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REVIEW ARTICLE

Conceptualizing minimalist footwear: an objective definition

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ABSTRACT
Running has been plagued with an alarmingly high incidence of injury, which has resulted in the exploration of interventions aimed at reducing the risk of running-related injury. One such intervention is the introduction of footwear that mimics barefoot running. These have been termed minimalist shoes. Minimalist footwear aims to reduce the risk of injury by promoting adaptations in running biomechanics that have been linked to a reduction in both impact and joint forces. However, some studies have found that minimalist footwear may be beneficial to the runner as they promote favourable biomechanical adaptations, whilst other studies have found the opposite to be true.
Reasons for these conflicting results could be attributed to the lack of a definition for minimalist footwear. The aim of this review article is to provide a structural definition for minimalist footwear based on studies that have examined the influence of footwear on biomechanical variables during running.
Based on current literature, we define minimalist footwear as a shoe with a highly flexible sole and upper that weighs 200g or less, has a heel stack height of 20mm or less and a heel-toe differential of 7mm or less.

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Footwear; injury & prevention; 3D analysis; running; biomechanics

Introduction

Running was once considered a sport for the elite in which only well-trained athletes took part. Since the running boom in the 1980's, the sport has seen a diversification of participants. No longer are runners lean and well-trained, but rather better represent the demographics and composition of the global population. This has ultimately lead to an alarmingly high incidence in running-related injury.

One method of mitigating the risk of injury is the modification of running footwear. When running increased in popularity, many believed that the high incidence of injury was due to the excessive impact forces experienced whilst running. This led to the introduction of thicker midsoles within running footwear, as it was believed that more cushioning would dampen these impact forces (Mcnair & Marshall, 1994). Interestingly, this did little to influence the incidence of running-related injury (Goss & Gross, 2012; Tam, Astephen Wilson, Noakes, & Tucker, 2014; Van Gent et al., 2007).

This lack of reduction in running injury incidence has drawn the attention of many researchers and minimalist running has been touted as a method for reducing such injuries. The premise of minimalist running is to utilize minimalist footwear that mimics the supposedly beneficial biomechanics associated with barefoot running (Bonacci, Vicenzino, Spratford, & Collins, 2014; Franz, Wierzbinski, & Kram, 2012; Lieberman et al., 2015), whilst still providing sufficient plantar protection (Rixe, Gallo, & Silvis, 2012).

Numerous studies have focused on determining whether minimalist shoes do in fact promote biomechanics similar to running barefoot (Hollander, Argubi-Wollesen, Reer, & Zech, 2015; McCallion, Donne, Fleming, & Blanksby, 2014; Sinclair, 2014; Squadrone, Rodano, Hamill, & Preatoni, 2014; Warne et al., 2014; Wit, Clercq, & Aerts, 2000). However, this topic is widely debated since the evidence is equivocal since very few definitions as to what structurally constitutes minimalist footwear exist. One working definition states that minimalist footwear "incorporates design aspects which aim to reduce mechanical and /or sensory interference between the shoe and the foot" (Rixe et al., 2012). This definition focuses on only one aspect of the functional outcomes of minimalist footwear, however, there is little agreement as to what structural specifications must be adhered to for a shoe to be considered as minimalist.

The lack of an objective definition stems from the inaccessibility of the variables stated by Esculier et al. (2015). For a definition to be applicable to the end user, it needs to include objective information on variables that are easily understood and attainable. Specifications such as mass, heel stack height and heel toe differential (Figure 1) are offered as background information of most shoes, whereas values for flexibility and materials used in the upper and toe box width are less common (Esculier, Dubois, Dionne, Leblond, & Roy, 2015).

Heel-toe differential (HTD) = HSH – FFSH

Shoe mass, heel stack height and heel toe differential may affect the biomechanics of running (Squadrone et al. (2014)). For example, Franz et al. (2012) found that shoes with less mass replicate the biomechanics of running barefoot since

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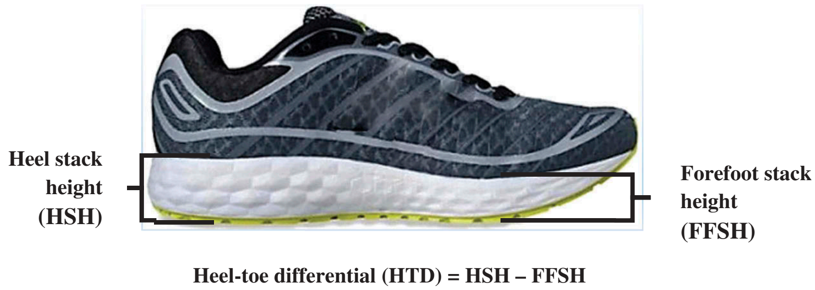

Figure 1. The structure of a typical running shoe and its important specifications.

increasing the mass at the distal end of the leg has a profound influence on running economy (Franz et al., 2012). Heel stack height (HSH) describes the amount of cushioning beneath the base of the heel of the runner, and may be associated with a reduction in impact force (Mcnair & Marshall, 1994). HSH is measured from the upper part of the innersole to the lower aspect of the outer sole of the shoe (depicted in Figure 1). Finally, heel-toe differential (HTD) is defined as the difference in stack height from the heel to the forefoot of the shoe (depicted in Figure 1), where a lower HTD has been found to replicate barefoot running (Horvais & Samozino, 2013).

In addition, it is generally considered that HSH and HTD are positively correlated to foot strike angle (FSA), whereby increasing these variables results in an increase in FSA (Horvais & Samozino, 2013). FSA refers to the angle that the sole of the foot makes with the ground at initial contact and is a determinant of the foot strike pattern, the point of contact of the foot with the ground. Foot strike pattern can be broadly categorised into a rear foot strike (RFS), midfoot strike (MFS) and forefoot strike (FFS) pattern. FSA is considered a strong indicator of global running biomechanics as it is influenced by changes in both knee and ankle kinematics. The use of an RFS pattern is associated with a high initial loading rate due to the presence of an impact transient (Lieberman et al., 2015) and higher knee extension moments (Kerrigan et al., 2009). Both of these biomechanical variables may be associated with greater risk of injury (Bonacci et al., 2014; Cavanagh & Lafortune, 1980; Crowell, Milner, Hamill, & Davis, 2010; Kerrigan et al., 2009; Milner, Ferber, Pollard, Hamill, & Davis, 2006; Zadpoor & Nikooyan, 2011; Zifchock, Davis, & Hamill, 2006).

Therefore, the aim of this article is to assess the current literature that has measured the effects of structural specifications in shoes, such as heel stack height, heel-toe differential and mass on FSA, and to determine the upper thresholds of these variables to define a minimalist shoe.

Heel stack height

Squadrone et al. (2014) attempted to determine the effect of minimalist shoes with different specifications on running biomechanics, and unsurprisingly found that shoes with a lower heel stack height were more successful at promoting running biomechanics that were representative of the barefoot condition (Squadrone et al., 2014). To the best of our knowledge, only one study has looked at the influence on midsole thickness (heel stack height) on running biomechanics, whilst controlling for other structural specifications (Chambon, Delattre, Guéguen, Berton, & Rao, 2014). This study found that the presence of a midsole is enough to cause significant differences between barefoot and shod conditions, possibly explaining why most runners adopt similar biomechanics when running in minimalist and traditionally cushioned shoes. In terms of a quantitative value for HSH, Sinclair (2014) found that a minimalist shoe with a relatively greater heel stack height of 26.0mm resembled the biomechanics of running in traditionally cushioned shoes rather than running barefoot, thus refuting the idea that all shoes that are labelled as minimalist actually mimic barefoot running biomechanics (Sinclair, 2014).

Heel-toe differential

Squadrone et al. (2014) also examined the effects of minimalist shoes running biomechanics with regards to heel-toe differential, finding that a lower HTD was more successful at promoting running biomechanics that were representative of the barefoot condition (Squadrone et al., 2014). In terms of quantitative values for HTD, both Squadrone and Gallozzi (2009) and Sinclair (2014) reported that running in a minimalist shoe with very little cushioning and a zero millimetre heel-toe differential results in similar kinetics and kinematics at foot strike when compared to running barefoot (Sinclair, 2014; Squadrone & Gallozzi, 2009).

Effects of structural specifications on FSA

Horvais and Samozino (2013) assessed the influence of HSH and HTD of FSA and found that both variables were positively correlated with FSA. Furthermore, when HSH and HTD were assessed independent of one another, the biggest discrepancy in FSA occurs with a heel stack height of 25mm and a heel-toe differential of 10mm (Figure 2). Finally, a change in heel-toe differential has little and inconsistent effects on FSA when the heel stack height is 25mm.

From Horvais and Samozino's work, certain quantitative conclusions can be drawn. Firstly, when controlling for heel stack height during running at 3.9 m/s, there is a pronounced increase in FSA when heel-toe differential is increased from 7mm to 10mm, whilst insignificant changes occur between 5mm and 7mm, as well as from 10mm to 15mm (Figure 2(a)). When assessing the influence of heel stack height independent of heel-toe differential, FSA increases linearly with heel

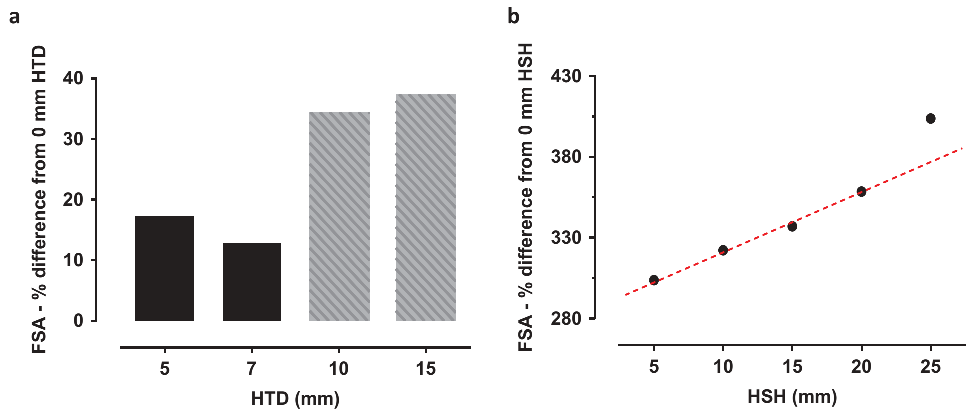

Figure 2. a) The percentage increase in foot strike angle (FSA) relative to the foot strike angle adopted in a shoe with a 0mm heel stack height (HSH) when independently assessing various heel-toe differential (HTD) values. b) The percentage increase in foot strike angle relative to the foot strike angle adopted in a shoe with a 0mm heel toe differential when independently assessing various heel stack height values. These graphs were independently constructed by using data from Horvais and Samozino (2013).

stack height from 5mm-20mm. However, there is a disproportionately large increase in FSA when heel stack height is 25mm (Figure 2(b)).

From this we can propose the upper thresholds of heel-toe differential and heel stack height by means of their influence on proximal kinematics. That is, the maximum heel-toe differential is 7mm, while the upper limit for heel stack height is 20mm. It must be noted that these limits are proposed with the best possible resolution provided by evidence to date, since the increments used in the research are large. It is possible that larger increments could change these limits slightly. Although these data represent the averages of 12 participants that ran in a total of 16 midsole geometry combinations, there are sufficient data points to take individual variation into account, whilst being able to assess each variable independently.

It is important to note the variability of footwear specifications found within studies that aim to assess the effect of minimalist shoes on running biomechanics. Table 1 depicts the variability of specifications found within shoes that have been studied and marketed as minimalist, as well as to the degree to which they were found to mimic barefoot running biomechanics (Bonacci et al., 2013; Hollander et al., 2015; Sinclair, 2014; Squadrone et al., 2014).

Mass of shoe

We compared these proposed maximum thresholds for HSH and HTD (20 and 7mm respectively), across previous studies that utilized various footwear described as minimalist. Additionally, we included an assessment of the shoe's effect on functional variables, such as FSA, patellar tendon force and sagittal ankle angle at contact (which have all been found to differ significantly between shod and barefoot running). We find that of all the shoes listed in Table 1, only five meet the proposed criteria relate to HSH and HTD. Interestingly, all five of these shoes promote biomechanics similar to that of barefoot running, and are different to shod running. However, this only takes HSH and HTD into account, and as previous definitions of minimalist footwear have suggested, the mass of the shoe is equally important. Of the five shoes that meet the proposed criteria, the Inov8 Bare-X 200 is the heaviest with a mass of 200g. This specification therefore represents the maximum value that when assessed in conjunction with HSH and HTS, adheres to the functional definition of a minimalist shoe i.e. to promote biomechanics similar to that of running barefoot.

Table 1. The variability in specifications for minimalist shoes used in current publications and their effectiveness in simulating barefoot running.

Author (year)	Shoe	Mass (g)	HSH (mm)	HTD (mm)	Variable considered	Similar to barefoot condition	Different from shod condition
Squadrone et al. (2014)	Saucony Kinvara 2	215	28.5	5.5	FSA	No	No
	Nike Free 3.0 V4	213	26.0	9.0	FSA	No	No
	Inov8 Bare-X 200[a]	200	8.0	0	FSA	Yes	Yes
	Newton Running MV2	171	22.0	0	FSA	No	No
	New Balance MR00GB[a]	165	13.0	1.0	FSA	Yes	Yes
	Vibram Fivefingersa	127	7.0	0.0	FSA	Yes	Yes
Sinclair (2014)	Vibram Fivefingersa	127	7.0	0.0	Patellar tendon force	Yes	Yes
	Inov8 Evoskina	135	3.0	0.0	Patellar tendon force	Yes	Yes
	Nike Free 3.0	213	26.0	9.0	Patellar tendon force	No	No
Bonacci et al. (2013)	Nike Free 3.0	196	26.0	9.0	Sagittal ankle angle at contact	No	No
	Nike LunaRacer2 (racing flat)	187	24.0	7.0	Sagittal ankle angle at contact	No	No
Hollander et al. (2015)	Nike Free 3.0	189	26.0	4.0	Sagittal ankle angle at contact	No	No
	Leguano	137	NA	0	Sagittal ankle angle at contact	No	Yes

a – indicates which shoes have a HSH of 20mm or less, as well as a HTD of 7mm or less.

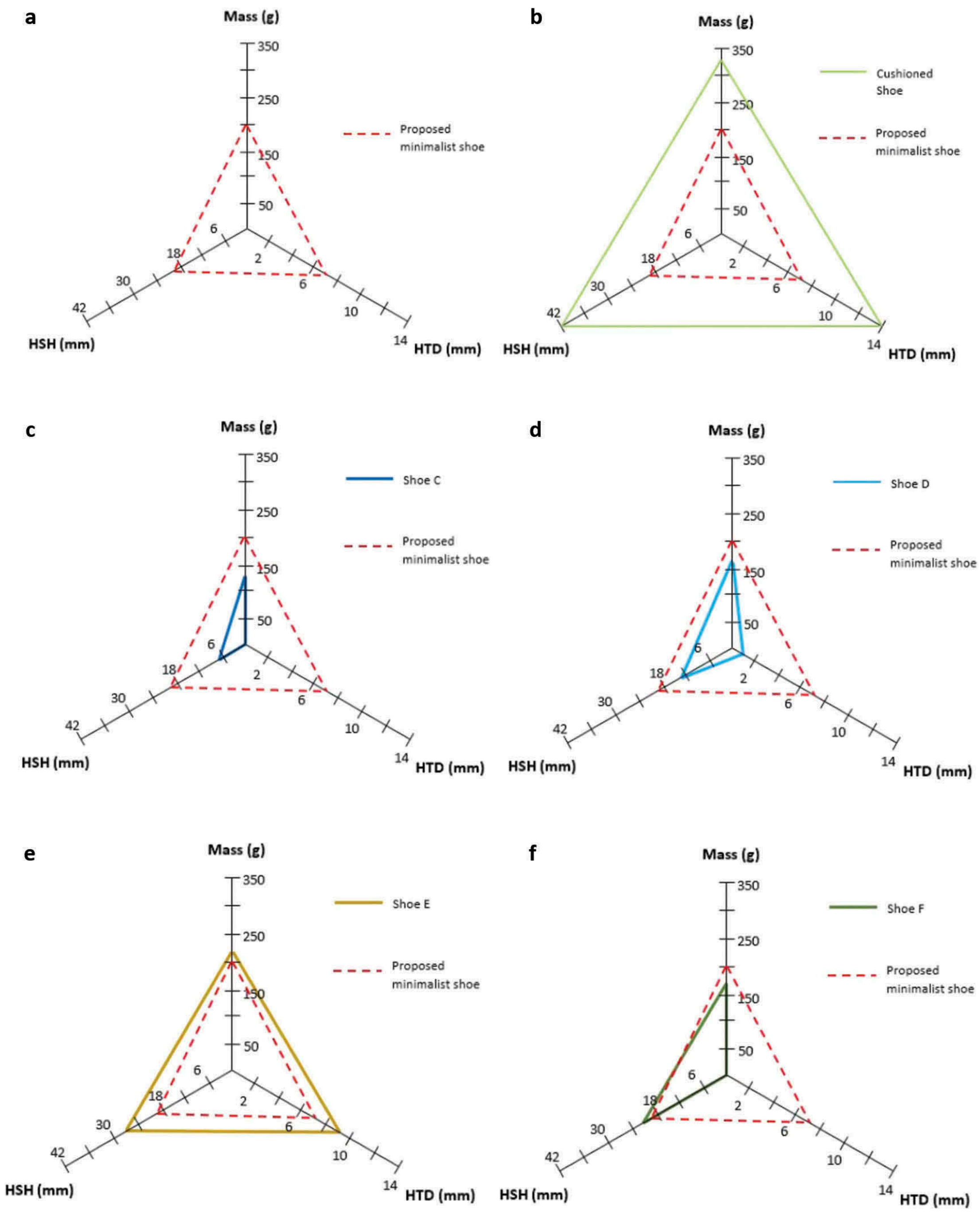

Figure 3. Comparison between shoes marketed and studied as minimalist [data used from Squadrone et al. (2014)]) and a proposed objective classification of minimalist shoes based on mass, heel-toe differential and heel stack height. a) The dashed line represents the proposed upper thresholds of mass, heel stack height and heel-toe differential of a minimalist shoe, with solid lines depicting the same variables in a range of five shoes. b) The proposed upper thresholds of a minimalist are compared to a traditionally cushioned shoe, and c-f) four minimalist shoes that are currently available in the market.
The figures represent the following shoes (represented as solid lines):B – Saucony ProGrid Glide; C – Vibram FiveFingers Seeya; D – New Balance MR00GB; E – Nike Free 3.0V4; F – Newton Running MV2

A new definition of minimalist footwear

As previously mentioned, the functional definition of a minimalist shoe is one that promotes kinematic similarities to that of running barefoot. According to this functional definition, by assessing previous literature we were able to determine the maximal specifications that constitute a minimalist shoe:

Mass: ≤ 200 grams

Heel stack height: ≤ 20 millimetres

Heel-toe differential: ≤ 7 millimetres

These values represent the upper thresholds for their respective specifications, and therefore only values equal to or lower than these proposed thresholds constitute minimalist footwear. Furthermore, a shoe must meet all three requirements to be considered as minimalist. Further, a minimalist shoe cannot possess any other device that is intended to control the motion of the shoe, such as a medical support, a stiff carbon fibre plate or any structure that alters the interaction of the shoe with the ground.

Reasons for excluding a measure of shoe flexibility and upper material construction stems purely from the difficulty in obtaining these specifications objectively, since this requires specialised equipment and construction information. Furthermore, it remains impractical since retailers rarely have objective information describing the flexibility of a shoe. Therefore, although flexibility is a highly important variable when defining a minimalist shoe, it remains impractical to the user, and future research may focus on assessing how flexibility influences biomechanics to add to the definition proposed here.

Below are comparisons between the shoes that were tested in the study conducted by Squadrone et al., and the upper thresholds for key specifications that we propose in our definition of a minimalist shoe. We have used a mass of 200g, heel stack height of 20mm and heel toe differential of 7mm for the purposes of this comparison. The figures below represent these key structural variables on a system of three axes, with other shoe variants presented for comparative purposes.

From Figure 3(b), we can see that the traditionally cushioned shoe does not meet any of the criteria for a structural minimalist shoe, whereas shoes C and D do, and therefore can be classified as minimalist shoes. Shoes E and F, although marketed as minimalist, fall outside of the proposed upper thresholds, and would therefore not be considered as minimalist shoes according to this proposed definition.

Final definition of a minimalist shoe: a shoe with a highly flexible sole and upper that weighs 200g or less, has a heel stack height of 20mm or less and a heel-toe differential of 7mm or less.

Clinical and scientific implications

Based on this definition, clinicians can advise their patients regarding to what constitutes a minimalist shoe.

Finally, future studies should look at the efficacy of minimalist shoes that promote kinematic adaptations in terms of reducing the risk of running-related injury, rather than drawing conclusions on minimalist footwear by grouping runners that adapt biomechanically, and those that do not.

Future studies should look at increasing the resolution of data as to provide a more accurate and scientifically validated set of upper thresholds for minimalist footwear specifications.

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Ethical Approval

Ethical approval for this study was granted by the Human Research Ethics Committee of the University of Cape Town guided by the principles of the Declaration of Helsinki (2013).

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