Why the optimal fitting of footwear is difficult

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ABSTRACT

Footwear has a long history and has evolved in to a necessary article whether it is fashion, safety or performance. However, fitting footwear is still an art and an ideal fit is predominantly by chance. Poor fitting affects the wearer's comfort and posture. The various attributes of a shoe contribute towards the comfort or discomfort of a shoe. For example, the heel inclination can change the wearer's spinal shape and body balance, affecting comfort. In this paper we describe the various parameters that affect a person's comfort and why an extra effort is necessary to achieve an optimum fit.

Keywords: high heeled shoe, posture, shoe design, COP, spinal shape, fit

1 INTRODUCTION

Drawings, more than 15,000 years old, found in Spanish caves have had people with wrapped furs and animal skins on their feet (Kurup et al., 2011). A recent discovery from a cave in Armenia has proved that customized shoes date back to around 5500 years (Pinhasi et al., 2010). Over the years, the utility of shoes have changed from protecting feet to more fashion. Long time ago, footwear were meant to protect feet from external hazards, but today footwear are claimed to encompass safety, style, and performance. As a result, fit has become one of the most important factors (Chiou et al., 1996, Luximon, and Goonetilleke, 2003, Kuklane, 2009, Lake, 2000, Dahmen, et al. 2001). Surveys have shown that the fit between the shoe and the foot is a prime consideration in the buying decision of a customer (Chong & Chan 1992). Hence achieving the right fit is quite important to the seller as well as the buyer. Fit can affect thermal comfort too. A person will be comfortable when the skin temperature of feet is around 33˚C at 60% relative humidity (Oakley, 1984). When the skin temperature of the feet drops to 25˚C, feet become cold and a further drop to

20˚C would make the person quite uncomfortable (Enander et al.,1979). Figure 1 shows the temperature distribution of a foot when wearing differing types of footwear with a room temperature around 23 ˚C. The images show that the closed shoe provides more insulation to retain the body heat while the open shoe has a thermal image profile similar to the barefoot condition. Thus, closed shoes have thermal benefits when the environmental temperatures are low.

2 TYPES OF FIT

In traditional mechanical engineering, mating parts have three types of fit depending on the application. F or example, a hub and shaft will have an interference fit (Norton, 2000); moving parts a loose fit and some others an in-between fit called a transition fit. It seems that the fit between feet and footwear can take any of these types of fit depending on the location. In other words, the differing parts of a foot may and should require a different category of fit depending on subjective preferences and the activity for which the wearer uses it. For example, a ski-boot may require an interference fit all around the foot so that there is minimal movement between the boot and the foot. A casual shoe, on the other hand, may require a loose fit as the shoe may be worn over a long period of time and the looseness can then accommodate the deformation and expansion of the foot over time. The subjective element can be due to the varying properties of the tissue, internal workings of the body primarily related to circulation, and the threshold of discomfort or pain to indicate the potential tissue damage. Many of the past studies have attempted to find the allowances in the different regions and have fallen short of mapping the entire foot. Instead, most researchers have focused on the critical areas of the foot where people have reported greater discomfort and at places where the mismatch could hinder performance. Even the ANSI/ASTM F539-78 (1986) standard concentrates predominantly on two areas when fitting footwear: the toes and the metatarsal region (ball joint).

Figure 1. Thermal images after wearing two types of footwear for one hour

3 SHOE FITTING

In a macro sense, footwear comprise an upper and a bottom. The shoe should have the right fit in the upper as well as the bottom. The upper part in most men's shoes has a fit-adjustment mechanism through the lacing and the stretch characteristics of the material. However, the amount of adjustment and the location of the adjustments are limited. In some shoes the material is reinforced or lined in certain areas to prevent the material from stretching. The bottom of a shoe is called a midsole/outsole combination or just an outsole depending on the type of shoe. The surface on which the foot contacts the shoe is called the footbed. The fit in the different regions within each of these units are very important and the type can range from a loose fit to an interference fit. In other words, different parts of the foot require a different type of fit depending on the structure of the foot and the purpose of the shoe. Witana et al (2004) showed that the foot and shoe should have an interference fit of 8 mm and 15 mm in the forefoot and midfoot regions respectively, for men's dress shoes. In a more recent study, Au et al. (2011) found the interference fit of ladies dress shoes to be 6.4, 12.1 and 10.7 mm for foot breadth, ball girth and waist girth. Tremaine and Awad (1998) proposed an interference fit of 6.35 mm for foot breadth. The numerous bones of varying size and shape require different types of fit and make fitting footwear to feet more difficult.

The footbed contacts the sole of the foot and is the only mechanism to transfer forces. The force distribution will depend on the fit between the foot and footbed. The optimal distribution for performance is not really known even though there are two schools of thought to localize the force in the bony region and distribute the load in the soft tissue region (Goonetilleke, 1998). The load distribution will determine the centre of pressure (COP), which in turn will dictate the stability, posture and the loads on joints and muscles to hold the body in a balanced state. The cause-effect relationships clearly show how fit can affect many variables such as balance, stability, posture and thereby comfort. Should the footbed have the same fit along the surface or should it differ in the differing areas to account for differences in stiffness and resilience of foot tissue? Many past studies have reported COP effects of high-heel shoes without much consideration of the fit at the footbed (Shimizu and Andrew, 1999, Snow, and Williams, 1994, Gefen et al., 2002, McBride, 1991, Han et al., 1999). We have shown (Weerasinghe, and Goonetilleke, 2011) the comfort in inversely proportional to the COP and modeled the relationship as: Comfort = 87.2 – 0.798*COP. So the ability to control the COP through appropriate load distribution can have a positive effect.

It is clear that the right-fit between the footbed and the foot sole is one of the most important issues to achieve the optimal load distribution. The structural integrity and human performance hinge on the proper fit between sole and footbed. Again, the many different regions make the issue complex. The human body can be considered to be in its ideal position when the foot touches the flat floor. Figure 2 shows the various parameters that govern the design of a high-heeled shoe. Most of our shoes have a heel height. Unless the heel is of the platform type, the hindfoot and forefoot will be at different heights. Hence the heel is generally sloping down followed by a curved surface to make a smooth transition to the lower part of the foot. The slope and the curved surface of the shank have their lengths constrained and cannot be more than about 72% of foot length (Xiong et al., 2009).

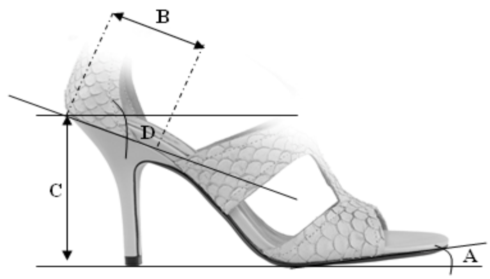
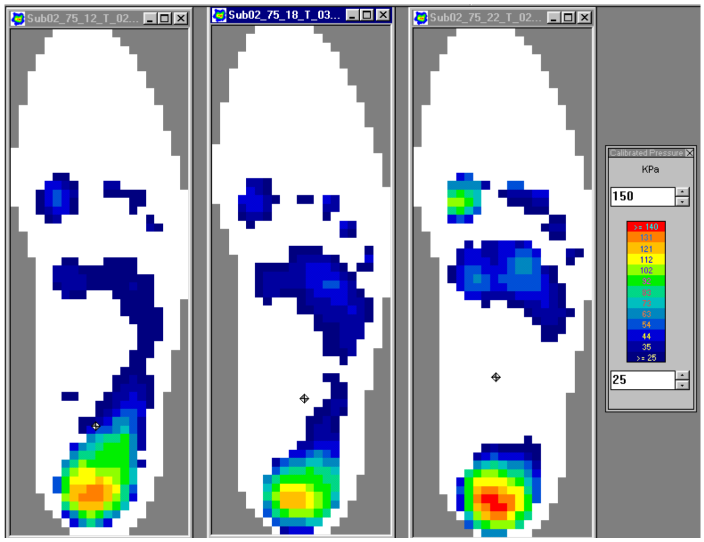


Figure 2. Design parameters of the footbed of a shoe. A= toe spring; B= seat length; C=heel height; D=wedge angle.

The structure of the foot can make these limitations possible. Around 25% of the bones in our body are in our feet. This gives our feet a high level of flexibility even though the flexibility or the range of motion is not the same in all parts of the foot. The forefoot is generally more flexible when compared with the hindfoot. Thus the curvature of the footbed should match the flexibility of the foot and this matching would determine the right fit between the sole and footbed.

A sub-optimal wedge angle and footbed curvature will tilt the body or make the foot slide forward causing discomfort because of looseness or tightness. Then, the foot is squeezed resulting in high-pressures that increase the tissue and joint deformations and hinder movement compromising the foot's performance. Such effects can result in temporary or permanent impairments some of which can be detrimental to the functioning of the feet. Common problems such as callouses and corns are due to undue pressure and relative movement between footbed and foot due to a poor fit of shape and a mismatch of material properties. Hallux valgus is a long-term effect of unwanted pressure in the MPJ area (SATRA, 1993). Figure 3 shows an example of the shift of COP with increasing wedge angle. It can also be seen that a right combination of wedge angle and shank shape can lower the pressures. The negative effects of the present day high-heeled shoes of an anterior shift of COP and an increase in plantar pressure have been shown by many (Gefen et al., 2001; Han, 1999; McBridge, 1991; Shimizu et al., 1999; Snow et al., 1994). The shift in COP results in a feeling of falling forward when wearing high-heeled shoes (Shimizu et al., 1999). Holtom (1995) has shown plantar foot pressure increments of 22%, 57%, and 76% with heel heights of 2 cm, 5 cm and 8.25 cm respectively. Contrary to all such studies, we have shown that COP can be shifted close to a barefoot stance when alterations to footbed geometry are made thereby affecting the fit between foot and footbed (Weerasinghe, and Goonetilleke, 2011).



(a) 12 deg (b) 18 deg (c) 22 deg

Figure 3. Effect of wedge angle and shank shape on pressure distribution and COP. (a) 12 deg (b) 18 deg (c) 22 deg

Body tilting and awkward postures as a result of a poorly fitting footbed can propagate up to the spine and beyond since people respond biomechanically like an inverted pendulum. A common belief is that high-heels make the body tilt so that the buttocks and breasts are emphasized (Danesi, 1999). However, some researchers have found opposite effects (Hansen and Childress, 2004). For example, Franklin et al. (1995) used a wooden board 5.1 cm high under the heels to study the standing posture and found that lumbar lordosis actually decreases as a result of a posterior tilt of the pelvis. Decreased lumbar lordosis is one of the common observations in the high heeled shoe wearers (Opila et al., 1987, Franklin et al., 1995, Lee et al., 2001). The inconsistencies among high-heeled posture related studies are possibly due to the use of heel blocks or shoes of a certain height with no control on fit, which is affected by the footbed parameters such as surface geometry (Franklin et al., 1995; Lee et al., 2001).

The footbed fit can affect the spinal shape as well. Figure 4 shows spinal shape data captured using a motion analysis system. The lower comfort ratings are those that are away from the neutral posture. In this case, the neutral posture is when the subject is standing on the ground barefooted. The importance of the footbed fit to minimize injury and increase comfort ought to be clear.

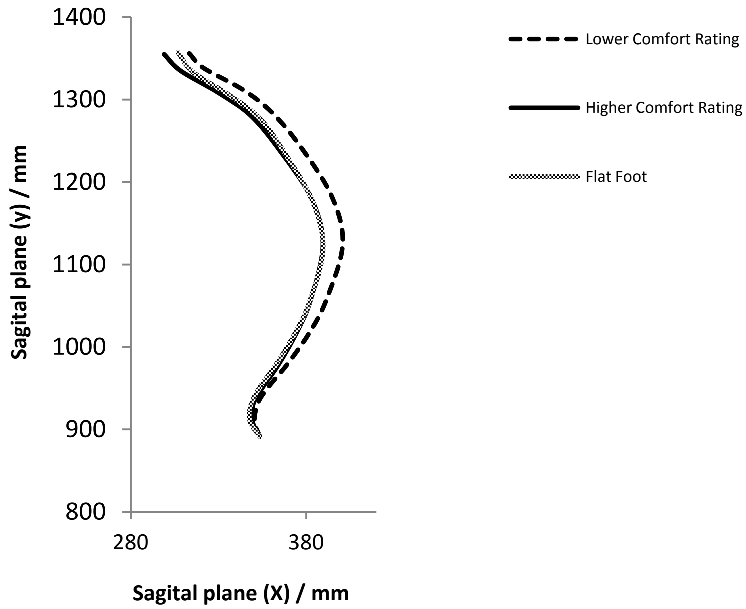


Figure 4. Spinal shape at different comfort rating AT 75mm heel height

4 CONCLUSION

Fit is no doubt an important element in mating parts. With rigid components the tolerances can be defined quite easily. With human tissue, the specification is more complex due to irregular shapes and differing tissue properties. A poor fit between feet and footwear can result in discomfort and injury in the long-term. Even though an optimal fit may be difficult to achieve, the added cost will be a fraction of the value associated with such a condition.

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