The Foot and Ankle Online Journal
Official Publication of the International Foot & Ankle Foundation
faoj.org / ISSN 1941-6806

Form determines function: Forgotten application to the human foot?

by Mick Wilkinson, PhD[1*] and Lee Saxby, BSc[1]

The Foot and Ankle Online Journal 9 (2): 5

There has been and continues to be much debate about the merits and detriments of barefoot and minimal-shoe running. Research on causes of running-related injury is also characterised by equivocal findings. A factor common to both issues is the structure and function of the foot. Comparatively, this has received little attention. This perspective piece argues that foot function and in particular, how foot structure determines function, has largely been overlooked, despite basic principles of physics dictating both the link between structure and function and the importance of function for stability in locomotion. We recommend that foot shape and function be considered in the interpretation of existing findings and be incorporated into future investigations interested in running mechanics, injury mechanisms and the effects of footwear on both.

Key words: human foot, mechanics, barefoot, locomotion

As stated by evolutionary biologist EO Wilson, "everything in biology is subject to the laws of physics and chemistry and has arisen through evolution by natural selection" [1]. Applying this logic to the study of human locomotion, and in particular the structure and role of the foot, can bring clarity to the interpretation of many past and recent studies on barefoot-versus-shod-and minimal-shoe locomotion, and the associated benefits and risks. Using laws and undisputed theories as filters through which to interpret study outcomes can provide a context to equivocal findings and also suggest fruitful lines of future inquiry.

The 'purpose' of the foot

Assigning a purpose to a biological structure is often criticised as teleological. However, as Nobel Laureate Albert Szent-Gyorgyi [2] wrote "teleology resembles an attractive lady of doubtful repute whose company we cherish but in whose company we do not like to be seen". Purpose provides the context without which many observations in nature make no sense. A teleological view is therefore adopted in this piece.

In an upright biped, the purpose of the foot is to support and control the direction of the body weight as it falls forwards during the stance phase of locomotion [3-5]. With this and fundamental physics in mind, a reverse-engineering approach suggests a larger base of support, that is widest at the front, would serve both purposes.

1 - Sport, Exercise and Rehabilitation, Northumbria University, UK.
* Correspondence - Mic.wilkinson@northumbria.ac.uk

It is not surprising therefore, that comparisons of habitually-unshod with habitually-shod populations consistently show wider (particularly at the front) feet in unshod populations, in agreement with that predicted by fundamental principles [6-10]. Studies on habitually-barefoot populations also demonstrate the benefits of a wide base of support in the form of more uniform distribution of pressure through the entire plantar surface during walking [9], and reduced peak pressure and pressure-time integral under the forefoot in running [11].

Structure determines function

There has been recent attention on the role of intrinsic foot musculature [12] and how barefoot / minimal footwear use might influence their strength and function [13]. However, it must be remembered that these muscles simply respond to the forces acting on them [3,12]. In the foot, the magnitude and direction of these forces will be partly determined by the shape of the foot, and in particular by the position of the hallux [14,15]. It has been suggested that the thickness, length and position of the hallux represents evolutionary adaptation to terrestrial-bipedal locomotion [14,16-19]. The effect of foot shape on control of the path of body weight through the foot has long been established and is explained by simple physics [14]. This questions a research focus on the strength and /or training of intrinsic-foot musculature without consideration of foot shape, as it is unlikely that strength of muscles in a structurally-compromised foot could overcome gravity and the ground-reaction force as effectively as a structurally-sound foot.

A logical prediction from an engineering view of an ideal foot is that a wider foot would offer a more stable base over which to pass the body weight, and a larger surface area over which to distribute pressure. Here, the hallux is of special importance [15]. Morton [14] demonstrated that the hallux position, secondary to a correctly aligned first metatarsal, directed body weight in the sagittal plane through the axis of leverage between the first and second metatarsal heads. He also demonstrated that a valgus position of the hallux resulted in excessive pronation, as the hallux was not mechanically positioned to control and direct the path of the body weight in the sagittal plane. This resulted in transfer of motion into the transverse and frontal planes. Chou et al [15] reported impaired single-leg balance and directional control of weight shifting when hallux use was constrained by a purpose-made splint. A recent study also highlighted that separation of the hallux from the second toe characterised the feet of a habitually-unshod Indian population [10] and differentiated them from a habitually-shod- Chinese population. A relationship between Morton's toe and peak pressure under the first metatarsal head in walking has also been demonstrated, providing support for the assertion that static-foot structure is an important determinant of foot function, specifically, the ability to direct body weight in the sagittal plane in locomotion [20]. More recently, Mei et al [11] demonstrated the importance of an abducted-hallux position in habitually-barefoot participants while running, showing the hallux to share and therefore reduce forefoot loading, possibly due to a wider surface area of support .

Given the mechanical effects of static foot shape, it is worthy of consideration as a mechanism underlying overuse injury in tissues and joints further up the kinetic chain. If force is not appropriately directed in the sagittal plane at the foot, it follows from basic physics that compensations and additional muscular work will have to ensue to counteract unwanted transverse-and frontal-plane motion. The knee joint in particular might be at risk, given its small capacity for non-sagittal-plane movement. Given that walking and running are derived capabilities in humans, and that humans are adapted to perform both activities with minimal energy expenditure [21], it is logical to suggest that a sagittal-plane joint, such as the knee, is best supported with a wide foot that controls and directs the body weight, such that motion at the knee is in the plane for which the joint has evolved.

The effects of footwear on foot structure and function

The plasticity of foot structure was well known and exploited by the Chinese in the ancient cultural practice of footbinding [6,22]. The timescale of structural alterations appears to be rapid, particularly in the young, where bones have yet to fully ossify. Hoffman [6] observed hallux deformation in a habitually-barefoot teenager required to wear shoes for just six weeks. In an adult-case-study patient, Knowles [23] showed reversal of hallux valgus after two years wearing anatomically-shaped shoes (i.e. tip of shoe medial to the medial border of the hallux). Other observational research [7] reported a highly-significant relationship between years of shoe wear and hallux-valgus angle in shoe-wearing communities, with hallux-valgus angle increasing in a linear fashion with years of shoe wear. The observed adaptation of foot structure to shoe wear is in accord with Wolfe's law, as is the reversal of deformity observed by Knowles [23].

The effect of footwear on foot structure and function will largely depend on the nature of the footwear. The oldest record of footwear dates back some 10000 years [24] with the footwear being a type of sandal. Open sandals have been and continue to be commonly used by hunter-gatherer populations [25]. Such footwear is unlikely to interfere with foot function and shape, but rather simply offers some protection for the plantar surface. In contrast, the highly cushioned, narrow, stiff-soled and toe-sprung footwear characteristic of the modern-running shoe is likely to compromise foot structure and function. Indeed, altered gait patterns, increased maximum impact force, reduced arch deformation and toe flexion have been reported in children running in conventional-running shoes compared to barefoot [26, 27]. Moreover, a comparison of shod and barefoot populations suggested that habitual-western-footwear use leads to stiffer feet with impaired function [28]. There is a dearth of longitudinal studies examining the effects of long-term shoe wear on foot function. A controlled-longitudinal study of the effect of footwear on foot structure and function would be valuable, but is certainly not without methodological challenges. In the absence of such data, the 'if-you-don't-use-it-you-lose-it' principle would suggest that reduced use of the arch and toes would lead to impaired function over time.

The relationship between loss of function and change in foot shape would be of particular interest, but again, previous observational data and simple mechanical principles suggest such a relationship. From an evolutionary perspective, footwear makes sense, particularly given the range of environments in which humans thrive. However, the mechanics and evolution of the foot dictate that such footwear should be anatomically shaped to allow natural-hallux position and function, and also flat and flexible enough to allow unimpeded movement of the foot and toes during locomotion. Such characteristics have been previously recommended [22].

Summary and recommendations

Fundamental physical and mechanical laws and evolutionary biology provide a context to understand structure and function of the human foot, and how both might be compromised by inappropriate footwear. The characteristics that a foot ought to possess to perform load bearing, cushioning and stability roles are observed in the feet of habitually-barefoot populations. Likewise, deformed structure and impaired function have been observed with habitual shoe wear. Future studies on factors related to both performance and injury, and acute-and chronic biomechanical investigations of barefoot-versus-shod running, should attempt to examine data in light of measures of foot structure. Furthermore, care should be exercised in footwear choice, particularly in children, where the effects of conventional footwear on locomotive patterns and foot function have been demonstrated. Interpreting research in light of physical laws and from an evolutionary perspective, might add clarity to a field of investigation that is characterized by equivocal findings.

References

1. Wilson, E.O. Consilience: The unity of knowledge. New York: Vintage Books; 1998.
2. Szent-Gyorgyi, A. The Living State, with observations on cancer. New York: Academic Press; 1972.
3. Mann, R. and V.T. Inman, Phasic Activity of Intrinsic Muscles of the Foot. J Bone Joint Surg. 1964; 46: 469-481. [PubMed]
4. Reeser, L.A., R.L. Susman, and J.T. Stern, Electromyographic Studies of the Human Foot: Experimental Approaches to Hominid Evolution. Foot Ankle. 1983; 3: 391-407. [PubMed]
5. Rolian, C., et al., Walking, running and the evolution of short toes in humans. J Exp Biol. 2009; 212: 713-721. [Link]
6. Hoffman, P., Conclusions drawn for a comparative study of the feet of barefooted and shoe-wearing peoples. J Bone Joint Surg. 1905; 3: 105-136. [Link]
7. Shine, I.B., Incidence of hallux valgus in a partially shoe-wearing community. Br Med J. 1965; 1: 1648-1650. [PubMed]
8. Morioka, M., T. Miura, and K. Kimura, Morphological and functional changes of feet and toes of Japanese forestry workers. J Hum Ergol. 1974; 3: 87-94. [PubMed]
9. D'Aout, K., et al., The effects of habitual footwear use: foot shape and function in ntaive barefoot walkers. Footwear Sci. 2009; 1: 81-94. [Link]
10. Shu, Y., et al., Foot morphological difference between habitually shod and unshod runners. PLoS ONE. 2015; 10: e0131385. [Link]
11. Mei, Q., et al., A comparative biomechanical analysis of habitually unshod and shod runners based on foot morphological difference. Hum Mov Sci. 2015; 42: 38-53. [PubMed]
12. Kelly, L.A., et al., Intrinsic foot muscles have the capacity to control deformation of the longitudinal arch. J R Soc Interface. 2014; 11: 20131188. [Link]
13. Miller, E.E., et al., The effect of minimal shoes on arch structure and intrinsic muscle strength. J Sport Health Sci. 2014; 3: 74-85. [Link]
14. Morton, D.J. The Human Foot: its evolution, physiology and functional disorders. New York: Columbia University Press; 1935.
15. Chou, S., et al., The role of the great toe in balance performance. J Orthop Res. 2009; 27: 549-554. [PubMed]
16. Weidenreich, F., Evolution of the human foot. Am J Phys Anthropol. 1923; 6: 1-10. [Link]
17. Elftman, H. and J. Manter, Chimpanzee and human feet in bipedal walking. Am J Phys Anthropol. 1935; 20: 69-79. [Link]
18. Mann, R.A. and J.L. Hagy, Function of toes in walking, jogging and running. Clin Orthop Relat Res. 1979; 142: 24-29. [PubMed]
19. Hughes, J., P. Clark, and L. Klenerman, The importance of toes in walking. J Bone Joint Surg. 1990; 72: 245-251. [Link]
20. Cavanagh, P.R., et al., The relationship of static foot structure to dynamic foot function. J Biomech. 1997; 30: 243-250. [PubMed]
21. Bramble, D. and D. Lieberman, Endurance running and the evolution of Homo. Nature 2004; 432: 345-352. [PubMed]
22. Stewart, S.F., Footgear - Its history, uses and abuses. Clin Orthop Relat Res. 1972; 88: 119-130. [PubMed]
23. Knowles, F.W., Effects of shoes on foot form: An anatomical experiment. Med J Aust. 1953; 1: 579-581. [PubMed]
24. Pinhasi, R., et al., First direct evidence of chalcolithic footwear from near eastern highlands. PLoS ONE. 2010; 5: e10984. [Link]
25. Lieberman, D.E., Strike type variation among Tarahumara Indians in minimal sandals versus conventional running shoes. J Sport Health Sci. 2014; 3: 86-94. [Link]
26. Wegener, C., et al., Effects of children's shoes on gait: a systematic review and meta analysis. J Foot Ankle Surg. 2011; 4: 1-13. [PubMed]
27. Hollander, K., et al., Effects of footwear on treadmill running biomechanics in preadolescent children. Gait Posture. 2014; 40: 381-385. [PubMed]
28. Kadambande, S., et al., Comparative anthropometric analysis of shod and unshod feet. Foot. 2006; 16: 188-191. [Link]