. Finally, the use of minimal footwear for healthy older individuals, as well as those with pathology such as knee osteoarthritis (OA) and diabetes, is discussed. We conclude with a summary of recommendations for future studies needed to address current research gaps. The topic of minimal footwear is one that is hotly debated in both clinical and scientific arenas. We hope this perspective article will begin to create a paradigm shift in the way we think about footwear, spark debate, and be a catalyst for additional research.

Address for correspondence: Irene S. Davis, Ph.D., P.T., Spaulding National Running Center, Department of Physical Medicine and Rehabilitation, Harvard Medical School, 1575 Cambridge Street, Cambridge, MA 02138 (E-mail: isdavis@mgh.harvard.edu).

Accepted for publication: March 1, 2021.
Editor: Roger M. Enoka, Ph.D.

0091-6331/4904/228–243
Exercise and Sport Sciences Reviews
DOI: 10.1249/JES.0000000000000263

IN THE BEGINNING

Most mammals walk and run on their toes, but humans evolved from African great apes that have plantigrade feet that are well adapted for climbing trees. African great apes have long, curved toes, an abducted hallux, a relatively short and flexible midfoot that lacks an arch, and a less developed calcaneus with a mobile ankle joint. However, over the 7 million years since the human and chimpanzee lineages diverged, hominin feet evolved substantially. This first occurred to facilitate bipedal walking and then later running over longer distances than apes (2). For example, human feet have adapted to include an enlarged calcaneus. This helped stabilize the rearfoot and bear repeated, higher stresses during the impact phase of walking considerably longer distances on two versus four legs (3). In addition, they developed an elongated midfoot that is stiffened by transverse and medial longitudinal arches (4,5) and a thicker plantar fascia (6). The hallux became elongated, and the toes became shorter and straighter with dorsally oriented metatarsophalangeal joints (7) (Fig. 1). Together, these adaptations compromise our ability to climb trees. However, they optimized the human foot for both walking and running (2).

For most of the last 7 million years, humans also walked and ran barefoot. They did this over a variety of surfaces from soft grasslands to hardpacked savannah. As such, humans have evolved with the ability to adjust their overall leg stiffness to the hardness of the substrate they negotiate to maintain a constant stiffness of the system. For example, they increase their leg stiffness when encountering soft surfaces and reduce their leg stiffness when encountering hard surfaces. This has been demonstrated in a number of modern studies (8–10) and underscores that humans are equipped to walk and run on a wide variety of surface stiffnesses.

Until about 600 generations ago, all humans were hunter-gatherers who walked on average 9–15 $km \cdot d^{-1}$, approximately 10–15,0000 steps, either barefoot or in minimal footwear (11). The oldest preserved sandals are about 10,000 yr old (12), and the oldest shoes are from about 6000 yr ago from Armenia (13). However, it is reasonable to hypothesize that footwear was available by at least 40,000 yr ago when needles and other tailoring technologies first appear in the archeological record (14). Around this time, there also is some evidence for a reduction in metatarsal robusticity (cross-sectional thickness relative to bone length). This indirectly suggests that the use of footwear such as sandals decreases bending forces on the midfoot during propulsion (15).

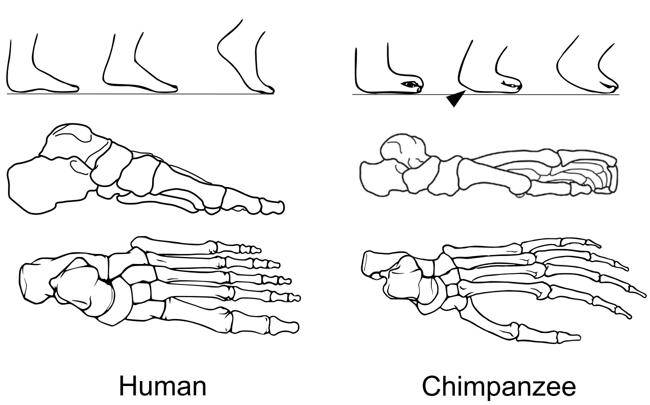

Figure 1. Comparison of the structure of the chimpanzee and human foot. Note the higher arch, more aligned hallux, and greater plantarflexion at push-off in the human foot. [Reprinted with permission from (2). Copyright © 2018 The Company of Biologists Ltd. All permission requests for this image should be made to the copyright holder.]

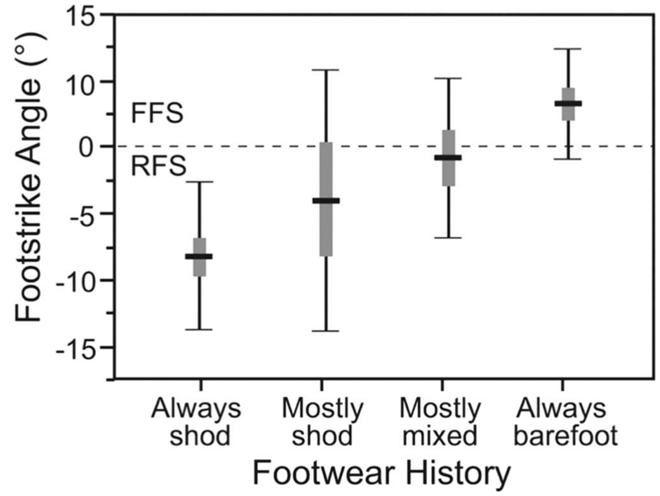

Figure 2. Relation between footwear history and footstrike angle in Kenyan runners. Note that as footwear usage decreased, runners adopted a more FFS pattern. (Reprinted from (20). CC BY 4.0.)

For most of human evolutionary history, shoes probably were used only occasionally. In addition, until recently, almost all footwear were minimal such as sandals or moccasin-like shoes. Features common in modern shoes such as toe springs, stiffened midsoles, elevated heels, and arch supports are generally quite recent. Ethylene-vinyl acetate-cushioned shoes have been available since only the 1970s (16). Features in these shoes provide some benefits, notably protection and comfort. However, these structured shoes potentially contribute to several hypothesized evolutionary mismatches. Evolutionary mismatches are conditions that are more prevalent or severe because bodies are inadequately or imperfectly adapted for novel environmental conditions (17). Put differently, although shoes provide some advantages, they may also have some drawbacks for which we are not well adapted.

Evolutionary mismatches related to footwear fall into three categories. First, cushioned (elastic) soles slow the rate of loading at impact and decrease sensory perception (18,19). As a result, people who habitually wear cushioned shoes experience higher ground reaction force impulses when walking (19), and they are more likely to rearfoot strike (RFS) when running (20). This results in an abrupt impact transient of the vertical ground reaction force not seen with forefoot striking (21) (Fig. 2). Second, these supportive shoes reduce the demand on the foot muscles, which can result in weaker feet, as evidenced from smaller muscle cross-sectional areas (22). Finally, structured shoes alter our foot mechanics. The added sole flares increase the external torques to the foot, creating abnormal loading to the foot and lower extremity (23). In addition, the arch support in structured shoes reduces the longitudinal and transverse arch compression during midstance (24), which is important for elastic energy storage. All of these changes potentially lead to mismatches between the way the foot was adapted to function and how it functions in structured shoes, which can lead to dysfunction and injury.

MINIMAL FOOTWEAR IN CHILDREN

The foot undergoes crucial developmental changes during childhood and adolescence. Although several bones ossify prenatally, the main ossification period extends over the first 10 yr of life (25). Epiphyseal union of all long bones in the foot, as well as the talus and calcaneus, occurs throughout late adolescence or early adulthood, representing the end of foot bone growth (26). The foot typically achieves its final length at an age of about 13 yr in girls and 15 yr in boys (27). The arch of the foot also develops during childhood. Although infants have no arch, it begins to develop once toddlers begin to walk. The shape of the arch is, thus, determined, not just by the shapes of the bones, but also by the muscles and ligaments.

Childhood and adolescence are critical periods in which the developing foot is more prone to external influences. One of these influences is incorrectly fitted footwear. The prevalence of incorrectly fitted footwear has been estimated to be up to 66% (too narrow) and 72% (too short) in school children (28). Improperly fitted footwear has been shown to increase the risk of foot deformities such as pes planus or hallux valgus in children and adolescents (29–31). In contrast, children and adolescents who grow up barefoot have been shown to have significantly higher arches than those who have grown up shod (32–35). One large-scale study reported on 2300 children in India between the ages of 3 and 15 yr (25). In one community, children were barefoot, in another they wore sandals, and in a third they wore closed-toe shoes. Flat footedness was most prevalent in the group that wore shoes and least prevalent in those who were barefoot.

Low arches are associated with pathologies such as pes planus deformity (29), which can lead to altered function. For example, children with low arches have been shown to walk with greater foot progression angle and greater external rotation of the lower extremity (30). Along with higher arches, children who are habitually barefoot also demonstrate improved jumping and balance skills (36). A recent, large-scale study compared Japanese children from two schools in the same city that incorporate a running program, with one being barefoot and the other shod (37). Children in the barefoot program exhibited significantly greater performance in jumping and sprinting, and a greater proportion ran with a midfoot or forefoot strike (FFS) pattern compared with the shod group.

Minimal footwear has been associated with the ability to mimic some of the barefoot walking characteristics in children (38,39). For example, Hillstrom *et al.* (38) compared the gait of toddlers with only a few months of walking experience as they walked barefoot, and in minimal and structured shoes. Similar plantar pressure distributions between the barefoot and minimal footwear were noted compared with more structured footwear. The authors conclude that this similarity may enhance proprioception, which they suggested was important for developing gait in young children. In addition, Wolf *et al.* (39) studied a cohort of 6- to 10-yr-old children. They noted that walking kinematics in minimal footwear were closer to the barefoot condition than in structured footwear in 12 of 15 parameters tested. They also noted that minimal footwear allowed the medial longitudinal arch to deform more naturally than in traditional, stiff footwear (39).

Running mechanics in children also are influenced by minimal footwear. Hollander *et al.* (40) conducted a comparison of minimal and cushioned footwear with barefoot running in 6-9-yr-old children. The greatest differences in mechanics were found between the cushioned and barefoot conditions, and the most similarities were noted between the minimal and barefoot conditions. For example, the rate of RFSs was highest for the cushioned shod running and lower but similar for the barefoot and minimally shod running. This pattern was also true for other variables. The impact force and step length were higher, and cadence was lowest in the cushioned shoe, but similar between the barefoot and minimal shoe conditions.

Based on these collective studies, minimal shoes may be optimal for the developing feet of children. These shoes are designed to better match the natural shape of the foot with additional width in the forefoot. This helps overcome the issue with improper fit of shoes, which is especially important for the developing foot. They seem to replicate many aspects of both walking and running mechanics as being barefoot while protecting the sole of the foot. Despite these potential benefits, recommendations for youth footwear, to date, still do not address minimal shoes (41,42).

MINIMAL FOOTWEAR IN ADULT RUNNING

Up until 60 yr ago, running shoes were quite minimal, typically consisting of a thin rubber sole and a canvas or leather top (1). These shoes were flexible and lacked any midsole cushioning, arch supports, or heel counter stiffeners. Although running injuries likely occurred, they were not reported in the literature until the 1970s, suggesting that this may have been when they began to become more prevalent. This coincided with the running boom as millions of untrained people started running. Unfortunately, we lack the data necessary to explore the causes of this apparent uptick in injuries. However, a number of sports medicine professionals at that time attributed them to untrained runners landing too hard and without adequate foot control (1). We hypothesize that, instead of these new runners developing the ability and strength to cushion and control their landings, footwear was adapted to do this passively for them. Shoe companies began to add midsole cushioning, arch support, and heel counter supports to address these deficiencies. Elevated heels were added to reduce the load on the Achilles tendon, and toe springs were added to reduce the work of the toe flexors (43). These changes were made with the goal of increasing comfort and reducing injury risk. However, we postulate that these changes in footwear, intended to assist the runner, may be increasing injury risk.

As we evolved to run without footwear, barefoot running provides a reference for our most natural running gait. Strike patterns of barefoot runners are noted to be variable, depending on running speed and substrate hardness (20). On softer surfaces, there is a greater tendency to RFS. However, habitual barefoot running is mostly associated with landing on the ball of the foot (referred to as a FFS pattern) (21). Those who are habituated to cushioned running shoes tend to land consistently on their heels (referred to as an RFS). A recent study demonstrated that the more time individuals spend running in cushioned shoes, the more likely they will be a rearfoot striker (Fig. 3) (20). This is because the cushioning allows landing on the heel without the pain that would be experienced if landing on it barefoot. An RFS places less demands on the calf musculature, which must contract eccentrically at the onset of stance in an FFS to control the heel descent (44). However, there are consequences of this RFS landing style. As stated previously, it results in an abrupt, characteristic impact transient in the vertical ground reaction force time series curve that is typically missing in FFS landings (Fig. 2) (21). Impactful loads have been shown to produce damage to both cartilage and bone in animal studies (45,46). This impact transient is associated with a steep rise to its peak, leading to a significantly increased loading rate compared with an FFS pattern (47,48). Increased loading rates have been associated with some of the most common running injuries such as tibial stress fractures, patellofemoral pain, and plantar fasciitis (49–54).

In an attempt to mimic barefoot running, the first modern, widely available minimal running shoe was introduced by Nike in 2005. Like many racing flats, the Nike Free lacked arch support and heel counter stiffness, and it had a flexible sole (Fig. 4A). However, it had a cushioned midsole, which permitted an RFS pattern (55). In the same year, the Vibram FiveFingers shoe (Fig. 4B) also became available. This shoe had five pockets for the toes, which allowed them to move independently from each other. The shoe was extremely flexible and had no midsole or heel counter. It was originally designed for boating but quickly was adopted by the barefoot running community who wanted a shoe that was as close to barefoot as possible. Other minimal shoes also began to emerge (Figs. 4C–E) However, traditionally shod runners who wanted the barefoot experience also began running in these shoes. Many simply replaced their cushioned shoes with minimal shoes without reducing their running mileage. These runners lacked the benefit of adaptation that the experienced barefoot runners had. Therefore, many of these runners sustained injuries to the foot and ankle due to the lack of cushioning and support that their traditional shoes offered. Reports of Achilles tendinitis, plantar fasciitis, and metatarsal stress fractures appeared in the literature (56–58).

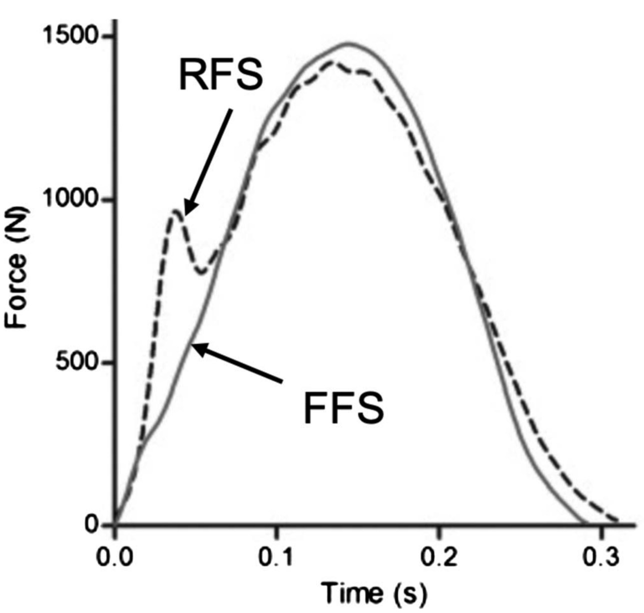

Figure 3. Comparison of the vertical ground reaction force during running of a rearfoot striker (RFS) and a forefoot striker (FFS). Note the abrupt impact force of the rearfoot striker that is missing in the forefoot striker. [Adapted from Samaan CD, Rainbow MJ, Davis IS. Reduction in ground reaction force variables with instructed barefoot running, J Sport Health Sci, 2014; 3(2):143–151. CC BY-NC-ND 4.0.]

This was unfortunate, as it may not have been the shoe but the lack of appropriate transition to it that led to the injuries. Although there continued to be steadfast believers in the minimal shoe, these injury reports led to a reduced enthusiasm for this type of footwear.

As a result of the reported injuries, some footwear companies decided to retreat from minimal shoes. Instead, they produced a shoe that had less cushioning and support than their traditional running shoe as a compromise to runners between minimal and cushioned shoes. These are sometimes classified as a partial minimal shoe and include shoes such as the New Balance Minimus and Saucony Kinvara shoes (Figs. 4F, G). However, studies have suggested that mechanics while running in partial minimal shoes are similar to those while running in traditional shoes and statistically different than running barefoot (59–61). Only when running in shoes with little or no cushioning are mechanics similar to barefoot running (60,62).

Minimal footwear promotes an FFS pattern, and this pattern has been shown to actually resolve some injuries. The benefit of an FFS pattern was demonstrated in a case series of 10 West Point cadets diagnosed with anterior compartment syndrome and recommended for fasciotomy surgery (63). The cadets underwent a 6-wk training intervention to transition from an RFS to an FFS to shift the load from the anterior lower leg musculature to the larger, posterior musculature. After the training, all compartment pressures returned to normal, with significant improvements in pain and function, as well as in their 2-mile run times. Most importantly, surgery was avoided in all cases. Another study involved 16 runners with patellofemoral pain who were randomized into a retraining group to transition to an FFS pattern or to a control group (64). Those who transitioned to the FFS pattern had near complete resolution of their knee pain. In addition, the patellofemoral contact stresses, which have been associated with this pain (65), were reduced by 50%. This likely is due to two factors. There is greater knee flexion at foot strike with an FFS pattern (66), which increases the contact area between the patella and femur (67). In addition, forces at the knee during early stance are lower due to the decreased slope of the vertical ground reaction force typically seen in an FFS pattern. Lower forces and greater contact areas lead to lower patellofemoral contact stresses and likely to reduced pain (65).

There is an important interaction between footwear and foot strike patterns that must be considered. An FFS runner in cushioned shoes demonstrates a lower vertical ground reaction force load rate compared with an RFS runner in cushioned shoes. However, the mediolateral and anteroposterior load rates of an FFS runner in cushioned are *increased* above that of an RFS runner (47,68,69). This likely is due to the elevated heel and lateral flare of a cushioned shoe. These structural features often place the foot in greater plantarflexion (70) (which is coupled with inversion) at foot strike than when running in a minimal shoe (Fig. 5). This is associated with greater posterior and medial ground reaction force load rates at foot strike. These increased posterior and medial load rates coupled with the decreased vertical load rate in FFS runners habituated to conventional shoes result in *similar resultant* load rates between them and RFS runners habituated to conventional shoes (Fig. 6) (47). However, when forefoot striking in minimal shoes, all components of the ground reaction

Figure 4. Top row: Early minimal shoes. A. Nike Free*; B. Vibram FiveFingers. Middle row: Examples of current minimal footwear. C. Vivobarefoot Stealth; D. Xero Prios; E. demonstration of the flexibility of minimal shoes. Bottom row: Examples of partial minimal shoes. F. New Balance Minimus; G. Saucony Kinvara. *Now considered a partial minimal shoe.

force load rates are significantly lower than when either rearfoot or forefoot striking in traditional shoes. Thus, forefoot striking in minimal shoes results in the lowest impact loading in all directions. Reducing impacts in the vertical direction has prospectively led to a 62% reduction in running injuries over the course of a year (53). Reducing impacts in all three directions may potentially lead to even fewer injuries, but this needs to be examined further.

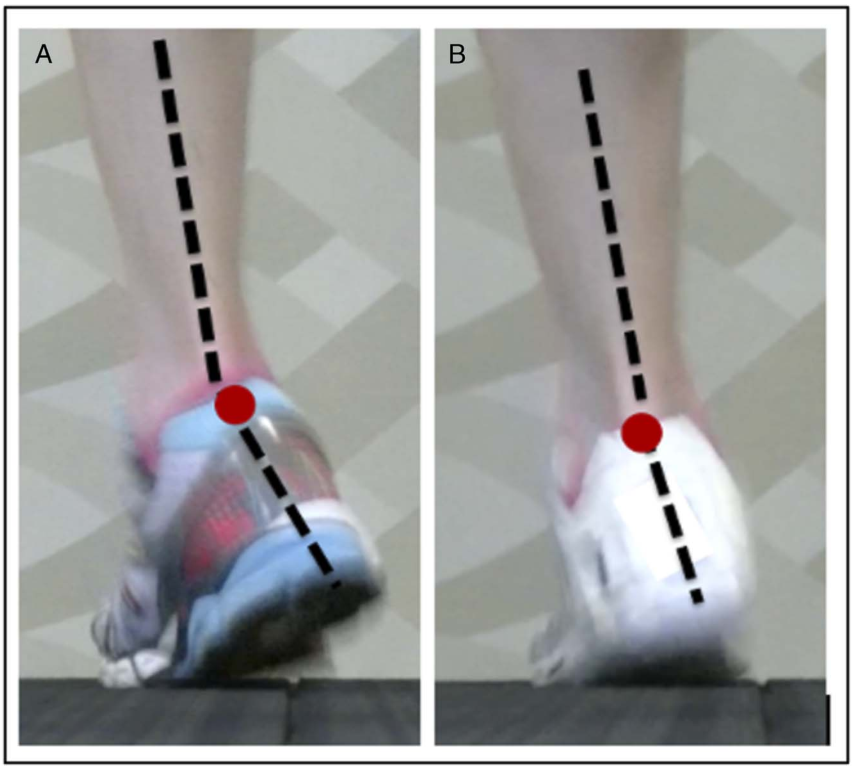

Figure 5. A. A habitual forefoot striker (FFS) runner landing in their cushioned shoe. B. The same runner in a minimal shoe. Note the reduction in plantarflexion and inversion in the minimal shoe.

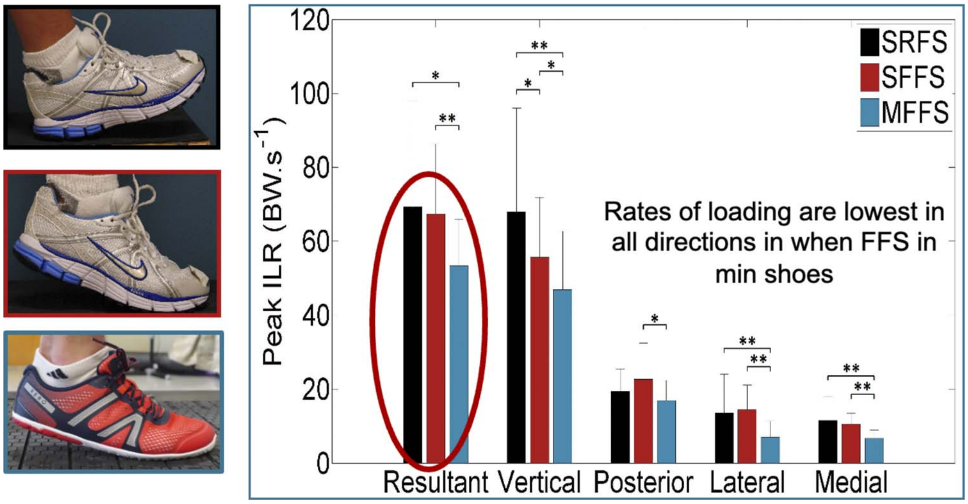

Figure 6. Comparison of load rates between habitual rearfoot striker (RFS) in standard shoes (SRFS), forefoot striker (FFS) in standard shoes (SFFS), and FFS in minimal shoes (MFFS). Note that resultant load rates are only lower in the FFS in the minimal shoe. [Adapted with permission from (47). Copyright © 2016 American College of Sports Medicine. All permission requests for this image should be made to the copyright holder.]

MINIMAL FOOTWEAR AND THE MUSCULOSKELETAL SYSTEM

The human musculoskeletal system normally adapts to the mechanical loads it experiences. As proposed by Frost's (71,72) mechanostat model, tissues responds to the mechanical demands placed on them by altering their mechanical properties to better meet the new demands. Although criteria governing this response are not well understood, there is emerging evidence that footwear may influence the adaptation of the musculoskeletal system including fibroadipose and dense connective tissue structures. The majority of this research has been conducted on adults.

Influence on Bone

There is a dearth of articles examining the effect of minimal footwear on bone health, and these articles focus on running. One study measured bone mineral density in runners before and after a structured, 26-week transition to running in minimal footwear (73). The authors reported no significant changes in the apparent density of the measured bones, including the tibia, calcaneus, and metatarsals. However, other more detailed measures of bone quality, such as cortical thickness and trabecular bone density, may be more indicative of strength. These measures are acquired using high-resolution, peripheral, quantitative computed tomography, which is not currently widely available. As its use becomes more prevalent, we will be able to better study the effect of progressive load on bone strength. The effect of minimal footwear on bone injury has been addressed in a few more studies. Bone marrow edema (BME) is used as an indication of both bone turnover and bone injury. Ridge *et al.* (74) reported on the Bone Marrow Edema Score after a largely unstructured, 10-wk transition to running their habitual mileage in minimal footwear. Increased edema was noted in 10 of the 19 runners. However, not all had pain that would indicate an injury. It was noted that those with the greatest amount of edema were the ones who reported pain. It is possible that some with lower levels of edema were cases of bone remodeling that would be expected with an increased load, as opposed to an injury. However, there have been other case reports of individuals with bony (primarily metatarsal) injuries associated with minimal footwear. In these cases, it was pain that sent them to seek medical attention (56,75), and definitive stress fractures were diagnosed. In both these reports, runners transitioned rapidly to their full mileage rather than progressing slowly. These studies indicate the need for engaging in a slow transition to minimal footwear for running to provide the time for adaptation. This gradual addition of loading may not only reduce injury risk but may also potentially result in some bone strengthening, according to Wolf's law.

Influence on Muscle

There have been a number of investigations of the effect of minimal footwear on muscle size and strength. A study by Holowka *et al.* (22) reported that habitual daily users of minimal footwear had larger abductor hallucis and abductor digiti minimi (ADM) muscles compared with a supportive shod population. This likely is due to the greater demand placed on these muscles when walking in unsupportive footwear. Other studies have shown foot muscles hypertrophy when transitioning to minimal footwear for walking (74). A recent study reported that an 8-wk, progressive walking program in minimal shoes increased intrinsic and extrinsic muscle size and strength (74). In fact, walking in these shoes produced similar increases in the size and strength of foot muscles as the strengthening program completed by the foot strengthening group (Fig. 7). As the loads of running are higher than those of walking, the potential for strengthening in minimal footwear is greater (76). Studies of minimal footwear use during running and athletic activities (76–79) have shown increases in the size and strength of a number of intrinsic and extrinsic foot muscles (EFM). In fact, every study that has examined the effect of minimal shoes on foot intrinsic and extrinsic foot muscle size or strength has reported increases (Table). The benefits of stronger intrinsic foot muscles include improved propulsion during walking and running (80,81) and control of midfoot deformation (81–84). In addition, simulated contraction of cadaveric foot intrinsic muscles during loading has been shown to reduce the bending strain in the metatarsals (85). Finally, a recent study has demonstrated that runners who completed an 8-wk foot exercise

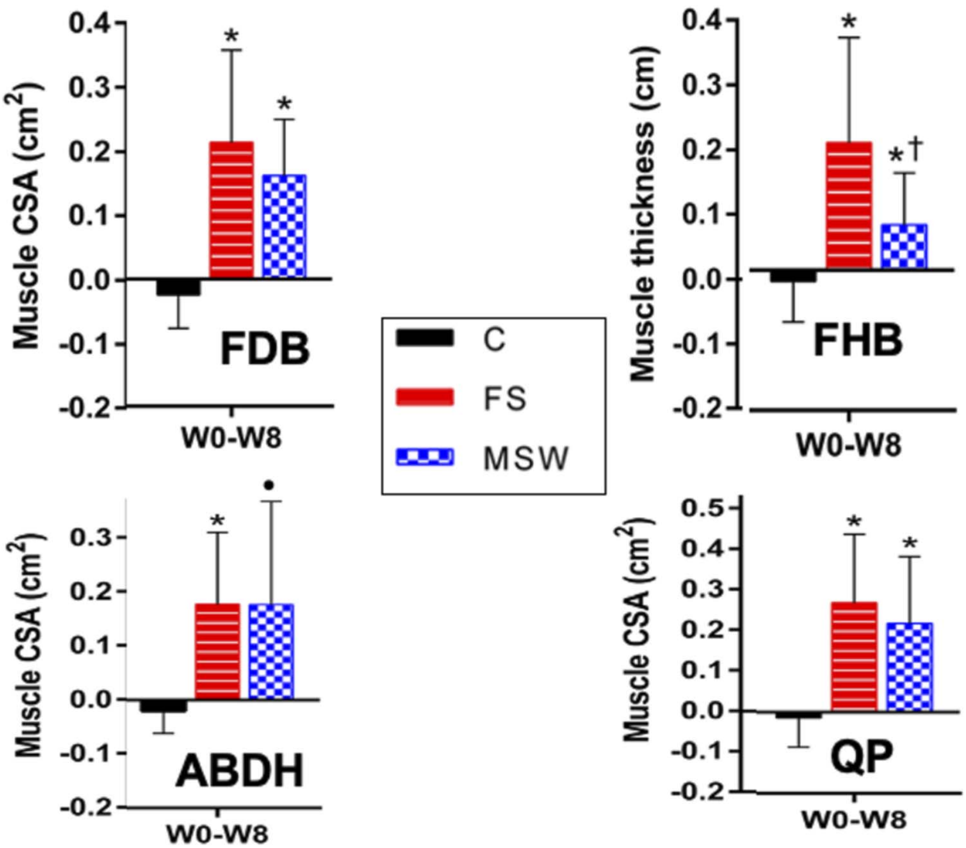

Figure 7. Comparison of muscle size changes between the control (C), foot strengthening (FS), and minimal shoe wear (MSW) groups for the flexor digitorum brevis (FDB), the flexor hallicus brevis (FHB), the abductor hallicus (ABDH), and the quadratus plantae (QP). Note the similar increases between the FS and MSW groups for three of the four muscles. [Adapted with permission from (74). Copyright © 2019 American College of Sports Medicine. All permission requests for this image should be made to the copyright holder.]

program were 2.4 times less likely than the control group to develop a running-related injury (86). Therefore, we postulate that a gradual transition to minimal shoes, which promote foot strengthening, may also reduce the risk for injury in runners.

Although habituating to minimal footwear results in foot muscle strengthening, muscle injuries can occur if transitioning is done too quickly. In 1 study, 7 of 14 runners reported pain in the gastrocnemius/soleus/Achilles tendon complex during a 12-wk transition to running in minimal footwear (57). Similar to bone injuries, it is possible that many of the muscle strains or soreness injuries could be prevented by a slow increase in activity in minimal footwear. A foot core program (87) has been shown to significantly increase the size and strength of the intrinsic and extrinsic foot muscles (74,88). The addition of such a program can also help prepare the foot for the transition and reduce injury risk during this period.

Foot orthotic devices provide support to the foot. They are often prescribed for long-term use, which may negatively affect the foot. As these devices support the arch, the demand on the foot intrinsic muscles is reduced. In fact, an article by Protopapas and Perry (89) reported a 10%–17% reduction in the foot intrinsic muscle sizes as a result of 12 wk of orthotic use. Therefore, just as minimal footwear that removes support from the foot has been shown to strengthen muscles, adding chronic support to the arch likely will weaken them. Therefore, if a foot injury requires additional temporary support of a foot orthosis, it should be gradually removed once the injury has healed to help strengthen the foot once it has recovered.

Influence on Tendon and Aponeurosis

The Achilles tendon is an important component of the stretch-shorten cycle of the triceps (TS) surae muscle-tendon unit. The tendon's mechanical properties, and particularly its material stiffness, affect force production and the performance of complex movement. There is some controversy regarding the capacity of mature tendon to adapt to loading. However, animal studies suggest that, like bone, the material properties of tendons can be dramatically increased with loading during growth and development (90). High peak loads have been shown to be most beneficial for homeostasis and adaptation of human tendon properties (91). An FFS strike pattern during running results in greater activation of the triceps surae and a higher rate and magnitude (8%–24%) of Achilles tendon loading than heel strike running (92–94). Hence, minimalist footwear is associated with a loading stimulus that is more likely to induce Achilles tendon adaptation. Indeed, runners who wear minimalist footwear have been shown to have greater stiffness and cross-sectional area of the Achilles tendon than traditionally shod runners (95,96). Moreover, the Achilles tendon of habitual FFS runners has been shown to be functionally stiffer during both walking and running, thereby aiding its "spring-like" function (97). Therefore, the

TABLE. Effect of physical activity (walking, running, and exercising) in minimal footwear on muscle size and strength

Authors	Intervention Type	Intervention Length	Measurement Variable(s)	Muscle(s)/Muscle Group	Muscle Size Change	Muscle Strength Change	Injuries Reported
Ridge *et al.*, 2019	Walking	8 wk	CSA	FHB, ABDH, FDB, QP, TA, TP, FDL	↑ all muscles		None
			Strength	GT flexion		↑ GT flexion	
				LT flexion		↑ LT flexion	
				Doming		↑ doming	
Campitelli *et al.*, 2016	Restricted walking	24 wk	Thickness	ABDH	RW: ↑ at 24 wk	N/A	None
	Unlimited walking				UW: ↑ at 12 wk, but not at 24 wk		
	Running				R: ↑ at 24 wk		
Fuller *et al.*, 2019	Running	26 wk	Strength	Plantarflexion	N/A	↑ PF strength with ↑ weekly training distances	Not reported
Joseph *et al.*, 2016	Running	6 months	Strength	Plantar flexion		↑	Not reported
			CSA	Achilles tendon	↑		
Johnson *et al.*, 2016	Running	10 wk	CSA/thickness	ABDH, FDB, FHB, EDB	↑ ABDH	N/A	8 of 18 runners had BME
							6 of 8 reported pain, 1 of 8 did not complete training log
Miller *et al.*, 2014	Running	12 wk	Muscle volume	ABDH, FDB, ADM	MF: ↑ FDB, ↑ADM; Con: ↑ FDB	N/A	Not reported
			CSA		MF = ↑ ADM		
Chen *et al.*, 2013	Running	6 months	Muscle volume	Lower leg, foot, rearfoot, and forefoot	↑ EFM and IFM (forefoot > rearfoot)	N/A	None
Goldmann *et al.*, 2013	Athletic exercises	3 wk, 5×/wk, 30 min/session	Strength (joint moments)	Toe flexors	N/A	↑ MPJ joint moments	Not reported
Brueggeman *et al.*, 2005	Athletic warm-up activities	5 months	CSA	FHL, FDL, TS, TP, TA, PER, ABDH, QP, ADM, FDB	↑ FHL, ADM, and QP		Not reported
			Strength	MPJ		↑ MPJ flexion	
				Plantarflexion		↑ plantarflexion	
			Torque	Subtalar inversion		↑ max inversion	

EDB, extensor digitorum brevis; FDL, flexor digitorum longus; FHL, flexor hallicus longus; GT, great toe; LT, lateral toe; MF, minimal footwear; MPJ, metatarsal-phalangeal joint; PER, peroneus; R, running; RW, restricted walking; TA, tibialis anterior; TP, tibialis posterior; UW, unlimited walking.

additional loading of the Achilles tendon associated with minimalist footwear likely results in a stiffer tendon. This may be beneficial for activities requiring rapid force development and protective against strain-induced injury for a given load.

The plantar fascia effectively connects the expanse of the medial longitudinal arch and has been regarded as the primary structure stabilizing the arch during weight-bearing. Along with the ligaments of the medial longitudinal arch, the plantar fascia also may contribute to the elastic behavior of the foot and to improved locomotor efficiency (98). However, the medial longitudinal arch also is traversed by the intrinsic muscles of the foot and the long tendons of extrinsic foot muscles. These muscles are well positioned to reduce the load borne by the plantar fascia (99–102). Running in minimal footwear is associated with intrinsic muscle hypertrophy (68–71), a thinner plantar fascia, and a less compliant medial longitudinal arch (103). These findings are consistent with a shared load bearing role between these structures. With stronger intrinsic muscles, the plantar fascia can be thinner and more compliant. When the muscles are weaker, the plantar fascia adapts to become thicker to control the arch deformation during loading. Indeed, a thickened and stiff investing muscle fascia has been implicated in the development of other pathologies, such as chronic compartment syndromes of the lower leg (104,105).

Fibroadipose Tissue

The calcaneal heel pad is a specialized fibroadipose tissue that is thought to play a number of mechanical roles during gait (106,107). The first is shock reduction. During walking, the heel pad undergoes approximately 9–11 mm of vertical deformation, which is thought to lower the peak impact force (108). However, the heel pad offers minimal resistance to the rapid deformation induced by initial heel strike, suggesting it has only a minor role in shock reduction during walking and running (109). The second role of the heel pad is energy dissipation. However, only about 1.0 J of the strain energy stored in the heel pad during walking is dissipated with unloading (110). This only equates to about 20% of the impact energy of the foot and approximately 1% of the total energy exchanged during a single gait cycle (~100 J for a 70-kg human) (111). This is less than that of the Achilles tendon (~2.5 J) and ligaments of the medial longitudinal arch (~3.1–4.5 J) (112–114). These structures reportedly behave as “springs” and are key structures associated with energy storage rather than energy dissipation. The energy dissipating properties of the heel pad are relatively insensitive to strain rate (111). Thus, the relatively low level of energy dissipation provided by the heel pad is unlikely to change substantially with increases in gait speed. This results in the heel pad being a less than ideal structure for dissipating the impacts associated with running (109). The third role of the heel pad is the protection against excessive plantar pressure. The mechanoreceptive and nociceptive nerve endings of fibroadipose tissues are localized between fat cells (115), and their sensitivity is related to the degree and rate of deformation of the tissue (116,117). This endows the fat pad with a proprioceptive role for monitoring mechanical vibrations associated with heel strike, as well as for detecting pain (118–120). Deformation of the heel pad during barefoot walking (approximately 60% or 10 mm) approaches that associated with the limits of pain tolerance. Hence, the FFS pattern adopted during barefoot running likely reflects a pain-avoidance strategy (121).

In conventional shoes, the heel pad is constrained and deforms only about 35% during walking and running (106,122). Therefore, conventional footwear likely lowers the potential for strain-related injury of the heel pad. However, by inducing a slower loading rate and a lower final strain in the tissue, it also has the potential to lower the sensitivity of the heel pad to detect pain and potentially harmful vibrations (108). Minimalist shoes, in contrast, tend to promote a forefoot foot strike gait pattern during running. Cadaveric studies have shown that the fibroadipose tissues of the forefoot have both a higher material stiffness and greater capacity to dissipate energy than the heel pad (123). These tissues also have a higher density of vibration-sensitive mechanoreceptors (124,125). Hence, fibroadipose tissues of the forefoot may better damp the impact vibrations associated with running than those of the heel and tend to be preferentially loaded in minimalist footwear.

MINIMAL FOOTWEAR IN OLDER ADULTS

Minimal Footwear in Healthy Older Adults

Minimal shoes have been shown to be beneficial for older adults. Shoes with cushioning are likely to filter out important sensory information (126,127), which is important for balance and stability, especially in aging populations. It has been shown that when sensory input is lost, such as through anesthetization of plantar afferent nerves, stability during quiet stance becomes impaired (128). This may explain why balance during standing and walking in an elderly population is improved in minimal shoes compared with cushioned ones (129). Second, although older adults tend to experience general lower extremity muscle weakening, there is a shift in joint power during walking gait from distal to proximal (130). This suggests that foot and ankle function degrades with age, which may increase the risk for falls in this population (131). Falls have been related to foot weakness (132,133), and unfortunately, the intrinsic foot muscles (IFM) have been noted to become weaker with age (134). Nearly one in four older adults experiences falls (131), which are the leading cause of injury-related deaths in older adults (135). Along with weakness and loss of function that accompany aging, chronic support of the foot can lead to further foot muscle weakening (6,89).

It has been reported that standard features of conventional shoes can be detrimental to the elderly. For example, these shoes often have constrictive toe boxes, which has been associated with hallux valgus (136) (Fig. 8). Other features, such as elevated heels, stiff uppers, and flared outer soles have been shown to negatively impact gait mechanics. For example, Aboutorabi *et al.* (137) conducted a systematic review of the effect of footwear on static and dynamic balance in elderly individuals. They reported that balance during standing posture and functional activities (*i.e.*, the timed get up and go and functional reach tests) was improved when soles were thin and hard. This recommended footwear shares some characteristics with minimal shoes, such as thin soles, low heel-to-toe drop, low weight, and lacking sole flares (138). Studies about the effect of minimal shoes on gait in this older population are still scarce. In one relevant study, Cudejko *et al.* (139) compared the center of pressure trajectory while older adults stood and walked in several footwear conditions. This included 11 variations of minimal shoes, a barefoot, and a conventional shoe condition. The older adults performed better on the timed up and go test with the minimal shoes compared with the conventional shoes The center of pressure excursion and velocity in the anteroposterior and mediolateral directions were also reduced during standing and walking in minimal shoes, indicating greater stability. Results between the minimal shoes and barefoot were similar. These collective results suggest that minimal shoes may offer a more stable alternative for healthy older adults.

Minimal Footwear in Older Adults With Knee OA

Knee OA is one of the most common musculoskeletal conditions of older adults. Although the etiology of knee OA is multifactorial (140), mechanical aspects such as the intra-articular loads are the primary risk factors for its development and

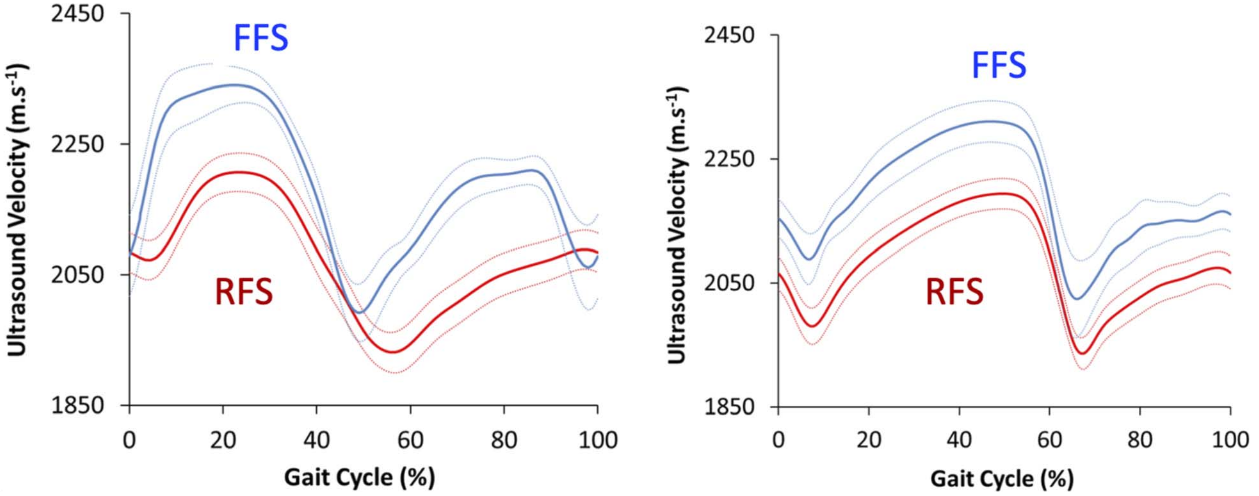

Figure 8. Comparison of Achilles tendon stiffness (as measured by the ultrasound velocity) between habitual rearfoot strike (RFS) and habitual forefoot strike (FFS) runners during walking (left) and running (right). Note the greater stiffness during both walking and running in the FFS runners. [Adapted with permission from (97). Copyright © 2019 Taylor & Francis. All permission requests for this image should be made to the copyright holder.]

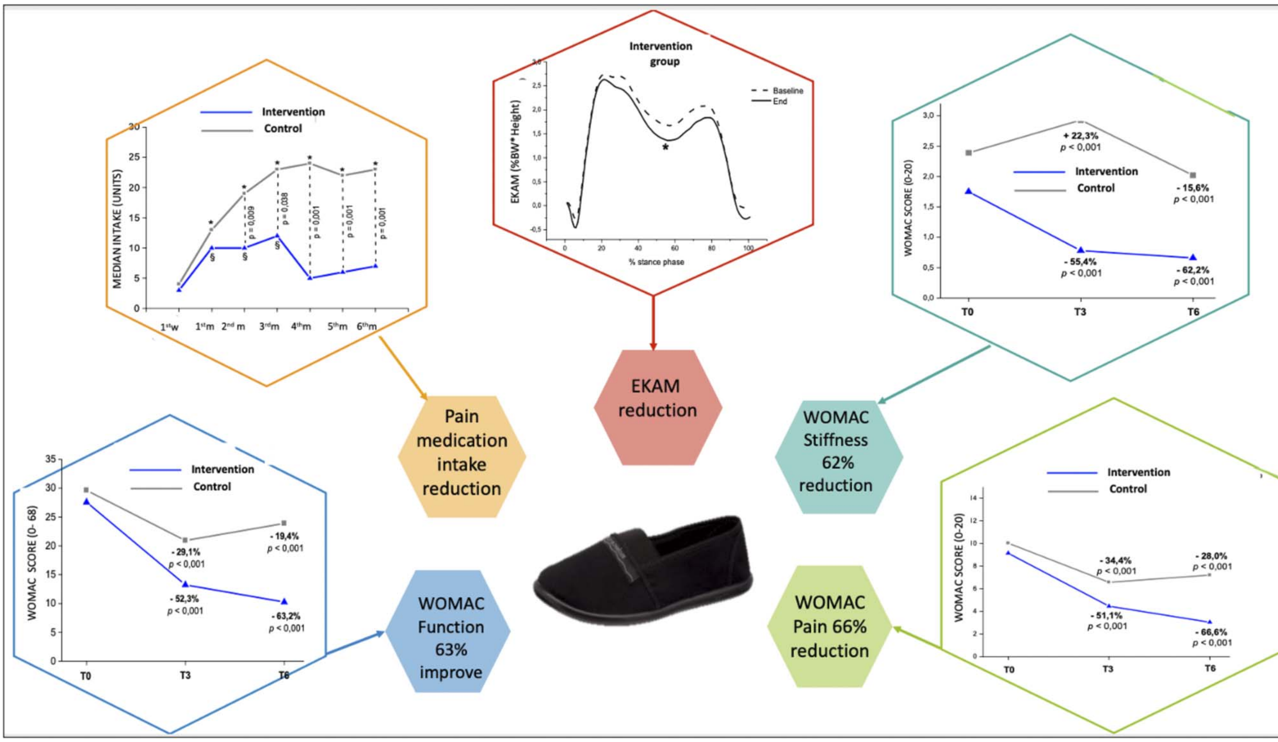

Figure 9. Results of a minimal shoe (Moleca shoe, center) intervention in women with knee osteoarthritis (OA). Note improvements in the Western Ontario and McMaster Universities Arthritis Index (WOMAC), pain medication intake, external knee adduction moment (EKAM), stiffness, and pain compared with the standard shoe intervention.

progression (141–143). The external knee adduction moment (EKAM) is often used as a surrogate measure for these internal loads. Increases in the EKAM have been reported to increase the risk for the severity (144) and progression (145,146) of knee OA. Specialized footwear is an emergent conservative strategy to reduce EKAM. This footwear has included variable-stiffness soles (147–150), rocker soles (151), and laterally wedged insoles (152–154). Although footwear with laterally wedged or arch support insoles results in a small reduction in the EKAM, this footwear type increases the frontal plane torques at the ankle. Preservation of normal ankle torques and kinematics is recommended to prevent adverse effects at the foot-ankle complex (155).

Among footwear interventions to reduce knee joint loads, minimal shoes have been one of the most promising both in the short term (156–159) and long term (160). Shakoor *et al.* (157) studied the acute effects of minimal footwear in patients with knee OA. The minimal shoe was custom engineered to mimic barefoot walking and was composed of a flexible poly carbon sole with flex grooves and a mesh top. They reported an 8% decrease in EKAM in a minimal shoe compared with self-chosen walking shoes and a 12% reduction compared with control (wearing a cushioned sports shoe). Others have compared the effect of a commercially available shoe, called the Moleca (Calçados Beira Rio S.A., Novo Hamburgo, RS, Brazil) shoe, to a modern heeled shoe on the gait of women with knee OA. The Moleca shoe (Fig. 9) is a low-cost women's canvas flat walking shoe. It has a flexible 5-mm antislip rubber sole, and its mean weight is 0.172 ± 0.019 kg. These features qualify it as a minimal shoe (109). In two cross-sectional studies, the Moleca shoe demonstrated reductions in EKAM of approximately 12% during walking and 15.5% during stair descent (158,159). Trombini-Souza *et al.* (160) then conducted a clinical trial with older women with knee OA randomized into the Moleca shoe or a neutral athletic shoe and followed them for 6 months. They reported a 22% reduction in EKAM in the minimal shoe group: nearly double that of the study of the acute effects (159). In addition, they experienced a 66% reduction in the Western Ontario and McMaster Universities Arthritis Index (WOMAC) pain domain, a 62% reduction in WOMAC stiffness domain, and a 63% improvement in WOMAC function domain. Pain medication also remained low and unchanged after 6 months. In stark contrast, the women in the control group experienced significant increases in EKAM (15.4%), WOMAC pain, stiffness, and a decrease in function. In addition, there was a 36% increase in the pain medication. Therefore, the minimal footwear resulted in less pain and better function than conventional footwear in patients with knee OA.

Minimal Footwear for Individuals With Early Stages of Diabetes

Diabetes mellitus is a metabolic disorder that results in high glucose levels in the blood that eventually can damage both motor and sensory nerves. With time, diabetic peripheral neuropathy can ensue and cause major problems with the foot. Approximately 50% of diabetics experience neuropathy between 25 and 30 yr after the diagnosis of diabetes (161). When it does develop, muscles become weakened and foot deformities, such as claw toes, can develop (162). This can result in an anterior displacement of the already thinning fat pad, increasing the exposure to the metatarsal heads (163). This, combined with the sensory loss, leads to ulcerations, most commonly at the metatarsal heads (164,165). Most individuals with diabetic

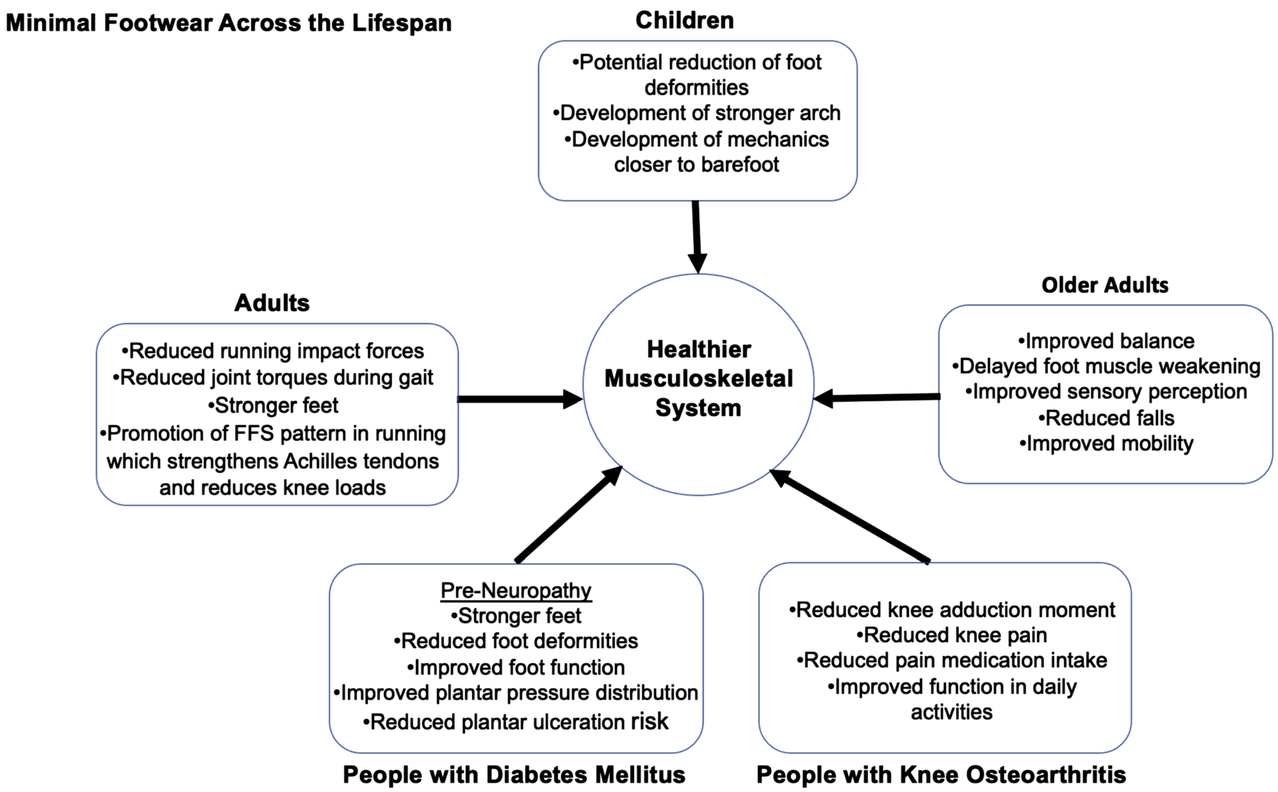

Figure 10. Schematic of the novel hypothesis that suggests that the use of minimal footwear across the lifespan will result in reduced injuries and a healthier musculoskeletal system. FFS, forefoot strike.

neuropathy are prescribed full contact soft foot orthosis and structured, cushioned shoes, often with a rocker bottom (166). This intervention is aimed at redistributing the plantar load and reducing the load on the metatarsal heads. However, this intervention strategy is typically used for all patients regardless of their risk for ulceration or musculoskeletal status. Unfortunately, if used before the neuropathy progression, this passive approach might result in foot muscle atrophy (6,89), leading to impairments in muscle strength and foot function. This can accelerate the degenerative changes that may occur.

Studies suggest that motor loss may occur before the sensory loss in the neuropathic process (128,167,168). Diabetic neuropathy has been shown to affect both the intrinsic and extrinsic muscles of the foot (169–174). The intrinsic muscles are small with short moment arms and primarily provide foot stability (74). The larger extrinsic muscles can generate more force and with larger moment arms produce joint rotations. These muscles serve as prime movers of the foot (74). Strength loss of both intrinsic and extrinsic foot muscles increases the risk for the development of foot deformities, which leads to an increased risk for ulceration (164,175). Therefore, foot strengthening should be part of a diabetic treatment approach *long before* the neuropathy progresses. Studies of weight-bearing exercises that address the foot and ankle have shown improvements in range of motion, plantar pressures, and overall gait mechanics (176–179). As a result, foot exercise prescription is now part of the International Working Group on the Diabetic Foot Guidelines 2019 (170).

Another way to encourage foot strengthening is through the use of minimal footwear in walking (74). Minimal shoes are not currently recommended for those with diabetes due to the lack of support and cushion that a neuropathic foot requires. However, those diagnosed with diabetes typically have many years before a neuropathy progresses. This could provide a fairly extensive time for individuals to address the strength of their feet. Usage of minimal footwear during this early stage of diabetes may enable patients to maintain their foot motion and muscle strength for a longer period. This may help delay the development of foot deformities that can result in pressure ulcerations. Minimal footwear coupled with a foot strengthening program may provide a way for individuals to maintain foot strength and function before development of neuropathy. These feet might be more resistant to dysfunction if the neuropathy develops. This type of a program would need to be monitored by a medical professional who could routinely assess the sensory and motor status of the individual.

SUMMARY

Although we have identified many of the benefits of minimal footwear use across the lifespan, there is still much more research that needs to be done.

Based on the gaps in the current literature, we need:

- large-scale prospective studies to compare the effects of conventional versus minimal shoes on foot development, biomechanics, and musculoskeletal health in both children and adults
- more studies on the effect of minimal shoe use during walking, as well as studies of other activities, on the musculoskeletal system

- a greater understanding of how to best transition into minimal footwear, including consideration of the adaptive response of tissue in differing foot types (*i.e.*, high arch and low arch)
- studies of optimal strengthening interventions for the intrinsic and extrinsic muscles to facilitate transition to minimal footwear
- prospective studies of the effect of intrinsic and extrinsic foot muscle strengthening on foot health
- studies using advanced methodologies, such as biplanar videoradiography, to study the effect of minimal footwear on the complex motions of the foot
- studies of the effect of minimal footwear use on foot strength, balance, and falls in older adults
- studies to determine which pathologic populations can benefit the most from minimal footwear

In summary, modern footwear represents an evolutionary mismatch that may increase the risk for injury. Therefore, we propose the following. Given that we are adapted to being barefoot, habitual locomotion in minimal footwear that is closer to the barefoot condition reduces the vulnerability of the musculoskeletal system to injury. The recent reemergence of minimal shoes was aimed at returning to a more barefoot-like locomotion, which is hypothesized to reduce injury risk. This article has summarized some of the advantages to wearing footwear that minimizes the interference on natural foot mechanics. We have presented evidence of benefits of minimal footwear both across the ages and in pathologic populations. These include stronger foot muscles, stiffer Achilles' tendons, softer landings, better balance, better function, lesser pain, lower knee loads, and reduced lower extremity torques (Fig. 10). One of the primary concerns surrounding minimal footwear is the risk of a transition-related injury. It is recommended that those habituated to conventional footwear need to transition into minimal footwear slowly, especially for higher-level activities such as running. Ideally, we start our youth early in minimal footwear so that the body will naturally adapt to it, eliminating any risks associated with transition.

Acknowledgments

Karsten Hollander received funding from the German Research Foundation (grant number HO 6214/2-1). Daniel Lieberman received funding from the American School of Prehistoric Research, Hintze Family Charitable Foundation. Isabel Sacco received funding from the State of São Paulo Research Foundation (FAPESP) (2015/14810-0) and National Council for Scientific and Technological Development (CNPq) (Process: 304124/2018-4).

References

1. Davis IS. The re-emergence of the minimal running shoe. *J. Orthop. Sports Phys. Ther.* 2014; 44(10):775–84.
2. Holowka NB, Lieberman DE. Rethinking the evolution of the human foot: insights from experimental research. *J. Exp. Biol.* 2018; 221(Pt. 17): jeb174425.
3. Latimer B, Lovejoy CO. The calcaneus of *Australopithecus afarensis* and its implications for the evolution of bipedality. *Am. J. Phys. Anthropol.* 1989; 78(3):369–86.
4. Holowka NB, O'Neill MC, Thompson NE, Demes B. Chimpanzee and human midfoot motion during bipedal walking and the evolution of the longitudinal arch of the foot. *J. Hum. Evol.* 2017; 104:23–31.
5. Venkadesan M, Yawar A, Eng CM, et al. Stiffness of the human foot and evolution of the transverse arch. *Nature.* 2020; 579(7797):97–100.
6. Sichting F, Holowka NB, Ebrecht F, Lieberman DE. Evolutionary anatomy of the plantar aponeurosis in primates, including humans. *J. Anat.* 2020; 237(1):85–104.
7. Rolian C, Lieberman DE, Hamill J, Scott JW, Werbel W. Walking, running and the evolution of short toes in humans. *J. Exp. Biol.* 2009; 212(Pt. 5):713–21.
8. Ferris DP, Farley CT. Interaction of leg stiffness and surface stiffness during human hopping. *J. Appl. Physiol.* 1997; 82(1):15–22.
9. Ferris DP, Liang KL, Farley CT. Runners adjust leg stiffness for their first step on a new running surface. *J. Biomech.* 1999; 32(8):787–94.
10. Ferris DP, Louie M, Farley CT. Running in the real world: adjusting leg stiffness for different surfaces. *Proc. Biol. Sci.* 1998; 265(1400):989–94.
11. Marlowe FW. Hunter-gatherers and human evolution. *Evol. Anthropol.* 2005; 14(2):54–67.
12. Connolly TJ, Barker P, Fowler CS, Hattori EM, Jenkins DL, Cannon WJ. Getting beyond the point: textiles of the terminal Pleistocene/Early Holocene in the northwestern Great Basin. *Am. Antiq.* 2016; 81(3):490–514.
13. Pinhasi R, Gasparian B, Areshian G, et al. First direct evidence of chalcolithic footwear from the near eastern highlands. *PLoS One.* 2010; 5(6):e10984.
14. Soffer O, Adovasio JM, Hyland DC. The "Venus" figurines. *Curr. Anthropol.* 2000; 41(4):511–37.
15. Trinkaus E. Anatomical evidence for the antiquity of human footwear use. *J. Archaeol. Sci.* 2005; 32(10):1515–26.
16. Shawcross R. *Shoes: An Illustrated History*. London: Bloomsbury Academic; 2014.
17. Lieberman DE. *The Story of the Human Body: Evolution, Health and Disease*. New York, Pantheon; 2013.
18. Addison BJ, Lieberman DE. Tradeoffs between impact loading rate, vertical impulse and effective mass for walkers and heel strike runners wearing footwear of varying stiffness. *J. Biomech.* 2015; 48(7):1318–24.
19. Holowka NB, Wynands B, Drechsel TJ, et al. Foot callus thickness does not trade off protection for tactile sensitivity during walking. *Nature.* 2019; 571(7764):261–4.
20. Lieberman DE, Castillo ER, Otarola-Castillo E, et al. Variation in foot strike patterns among habitually barefoot and shod runners in Kenya. *PLoS One.* 2015; 10(7):e0131354.
21. Lieberman DE, Venkadesan M, Werbel WA, et al. Foot strike patterns and collision forces in habitually barefoot versus shod runners. *Nature.* 2010; 463(7280):531–5.
22. Holowka NB, Wallace IJ, Lieberman DE. Foot strength and stiffness are related to footwear use in a comparison of minimally- vs. conventionally-shod populations. *Sci. Rep.* 2018; 8(1):3679.
23. 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):1058–63.
24. Kelly LA, Lichtwark GA, Farris DJ, Cresswell A. Shoes alter the spring-like function of the human foot during running. *J. R. Soc. Interface.* 2016; 13(119):20160174.
25. Kelikian AS, Sarrafian SK. *Sarrafian's Anatomy of the Foot and Ankle: Descriptive, Topographic, Functional.* Philadelphia (PA): Wolters Kluwer Health/Lippincott Williams & Wilkins; 2011.
26. Cardoso HFV, Severino RSS. The chronology of epiphyseal union in the hand and foot from dry bone observations. *Int. J. Osteoarchaeol.* 2010; 20(6):737–46.
27. Anderson M, Blais M, Green WT. Growth of the normal foot during childhood and adolescence; length of the foot and interrelations of foot, stature, and lower extremity as seen in serial records of children between 1–18 years of age. *Am. J. Phys. Anthropol.* 1956; 14(2):287–308.
28. Gonzalez Elena ML, Cordoba-Fernandez A. Footwear fit in schoolchildren of southern Spain: a population study. *BMC Musculoskelet. Disord.* 2019; 20(1):208.
29. Buldt AK, Menz HB. Incorrectly fitted footwear, foot pain and foot disorders: a systematic search and narrative review of the literature. *J. Foot Ankle Res.* 2018; 11:43.
30. Rao UB, Joseph B. The influence of footwear on the prevalence of flat foot. A survey of 2300 children. *J. Bone Joint Surg. Br.* 1992; 74(4):525–7.
31. Klein C, Groll-Knapp E, Kundi M, Kinz W. Increased hallux angle in children and its association with insufficient length of footwear: a community based cross-sectional study. *BMC Musculoskelet. Disord.* 2009; 10:159.
32. Echarri JJ, Forriol F. The development in footprint morphology in 1851 Congolese children from urban and rural areas, and the relationship between this and wearing shoes. *J. Pediatr. Orthop. B.* 2003; 12(2):141–6.

33. Hollander K, de Villiers JE, Sehner S, et al. Growing-up (habitually) barefoot influences the development of foot and arch morphology in children and adolescents. *Sci. Rep.* 2017; 7(1):8079.
34. Hollander K, Heidt C, VAN DER Zwaard BC, Braumann KM, Zech A. Long-term effects of habitual barefoot running and walking: a systematic review. *Med. Sci. Sports Exerc.* 2017; 49(4):752–62.
35. Hollander K, van der Zwaard BC, de Villiers JE, Braumann KM, Venter R, Zech A. The effects of being habitually barefoot on foot mechanics and motor performance in children and adolescents aged 6–18 years: study protocol for a multicenter cross-sectional study (barefoot LIFE project). *J. Foot Ankle Res.* 2016; 9(1):36.
36. Zech A, Venter R, de Villiers JE, Sehner S, Wegscheider K, Hollander K. Motor skills of children and adolescents are influenced by growing up barefoot or shod. *Front. Pediatr.* 2018; 6:115.
37. Mizushima J, Keogh JWL, Maeda K, et al. Long-term effects of school barefoot running program on sprinting biomechanics in children: a case-control study. *Gait Posture.* 2021; 83:9–14.
38. Hillstrom HJ, Buckland MA, Slevin CM, et al. Effect of shoe flexibility on plantar loading in children learning to walk. *J. Am. Podiatr. Med. Assoc.* 2013; 103(4):297–305.
39. Wolf S, Simon J, Patikas D, Schuster W, Armbrust P, Doderlein L. Foot motion in children shoes: a comparison of barefoot walking with shod walking in conventional and flexible shoes. *Gait Posture.* 2008; 27(1):51–9.
40. Hollander K, Riebe D, Campe S, Braumann KM, Zech A. Effects of footwear on treadmill running biomechanics in preadolescent children. *Gait Posture.* 2014; 40(3):381–5.
41. Staheli LT. Shoes for children: a review. *Pediatrics.* 1991; 88(2):371–5.
42. Davies N, Branthwaite H, Chockalingam N. Where should a school shoe provide flexibility and support for the asymptomatic 6- to 10-year-olds and on what information is this based? A Delphi yielded consensus. *Prosthetics Orthot. Int.* 2015; 39(3):213–8.
43. Sichting F, Holowka NB, Hansen OB, Lieberman DE. Effect of the upward curvature of toe springs on walking biomechanics in humans. *Sci. Rep.* 2020; 10(1):14643.
44. Kuhman D, Melcher D, Paquette MR. Ankle and knee kinetics between strike patterns at common training speeds in competitive male runners. *Eur. J. Sport Sci.* 2016; 16(4):433–40.
45. Radin EL, Parker HG, Pugh JW, Steinberg RS, Paul IL, Rose RM. Response of joints to impact loading. 3. Relationship between trabecular microfractures and cartilage degeneration. *J. Biomech.* 1973; 6:51–7.
46. Radin EL, Paul IL. Response of joints to impact loading. I. In vitro wear. *Arthritis Rheum.* 1971; 14(3):356–62.
47. Rice HM, Jamison ST, Davis IS. Footwear matters: influence of footwear and foot strike on load rates during running. *Med. Sci. Sports Exerc.* 2016; 48(12):2462–8.
48. Hamill J, Gruber AH. Is changing footstrike pattern beneficial to runners? *J. Sport Health Sci.* 2017; 6(2):146–53.
49. 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):23–8.
50. Johnson CD, Tenforde AS, Outerleys J, Reilly J, Davis IS. Impact-related ground reaction forces are more strongly associated with some running injuries than others. *Am. J. Sports Med.* 2020; 48(12):3072–80.
51. Pohl MB, Hamill J, Davis IS. Biomechanical and anatomic factors associated with a history of plantar fasciitis in female runners. *Clin. J. Sport Med.* 2009; 19(5):372–6.
52. Davis IS, Bowser BJ, Mullineaux DR. Greater vertical impact loading in female runners with medically diagnosed injuries: a prospective investigation. *Br. J. Sports Med.* 2016; 50(14):887–92.
53. Chan ZYS, Zhang JH, Au IPH, et al. Gait retraining for the reduction of injury occurrence in novice distance runners: 1-year follow-up of a randomized controlled trial. *Am. J. Sports Med.* 2018; 46(2):388–95.
54. Futrell EE, Jamison ST, Tenforde AS, Davis IS. Relationships between habitual cadence, footstrike, and vertical load rates in runners. *Med. Sci. Sports Exerc.* 2018; 50(9):1837–41.
55. Willy RW, Davis IS. Kinematic and kinetic comparison of running in standard and minimalist shoes. *Med. Sci. Sports Exerc.* 2014; 46(2):318–23.
56. Salzler MJ, Bluman EM, Noonan S, Chiodo CP, de Asla RJ. Injuries observed in minimalist runners. *Foot Ankle Int.* 2012; 33(4):262–6.
57. Salzler MJ, Kirwan HJ, Scarborough DM, Walker JT, Guarino AJ, Berkson EM. Injuries observed in a prospective transition from traditional to minimalist footwear: correlation of high impact transient forces and lower injury severity. *Phys. Sportsmed.* 2016; 44(4):373–9.
58. 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):1363–8.
59. 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):387–92.
60. Squadrone R, Gallozzi C. Biomechanical and physiological comparison of barefoot and two shod conditions in experienced barefoot runners. *J. Sports Med. Phys. Fitness.* 2009; 49(1):6–13.
61. Hollander K, Argubi-Wollesen A, Reer R, Zech A. Comparison of minimalist footwear strategies for simulating barefoot running: a randomized crossover study. *PLoS One.* 2015; 10(5):e0125880.
62. Squadrone R, Rodano R, Hamill J, Preatoni E. Acute effect of different minimalist shoes on foot strike pattern and kinematics in rearfoot strikers during running. *J. Sports Sci.* 2015; 33(11):1196–204.
63. 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):1060–7.
64. Roper JL, Harding EM, Doerfler D, et al. The effects of gait retraining in runners with patellofemoral pain: a randomized trial. *Clin. Biomech. (Bristol, Avon).* 2016; 35:14–22.
65. Powers CM. The influence of altered lower-extremity kinematics on patellofemoral joint dysfunction: a theoretical perspective. *J. Orthop. Sports Phys. Ther.* 2003; 33(11):639–46.
66. Almeida MO, Davis IS, Lopes AD. Biomechanical differences of foot-strike patterns during running: a systematic review with meta-analysis. *J. Orthop. Sports Phys. Ther.* 2015; 45(10):738–55.
67. Powers CM, Lilley JC, Lee TQ. The effects of axial and multi-plane loading of the extensor mechanism on the patellofemoral joint. *Clin. Biomech. (Bristol, Avon).* 1998; 13(8):616–24.
68. Boyer ER, Rooney BD, Derrick TR. Rearfoot and midfoot or forefoot impacts in habitually shod runners. *Med. Sci. Sports Exerc.* 2014; 46(7):1384–91.
69. Nordin AD, Dufek JS. Footwear and footstrike change loading patterns in running. *J. Sports Sci.* 2020; 38(16):1869–76.
70. Fokkema T, Outerleys J, Matias AB, Clansey AC, Davis IS. Differences in foot kinematics between forefoot strikers in minimalist and conventional running shoes. *Med. Sci. Sports Exerc.* 2019; 51(6S):774–5.
71. Frost HM. Bone "mass" and the "mechanostat": a proposal. *Anat. Rec.* 1987; 219(1):1–9.
72. Frost HM. Bone's mechanostat: a 2003 update. *Anat. Rec. A Discov. Mol. Cell Evol. Biol.* 2003; 275(2):1081–101.
73. Fuller JT, Thewlis D, Tsiros MD, Brown NAT, Hamill J, Buckley JD. Longer-term effects of minimalist shoes on running performance, strength and bone density: a 20-week follow-up study. *Eur. J. Sport Sci.* 2019; 19(3):402–12.
74. Ridge ST, Olsen MT, Bruening DA, et al. Walking in minimalist shoes is effective for strengthening foot muscles. *Med. Sci. Sports Exerc.* 2019; 51(1):104–13.
75. Giuliani J, Masini B, Alitz C, Owens BD. Barefoot-simulating footwear associated with metatarsal stress injury in 2 runners. *Orthopedics.* 2011; 34(7):e320–3.
76. Chen TL, Sze LK, Davis IS, Cheung RT. Effects of training in minimalist shoes on the intrinsic and extrinsic foot muscle volume. *Clin. Biomech. (Bristol, Avon).* 2016; 36:8–13.
77. Goldmann J-P, Potthast W, Brüggemann G-P. Athletic training with minimal footwear strengthens toe flexor muscles. *Footwear Science.* 2013; 5(1):19–25.
78. Johnson AW, Myrer JW, Mitchell UH, Hunter I, Ridge ST. The effects of a transition to minimalist shoe running on intrinsic foot muscle size. *Int. J. Sports Med.* 2016; 37(2):154–8.
79. Miller EE, Whitcome KK, Lieberman DE, Norton HL, Dyer RE. The effect of minimal shoes on arch structure and intrinsic foot muscle strength. *J. Sport Health Sci.* 2014; 3(2):74–85.
80. Farris DJ, Kelly LA, Cresswell AG, Lichtwark GA. The functional importance of human foot muscles for bipedal locomotion. *Proc. Natl. Acad. Sci. U. S. A.* 2019; 116(5):1645–50.

81. Papachatzis N, Malcolm P, Nelson CA, Takahashi KZ. Walking with added mass magnifies salient features of human foot energetics. *J. Exp. Biol.* 2020; 223(Pt 12):jeb207472.
82. Kelly LA, Farris DJ, Cresswell AG, Lichtwark GA. Intrinsic foot muscles contribute to elastic energy storage and return in the human foot. *J. Appl. Physiol.* 2019; 126(1):231–8.
83. Kelly LA, Cresswell AG, Racinais S, Whiteley R, Lichtwark G. Intrinsic foot muscles have the capacity to control deformation of the longitudinal arch. *J. R. Soc. Interface.* 2014; 11(93):20131188.
84. Riddick R, Farris DJ, Kelly LA. The foot is more than a spring: human foot muscles perform work to adapt to the energetic requirements of locomotion. *J. R. Soc. Interface.* 2019; 16(150):20180680.
85. Sharkey NA, Ferris L, Smith TS, Matthews DK. Strain and loading of the second metatarsal during heel-lift. *J. Bone Joint Surg. Am.* 1995; 77(7):1050–7.
86. Taddei UT, Matias AB, Duarte M, Sacco ICN. Foot core training to prevent running-related injuries: a survival analysis of a single-blind, randomized controlled trial. *Am. J. Sports Med.* 2020; 48(14):3610–9.
87. McKeon PO, Hertel J, Bramble D, Davis I. The foot core system: a new paradigm for understanding intrinsic foot muscle function. *Br. J. Sports Med.* 2015; 49(5):290.
88. Taddei UT, Matias AB, Ribeiro FIA, Bus SA, Sacco ICN. Effects of a foot strengthening program on foot muscle morphology and running mechanics: a proof-of-concept, single-blind randomized controlled trial. *Phys. Ther. Sport.* 2020; 42:107–15.
89. Protopapas K, Perry SD. The effect of a 12-week custom foot orthotic intervention on muscle size and muscle activity of the intrinsic foot muscle of young adults during gait termination. *Clin. Biomech. (Bristol, Avon).* 2020; 78:105063.
90. Svensson RB, Heinemeier KM, Couppe C, Kjaer M, Magnusson SP. Effect of aging and exercise on the tendon. *J. Appl. Physiol.* 2016; 121(6):1237–46.
91. Arampatzis A, Karamanidis K, Albracht K. Adaptational responses of the human Achilles tendon by modulation of the applied cyclic strain magnitude. *J. Exp. Biol.* 2007; 210(Pt. 15):2743–53.
92. Almonroeder T, Willson JD, Kernozek TW. The effect of foot strike pattern on Achilles tendon load during running. *Ann. Biomed. Eng.* 2013; 41(8):1758–66.
93. Lyght M, Nockerts M, Kernozek TW, Ragan R. Effects of foot strike and step frequency on Achilles tendon stress during running. *J. Appl. Biomech.* 2016; 32(4):365–72.
94. 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):490–4.
95. Histen K, Arntsen J, L'Hereux L, et al. Achilles tendon properties of minimalist and traditionally shod runners. *J. Sport Rehabil.* 2017; 26(2):159–64.
96. Zhang XN, Luo Z, Wang JQ, Yang Y, Fu WJ. Ultrasound-based mechanical adaptation of Achilles tendon after 12-week running with minimalist shoes. *J. Med. Imaging Health Inform.* 2020; 10(5):1205–9.
97. Wearing SC, Davis IS, Brauner T, Hooper SL, Horstmann T. Do habitual foot-strike patterns in running influence functional Achilles tendon properties during gait? *J. Sports Sci.* 2019; 37(23):2735–43.
98. McDonald KA, Stearne SM, Alderson JA, North I, Pires NJ, Rubenson J. The role of arch compression and metatarsophalangeal joint dynamics in modulating plantar fascia strain in running. *PLoS One.* 2016; 11(4): e0152602.
99. Wearing SC, Smeathers JE, Urry SR, Hennig EM, Hills AP. The pathomechanics of plantar fasciitis. *Sports Med.* 2006; 36(7):585–611.
100. Kelly LA, Lichtwark G, Cresswell AG. Active regulation of longitudinal arch compression and recoil during walking and running. *J. R. Soc. Interface.* 2015; 12(102):20141076.
101. Fiolkowski P, Brunt D, Bishop M, Woo R, Horodyski M. Intrinsic pedal musculature support of the medial longitudinal arch: an electromyography study. *J. Foot Ankle Surg.* 2003; 42(6):327–33.
102. Headlee DL, Leonard JL, Hart JM, Ingersoll CD, Hertel J. Fatigue of the plantar intrinsic foot muscles increases navicular drop. *J. Electromyogr. Kinesiol.* 2008; 18(3):420–5.
103. Zhang X, Delabastita T, Lissens J, De Beenhouwer F, Vanwanseele B. The morphology of foot soft tissues is associated with running shoe type in healthy recreational runners. *J. Sci. Med. Sport.* 2018; 21(7):686–90.
104. Turnipseed WD, Hurschler C, Vanderby R Jr. The effects of elevated compartment pressure on tibial arteriovenous flow and relationship of mechanical and biochemical characteristics of fascia to genesis of chronic anterior compartment syndrome. *J. Vasc. Surg.* 1995; 21(5):810–6; discussion 816-7.
105. Hurschler C, Vanderby R Jr., Martinez DA, Vailas AC, Turnipseed WD. Mechanical and biochemical analyses of tibial compartment fascia in chronic compartment syndrome. *Ann. Biomed. Eng.* 1994; 22(3):272–9.
106. Aerts P, Ker RF, de Clercq D, Ilsley DW. The effects of isolation on the mechanics of the human heel pad. *J. Anat.* 1996; 188(Pt. 2):417–23.
107. De Clercq D, Aerts P, Kunnen M. The mechanical characteristics of the human heel pad during foot strike in running: an in vivo cineradiographic study. *J. Biomech.* 1994; 27(10):1213–22.
108. Wearing SC, Smeathers JE, Urry SR, Sullivan PM, Yates B, Dubois P. Plantar enthesopathy: thickening of the enthesis is correlated with energy dissipation of the plantar fat pad during walking. *Am. J. Sports Med.* 2010; 38(12):2522–7.
109. Wearing SC, Hooper SL, Dubois P, Smeathers JE, Dietze A. Force-deformation properties of the human heel pad during barefoot walking. *Med. Sci. Sports Exerc.* 2014; 46(8):1588–94.
110. Wearing SC, Smeathers JE, Yates B, Urry SR, Dubois P. Bulk compressive properties of the heel fat pad during walking: a pilot investigation in plantar heel pain. *Clin. Biomech. (Bristol, Avon).* 2009; 24(4):397–402.
111. Ker RF. The time-dependent mechanical properties of the human heel pad in the context of locomotion. *J. Exp. Biol.* 1996; 199(Pt 7):1501–8.
112. Ker RF, Bennett MB, Bibby SR, Kester RC, Alexander RM. The spring in the arch of the human foot. *Nature.* 1987; 325(7000):147–9.
113. Wager JC, Challis JH. Elastic energy within the human plantar aponeurosis contributes to arch shortening during the push-off phase of running. *J. Biomech.* 2016; 49(5):704–9.
114. McNeill Alexander R. Human elasticity. *Phys. Educ.* 1994; 29:358–62.
115. Jahss MH, Michelson JD, Desai P, et al. Investigations into the fat pads of the sole of the foot: anatomy and histology. *Foot Ankle.* 1992; 13(5):233–42.
116. Lynn B. The nature and location of certain phasic mechanoreceptors in the cat's foot. *J. Physiol.* 1969; 201(3):765–73.
117. Strzalkowski NDJ, Peters RM, Inglis JT, Bent LR. Cutaneous afferent innervation of the human foot sole: what can we learn from single-unit recordings? *J. Neurophysiol.* 2018; 120(3):1233–46.
118. Kohles SS, Bradshaw S, Mason SS, Looft FJ. A multivariate logistical model for identifying the compressive sensitivity of single rat tactile receptors as nanobiosensors. *J. Nanotechnol. Eng. Med.* 2011; 2(1):10.1115/1.4002750.
119. Holmes MH, Bell J. A model of a sensory mechanoreceptor derived from homogenization. *SIAM J. Appl. Math.* 1990; 50(1):147–66.
120. Simonetti S, Dahl K, Krarup C. Different indentation velocities activate different populations of mechanoreceptors in humans. *Muscle Nerve.* 1998; 21(7):858–68.
121. Gruber AH, Silvernail JF, Brueggemann P, Rohr E, Hamill J. Footfall patterns during barefoot running on harder and softer surfaces. *Footwear Sci.* 2013; 5(1):39–44.
122. Telfer S, Woodburn J, Turner DE. Measurement of functional heel pad behaviour in-shoe during gait using orthotic embedded ultrasonography. *Gait Posture.* 2014; 39(1):328–32.
123. Pai S, Ledoux WR. The compressive mechanical properties of diabetic and non-diabetic plantar soft tissue. *J. Biomech.* 2010; 43(9):1754–60.
124. Chao CY, Zheng YP, Cheing GL. Epidermal thickness and biomechanical properties of plantar tissues in diabetic foot. *Ultrasound Med. Biol.* 2011; 37(7):1029–38.
125. Sugai N, Cho KH, Murakami G, Abe H, Uchiyama E, Kura H. Distribution of sole Pacinian corpuscles: a histological study using near-term human feet. *Surg. Radiol. Anat.* 2021; 43:1031–9.
126. Maki BE, Perry SD, Norrie RG, McIlroy WE. Effect of facilitation of sensation from plantar foot-surface boundaries on postural stabilization in young and older adults. *J. Gerontol. A Biol. Sci. Med. Sci.* 1999; 54(6):M281–7.
127. Robbins S, Waked E, Allard P, McClaran J, Krouglicof N. Foot position awareness in younger and older men: the influence of footwear sole properties. *J. Am. Geriatr. Soc.* 1997; 45(1):61–6.
128. Meyer PF, Oddsson LI, De Luca CJ. The role of plantar cutaneous sensation in unperturbed stance. *Exp. Brain Res.* 2004; 156(4):505–12.
129. Cudejko T, Gardiner J, Akpan A, D'Août K. Minimal shoes improve stability and mobility in persons with a history of falls. *Sci. Rep.* 2020; 10(1):21755.

130. DeVita P, Hortobagyi T. Age causes a redistribution of joint torques and powers during gait. *J. Appl. Physiol.* 2000; 88(5):1804–11.
131. Peeters G, van Schoor NM, Cooper R, Tooth L, Kenny RA. Should prevention of falls start earlier? Co-ordinated analyses of harmonised data on falls in middle-aged adults across four population-based cohort studies. *PLoS One*. 2018; 13(8):e0201989.
132. Menz HB, Auhl M, Spink MJ. Foot problems as a risk factor for falls in community-dwelling older people: a systematic review and meta-analysis. *Maturitas*. 2018; 118:7–14.
133. Mickle KJ, Munro BJ, Lord SR, Menz HB, Steele JR. ISB clinical biomechanics award 2009: toe weakness and deformity increase the risk of falls in older people. *Clin. Biomech. (Bristol, Avon)*. 2009; 24(10):787–91.
134. Mickle KJ, Angin S, Crofts G, Nester CJ. Effects of age on strength and morphology of toe flexor muscles. *J. Orthop. Sports Phys. Ther.* 2016; 46(12):1065–70.
135. Rubenstein LZ. Falls in older people: epidemiology, risk factors and strategies for prevention. *Age Ageing*. 2006; 35(Suppl. 2):ii37–41.
136. Munteanu SE, Menz HB, Wark JD, et al. Hallux valgus, by nature or nurture? A twin study. *Arthritis Care Res*. 2017; 69(9):1421–8.
137. Aboutorabi A, Bahramizadeh M, Arazpour M, et al. A systematic review of the effect of foot orthoses and shoe characteristics on balance in healthy older subjects. *Prosthetics Orthot. Int.* 2016; 40(2):170–81.
138. Esculier JF, Dubois B, Dionne CE, Leblond J, Roy JS. A consensus definition and rating scale for minimalist shoes. *J. Foot Ankle Res*. 2015; 8:42.
139. Cudejko T, Gardiner J, Akpan A, D'Aout K. Minimal footwear improves stability and physical function in middle-aged and older people compared to conventional shoes. *Clin. Biomech. (Bristol, Avon)*. 2020; 71:139–45.
140. Berenbaum F, Wallace IJ, Lieberman DE, Felson DT. Modern-day environmental factors in the pathogenesis of osteoarthritis. *Nat. Rev. Rheumatol.* 2018; 14(11):674–81.
141. Wilson DR, McWalter EJ, Johnston JD. The measurement of joint mechanics and their role in osteoarthritis genesis and progression. *Rheum. Dis. Clin. N. Am.* 2008; 34(3):605–22.
142. Andriacchi TP, Favre J. The nature of in vivo mechanical signals that influence cartilage health and progression to knee osteoarthritis. *Curr. Rheumatol. Rep*. 2014; 16(11):463.
143. Andriacchi TP, Favre J, Erhart-Hledik JC, Chu CR. A systems view of risk factors for knee osteoarthritis reveals insights into the pathogenesis of the disease. *Ann. Biomed. Eng*. 2015; 43(2):376–87.
144. Sharma L, Hurwitz DE, Thonar EJ, et al. Knee adduction moment, serum hyaluronan level, and disease severity in medial tibiofemoral osteoarthritis. *Arthritis Rheum*. 1998; 41(7):1233–40.
145. Miyazaki T, Wada M, Kawahara H, Sato M, Baba H, Shimada S. Dynamic load at baseline can predict radiographic disease progression in medial compartment knee osteoarthritis. *Ann. Rheum. Dis*. 2002; 61(7):617–22.
146. Mündermann A, Dyrby CO, Hurwitz DE, Sharma L, Andriacchi TP. Potential strategies to reduce medial compartment loading in patients with knee osteoarthritis of varying severity: reduced walking speed. *Arthritis Rheum*. 2004; 50(4):1172–8.
147. Erhart JC, Mundermann A, Elspas B, Giori NJ, Andriacchi TP. A variable-stiffness shoe lowers the knee adduction moment in subjects with symptoms of medial compartment knee osteoarthritis. *J. Biomech*. 2008; 41(12):2720–5.
148. Bennell KL, Kean CO, Wrigley TV, Hinman RS. Effects of a modified shoe on knee load in people with and those without knee osteoarthritis. *Arthritis Rheum*. 2013; 65(3):701–9.
149. Kean CO, Bennell KL, Wrigley TV, Hinman RS. Modified walking shoes for knee osteoarthritis: mechanisms for reductions in the knee adduction moment. *J. Biomech*. 2013; 46(12):2060–6.
150. Erhart-Hledik JC, Elspas B, Giori NJ, Andriacchi TP. Effect of variable-stiffness walking shoes on knee adduction moment, pain, and function in subjects with medial compartment knee osteoarthritis after 1 year. *J. Orthop. Res*. 2012; 30(4):514–21.
151. Zafar AQ, Zamani R, Akrami M. The effectiveness of foot orthoses in the treatment of medial knee osteoarthritis: a systematic review. *Gait Posture*. 2020; 76:238–51.
152. Parkes MJ, Maricar N, Lunt M, et al. Lateral wedge insoles as a conservative treatment for pain in patients with medial knee osteoarthritis: a meta-analysis. *JAMA*. 2013; 310(7):722–30.
153. Barrios JA, Butler RJ, Crenshaw JR, Royer TD, Davis IS. Mechanical effectiveness of lateral foot wedging in medial knee osteoarthritis after 1 year of wear. *J. Orthop. Res*. 2013; 31(5):659–64.
154. Barrios JA, Crenshaw JR, Royer TD, Davis IS. Walking shoes and laterally wedged orthoses in the clinical management of medial tibiofemoral osteoarthritis: a one-year prospective controlled trial. *Knee*. 2009; 16(2):136–42.
155. Shaw KE, Charlton JM, Perry CKL, et al. The effects of shoe-worn insoles on gait biomechanics in people with knee osteoarthritis: a systematic review and meta-analysis. *Br. J. Sports Med*. 2018; 52(4):238–53.
156. Shakoor N, Block JA. Walking barefoot decreases loading on the lower extremity joints in knee osteoarthritis. *Arthritis Rheum*. 2006; 54(9):2923–7.
157. Shakoor N, Lidtke RH, Sengupta M, Fogg LF, Block JA. Effects of specialized footwear on joint loads in osteoarthritis of the knee. *Arthritis Rheum*. 2008; 59(9):1214–20.
158. Sacco IC, Trombini-Souza F, Butugan MK, Pássaro AC, Arnone AC, Fuller R. Joint loading decreased by inexpensive and minimalist footwear in elderly women with knee osteoarthritis during stair descent. *Arthritis Care Res (Hoboken)*. 2012; 64(3):368–74.
159. Trombini-Souza F, Kimura A, Ribeiro AP, et al. Inexpensive footwear decreases joint loading in elderly women with knee osteoarthritis. *Gait Posture*. 2011; 34(1):126–30.
160. Trombini-Souza F, Matias AB, Yokota M, et al. Long-term use of minimal footwear on pain, self-reported function, analgesic intake, and joint loading in elderly women with knee osteoarthritis: a randomized controlled trial. *Clin. Biomech. (Bristol, Avon)*. 2015; 30(10):1194–201.
161. Tesfaye S, Boulton AJ, Dyck PJ, et al, Toronto Diabetic Neuropathy Expert Group. Diabetic neuropathies: update on definitions, diagnostic criteria, estimation of severity, and treatments. *Diabetes Care*. 2010; 33(10):2285–93.
162. Cheuy VA, Hastings MK, Commean PK, Ward SR, Mueller MJ. Intrinsic foot muscle deterioration is associated with metatarsophalangeal joint angle in people with diabetes and neuropathy. *Clin. Biomech. (Bristol, Avon)*. 2013; 28(9–10):1055–60.
163. Bus SA, Yang QX, Wang JH, Smith MB, Wunderlich R, Cavanagh PR. Intrinsic muscle atrophy and toe deformity in the diabetic neuropathic foot: a magnetic resonance imaging study. *Diabetes Care*. 2002; 25(8):1444–50.
164. Monteiro-Soares M, Boyko EJ, Ribeiro J, Ribeiro I, Dinis-Ribeiro M. Predictive factors for diabetic foot ulceration: a systematic review. *Diabetes Metab. Res. Rev*. 2012; 28(7):574–600.
165. Pataky Z, Assal JP, Conne P, Vuagnat H, Golay A. Plantar pressure distribution in type 2 diabetic patients without peripheral neuropathy and peripheral vascular disease. *Diabet. Med*. 2005; 22(6):762–7.
166. van Netten JJ, Sacco ICN, Lavery LA, et al. Treatment of modifiable risk factors for foot ulceration in persons with diabetes: a systematic review. *Diabetes Metab. Res. Rev*. 2020; 36(Suppl. 1):e3271.
167. Butugan MK, Sartor CD, Watari R, et al. Multichannel EMG-based estimation of fiber conduction velocity during isometric contraction of patients with different stages of diabetic neuropathy. *J. Electromyogr. Kinesiol.* 2014; 24(4):465–72.
168. Suda EY, Madeleine P, Hirata RP, Samani A, Kawamura TT, Sacco IC. Reduced complexity of force and muscle activity during low level isometric contractions of the ankle in diabetic individuals. *Clin. Biomech. (Bristol, Avon)*. 2017; 42:38–46.
169. Andersen H, Nielsen S, Mogensen CE, Jakobsen J. Muscle strength in type 2 diabetes. *Diabetes*. 2004; 53(6):1543–8.
170. Bus SA, Lavery LA, Monteiro-Soares M, et al, International Working Group on the Diabetic Foot. Guidelines on the prevention of foot ulcers in persons with diabetes (IWGDF 2019 update). *Diabetes Metab. Res. Rev*. 2020; 36(Suppl. 1):e3269.
171. Leenders M, Verdijk LB, van der Hoeven L, et al. Patients with type 2 diabetes show a greater decline in muscle mass, muscle strength, and functional capacity with aging. *J. Am. Med. Dir. Assoc*. 2013; 14(8):585–92.
172. Martinelli AR, Mantovani AM, Nozabieli AJ, et al. Muscle strength and ankle mobility for the gait parameters in diabetic neuropathies. *Foot (Edinb.)*. 2013; 23(1):17–21.
173. Henderson AD, Johnson AW, Rasmussen LG, et al. Early-stage diabetic neuropathy reduces foot strength and intrinsic but not extrinsic foot muscle size. *J. Diabetes Res*. 2020; 2020:9536362.

174. IJzerman TH, Schaper NC, Melai T, Meijer K, Willems PJ, Savelberg HH. Lower extremity muscle strength is reduced in people with type 2 diabetes, with and without polyneuropathy, and is associated with impaired mobility and reduced quality of life. *Diabetes Res. Clin. Pract.* 2012; 95(3):345–51.
175. Sacco IC, Sartor CD. From treatment to preventive actions: improving function in patients with diabetic polyneuropathy. *Diabetes Metab. Res. Rev.* 2016; 32(Suppl. 1):206–12.
176. Cerrahoglu L, Kosan U, Sirin TC, Ulusoy A. Range of motion and plantar pressure evaluation for the effects of self-care foot exercises on diabetic patients with and without neuropathy. *J. Am. Podiatr. Med. Assoc.* 2016; 106(3):189–200.
177. Fayed E, Badr N, Mahmoud S, Hakim S. Exercise therapy improves plantar pressure distribution in patients with diabetic peripheral neuropathy. *Int. J. PharmTech Res.* 2016; 9(5):151–9.
178. Kanchanasamut W, Pensri P. Effects of weight-bearing exercise on a mini-trampoline on foot mobility, plantar pressure and sensation of diabetic neuropathic feet; a preliminary study. *Diabet Foot Ankle.* 2017; 8(1):1287239.
179. Sartor CD, Hasue RH, Cacciari LP, et al. Effects of strengthening, stretching and functional training on foot function in patients with diabetic neuropathy: results of a randomized controlled trial. *BMC Musculoskelet. Disord.* 2014; 15:137.