The Quality of Footwear Fit: What we know, don't know and should know

Ravindra S. Goonetilleke[+], Ameersing Luximon, and Kwok L. Tsui
Department of Industrial Engineering and Engineering Management
Hong Kong University of Science and Technology
Clear Water Bay, Hong Kong
[+]Email: ravindra @ust.hk

Even though fit ranks as one of the most important considerations in the purchase of a shoe, the quality of fit has no metric and is hence poorly assessed. Manufacturers, retailers, and customers tend to use trial and error techniques to improve footwear fit. This approach is rather cumbersome and very unscientific. In this paper, we present a methodology to assess and thereby quantify footwear fit so that comfort can be predicted and consequently improved lasts and shoes can be produced that match different shapes of feet.

INTRODUCTION

The Japanese Industrial Standard JIS Z 8101-1981 defines quality as the totality of the characteristics and performance that can be used to determine whether or not a product or service fulfills its intended application. Product quality is generally evaluated on the basis of whether or not the product carries out its intended functions and the extent to which a product meets the requirements of the user. Monitoring and correcting whether the product meets its intended functions are aspects that have been extensively discussed in the quality literature. However, the same is not true in the "buying process modification" when a product does not meet the user's perceived requirements. This is especially the case when human body parts need to match with the product components or characteristics. The primary problem in all such cases is the lack of an evaluation metric(s).

Product performance can be broadly evaluated based on its *function* (that is the product works as designed), *form* (appealing to the eye), and *fit* ("matches" the purpose). In many cases, fit can govern function and is hence an important property. In traditional mechanical engineering applications, there are different types of fit depending on function. For example, a bearing requires an interference fit on a shaft. In this case, the difference between the shaft diameter and the internal diameter of the bearing has to be within a given tolerance in order to produce the required interference fit. In applications involving people, on the other hand, fit is generally not well defined. A good example is shoe fit. Clinical reports of foot problems such as blistering, chafing, black toes, bunions, pain, and tired feet are evidence of poor fitting shoes. Footwear fit has been understood to mean the preference for a shoe to accommodate an individual's foot. As Kolarik (1995, pp. 41) states, "... a customer may demand shoes that fit right (a "true" quality characteristic). The customer will judge his or her shoe fit by wearing the shoes ...".

THE RIGHT FIT

When the foot-shoe "tightness" exceeds a certain threshold, discomfort or pain results. The discomfort hypothesis that was proposed by Goonetilleke (1998) could be used to delineate the phase change between comfort and discomfort if the threshold for the complete surface of the foot is known. In other words, quantification of fit will allow for the prediction of discomfort and pain. Such quantifications can save time and money in reducing the lengthy fit testing that is normally performed when prototype shoes are made.

If the shoe is "loose" on the foot, it is generally not as uncomfortable (even though function may be impaired) as when it is tight. In either case, the acceptable looseness/tightness is subjective and rarely quantified. Worst of all, the customer cannot predict the "fit-drift" and the bearability or even acceptability of the shoe-foot fit in the long term.

Ergonomists have been striving to achieve the right fit between people and the tools or equipment they use, but this so called "right fit" or compatibility is generally unknown in many circumstances (Karwowski and Jamaldin, 1996). Footwear manufacturers have not designed or developed a true quality characteristic to evaluate the fit between a person's foot and the footwear he or she wears. As Kolarik (1995) pointed out, the customer evaluates the quality of fit by *wearing* the shoe. The perceived fit depends on many factors. Some of which are time of day, activity performed, a person's health status, and so forth. As a result, footwear purchased at some time on some day may not fit as well on a different day or throughout the complete day. The size variations of feet are always an excuse to avoid quantifying the fit between shoes and feet. However, from a quality control point of view, it is always more informative to use a quantitative measure to evaluate the fit of footwear, even when foot size variations are present. In terms of statistical process control (SPC), the foot size variation can be considered as a common cause variation and the shoe size misfit can be considered as a special cause variation. Similar to SPC problems, it may be possible to use control chart methods to quantify the foot size variation, to identify the shoe size misfit, and to track the shoe deformation. It will be interesting to modify the current SPC methods to develop appropriate tools for monitoring foot size and shoe size variations to improve the quality of footwear fit.

The stated fit-problem is exacerbated when selecting children's shoes. An adult, who may press on the toe area to get an indication of the available toe space, evaluates the fit of a child's shoe. How acceptable is such a fit? Is length the only critical measure for footwear fit? Most fit problems are generally around the "width" dimension since the commonly used shoe sizing system is predominantly in the length dimension. How much do we know about this "width" dimension? Pain or discomfort in the ball area of the foot (metatarsophalangeal joint area) is almost always associated with a narrow shoe. At the same time, people find good-fitting shoes that are sleek and narrow. How could this happen? The objective of this paper is to explain such misconceptions related to footwear fit and how they can be overcome using a quantitative measure of fit.

What we know

Even though no one may really care, our shoes generally wear on the outside part of the heel whereas the slippers we use show wear on the inside part (medial) of the heel. If the wear is to be uniform in the heel area, then one alternative is to make the outside part of the heel of a shoe and the inside part of the heel of a slipper with a material having good wear properties. Footwear manufacturers adopt this "doctor" approach of "treating the symptoms" without caring about the underlying cause of such symptoms. The reasons for the difference in wear can be explained using the concept of flare and the concept of "holding" or "clamping". This concept of "holding" is critical in the development of the fit metric.

Another important fact is that we need to break-in new shoes for quite some time before they can be worn without any discomfort. In engineering applications, the break-in period is meant to take care of "surface imperfections" and to minimize seizure as a result of close-fitting parts. With new shoes, the break-in period is intended to deform the upper material to fit the shape of the foot. During the break-in period, we expect the shoe to "mold" to the shape of the foot. Any material resistance to this change results in discomfort or pain. If the material is soft and flexible, the shoe will lose its shape and if the material is reinforced and rigid, discomfort will result if the foot-shoe fit is not proper. Either one of the two options is not suitable. What is the cause(s) for such a misfit even when a shoe has been sized to the correct length?

A shoe (and the last or shoe mold) is characterized by its longitudinal "curvature" as being "straight" or curved (Cavanagh, 1980; Cheskin, 1987). On some shoe (and last) bottoms, the longitudinal centerline is relatively straight, making it sometimes difficult to distinguish the left and right sides (Figure 1). On others, known as *curved*, *racing* or *inflared* lasts, there exists a distinct inward turn towards the medial side of the foot (Figure 1). The term curved last is a misnomer since in reality it is a piecewise linear centerline (Goonetilleke and Luximon, in press). The amount of turn is characterized using a measure called *flare*. Today, identical left and right shoes are rarely seen even though they were common in the 19th century. Most shoes have a 6-degree (Holscher and Hu, 1976) or 7 degree (Cheskin, 1987) flare angle. The origin of the curved last (or shoe) was based on the writings of Meyer (1860) who suggested that the straight lasted shoe did not fit the curved foot and was a major cause of foot problems. Have human feet remained the same over the last century or more even though Cheskin (1987) also *claimed*, without any formal proof, that most feet have a slight inward curve? Even so, many researchers have argued the necessity for straight lasts (Holscher and Hu, 1976; Rossi, 1988). Hence, we need to question whether shoe manufacturers have taken Meyer's concept to the extreme, thereby exacerbating foot problems due to a mismatched flare. The popularity of inflared lasts may be due to the fact that the foot actually has a significant flare, or it may reflect an aesthetic consideration in favor of a longer first toe such that each shoe has a built-in medio-lateral symmetry rather than a longer medial side.

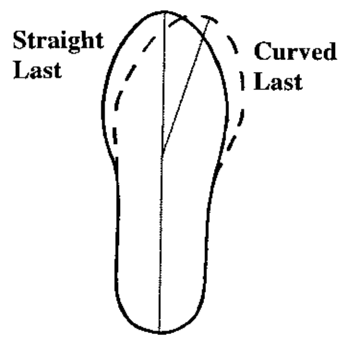
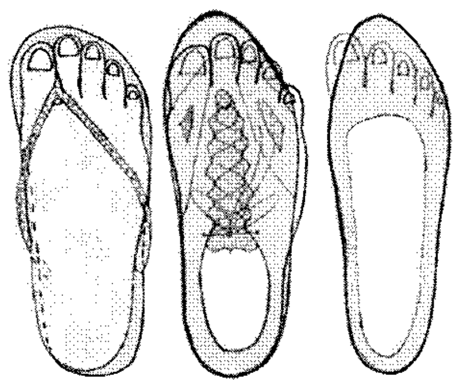


Figure 1. Straight and Curve lasts

In ergonomics, "neutral posture" is claimed to be essential to minimize overuse injuries (Putz-Anderson, 1988). An excessive flare or an insufficient flare in footwear will result in deviations from neutral postures. Thus, the neutral alignment that the foot seeks may be altered by an incongruous shoe resulting in the impairment of stability, strength and potential injury. It is interesting to note that fitting footwear (ANSI/ASTM F539-78, 1986) concentrates predominantly on two areas: the toes and the metatarsal region (ball joint). The foot measuring devices such as the Brannock, Ritz stick, and Scholl have also concentrated on these two areas by measuring the length along the foot and the maximum width at around the metatarsophalangeal joint area. It is therefore not surprising that different models of shoes fit differently because of the inflare built into them.

The only reference to flare can be found in the British Standard (BS) 5943 (1980) in relation to orthopedic footwear. The British Standard emphasizes the need for forefoot alignment. However, that description is somewhat inadequate. It indicates that the foot alignment needs to be checked in the plan view by making sure that there is no centrally directed pressure on the first toe (big) and the smallest (5th) toe. In other words this standard is a recommendation to check the flare matches between shoes and feet.



(a) (b) (c)

Figure 2. (a) Foot positioning when wearing a slipper (b) Misfit on lateral side of foot (c) misfit on medial side of foot.

Mismatched flare between the shoes we wear and our feet is a primary factor for discomfort in the ball area and in the formation of bunions. Figure 2b and 2c show examples of medial and lateral deformation of the forefoot to fit into a shoe with mismatched flare. The way our feet are "held" will determine how the foot functions and articulates to "sit" inside the shoe. When wearing a slipper (Figure 2a), the strap will dictate the position of the foot. Due to the arch, the foot will move medially to "lock" on to the strap. This results in the foot "sitting" more towards the medial side and hence wear on the inside of the slipper is to be expected. With a shoe, the reverse happens. The feet are not as free to move with a shoe due to the extensive covering on the foot. With shoes, the feet are "clamped" in the heel area due to the stiff material in the heel counter (heel-cup). Hence the shoe or foot can deform only in the forefoot region as a result of the greater flexibility in the forefoot region. Thus, mismatched flare will always result in discomfort in the metatarsophalangeal joint region unless the shoe is much wider than the foot. Mismatched flare results in sizing problems too.

A last is measured by the so-called "stick length" (shoe size), which is the distance between the two extreme points (corresponding to the posterior point of the heel and the anterior point of the longest toe). Shoe curvature or flare will affect the stick length (Figure 1). A greater curvature gives a shorter stick length (or shoe size), the primary criterion for matching feet to shoes. Foot length is measured as the maximum distance from the heel point to the toes and is generally measured along the axis of the Brannock size measurement device. If the shoe curvature does not perfectly fit the foot, the forefoot will have to deform (temporarily in the short-term, but permanently if the same flare shoe is worn for a long time) to adapt to the shape of the shoe. This deformation results in a mismatch between the shoe size (or stick length) and the foot length measured along the Brannock axis. Size differences among different manufacturers and different models of shoes are predominantly a result of the last curvature.

What we should know

A study was performed to evaluate the differences between the so-called good fitting shoes and poor fitting shoes. Subjective evaluations pointed to problems as a result of mismatches in the 2-dimensional foot outline and the shoe outline. A mismatched height dimension, generally, creates fewer complaints due to the stretch properties of the uppers and the availability of lacing to adjust the tightness in the "height" dimension. We found that the 2-D outlines can indeed reveal most of the footwear fit problems that people encounter.

By aligning the foot outline and the shoe outline in the heel area, we can quantify the fit mismatch (Figure 3). If the foot is within the boundaries of the shoe, the shoe can be said to be "loose" in the area. Tightness results when the foot outline is outside the shoe boundary. The differences between the shoe outline and the foot outline were quantified using the dimensional difference ("error") as shown in Figure 4. Error was measured as the normal distance from any point on the foot to the shoe outline. We defined tightness as a negative-error and looseness as a positive-error. The variation in error for a good fitting shoe and poorly fitting shoe is shown in Figure 4. The effects of flare are very clear from Figure 4. When the shoe heel region is aligned with the heel, mismatches in the shape between the shoe and the foot requires the shoe or foot to deform. If the shoe does not match the foot, the foot will articulate in the forefoot area in order to "sit" inside the shoe. Mismatched flare will always result in an excess level of error in the metatarsal region as shown in Figure 4. The example shown in Figure 4 can explain why narrow shoes can result in a better fit. When the flare of the shoe matches that of the foot, positive and negative errors are both reduced and hence a narrow shoe with the right flare will fit better than a wider shoe with the incorrect amount of flare. The curves shown in Figure 4 can even be adjusted to account for variations in fit when using socks of different thicknesses. The shape of the "error" curve and the descriptive statistics of the error measure can be used to quantify the quality of the fit.

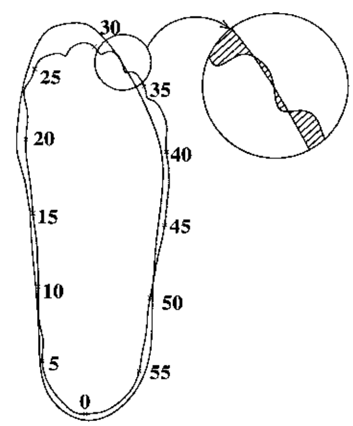


Figure 3. An unconstrained foot and its relative position inside a shoe. The numbers correspond to the length (in cm) along the perimeter.

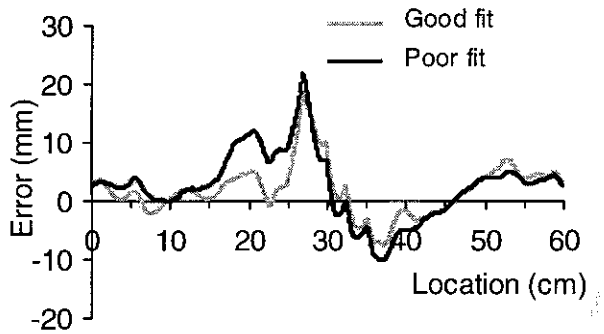


Figure 4. Dimensional difference (Error) between foot and shoe against foot location as marked in Figure 3. Errors are calculated with respect to the unconstrained foot when wearing socks.

What we don't know

Even though the mechanisms causing discomfort are known (Goonetilleke, 1998), the variations in the level of discomfort with varying pressure are still not quantified completely. The availability of this information and the quality of the fit measure proposed in this paper can lead to significant improvements in the prediction of footwear fit.

CONCLUSIONS

Kolarik (1995) stated "The customer will judge his or her shoe fit by wearing the shoes, but at the factory we must use "substitute " characteristic like length, width, and so on, to design, develop and produce our product". The use of the "error" metric can not only improve fit but will allow footwear manufacturers to design lasts that match a given population. Some of our current work also involve determining the minimum number of points to model the shape of feet and the development of parameters to quantify the shape of different feet so that the mapping from feet to shoes is straightforward.

ACKNOWLEDGMENTS

The work described in this paper was fully supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. HKUST 798/96E). A special thanks to Dr. Virginia Unkefer for reviewing the manuscript.

References

ANSI/ASTM F539-78 (1986). Standard practice for fitting athletic footwear, 229-235.

British Standard (1980). Methods for measurement and recording for orthopaedic footwear. BS 5943, 1980.

Cavanagh, P. R. (1980). The running shoe book. Mountain View, CA: Anderson World.

Cheskin, M. P. (1987). The Complete Handbook of Athletic Footwear. New York: Fairchild Publications.

Goonetilleke, R. S. (1998). Designing to Minimize Discomfort. Ergonomics in Design, 6(3), pp. 12-19.

Goonetilleke, R. S. and Luximon, A. (in press). Foot flare and Foot axis. Human Factors.

Holscher E. C. and Hu K. K. (1976). Detrimental Results with the common Inflared Shoe. Orthopedic Clinics of North America, 7, 1011-1018.

Karwowski, W. and Jamaldin, B. (1996). Methodological framework for quantifying compatibility of complex ergonomic systems. In Proceedings of the 4th Pan-Pacific Conference on Occupational Ergonomics (pp. 676-679). Taipei, Taiwan: Ergonomics Society of Taiwan.

Kolarik, W. J. (1995). Creating Quality. New York: McGraw-Hill.

Meyer, H. (1860). Why the Shoe Pinches. Quoted from Cavanagh, P. R. (1980). The running shoe book. Mountain View, CA: Anderson World.

Putz-Anderson, V. (1988). Cumulative Trauma Disorders. NY: Taylor and Francis.

Rossi, W. A. (1988). The futile search for the perfect shoe fit. Journal of Testing and Evaluation, 16, 393-403.