Chronic Injuries Due to Running and a Possible Cure with the Barefoot Style

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Principles of Gait

The normal human walking gait cycle can be thought of as an inverted pendulum where the body swings over the lower extremity during stance phase.[1] The other part of the cycle is swing phase where the lower extremity is brought forward to repeat the stance phase once more. A portion of the gait cycle of either lower extremity overlaps with the other and this is called the double-stance phase.[2,3] Other gait cycles include running and sprinting.[1] These both involve something called a double-float phase where neither extremity is in contact with the ground.[3] These gait cycles also do not have a double-stance phase. Progression from walking to running to sprinting also involves a relative shortening of the stance phase, relative lengthening of the swing phase, and a shortening of the time it takes to complete a full gait cycle.[1,3]

Chronic Injury Theory

Chronic injury to the human body is related to classical mechanics principles.[4,5] Tensile forces (stress) cause tissue to elongate (strain). Energy is stored as elastic potential energy and if this deformation is within the physiologic range, the tissue will recoil and return most of the energy that had been absorbed during tissue stretching. Ninety five percent of this energy is returned to the system in the form of kinetic energy and the rest is dissipated as heat from friction in normal physiologic conditions.

Repetitive stress injuries, which are common amongst runners result from an accumulation of microdamage from repeated application of stress.[3,6] This leads to strain, or deformation. At first, this falls within the physiologic range of elastic deformation. With excessive running, bones can be subjected to supraphysiologic plastic deformation and soft tissues can be subjected to supraphysiologic viscous deformation. High strain and high rates of application of that strain can lead to fatigue damage.[6,7] In bone, this manifests as microcracks, and as failures of collagen cross-links in soft tissue. These small-scale failures allow elastic hysteresis, which is the difference between the energy required (stress) to generate a given strain (deformation) and the elastic energy stored for a given cycle of loading. In other words, the accumulation of microdamage makes bones and soft tissues weaker and then less force is required to further the damage.

Repeated applications of this supraphysiologic load generates repeated cycles of hysteresis and leads to unrecoverable energy loss during unloading.[6] That energy is now being converted to tissue damage, or injury. Elastic hysteresis is more pronounced with higher rates of loading. Imagine the difference between being hit on the head with a 5 pound metal hammer versus a 5 pound padded, soft mallet. The total energy absorbed can be the same while the resulting damage is very different.

In bone, if fatigue damage accumulates more rapidly than remodeling can remove it, then fatigue failure may occur. Fatigue failure is also known as a stress fracture.[8] In soft tissues such as tendons and ligaments, stresses that cause supraphysiologic strains can initiate microscopic failure as collagen cross-links begin to fail. Repeated strain levels or a single strain above a given magnitude and/or rate can cause tensile failure of the fibers and sheer failure.[6] This catastrophic failure is manifested as tendon or ligament rupture.

Chronic Running Injuries

Chronic running injuries include a wide variety of ailments, but the most common are muscle strains, patellofemoral pain syndrome, IT band syndrome, Achilles tendinopathies, plantar fasciitis, stress fractures, and medial tibial stress syndrome.[6,8] This last injury had previously been included under the term "Shin Splints." "Shin splints" are now either categorized as medial tibial stress syndrome (MTSS) and tibial periostitis.[9] MTSS specifically excludes exertional compartment syndrome and tibial stress fractures, which are also common chronic running injuries.[9] Acute traumatic injuries are different class of injury completely and will not be discussed here.

Risk factors for running injuries have been studied extensively. The number one risk factor is just being a runner.[3,4,10] Observational studies conclude that between 20% and 80% of runners have some kind of injury per year.[5] Therefore, after running for many years, essentially all runners will have some kind of injury at some point.[3,10] These injuries are predominantly about the knee. Extensive review papers attempting to identify risk factors for running injuries are only able to find strong evidence that a history of injury and greater distance training per week are predictive of future injury.[3] All other factors, those that most people might say could be related to running injury (such as physiological anomalies, level of experience, days trained per week, age of shoes, etc) have only limited or evidence. Essentially all of the commonly listed risk factors for injury are highly questionable.

New studies have taken a different approach in attempting to identify the cause of chronic running injuries: examine the stride and impact characteristics of runners.[6,7] A cross sectional study examining the running mechanics and anatomy of runners who had experienced tibial stress fractures versus matched runners who had not showed that the only significant differences were in

vertical loading rates and tibial shock at foot strike.[11] The peak impact did not change, but the slope of the line was steeper. Recall the 5 pound steel hammer versus the mallet.

The Barefoot Style

Much of the research done on running mechanics recently has come to light due to a best-selling popular press book by Christopher McDougall called *Born to Run*.[12] Many runners and non-runners now discuss the merits and demerits of barefoot running, and controversy abounds. Many arguments on both sides of the issue begin (and sometimes end) with anecdotal evidence. However, recent, and some older less well-known studies can inform the anecdotal discussions.

Vin Lananna of Oregon is one of the most successful college track coaches ever. He has said, "When my runners train barefoot, they run faster and suffer fewer injuries."[12] A study by Richards et al. in 2009 in the *British Journal of Sports Medicine* systematically reviewed the evidence for prescription of distance running shoes.[13] Specifically, evidence was sought to support the use and recommendation of running shoes featuring elevated heels and pronation control systems tailored to the individual's foot type. No studies meeting criterion were found. Moreover, evidence about the modern running shoe, which typically features pronation control and elevated/cushioned heels (PCECH shoes), showed either inconclusive/conflicting evidence, or evidence to the contrary.[13] Evidence for prescribing PCECH shoes can be found in 2 papers from 2005, yet these are only expert opinions.[14] Recommendations from multiple international and national sports agencies almost always include references to specific models of Asics shoes, 1 of which has openly acknowledged a sponsorship arrangement with the company. In conclusion, PCECH shoes have never been tested in randomized controlled trials and their effects on injury rates, enjoyment, performance, osteoarthritis risk, physical activity levels and overall athlete health and well-being are unknown. The oft-repeated recommendation by physicians (and other professionals) to runners to use modern running shoes is not evidence-based.

However, if there is a controversy about running shoes and support for the modern running shoe is questioned, what of the evidence for barefoot style running? These studies do exist, and they mostly focus on foot strike characteristics.[15-17] The 2 main types of running foot strikes are the heel strike and the forefoot strike.[4] In the heel strike, a dorsiflexed ankle leads to a relatively stiff and noncompliant limb contacting the ground in front of the center of gravity of the runner. Approaching midstance, the relatively weak dorsiflexion muscles in the leg (tibialis anterior and toe extensors) are loaded eccentrically as they resist plantarflexion forces. In forefoot strikes, a plantarflexed ankle and inverted foot lead to a relatively supple and compliant limb contacting the ground under the center of gravity of the runner. Approaching midstance, the relatively large and powerful plantarflexion muscles in the leg (gastroc-soleus complex, tibialis posterior and toe flexors) are loaded eccentrically as they resist dorsiflexion forces and allow for a physiologic pronation movement. In addition, the heel strike does not really load the arch of the foot at all and the forefoot strike depends on and encourages both the transverse and longitudinal arches of the foot.[4]

Another anecdote comes from Arthur Lydiard, who taught Nike cofounder Bill Bowerman about jogging and was a much more successful running coach himself. "We ran in canvas shoes. We didn't get plantar fasciitis, we didn't pronate or supinate, we might have lost a bit of skin from the rough canvas when we were running marathons, but generally speaking, we didn't have foot problems. Paying several hundred dollars for the latest in high-tech running shoes is no guarantee you'll avoid any of these injuries and can even guarantee that you will suffer from them in one form or another."[18]

A study by Daoud et al. in *Medicine & Science in Sports & Exercise* in 2012 retrospectively analyzed foot strikes and injury rates in endurance runners.[4] Analysis of these collegiate middle and long-distance runners showed that those who exhibited a rearfoot strike had double the rate of repetitive stress injuries per year.[4] This relative risk substantially dwarfs any other finding by any other study to date looking at risk factors for chronic injury. As this study was retrospective, the authors agreed that a prospective study would help to identify cause and effect of foot strike with chronic running injury.

A prospective study by Milner et al. attempted to answer this question.[11] Impact loads of rearfoot strike runners who go on to develop a running injury was compared to those who have never been injured. After 2 years, it was found that impact loading rate and tibial shock amplified the risk of developing a running-related injury.[11]

The Null Hypothesis

Many who hear about barefoot-style running dismiss it as a fad that will blow over soon. These people, who include highly trained orthopaedists in sports and other disciplines fail to grasp that the true fad is shoes, not the lack of them. The principle of the null hypothesis is informative.[17] The null hypothesis is the general, or default position. The null hypothesis can never be proven and a set of data can either reject the null hypothesis or fail to reject it. In this light, which is the null hypothesis, barefoot and barefoot style running or shod running in the modern PCECH shoes?

A paper called "The Evolution of Marathon Running Capabilities in Humans" posits that today's

humans are descendents of an elite distance running population.[19] Cursors (animals with specializations for running) are either predators or prey. Humans are outsprinted by cursors because we cannot gallop. Our running gait is most similar to quadruped trotting, which does not permit fast speeds in quadrupeds.[19] Our endurance running speed of 4 to 6 meters per second (m/s) exceeds the trot/gallop transition speed of any other mammal. This is significant because trotting is the quadruped endurance gait. Unless conditions are very cool, quadrupeds will quickly overheat and fatigue while galloping. For example, dogs and horses can maintain gallop speeds of 3.8 and 9 m/s respectively for only about 15 minutes. In long distance runs, horses are constrained to a canter, or slow gallop of 5.8 m/s and can maintain this for only about 20 km per day. Thus, at marathon-length distances, humans can outrun almost any other mammal.[19] A number of races across the world pit humans against horses. One such race in Wales had humans win 2 of the 9 races between 2003 and 2011. However, in the races humans lost, it is usually by less than 15 minutes, and sometimes by only seconds.

The authors theorize that humans evolved these capabilities about 2 million years ago with Homo Erectus.[19] This might explain the previously enigmatic reproductive supremacy of genus Homo over Australopethicus who was thought to be smarter, stronger, and bigger. Persistence hunting involves a hunter in hot/arid conditions who kills an animal by following it and keeping it above its trot/gallop transition for several hours. The animal is eventually driven to hyperthermia and essentially lays down before the hunter, unable to continue fleeing. This hunting method is still practiced by some Kalahari bushmen and a few other aboriginal tribes in remote parts of the world.[19]

Primitive Versus Modern

Many might say that stories and theories about cavemen are interesting, but they should not guide decisions about health and fitness today because their life expectancy was rarely past the second decade. However, we cannot necessarily claim that our feet are healthier than more primitive peoples. Dr. Udaya Rao, in India once said: "In our clinic we have never seen a child from the farming community or from the family of a manual laborer who complained of flat foot. The few who do…are from affluent urban families and they all wear shoes."[19]

In fact, multiple studies dating back to 1958 support this statement.[20-22] The use of footwear has been linked to increasing the risk of hallux valgus (Sim-Fook in 1958 and Shine in 1965)[20,21] and decreasing hallux varus (Joseph 1987).[22] Two observational studies looked at the rates of flat feet in India. They found that earlier shoe wear (more than 8 hours per day before the age of 6) correlated with significantly higher rates (about double) of flexible flat feet.[19,22,23]

Even modern shoe "experts" have begun to realize that their solution to runners' problems might not be the right one. Jeff Pisciotta, a senior researcher at Nike Sports Research Lab observed: "When you put a shoe on, it starts to take over some of the control…We found pockets of people all over the globe who are still running barefoot, and what you find is that during propulsion and landing, they have far more range of motion in the foot and engage more of the toe. Their feet flex, spread, splay, and grip the surface, meaning you have less pronation and more distribution of pressure."[12]

D'AoÛt et al., in a 2009 study, noted that habitual footwear use leads to higher concentrations of peak foot pressures in small areas of the fore and hind foot. In addition, habitually barefoot people have a flatter initial foot placement, correlating with the difference between forefoot strike runners compared to rearfoot strike runners.[16]

Evolutionary Medicine

As noted, some argue that humans have been running for millions of years, and this running was done barefoot on hard, rough surfaces. The lack of any decrease in running-related injuries over the last 30 years has led some to question the modern approach to a problem that essentially all runners will encounter at some point. Lieberman hypothesized in 2012 that the human body adapted to running with a barefoot style whose kinematic characteristics generate less forceful impact peaks, use more proprioception, and that this may strengthen the feet to help avoid injury.[17] A key component of evolutionary medicine is the Evolutionary Mismatch Hypothesis, which states that rapid changes in culture can outpace natural selection, often to the detriment of our health.[17] For example, agricultural living changed lifestyle and diet rapidly and allowed us too great a supply of historically rare fats and sugars that have contributed to our epidemic of obesity. The Evolutionary Mismatch Hypothesis may apply to shoes and running.

Lieberman shows how modern shoes encourage an overstride and heel strike whose rate of loading of ground reaction forces as they relate to the moment arm involved are 3 to 4 times those of a forefoot strike with a short stride contacting the ground below the center of gravity of the runner.[17] The differences between the 2 strides and the difficulty of running in a more natural manner with a modern shoe can be understood by imagining someone trying to jump using their heels instead of their toes. Running is similar to jumping repeatedly. Lieberman also discusses the anatomical adaptations we are losing by using shoes. Eccentric loading of muscles is known to cause more muscle hypertrophy and strengthening. Shoes insulate

the foot's intrinsic and extrinsic muscles from eccentric loading. In addition, heel strike places the metatarsals on cantilever bend while the "arch support" of modern shoes counteracts the foot's natural 3-point bending mechanics and resulting arch lengthening which would have engaged the intrinsics in eccentric loading.[17] Bruggeman in 2005 showed that training for 5 months in minimalist shoes led to significantly larger and stronger extrinsic musculature in the leg which supports the structure of the foot.[25]

Another question, aside from the question of barefoot style running relating to injury, is whether it affects performance. Jenkins in 2010 showed that barefoot running has no appreciable negative effects on performance.[15] Indeed, Abebe Bikila and Zola Budd have set world records in the marathon and shorter distances running barefoot. Calculations show that barefoot running has a 1% to 4% lower energy cost of transport and that minimalist running (taking into account stride rate, shoe mass, and strike type) has a 2.5-3.3% lower energy cost of transport.[15]

The Transition Back to the "Evolutionary Default"

Since this topic has burst onto the scene in the last few years, many runners have become "converted" and transitioned, only to trade one injury set for another. These injuries are almost always associated with a too-rapid transition. A forefoot strike places higher loads on the plantarflexion muscles and Achilles tendon which can lead to calf strains and Achilles tendinopathies. In addition, the increased bending forces on the midfoot and forefoot require strong metatarsals and extensor/dorsiflexor musculature to counteract the stronger flexor/plantarflexor muscles. In addition, poor form, including overstride, can bring impact peaks load rates of forefoot strike runners close to the high magnitude of rearfoot strike runners.

Defined strategies for transitioning to barefoot style running are outlined by both Vibram (the company whose FiveFinger® boating shoes have found a second life as a popular barefoot style running shoe) and Harvard's Lieberman (who published many of the studies mentioned in this article). Vibram's plan uses a percentage of the runner's normal distance and Lieberman's plan outlines specific distances to be run.[26,27] Both have a range for slow and fast transitions, but neither plan transitions the runner sooner than 2 months and both have provisions to slow or pause the transition if any soreness or pain is experienced. Indeed, the median transition times for each plan are closer to 3 months or much longer than this with the Lieberman plan. This is supported by a 2012 case series on injuries observed in 10 minimalist runners by a few foot and ankle-trained orthopaedic surgeons.[28] The injuries they saw correlate with the biomechanical reasoning discussed the in the preceding paragraph. All of the runners transitioned too quickly and half had no transition time at all and merely switched all at once. The admission that most of them sought softer surfaces to run on is actually evidence of poor form, since good form should allow for lower peak loading rates to the lower extremity with barefoot running on concrete.

How Did We Get to Where We Are?

Some podiatrists see the human foot as "nature's mistake" and that it is their job to fix it. Before orthopaedists scoff, remember that many spine surgeons see the lumbar spine as "nature's mistake." Dr. Murray Weisenfeld, a leading sports podiatrist wrote the book The Runner's Repair Manual, one of the top-selling foot-care books of all time.[29] In the introduction, he states: "Man's foot was not originally designed for walking, much less running long distances…Man's foot is not yet completely adapted to the ground. Only a portion of the population has been endowed with well ground-adapted feet."[29]

Bill Bowerman, the University of Oregon track coach, was one of the winningest coaches in college track history. He did not even start running until age 50, which was 14 years after having already been first a football, then a track coach at Oregon. He discovered jogging after being introduced by Arthur Lydiard in Australia. He then wrote the best-selling book *Jogging* that ignited a jogging/running craze in the US.[30] After experimenting with shoe design, he founded Nike, whose shoes were initially minimalist shoes. These shoes soon morphed into shoes with highly padded heels and large forefoot/heel height difference. Soon after this, the shoes incorporated early attempts at "motion control" in order to counteract the pronation forces induced by the tall, wide heel. Other shoe companies followed suit.

Running form has changed since the invention of the modern running shoe, pioneered by Bowerman's Nike shoes. These shoes could have attracted converts from the previous, classical running style since they might give the benefit of instantaneous speed at the cost of chronic injury by allowing a longer stride than biology does alone. In Fred Wilt's 1959 book, he detailed the running techniques of 80 of the world's fastest runners.[31] "The forward foot moves toward the track in a downward, backward, 'stroking' motion (not punching or pounding) and the outer edge of the ball of the foot makes first contact with the track. Running progression results from these forces pushing behind the center of gravity of the body."[31]

In Bowerman's 1977 *Jogging*, he predicts that the "heel-to-toe [stride would be] the least tiring over long distances."[30] The longer stride might allow for temporary speed benefits, even if it is less or more tiring over distances. However, if these shoes are used over the course of a lifetime and throughout all training for running, then they could fundamentally change feet from their evolutionarily customized role as the robust contact points of a running species.

What Can I Tell My Patients?

The American Academy of Orthopaedic Surgeons Clinical Guideline on the Treatment of Osteoarthtritis (OA) of the Knee gives specific guidance for how orthopaedic surgeons should counsel patients.[31] Under "Patient Education and Lifestyle Modification," recommendation #1 outlines some limitations and activity modification options: We suggest patients with symptomatic OA of the knee be encouraged to participate in self-management educational programs such as those conducted by the Arthritis Foundation, and incorporate activity modifications (e.g. walking instead of running; alternative activities) into their lifestyle.[31]

Recommendation #4 goes on to elaborate positive options for fitness: We recommend patients with symptomatic OA of the knee be encouraged to participate in low-impact aerobic fitness exercises.[31]

Thus, in light of the conclusions from the above studies, one activity with quantitatively lower impact than running with a heel strike would be barefoot-style running. A possible modification of these official guidelines might look like this: Patients with osteoarthritis about the knee may be encouraged to run using a barefoot style, either beginning or transitioning slowly and while paying attention to possible transition injuries.

Summary and Implications

Recent interest in minimalist or barefoot-style running was largely sparked by a best-selling book on the subject, Born to Run. This has led to a rediscovery of existing research, and also an interest in new research on the topic of barefoot-style running. Chronic running injuries are likely due to high loading rates combined with loading characteristics that are mismatched to human physiology that may have been customized for long-distance running by eons of natural selection. Even though the human species may be the best long-distance running mammal on the planet, a running form that is evolutionarily mismatched to the optimized biomechanics of humans may be what is being used. This mismatch might give the short-term benefit of speed at the long-term cost of chronic injury. Whether or not barefoot-style running is slower or faster than running with modern shoes is still unresolved.

Critics of the barefoot-style point out that even the Africans setting world records in the marathon are using modern shoes and taking longer strides, while often exhibiting a heel strike stride. This does not change the fact that they likely grew up running barefoot. Runners who have run barefoot their entire lives will have a significantly different physiology, including specific bone modeling, intrinsic and extrinsic foot supporting musculature, and running style. These runners, whose feet and lower extremities are much more robust than those of a Westerner who has used shoes which encouraged a non-physiologic stride, will be able to withstand the abnormal stresses placed on their anatomy much better. They will also likely be able to take advantage of any speed benefits which a longer stride could afford, even if it is at the expense of a higher risk of chronic injury in runners without the robust physiology they have.

One key point critics have the most difficult time confronting is that the null hypothesis, or default, is barefoot-style running and that evidence must either reject it or fail to reject it. Westerners grow up wearing shoes from infancy and think that walking and running with modern shoes is more natural than not using them at all. Just like a fish does not notice the water it has always known, Westerners are blinded by the reality in which they have been immersed all their lives. Barefoot running is the null hypothesis, yet more research is still needed to disabuse physicians and laypeople alike that it may be superior to shoes respecting both chronic injury, and performance.

References

1. Novacheck TF. The biomechanics of running. *Gait Posture*. 1998;7(1):77-95.

2. Chambers HG, Sutherland DH. A practical guide to gait analysis. *J Am Acad Orthop Surg*. 2002;10(3):222-231.

3. Novacheck TF. Running injuries: a biomechanical approach. *Instr Course Lect*. 1998;47:397-406.

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

5. Lun V, Meeuwisse WH, Stergiou P, Stefanyshyn D. Relation between running injury and static lower limb alignment in recreational runners. *Br J Sports Med*. 2004;38(5):576-580.

6. Davis IS, Bradley BB, Mullineaux D. Do impacts cause running injuries? A prospective Investigation. *Am Soc Biomech Annual Meeting*. 2010.

7. Chavet P, Lafortune MA, Gray JR. Asymmetry of lower extremity responses to external impact loading. *Hum Movement Sci*. 1997;16(4):391-406.

8. Shindle MK, Endo Y, Warren RF, et al. Stress fractures about the tibia, foot, and ankle. *J Am Acad Orthop Surg*. 2012;20(3):167-176.

9. Galbraith RM, Lavallee ME. Medial tibial stress syndrome: conservative treatment options. *Curr Rev Musculoskelet Med*. 2009;2(3):127-133.

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

11. Milner CE, Ferber R, Pollard CD, Hamill J, Davis IS. Biomechanical factors associated with tibial stress fracture in female runners. *Med Sci Sports Exerc*. 2006;38(2):323-328.

12. McDougall C. *Born To Run: A Hidden Tribe, Superathletes, and the Greatest Race the World Has Never Seen.* 1st ed. New York: Alfred A. Knopf; 2009.

13. Richards CE, Magin PJ, Callister R. Is your prescription of distance running shoes evidence-based? *Br J Sports Med*. 2009;43(3):159-162.

14. Nigg BM. *Biomechanics of Sports Shoes.* Calgary (Canada): Topline Printing; 2010.

15. Jenkins DW, Cauthon DJ. Barefoot running claims and controversies: a review of the literature. *J Am Podiatr Med Assoc*. 2011;101(3):231-246.

16. D'AoÛt K, Pataky TC, De Clercq D, Aerts P. The effects of habitual footwear use: foot shape and function in native barefoot walkers. *Footwear Sci*. 2009;1(2):81-94.

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

18. Lydiard A. *Running to the Top.* 3rd ed. United Kingdom: Meyer & Meyer Sport; 2011.

19. Lieberman DE, Bramble DM. The evolution of marathon running : capabilities in humans. *Sports Med*. 2007;37(4-5):288-290.

20. 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):525-527.

21. Sim-Fook L, Hodgson AR. A comparison of foot forms among the non-shoe and shoe-wearing Chinese population. *J Bone Joint Surg Am*. 1958;40-A(5):1058-1062.

22. Shine LB. Incidence of hallux valgus in a partially shoe-wearing community. *Br Med J*. 1965;1(5451):1648-1650.

23. Joseph B, Chacko V, Abraham T, Jacob M. Pathomechanics of congenital and acquired hallux varus: a clinical and anatomical study. *Foot Ankle*. 1987;8(3):137-143.

24. Sachithanandam V, Joseph B. The influence of footwear on the prevalence of flat foot. A survey of 1846 skeletally mature persons. *J Bone Joint Surg Br*. 1995;77-B(2):254-257.

25. Bruggeman GP, Potthast W, Braunstein B, Niehoff A. Effect of increased mechanical stimuli on foot muscles functional capacity. Paper presented at: ISB Congress, American Society of Biomechanics 2005; Cleveland.

26. Vibram FiveFingers. Barefoot running [Web page]. http://www.vibramfivefingers.com/education/barefoot_running.htm. Accessed May 20, 2013.

27. Biomechanics of foot strikes and applications to running barefoot or in minimal footwear [homepage]. Tips on transitioning to forefoot or midfoot striking. http://www.barefootrunning.fas.harvard.edu/5BarefootRunning&TrainingTips.html. Accessed May 20, 2013.

28. Ridge ST, Johnson AW, Mitchell UH, et al. Foot bone marrow edema after 10-week transition to minimalist running shoes. *Med Sci Sports Exerc*. Accepted for publication January 7,2013.

29. Weisenfeld MF, Burr B. *The Runners' Repair Manual : A Complete Program for Diagnosing and Treating Your Foot, Leg, and Back Problems.* New York: St. Martin's Press; 1980.

30. Bowerman WJ, Harris WE. *Jogging: A Physical Fitness Program for All Ages.* Grosset and Dunlap; 1967.

31. Wilt F. *How They Train: Long Distances.* Tafnews Press; 1959.

32. Richmond J, Hunter D, Irrgang J, et al. American Academy of Orthopaedic Surgeons clinical practice guideline on the treatment of osteoarthritis (OA) of the knee. *J Bone Joint Surg Am*. 2010;92(4):990-993.