Designing footwear: back to basics in an effort to design for people

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Abstract
Even though footwear sales are increasing every year, the performance characteristics of shoes are not showing a proportional change. Product performance can be broadly evaluated based on its function, form, and fit (F^3). Even though it is well known that fit or product compatibility is necessary for a person to experience comfort, safety and satisfaction during use, form has dominated the design and development of footwear over the last few decades. Recent studies, using basic physical variables, have shown how perceived characteristics of fit, cushioning and so on can be quantified using objective measures so that elaborate performance models can be developed for the foot-footwear system.

Keywords Footwear, feet, custom design, fit

1. Introduction

In recent years, footwear sales have shown significant growth. For example, American consumers' spending on athletic footwear rose 3.6% in 2000 to $15.07 billion after two years of declining spending. In the year 2000, Americans purchased 405.4 million pairs of shoes at an average price per pair of US$37.17 (Sporting Goods Manufacturers Association, 2003).

In addition to quantity, the variation of footwear available in the market today is increasing exponentially in order to cater to varied perceptions of fashion and style. Manufacturers attempt to design and develop footwear so that they provide a covering for the foot while exhibiting fashion or style. Reebok claims, "Performance products are also designed to reflect a sense of fashion and style" (Reebok, 2003, page 3). This is a result of the approach that footwear manufacturers have taken over the last decade. In the 1990s, shoe companies became fashion and marketing giants. For example, in 1996, Nike is estimated to have spent $643 million marketing its shoes, compared with $42 million spent by the then number-five footwear manufacturer, Converse (Vanderbilt, 1998). The endorsement contracts of Nike amounts to USD 274.2 million for the year ending May 31 2003 (Nike 2003) while that of Reebok is USD 51.7 million for the year 2003. With the differing marketing promotions, athlete endorsements, and sponsorships, the price of footwear tends to have very high variations. Brand name fashion shoes can cost as much as USD 500 while generic brands can be as low as USD 5-10. The difference in price can also be attributed to the many different facets of product design and development. These include materials used, production processes, quality control standards and so on (see Figure 1).

Product performance on the other hand, can be broadly evaluated based on its function, form, and fit. It is well known that fit or product compatibility is necessary for a person to experience comfort, safety and satisfaction during use. However, compatibility is not so well known for all types of interaction between people and equipment. Form has been the dominating factor in the sale of footwear over the last few decades. Even though technology enhancements are thought to improve the functioning of footwear, some of them are simply ornaments to enhance form rather than functional elements that protect people's feet. Given the tremendous flexibility of the foot, it is important that the foot be accommodated in a way that allows a foot to function as "designed". Ergonomics dictates good posture and many other specialized areas such as quality control, perception, and biomechanics can be reasonably well integrated into the design and development of footwear.

2. Fit and sizing

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 as well defined. Clinical reports of foot problems such as blistering, chafing, black toes, bunions, pain, and tired feet are quite good evidence of poor fitting shoes. The need for a quality characteristic to evaluate the fit between a person's foot and the footwear he or she wears is of utmost importance for the scientific development of lasts and for improvement of footwear fit. Most shoe manufacturers still depend on artistic *lasts* for shoes even though many of the designer shoe manufacturers have now realized that comfort is an important criterion for survival in this vastly improving trade. A shoe *last*, which is a 3D mold representing the shape of the foot, gives the shoe its shape (Cavanagh, 1980). This master *last* is usually built to a men's size 9D or woman's size 7D for the American population (Cavanagh, 1980). The different shoe sizes are then generated from the master *last* using a procedure known as grading (Mann and Zacharias, 1952; Clarks, 1989). In order to keep shoe sizing simple, foot length and foot width are generally used (Cheskin, 1987), even though the size makings are rarely exact (SATRA, 1993).

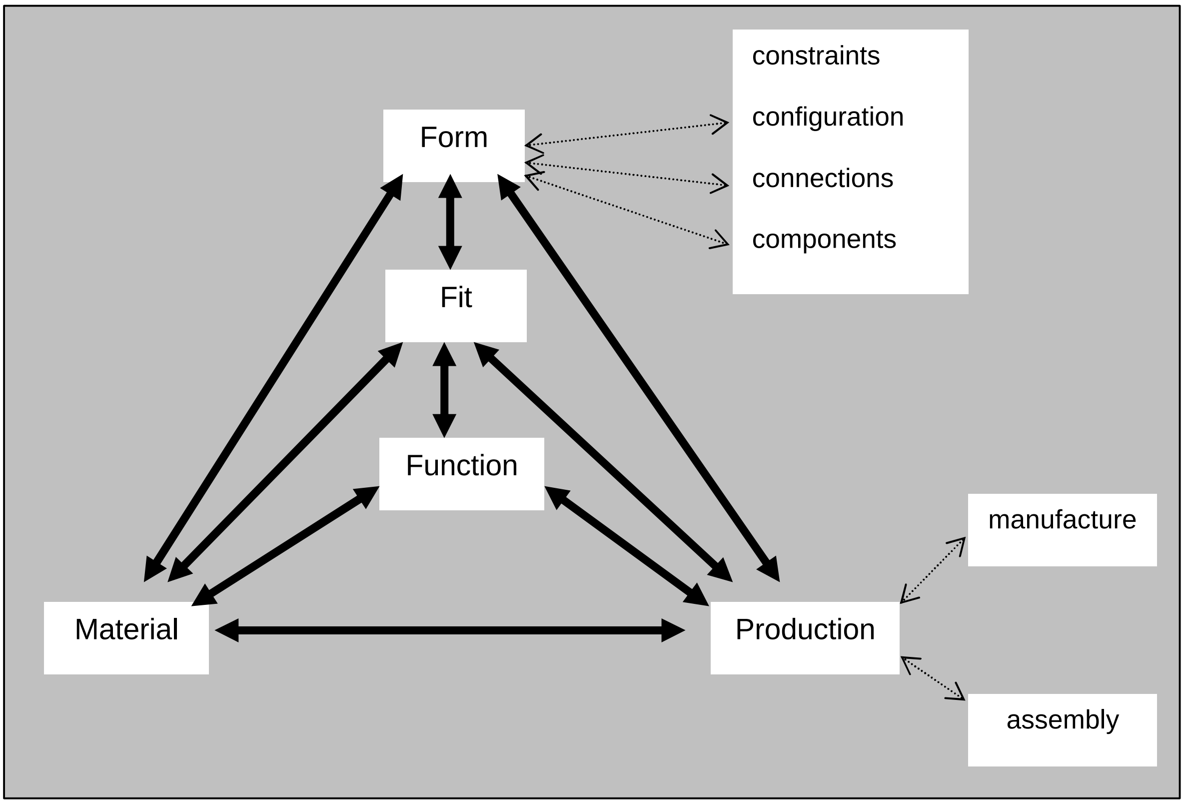

Figure 1. Elements of footwear design (Adapted from Ullman, 1997)

Proper fitting of footwear to feet involves understanding feet, shoes, and the selection of shoes to achieve a required fit. With respect to feet, many sources of foot anthropometry are available (e.g., Randall et al., 1951; Jeffery and Thurstone, 1955). Up until sometime in the 18th century, shoes were symmetric and could be worn on either foot. People were able to extend the durability of shoes by interchanging them similar to rotating tires in a vehicle. Similarly, the history of shoe sizing is also quite interesting. The measurement that three barleycorns placed end to end would equal 1 inch has been traced way back to the 7th century. At that time, it was not a universal measurement. In 1324, Edward II decreed that three barleycorns placed end to end would be the "official" inch. After that, shoemakers began to use the barleycorn inch measurement. The largest foot was equivalent to 39 barleycorns (13 inches) and was designated as size 13. All other sizes were relative to this size 13 and differed by 1 barleycorn (or 1/3 inch). Even with the rapid advancement in technology over the centuries, it is quite surprising that this same measurement system is still in use today.

The footwear sizing system is primarily based on foot length and is sometimes based on foot length and foot width. Footwear manufacturers however, resort to using length, width and girth measures, and a mismatch in any dimension generally results in poor fitting (Figure 2).

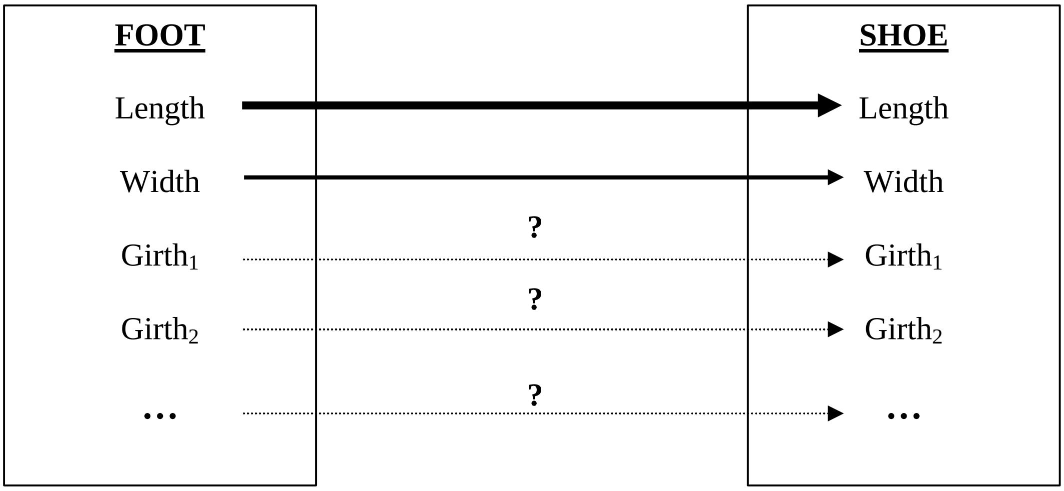

Figure 2. Foot to shoe mapping for fitting feet (the thickness of the line is an indication of the priority during matching. Dotted lines indicate measures that are rarely matched during fitting)

Foot length and width measurements and shoe sizing are generally performed using equipment such as the Brannock device (Brannock, 2002). Instructions related to the use of this device states that proper footwear fitting should consider heel-to-toe length of the foot as well as the arch length. When such differences exist, the correct shoe size is determined using the larger of the two measures, arch length or overall heel-toe length. If the arch length is larger than heel-toe length, the Brannock manufacturer recommends that shoe size be chosen to correspond to the arch length. This inevitably results in a shoe that may be longer than required but allows proper functioning of the metatarsal joint. Similarly, if the heel-toe length is larger than the arch length, the required shoe size is supposed to correspond to the heel-toe length as otherwise the shoe will be too short. In this case, the flex-grooves of the shoe (the place the shoe bends or the place where one sees creases on the shoe) may not be properly positioned and hence foot functioning may be impaired. In short, the foot-footwear system is bound to be less than optimal unless people have the ability to purchase custom footwear. And, even with custom footwear, the manufacturer can be in dilemma as to what foot or shoe dimensions would be critical for good fit.

Randall et al. (1951), after analyzing the data from the Fort Knox study of Freedman et al (1946), pointed out that dorsal arch height (a measure of foot height) and plantar arch height, foot flare, and the angular orientation of the metatarsals are critical for fit. Jeffery and Thurstone (1955), also using the data from the Fort Knox study, have found that the first four factors of length, flare, width and height among a total of 10 factors represented the variations of 29 variables. Janisse (1992) claims that proper fit is achieved when shoe shape is matched to foot shape with the two primary components of proper fit being shoe shape and shoe size. Many footwear fitters have recommended the following procedure when fitting shoes:

1. Measure and fit shoes at the end of a day rather than at the beginning due to deformation and swelling
2. Fit shoes to the longer foot with a toe clearance of 9 to 12 mm at the longest toe.

Tremaine and Awad (1998) have also outlined two important procedures that are hardly used by anyone. These are:

1. Comparing the shoe outline with the foot outline drawn when a person is standing and
2. Comparing the widest part of the forefoot with the widest part of the shoe. The shoe is supposed to have a width that is equal to or no more than 6mm less than forefoot width. Athletic shoes are supposed to have the same width as the forefoot width due to high stress during sports and exercise.

Even though different guidelines (most of which have not been validated) are available, the ultimate selection is generally based on a person's feel or perception of fit. Recent studies have attempted to quantify this feel using objective dimensions. The way the foot sits inside a shoe is important in terms of foot posture. Thus, foot shape and foot curvature play an important role as shown by Goonetilleke and Luximon (1999). Some of the more recent work (Witana et al., 2003) in relation to fit, using a quality control approach, will be discussed in the presentation.

3. Cushioning

During walking, the ground reaction force is approximately 1.25 times the body weight and during running, the ground reaction force can reach levels of 2 to 3 times the body weight (Cavangh and LaFortune, 1980, Dickinson et al, 1985). Thus, midsole cushioning is supposed to attenuate or dampen the impact forces acting on the body during usage. Shoe designs attempt to concentrate on stability and cushioning in addition to weight and durability. Good support (that is, stability) may feel uncomfortable to a person while too much cushioning will make activities such as walking and running quite difficult. Most research has concentrated on comparing different shoes or materials rather than comparing the basic physical characteristics of the materials that are used.

Cushioning technology is quite varied with manufacturers marketing air soles, pads, pods, gel or fluid soles and so on. A 1997 Salomon Brothers industry report stated, "No company has publicized that its cushioning technologies outperforms another because generally these cushioning technologies perform no better than regular polyurethane (PU) or ethylene-vinyl-acetate (EVA) foam. Investing in the creation and strong marketing of these technologies provides credibility to companies that their product will actually help with true athletic performance, and thus helps give a specific brand an aura of being an authentic athletic brand" (extracted from Vanderbilt, 1998, p52).

Even though midsole cushioning is supposed to attenuate or dampen the forces on the body, the actual force acting on the body remains relatively unchanged with footwear (McPoil, 2000). Thus, most problems arise when a wearer of a shoe perceives a relatively false sense of security when a footbed and foot covering are present. Robbins and Waked (1997) have shown how this false sense of security increased impact and injury with users of expensive shoes. In other words, users of (expensive) shoes tend to underestimate the loads (or alternatively expect the shoes to protect their feet) and hence are more prone to injury. Goonetilleke (1992) reported a similar finding, where three-quarter cut aerobic shoes that are somewhat between a basketball shoe and a running shoe, were associated with higher number of aerobic injuries. Even though the actual cause of the higher number of injuries was unknown, it was perceived that the wearers had a false sense of security about ankle protection with the three-quarter-ankle shoes.

In the early days, rubber was used as a cushioning material. In recent years, shoe manufacturers have resorted to using PU and EVA or similar foams. Most of the midsole foams in common use today are viscoelastic materials, i.e., they exhibit viscous and elastic properties. Thus, the physical properties that characterize these foams can be quite varied. Foam-cushioning glossaries give many different physical parameters that may be related to perceived cushioning. Some of these are:

1. Compression set. This is the permanent surface depression when a sample that is compressed to 90% of its thickness and held for 22 hours is released of its load.
2. Density. One of the few physical parameters used in footwear production. High-density foam is less likely to bottom-out. Footwear manufacturers, generally attempt to specify the cushioning properties using foam density alone.
3. Hysteresis. This is the ability of foam to maintain its original characteristics after loading. For a foam, it is measured as the percent of 25%IFD loss when a compression tester returns to its 25% IFD position after being subjected to 65% compression (Figure 3).
4. Indentation Force Deflection (IFD). This is a measure of the load bearing capacity or the firmness. IFD is generally measured as 25%IFD and 65% IFD. X% IFD refers to the load required to compress the test sample by X% of its original thickness. For example, 25% IFD is the load required to compress say, a 40mm thick test sample to 30 mm thickness. The higher the 25%IFD, the firmer the surface feels. High 25% IFD values indicate a stiff or boardy surface. Low-density foams will have low 65% IFD values and hence will tend to bottom-out and will not support the load. High 65% IFD values on the other hand, resist bottoming-out of the foam (Figure 3).
5. Resiliency. Typically, a ball rebound test is used to measure resiliency. A steel ball is dropped from a fixed height on to the sample. The rebound height measured as a percentage of the original height is an indication of resilience. A boardy foam will have low resilience.
6. Flex Fatigue. This is a softening or a loss of firmness. Generally measured by repeatedly compressing a foam sample and measuring the change in IFD.
7. Support Factor also called the Sac Factor = (65% IFD / 25%IFD). The higher the number, the greater the difference between the surface firmness and the deep-down support. Foam manufacturers use this factor as a means of measuring positive sensations (comfort?). For example, higher support factors may allow desirable surface softness and firm inner support.

Using the above considerations van Leuwen et al (1973) have categorized cushioning qualities into two important parameters of Comfort and Support. They defined Comfort as the ability of the cushioning material to deform and conform to body shape so that pressure concentration is avoided. They also defined Support as the ability of the cushioning material to hold the body in a relaxed position and allowing free body movement so that body can push against the material. The region in-between 1% and 10% determines the initial or surface softness. Similar to the Sac Factor the ratio of the load at 25%IFD to the load at 5% IFD is defined as the Initial Softness Ratio (ISR). A high ISR indicates a softer feel.

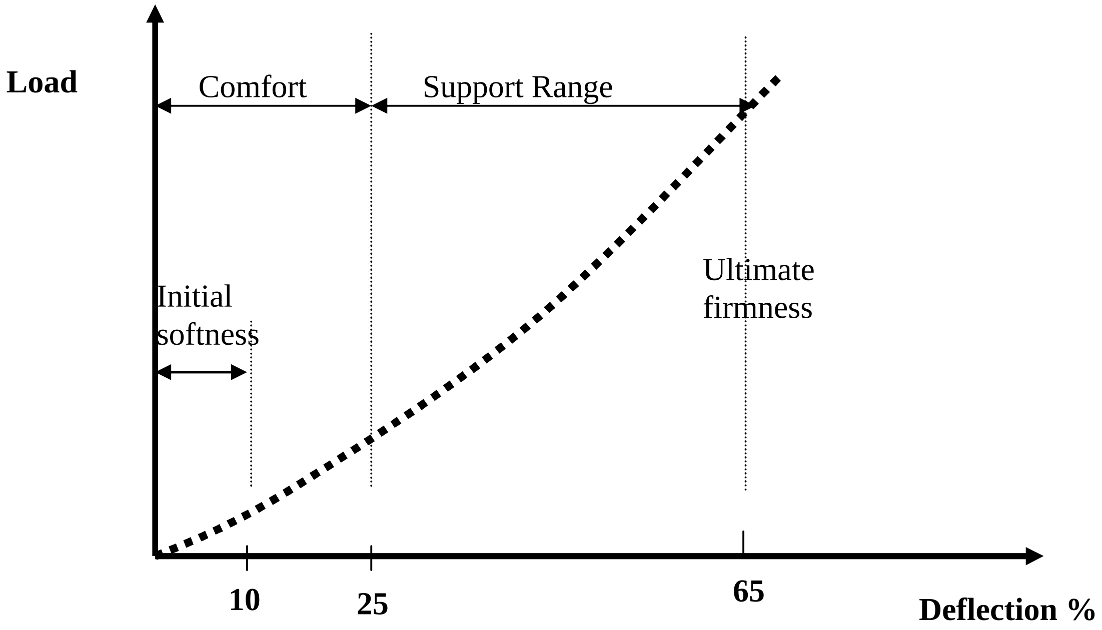

Figure 3. An example load-deflection curve for midsole material

Figure 4 shows the effects of hysteresis. If the unloading curve is close to the loading curve, the material or system exhibits “fight-back”, and it can be an undesirable quality, as the material will follow the body too closely as the load is removed. At the same time, if the recovery of the cushion is too slow after removing load, the cushion is “dead” or lacks dynamism. The ideal cushioning behavior is thus a material with good dynamics without “fight-back”.

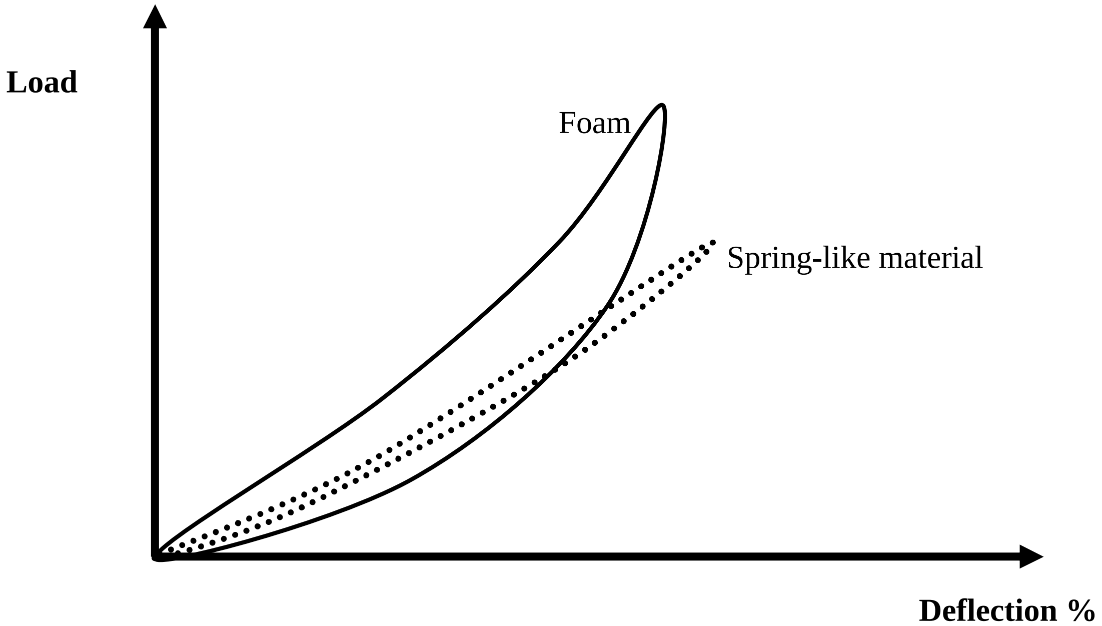

Figure 4. Illustration of hysteresis loops. The spring like material illustrates “fight-back”, whereas foam helps remove this “fight-back”.

A number of standard test methods are available for measuring the physical properties of the commonly used foam type midsole materials. Some of these are:

1. Apparent density determination - ISO 845; BS 4443: Part 1: 1979 (Methods 1 and 2)

2. Compression set of flexible foam and microcellular foam - ISO 1856/72; BS 4443: 1979 (method 6); ASTM D1564-71
3. Compression stress/strain characteristics - ISO DIS 3386/79; BS 4443: part 1 (Method 5); ASTM D1564-71
4. Hardness measurement - ASTM D2240-75
5. Abrasion test used for testing shoe soles - DIN 53516
6. Indentation hardness characteristic representative of the load-bearing properties of a foam. Inentation forces are measured at 25%, 40% and 65% indentations. - ISO 2439/72; BS 4443: Part 2: 1979 (Method 7); ASTM D1564-71; DIN 53576)
7. Dynamic fatigue test, a constant pounding test, accelerates the cushioning losses expected in normal operation - ISO 3385/75; BS 4443: part 5: 1980 (Method 13); DIN 53574

The above tests or similar tests are important for various reasons. For example, during activity, the midsole of a shoe is compressed with each impact. At impact, some of the work is transformed into strain energy and is stored in the elastically deformed material while the remainder of the work is dissipated as heat (Shorten, 1993). When the midsole is unloaded, the material undergoes elastic recovery as it regains its original shape. The foam hysteresis is a good indicator of this change. The heat build-up within the midsole during activity eventually leads to a reduction in the cushioning efficiency (Kenoshita and Bates, 1996).

Goonetilleke (1999) investigated some of the aforementioned parameters (Figure 5) and showed that the perceived level of cushioning during standing and running can be predicted from the time to peak deceleration and/or stiffness (or compression) values obtained from an impact tester. It was also shown that the magnitude of the peak deceleration on the impact tester appears to be a good predictor of perceived level of cushioning when walking, The results were used to explain and link the differences that exist in the ergonomics and biomechanics literature related to cushioning.

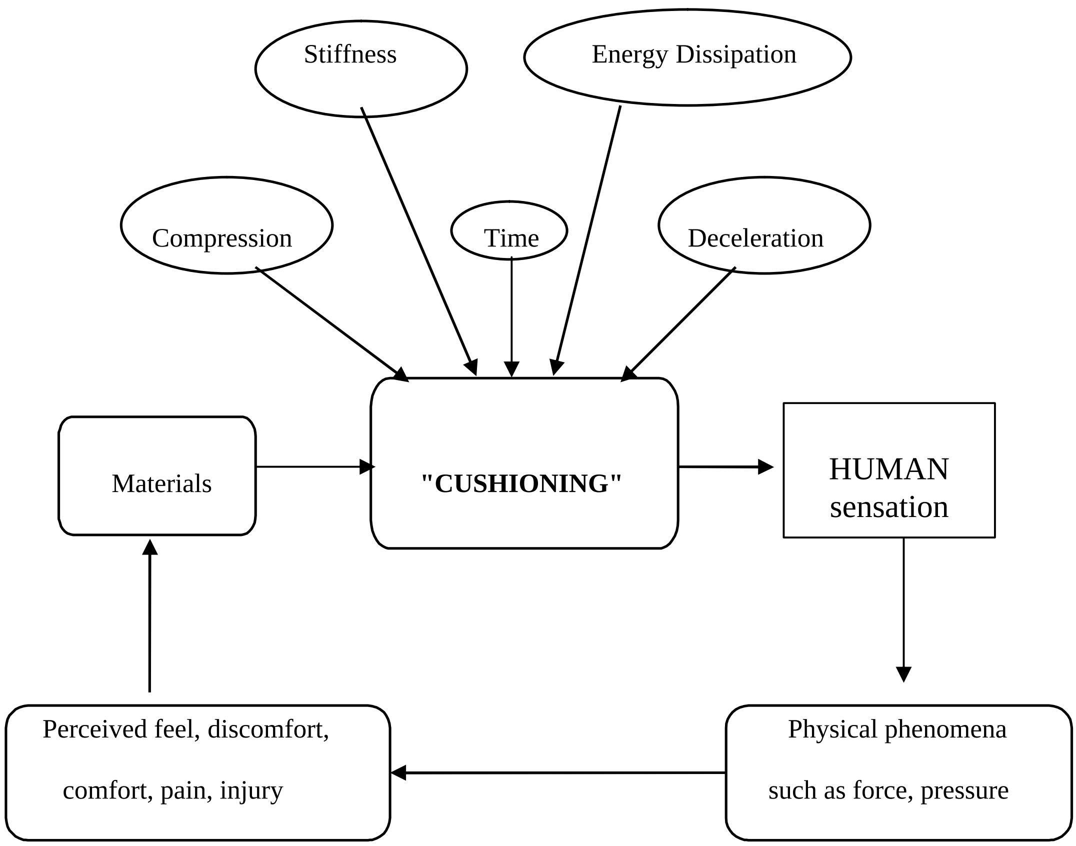

Figure 5. Contributors to cushioning and their effects (Goonetilleke, 1999)

4. Conclusions

It is clear that going back to basics in terms of sensation, biomechanics, use of quality control techniques, and material testing can drive the footwear industry to new heights. Consumers are looking for more comfortable footwear even at the expense of fashion and style especially those who need to be on their feet for long periods of time. Designing the foot covering to hold the foot in the right places while supporting the body weight at the right locations is the key to the development of footwear. Even though some recent studies are geared in this direction, a lot more work is required from Human Factors and Ergonomics professionals to make footwear more user-friendly and comfortable.

5. Acknowledgments

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