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Dynamic footwear fit model similar to NIOSH lifting equation

Ameersing Luximon*

Institute of Textiles and Clothing, The Hong Kong Polytechnic University, Hung Hom, Hong Kong

Abstract

Improper footwear design causes injuries and illnesses, and hence it is important to understand not only the foot but also the footwear. In order to reduce injuries and illnesses, the foot and footwear have to match in such a way to avoid high pressure points and friction due to movements. As far as footwear fit is concerned, literature review has indicated that static footwear fit has mostly been studied, even though dynamic pressure, friction, and foot movement beyond the normal range of motion will cause different type of injuries and illnesses when compared to static fit. Therefore, this paper proposes a theoretical model for dynamic fit. The dynamic footwear fit model is developed similar to the NIOSH lifting equation. The dynamic fit is related to static fit and several multipliers related to footwear design, material properties, and time factor. More research is being carried out to set the parameter values of the theoretical model. The importance of this model is useful for quantification of dynamic footwear fit as it is more related to the actual situation. Better footwear fit, both static and dynamic, will generally improve foot health.

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1. Introduction

The human foot, an unsymmetrical object, consists of complex arrangements of 26 bones and other tissues. There are considerable differences within person (right and left foot, weight-bearing, dynamic and thermal conditions) and between person (gender, age and race) [1].

* Corresponding author. Tel.: 852 2766 6449; fax: 852 2773 1432.

Thus feet have been classified according to racial differences, arch type, rear foot position, big toe length and foot print indices. In addition, research has indicated the importance of foot curvature (or flare angle) [1,2]. Factor analysis of anthropometric data has shown that the first 4 important parameters were length, height, flare and width [3] and these parameters should be considered in sizing. Anthropometric measures are essential, but they may not be sufficient for 3D footwear fit calculation. Given that 3D foot shape influence fit, emergence of 3D laser scanners and digital imaging technologies [4] is enabling the quick quantification of 3D foot shape. In addition, cheaper foot scanners using photographic method have being developed [5]. Lot of research has been done to process 3D foot data in terms of extraction of anthropometric measures from 3D shape, gender differences and static footwear fit mapping. Given the need for cheap 3D foot data, low cost foot scanning method using web cameras have even been developed [6,7,8]. One the static foot shape has been acquired there is a need to understand dynamic foot shape.

In dynamic situation (Fig. 1), the foot is undergoes deformation, hence the foot shape is not same as the static shape. Normally, the foot has $28\pm 6.9^\circ$ abduction and $28\pm 4.8^\circ$ adduction; $37\pm 4.5^\circ$ inversion and $21\pm 5.0^\circ$ eversion; and $13\pm 4.4^\circ$ dorsiflexion and $56\pm 6.1^\circ$ plantarflexion [9,10]. The normal foot range of motion is used for foot evaluation, and it is widely accepted that foot movement beyond the normal range causes foot injury, mainly ankle sprains [11,12]. Even though 3D laser scanning technology is widely used, capture of dynamic foot shape is still at its infancy [13, 14]. Improved dynamic foot scanners will improve the accuracy of dynamic foot modelling [15].

While much research has been done related to feet, research on footwear fit has been lacking. Recent studies include development of a measure for footwear fit in 2D [16] and subjective evaluation of fit and comfort [17]. Several guides have been proposed for footwear fit checking and evaluation [18]. In addition to foot and shoe-last research, several studies have been done related to footwear. A measure of 3D static footwear fit [19,20,21] has been proposed error computation between foot and shoe-last. This shoe-last [22] is not exactly same as inside shoe-shape. The static footwear fit model can be improved by converting shoe-last shape to inside shoe-shape, and then calculating error between foot and 'inside shoe shape' [23,24]. Since footwear fit is influenced by materials, research on footwear materials need to be carefully considered [25,26].

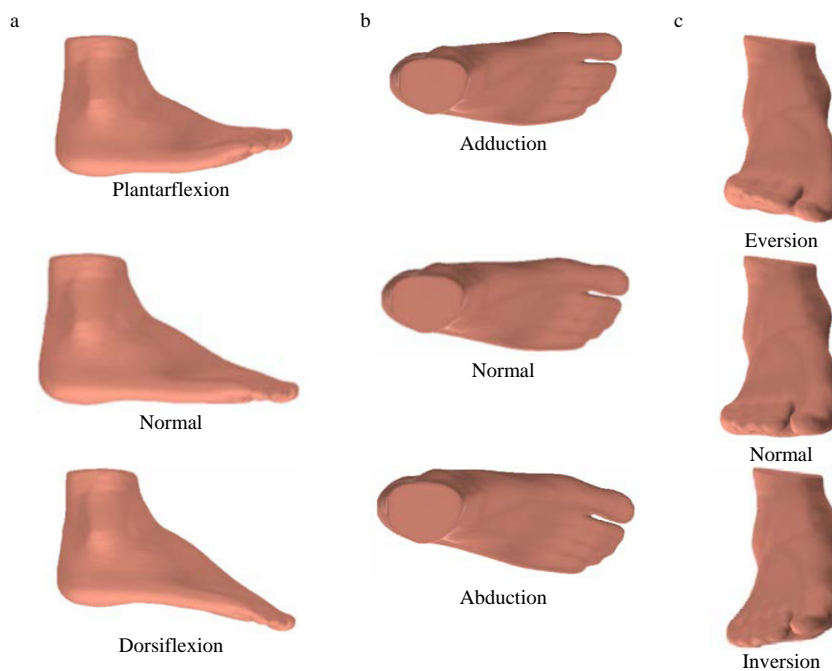


Fig. 1. Digital foot model for simulating foot motion (a) Plantar-flexion/ Dorsi-flexion; (b) Abduction/Adduction; (c) Eversion/ Inversion.

2. NIOSH lifting equation

The National institute for occupational safety and health (NIOSH) has recognized the problems related to work injuries, especially due to lifting. NIOSH has also understood the complexities of the lifting problem and the need to develop criteria for calculating lifting loads for different situation. Thus in 1991, they proposed a revised NIOSH lifting equation [27]. The recommended weight limit (RWL) for lifting is a recommended load that healthy workers can perform for up to 8 hrs. RWL is related to load constant (LC) of 23 Kg and several multipliers (Horizontal multiplier (HM), vertical multiplier (VM), distance multiplier (DM), asymmetric multiplier (AM), frequency multiplier (FM) and coupling multiplier(CM)). The multipliers range from 0 to 1. A value of 1 for the multiplier indicates good working posture and a value of 1 indicate improper posture, high frequency, or difficult working environments. Hence the maximum RWL limit is LC, when all multipliers are 1. If any multiplier moves toward 0, then the RWL reduces towards 0.

3. Dynamic fit equation

The dynamic fit equation is modeled similar to the NIOSH lifting equation. The dynamic fit (D_f) is related to a fit constant (S_{f0}) and several multipliers (Equ. 1). The fit constant (S_{f0}) is related to static fit. The multiplier M_h is related to heel height. The multiplier M_d is related to foot dynamics. The multiplier M_s is related to shoe style, design and construction. The multiplier M_o is related to outsole design and materials. The multiplier M_u is related to upper design and materials. The multiplier M_t is related to time factor.

$$D_f = S_f \times M_h \times M_d \times M_s \times M_o \times M_u \times M_t \quad (1)$$

S_{f0} Static fit based on 3D foot shape and inside shoe shape

M_h Multiplier for heel height

M_d Multiplier for foot dynamics

M_s Multiplier for Shoe style and design

M_o Multiplier for outsole material properties

M_u Multiplier for Shoe upper material properties

M_t Multiplier for time factor

3.1. Static fit (S_{f0})

Just like the load constant, the static fit provide a means to best scenario for the fit measure. The static fit is the measure of fit when wearing low heel footwear for short time. Low heels are generally a heel height of 1 inch (25.4 mm) or lower. Short time is related to time for fit testing, which are generally few minutes. For the sake of completeness short time can be time less than 5 minutes. Static fit can be measured subjectively or objectively. When measured subjectively, the perfect static fit will have a rating of 100 and completely no fit will have a rating of 0.

When measured objectively, static fit can be related to anthropometric measures. For example, the minimum length and width size internal among different sizing system is equal to 5mm. First the shoe length is adjusted to account for toe lengths. Usually for rounded toe, the shoe length is 10mm longer than the foot length. Thus, if the difference of foot length and adjusted shoe length is within ± 2.5 mm, and the difference of foot girth and shoe girth at the ball is within ± 2.5 mm, we can assume that the fit is perfect (i.e a rating of 100). When considering the 3D foot shape, the static fit is the dimensional difference between the foot and the inside shoe shape. Since the foot shape deforms slightly to fit inside the shoe and the deformation is non-uniform, experimental research [28] has been used to find the mean dimensional differences between foot and shoe-last. Results have shown that it is around 4mm for all the different regions of the foot while the subjective rating is near to "exact fitting" (not too loose and not too tight). For simplicity and compared to minimum size interval of 5mm, dimensional differences of ≤ 5 mm can be assumed as good static fit and given a rating of 100. Larger dimensional differences indicate tight fit or loose fit, and are not desired and will be given rating of less than 100.

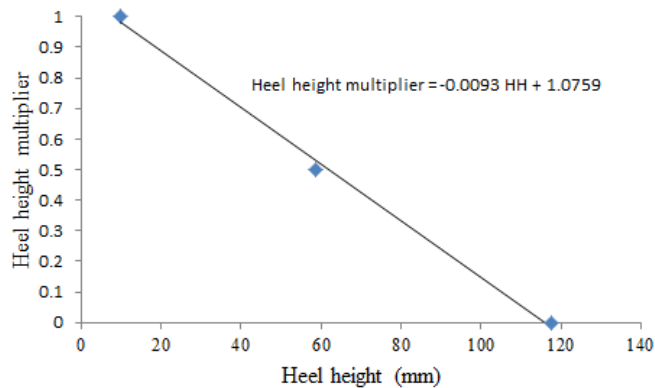


Fig. 2. Heel height multiplier.

3.2. Heel height multiplier (M_h)

When the shoe is at low heel and used for mainly walking, then the heel height multiplier is set to 1. When the heel height is increased the M_h is reduced. Since the limit of heel height (HH) is affected by the foot length (FL), the M_h is related to the ratio of the foot length divided by heel height (FL/HH). For a given standard shoe size of 36, which can accommodate a foot length of 235mm, if the heel height is 10mm, $FL/HH = 235/10 = 23.5$ mm. For simplicity, if $FL/HH > 20$ (which consider $HH = 11.75$ mm), then the $M_h = 1$. Mid heel heights are around 60mm, and the $FL/HH = 3.9$. For simplicity, if $FL/HH = 4$ ($HH=58.75$ mm), then the $M_h = 0.5$. High heel heights are around 120mm generally affect foot shape and causes foot illnesses and injuries. For $HH = 120$ mm, $FL/HH = 1.9$. For simplicity, if $FL/HH = 2$ ($HH=117.5$ mm), then the $M_h = 0$. The Heel height multiplier can be calculated based on the heel heights as shown in Fig. 2.

3.3. Dynamic multiplier (M_d)

The foot is rarely static, thus there is a need to consider dynamic situations. As discussed the foot range of motion outside the shoe are $28 \pm 6.9^\circ$ abduction and $28 \pm 4.8^\circ$ adduction; $37 \pm 4.5^\circ$ inversion and $21 \pm 5.0^\circ$ eversion; and $13 \pm 4.4^\circ$ dorsiflexion and $56 \pm 6.1^\circ$ plantarflexion. When the foot is subjected to movements beyond this range the foot will be injured. Thus for the dynamic multiplier, if the range of motion is similar to walking, then the dynamic multiplier is 1. When the range of motion is at a lower limit (For example, -2SD), then the dynamic multiplier can be set to 0.5. For example, abduction $\approx 14^\circ$; adduction $\approx 18^\circ$; inversion $\approx 28^\circ$; eversion $\approx 11^\circ$; dorsiflexion $\approx 4.2^\circ$ and plantarflexion $\approx 43.8^\circ$. When the range of motion is at the average limit, then the dynamic multiplier can be set to 0 (or low, since only 50% of people can achieve this level of range of motion). For example, abduction $> 28^\circ$; adduction $> 28^\circ$; inversion $= 37^\circ$; eversion = 21° ; dorsiflexion = 13° and plantarflexion 56° .

3.4. Shoe style and design multiplier (M_s)

The shoe style and design multiplier is related to the design and construction of the shoe. A shoe with good support without any undue pressure is preferred. Different shoe design and construction allows different level of support and movement to the foot. For example a boot reduces the movement at the ankle, while sandals does not support the foot leading to injuries. In addition, some shoe can have fastening mechanisms that are adjustable, while other such as the pump shoes does not have any adjustments. Shoe style and design multiplier is set to 1, for shoes that cover the foot completely below the ankle and does not any high pressure points. Shoe style and design multiplier is set to 0, for shoes that cover the foot barely (or above the knee) and have pressure points that affect normal foot function. The pressure points might be on blood vessels affecting blood flow or making the foot numb.

Shoe style and design multiplier is also set to 0, if the shoe overall design and construction will hurt the foot in any way.

3.5. Outsole multiplier (M_o)

The outsole multiplier is related to weight of outsole; material properties of the outsole; cushioning properties of the outsole; slip resistance of the outsole part that is touching the ground; the location of the flex line; and outsole construction. For reference, EVA outsole with rubber bottom will have a higher outsole multiplier value than PU outsole. The hard outsole of dress shoes will have lower outsole multiplier value when compared to sports shoes. Outsole that is heavy; slippery; lack cushioning; and flex at the center will have outsole multiplier value of 0. Outsoles that are light weight; non-slippery; have good cushioning; and the flex is at the ball joint will have outsole multiplier value near to 1. The outsole multiplier value will also be gradually reduced based on platform height. Normally platform height of 1 inch or lower (25.4mm) is acceptable. A platform height of 6 inch (150mm) is dangerous; hence the outsole multiplier is set to 0.5. A platform height of 10 inch (254mm) should be avoided; hence the outsole multiplier is set to 0.

3.6. Upper multiplier (M_u)

The upper multiplier is related to material properties of the upper and the socks. Breathable, flexible and lighter materials that provide adequate support will have an upper material multiplier value of 1. When the upper material is non-breathable, hard, inflexible, and incompatible to the skin (irritating to skin); then the upper multiplier is set to 0. The actual value of the upper multiplier can be calculated based on the properties of leather for upper and cotton sock. Synthetic uppers and socks will have lower upper multiplier values.

3.7. Time multiplier (M_t)

In the NIOSH lifting equation, the recommended weight limit (RWL) is for work for up to 8 hrs. Just for reference we use an 8 Hrs of work reference. During the 8hrs period the workers are supposed to have rest. If the shoe is worn continuously and in dynamic situation for greater than 8 hrs, then the time multiplier = 0. If the wearer has some rest and removes his shoes for some time, then the time multiplier is improved (> 0). If the shoe is worn continuously and in dynamic situation for 4 hrs, then the time multiplier = 0.5. Similarly, if the wearer takes rests and removes or adjusts his shoes then the multiplier value will be higher. If the shoe is worn for less than 1 hr, the time multiplier = 1. Of course the values of the time multiplier are suggestions and the values can be adjusted with more research.

4. Conclusion and discussion

Many researches have shown the importance of footwear fit to reduce injuries and illnesses. In spite of all the knowledge and extensive footwear research, the basic concept of footwear fit is still unclear. This paper proposed a theoretical model for dynamic fit similar to the NIOSH lifting equation. The proposed dynamic footwear fit model is related to static fit and several multipliers. The multipliers are related to footwear design, outsole material properties, upper material properties and foot dynamics (including heel height). The exact value and range of the multipliers have not been calculated in detail as more research is required to set accurate limits. The model is useful for quantification of dynamic footwear fit and will generally improve foot health. This research can also be extended to dynamic fit and comfort model by including a psychological factor and redefining the multipliers.

Acknowledgements

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