Foot-ground interfaces exist in many different forms. Frequently the interface is a shoe or floor mat, and sometimes it is a carpet-like material, such as an Astroturf, providing specific biomechanical characteristics to help one perform effectively. Hence these interfaces can play an important role in improving functionality or performance, preventing injury, and reducing discomfort.

Human movement generally involves repeated loading at the foot-floor interface, resulting in force transmission through the human feet and toward the upper extremities. Proper cushioning attenuates these impact forces and protects the musculoskeletal system from potential injury (Schwellnus, Jordaan, & Noakes, 1990). The literature indicates that the term cushioning is used to describe only those aspects of the foot-floor interface that are concerned with reduction of the transmitted forces. As a result, the foot-floor interface literature is split into two distinct categories, related to injury and discomfort. In the biomechanics literature, injury has been linked to shock absorption, whereas the ergonomics literature primarily focuses on discomfort and has always made reference to the hardness or compression of materials, or both.

This paper is meant to develop a more unified approach to understanding cushioning. Aspects associated with cushioning – namely, injury, discomfort, and functionality – and their weaknesses will now be discussed.

**Cushioning and Injury**

Impact loads generated at the feet during activity have been implicated in a range of injury problems, such as stress fractures (Milgrom, Giladi, & Stein, 1985), Type 1 shin splints (Detmer, 1986), cartilage breakdown (Simon, Radin, Paul, & Rose, 1972), osteoarthritis (Radin, Paul, & Rose, 1972), knee injuries (Newell & Bramwell, 1984), and low back pain (Voloshin...
& Wosk, 1982). Hence, it is not surprising that a majority of consumers look for certain characteristics in footwear materials based on experience, prior injury, or marketing claims. As an example, the Japanese consider shoes’ shock-absorbing properties to be the most important factor when used during sports activities (Hong Kong Trade Development Council, 1993). However, the definition of shock absorption and the range of its acceptable values are not clear.

In addition to the relationship between impact loads and injury, the literature also discusses footwear and injuries. For example, Gardner, Dziados, and Jones (1988) found that the running shoe age was a significant risk factor in the development of stress fractures. This finding has been attributed by Cook, Kester, and Brunet (1985) to the loss, with increased use, of either the mechanical-support or the shock-absorbing properties of the footwear midsole. Schwellnus et al. (1990) reported that neoprene insoles can significantly reduce the incidence of tibial stress syndrome through better shock absorption. Some have also found neoprene insoles to reduce transmitted forces better than viscoelastic insoles (Brodsky, Kourosh, & Stills, 1988). Note that the Nigg, Herzog, and Read (1988) study showed no reduction in vertical impact forces during running when viscoelastic insoles were compared with conventional running shoe insoles. In summary, even though the injuries experienced have been mostly repetitive strain injuries rather than acute injuries, the shock-absorption property has been identified as a primary factor in the prevention of injury. In the engineering literature, shock absorption is generally related to damping phenomena. However, the literature related to injury seems to imply that shock “absorption” is a reduction in impact force magnitude. Alternatively, it is meant to be a gradual increase in the load with slow deceleration (as opposed to an impact load, which is a rapid increase in load). Can the shock-absorption or deceleration property be perceived during running? Or, are perceived levels of cushioning during running based on shock-absorption characteristics?

Cushioning and Discomfort

Foot cushioning devices have been used by many researchers in relieving low back pain (Wosk & Voloshin, 1985), Achilles tendinitis (Lowdon, Bader, & Mowat, 1984), foot pressure in diabetic neuropathy (Boulton, Franks, & Betts, 1984), and so forth. Basford and Smith (1988) found that adding a viscoelastic insole to a shoe improved comfort while reducing back, leg, and foot pain in participants whose jobs required standing at least 75% of the time. In their experiment, the lighter participants and those with smaller feet were given insoles with a 40/45 Shore hardness rating and the heavier participants were given insoles with a 45/50 Shore hardness rating. Hence, it is clear that the authors assumed that cushioning comfort is related to the hardness of the insoles (material). However, is this really so?

High plantar pressures have also been linked to foot pain and discomfort (Godfrey, Lawson, & Stewart, 1967; Silvino, Evanski, & Waugh, 1980). Leber and Evanski (1986) performed a study to compare the effectiveness of reducing plantar pressure using seven different materials. A similar comparison study, related to flooring conditions on standing tolerance, was reported by Redfern and Chaffin (1988). However, as the types of insoles and foot-floor interfaces on the market increase in number, such comparisons become almost impossible to perform and somewhat meaningless.

The effects of floor surfaces during standing work have been researched by many (Redfern & Chaffin, 1995; Rys & Konz, 1990; Zhang, Drury, & Wooley, 1991). Others have evaluated the effect of insoles in reducing back, leg, and foot pain during standing work (Basford & Smith, 1988). For example, Konz and colleagues (e.g., Rys & Konz 1989, 1990) have performed many studies evaluating physical, physiological, and psychophysical changes with commercially available mats. In their 1990 study, they found that the subjective rating of comfort was the most sensitive criterion, compared with calf temperature and instep skin temperature. They concluded, with surprise, that floor mat comfort was inversely related to mat compression. In the same study they found that concrete, which had the lowest compression compared with any of the mats tested, had the lowest comfort rating. Hence it appears that comfort rating is related to the compression (or deflection) of a mat through an inverted U curve.
In a similar study, Redfern and Chaffin (1988, 1995) concluded that the effectiveness of a floor to relieve perceived tiredness is a function of the material hardness and its depth before bottoming out. However, they also noted that very “soft” materials had relatively high perceived tiredness ratings, thereby suggesting a similar curve for the tiredness-hardness relationship. It is worthwhile to note Redfern and Chaffin’s (1995) observation that the perception of softness of a material is a possible indicator of reduced tiredness in workers. They concluded that one can only suggest guidelines, not make definitive recommendations regarding flooring design.

Zhang et al. (1991) found perceived discomfort to increase at a lower rate over time with soft-soled shoes than with hard shoes. They concluded that even though there are temporal changes during prolonged standing, none of the commercial mats tested were effective during constrained standing, despite their advertising claims. Goonetilleke (1992) obtained a similar result, in a somewhat different but related setting, in an extensive survey in which the floor surface was shown to have no relationship to aerobic dance injury when participants wore appropriate footwear. In summary, both hardness and compression have been linked to discomfort.

The literature on cushioning falls into a framework similar to that shown in Figure 1. In many cases, different materials and some of their characteristics have been related to injury, pain, comfort, and discomfort. Such an approach is tedious and time consuming. Injury is preceded by pain or discomfort (Hagberg et al., 1995), and comfort was defined by Hertzberg (1958) as the lack of discomfort. The latter premise, however, has been challenged by Zhang, Helander, and Drury (1996). Overall, there appears to be consensus that pain or injury is generally preceded by discomfort. Hence, one may ask, why is injury linked to shock absorption (or, more precisely, deceleration) and discomfort or pain linked to compression or hardness? Are shock absorption and compression the only important and required properties of materials for human-product interfaces? Pilots using headsets for extensive periods of time have found pressure relief through the use of slow-recovery foam, which implies that comfort is linked also to energy dissipation and material resistance or stiffness. Interface pressure and associated feelings of discomfort are caused by the distribution or concentration of forces and may be associated with the compression and/or stiffness characteristics of a material (Goonetilleke, 1998). Can all these material characteristics be perceived at the same time, or is the perceived property dependent on the magnitude of the interface force?

Comfort is a multifaceted entity. Also, discomfort and comfort measures are a complex mapping to the sensation or perception domain. A participant’s inability to differentiate fatigue and discomfort further complicates the issue (Redfern & Chaffin, 1995). Hence, it is more appropriate to split the material-comfort mapping from materials to perceived cushioning and then from perceived cushioning to

![Figure 1. Existing foot-floor interface research.](https://www.hfs.sagepub.com)

---

**Table 1.** Existing foot-floor interface research.

<table>
<thead>
<tr>
<th>Materials &quot;black box&quot;</th>
<th>Hardness or Compression</th>
<th>Shock Absorption</th>
<th>Human Interface</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Comfort and/or Discomfort</td>
</tr>
</tbody>
</table>

Downloaded from hrs.sagepub.com at HFES-Human Factors and Ergonomics Society on December 14, 2014
comfort, discomfort, or fatigue. This is clear from the Redfern and Chaffin (1995) and Zhang et al. (1991) studies, in which the duration effects of foot-floor interfaces on whole-body discomfort were different. Duration effects are primarily a result of the body forces (or more appropriately, the body deformations) rather than the “applier,” the foot-floor interface. The foot-floor interface is somewhat static, and the material to perceived cushioning mapping should also be static. Hence a breakdown of the overall material-comfort (or discomfort) mapping as shown in Figure 2 is more suitable to further understand discomfort or fatigue relationships.

It is no doubt an interesting exercise to evaluate commercially available products and to place them on a comfort-compression, tiredness-hardness, or similar type of map. However, technological improvements, such as advances in composite materials, can alter significantly the physical or mechanical characteristics of products and alter the position of a product on such a map. Product and usability testing are important for product-evaluation purposes and best-in-class assessments, but they do not explain the underlying causes of “good” or “bad” products or perceived feelings of the wearer, which are the most important elements in designing products right the first time. It would be better to develop an acceptable and relevant characterization procedure that can provide a means to improve wearer comfort and also reduce fatigue and injury during activity. Such an approach will allow designers and developers of products to understand which particular cushioning characteristics are perceived by humans in any given activity being performed. For example, in high-loading situations such as running, do people perceive the shock absorption property? In other situations, such as standing, do people sense the hardness or compression property of the material? Ultimately, it is hoped that cushioning can be better defined and that the process by which people perceive cushioning can be better understood.

**Cushioning and Functionality**

Whether during standing or sports participation, many “mechanical” systems of differing characteristics are present at the foot-ground interface. All these systems tend to act serially (see Figure 3). One important system is the floor surface; a second is the foot-ground interface (i.e., the shoe). Depending on the number of systems present, the overall characteristics of a composite surface can be significantly different when compared with those of any one surface, as is shown in the following formulation. For
materials obeying Hooke’s law, the following is true (Gere & Timoshenko, 1990, p. 53):

\[ E = \text{stress/strain} = (F/A)/(D/L), \]  

(1)

where \( E \) = modulus of elasticity (N/m²), \( F \) = force acting at the foot-shoe interface (N), \( A \) = surface area (m²), \( D \) = deformation (m), and \( L \) = thickness of the material (m). Rearranging the formula as

\[ F = (AED)/L \]  

(2)

results in

\[ K = \text{spring constant or stiffness (N/m)} = \frac{F}{D} = \frac{AE}{L}. \]  

(3)

If \( n \) number of surfaces are in series (one on top of the other), then the combined deformation \( (D_{\text{total}}) \) is the sum of each surface deformation.

\[ D_{\text{total}} = D_1 + D_2 + \ldots + D_n = \sum_{\text{for all } i} D_i \]  

(4)

Assume that the surfaces possess only a spring-like element and no damping (natural rubber is a good example). Because the force acting on each surface should be the same, the overall spring constant or stiffness can be calculated as

\[ \frac{1}{K_{\text{total}}} = \sum_{\text{for all } i} \frac{1}{K_i}. \]  

(5)

Equation 5 shows that the spring constant or stiffness of the material is significantly altered by the presence of other materials in the series.

When fatigue and discomfort are studied in an industrial setting, it becomes necessary to look into this series effect of all elements between the plantar side of the foot and the ground. Traditionally, studies related to comfort or discomfort have ignored the cushioning characteristics of shoes; in studies of components such as insoles and floor surfaces, one of the most important elements, the shoe, is ignored. In real life, the series effect of the shoe alters the overall system characteristics, thereby posing a serious problem to the practical implications of published results.

A cushioning system functions by increasing the duration of an impact, thereby reducing the shock load transmitted to the musculoskeletal system. Cushioning has been found to reduce the local pressures and axial shock in the lower extremity (“Athletic Shoe Cushioning,” 1988). Most aspects of the foot-floor interface that have been studied in the past fall into the broad category of cushioning. For example, the so-called shock-absorbing properties can be measured through deceleration characteristics of a material. Another possible measure is the rebound resilience \((R)\), a dimensionless quantity, which is defined as the ratio of the energy returned to the energy applied to a test piece as a result of an impact (Bassi, 1978).

\[ \text{Rebound resilience (R)} = \frac{\text{Energy returned}}{\text{Energy applied}} \]  

(6)

Often, percentage energy loss \((E)\), another dimensionless quantity, is used instead of rebound resilience. This measure quantifies the

---

**Figure 3.** A spring system.
proportion of energy lost compared with the amount of energy applied. The area under the hysteresis loop in the force-displacement curve is the amount of energy lost (Figure 4). In this study, percentage energy loss will be used and is defined as follows:

\[
\text{Percentage energy loss (E)} = \frac{\text{Energy loss} \times 100}{\text{Energy applied}} \tag{7}
\]

\[
= \frac{(\text{Energy applied} - \text{Energy returned}) \times 100}{\text{Energy applied}} \tag{8}
\]

\[
= (1 - R) \times 100 \tag{9}
\]

**Material Testing**

Material testing is not new, and many methods exist for measuring material properties (Cavanagh, 1980; Fredrick, 1984; Nigg & Kerr, 1983). The simplest and most easily determined parameter is static stiffness or static deflection. The American Society for Testing and Materials (ASTM; 1976) D 1667-76 specifies a procedure to measure the static stiffness for foam rubbers and plastics using an Instron (Canton, MA) Universal machine, a material testing machine from MTS Systems Corp. (Minneapolis, MN), or a similar type of machine. Other methods that involve impacting have been published by other sources and standard institutions; for example, ASTM D-1054-66 (ASTM, 1966), ISO R1767 (International Organization for Standardization, 1971), and ISO-DIS 4462 (International Organization for Standardization, 1975). However, static stiffness may not be a good measure for real-life situations involving human movement.

Campbell, Newell, and McLure (1982) categorized materials based on compression characteristics using a modified ASTM-D 1667-76 procedure. The materials in that study were separated into three categories (very stiff, moderately deformable, and highly deformable) based on the shape of the stress-strain curves obtained from an Instron Universal Testing machine. The classification was somewhat arbitrary and was based on how the curves looked rather than on any objective criteria. Even though the materials were classified into three groups, it is unknown whether humans can distinguish the three categories of stiffness or the Young’s modulus associated with them. Because of the classification weaknesses, Campbell et al. concluded that the suitability of a material for use as an orthotic insole cannot be based exclusively on such a categorization.

With the development of manufactured materials, it becomes important to characterize appropriately the static as well as dynamic properties of human interfaces. The Instron Universal instrument and similar machines have been standard measuring devices for compression testing in which forces are applied to the test samples at a preselected rate. These machines cannot load the specimens as quickly as drop or free-fall tests. As a result, they may not be as useful for the characterization of dynamic properties as they are in testing static properties.

Dynamic cushioning characteristics and curves have been used for shock control in the packaging industry for many years (Arimond, 1987). The Stuttgart artificial athlete (Brown, 1987; Deutsche Industrie Norm, 1991, 1992) and the impact tester (Cavanagh, Williams, & Clarke, 1979) are universally used devices that can measure dynamic stiffness. Such measures have been used for the prediction of injuries. For example, Andreasson and Peterson (1986) have suggested that injuries occur with running shoes when the overall spring constant...
(k) on impact exceeds 100 kN/m (equivalent to 3.2 MPa in dynamical modulus). Brown (1987) suggested the use of the peak force that is generated as a measure of the stiffness of the material in impact conditions.

The response characteristics of many cushioning systems depend on the rate of loading. With the extensive use of viscoelastic materials for surfaces, dynamic material properties generated by an impact tester may play an important role in comfort, cushioning, or both. Even though the term cushioning is ubiquitous, it lacks a good definition. For example, the Oxford English Dictionary (1989) defines a cushion as “A case of cloth, silk, etc. stuffed with some soft, elastic material used to give support or ease to the body when sitting, reclining or kneeling” [italics added]. The Random House Webster’s College Dictionary (1995) defines cushioning as “anything similar in form or function, such as a pad to prevent excessive pressure,” “something to absorb or counteract shock, jar, or jolt,” or “to lessen or soften the effects of; to cushion a blow” [italics added]. Even the dictionaries imply differences in the technical definition for cushioning. Words used to describe it include “soft,” “elastic,” “absorb shock,” “reduce pressure,” and so forth, all of which can be represented by a mechanical property. In addition to helping to understand cushioning better, it is hoped that knowledge of the material-cushioning mapping will reduce the inaccuracies of extrapolating and assuming the properties of materials (or surfaces) that cause increased levels of discomfort, injury, or both.

**Study Objectives**

The objectives of this study were to investigate the material properties contributing to perceived cushioning and thereby understand the differences in the biomechanics and ergonomics literature. This study is a means to understand the sensing mechanism so that discomfort, fatigue, and so forth can be better understood, as shown in Figure 2.

Perceived ratings have been found to be the most sensitive dependent variables in studies involving cushioning (Redfern & Chaffin, 1995; Rys & Konz, 1990). Other studies, such as that of Zhang et al. (1991), have relied on perceived ratings. In addition, cushioning has been related to shock absorption or compression. Hence, it is hypothesized that perceived level of cushioning (PLC) may be related to the material properties of deceleration, compression, percentage energy loss, and stiffness (Figure 2), depending on the activity performed. Three activities were chosen: standing, walking, and running. Each of these activities was investigated in one experiment.

As discussed before, the foot-floor interface is somewhat static, and therefore the perceived sensation ought to be static (Figure 2). In other words, PLC should be independent of duration. Thus, in this study, PLC was evaluated over a short duration to eliminate any confounding effects.

**METHODOLOGY**

**Apparatus**

An impact tester (Cavanagh et al., 1979; “Physical Tests,” 1990) was used to quantify the material properties of the shoes. Designed to simulate the impact between the human heel and a “cushioning” system, the impact tester consists of an electromechanically operated impact head with a mass of 7.8 kg and a head diameter of 2.5 cm, which is dropped onto a test sample. Computer linked force, velocity, and displacement transducers measure impact dynamics. The results are recorded and analyzed. The material properties that can be obtained from the impact tester are as follows: (a) maximum deceleration (measured in g); (b) time taken to reach maximum deceleration (ms); (c) maximum compression (mm); (d) percentage energy loss (E), a dimensionless quantity, or the percentage energy dissipated (measured using the hysteresis loop in the force-displacement curve) through the material during impact (Figure 4); and (e) dynamic stiffness (kN/m) of the material (calculated from the loading portion of the force-displacement curve). The head velocity at impact was controlled to be 1.2 m/s.

**Materials**

Three pairs of size 9 shoes with different midsole characteristics were used. Two of the pairs (A and B) were designed and manufactured...
to be identical except for the cushioning material in the heel portion of the shoe. Heel cushioning has been shown to significantly affect the overall cushioning in a shoe (Goonetilleke & Cann, 1995). The left and right of each pair were “matched” by the maximum deceleration value, time to maximum deceleration, and the maximum deflection. The percentage energy loss was different between the two pairs but similar between the left and right shoe of each pair.

\[ X(\text{left}) \approx X(\text{right}), \text{ where } X = A, B, \text{ or } C. \] (10)

The third pair (C), a control, had a lower stiffness than Pair A and Pair B. The control shoe (C) had a resilience similar to that of Shoe B but different stiffness characteristics. All three pairs were used in three experiments (standing, walking, and running). The material properties of each shoe are shown in Figures 5 and 6.

**Participants**

The 60 male participants were split into three groups of 20 each for Experiment 1 (standing), Experiment 2 (walking), and Experiment 3 (running). All wore size 9 shoes.

**Procedure**

In each experiment (standing, walking, and running), the participants rated the PLC for the left and right shoes separately. Because the objective of the study was to understand perceived cushioning, the term was not defined so as to avoid biasing the participants. All participants understood the term cushioning and the objectives of the study. Two trials of a specific order were used. To reduce any bias, the control shoe (C) was tested in a predetermined sequence as follows: C-A-C-B or C-B-C-A. To distinguish the two presentations of the

---

Figure 5. Material properties (peak deceleration, time to peak deceleration, and maximum compression) of Shoes A, B, and C.

Figure 6. Material properties (percentage energy loss and stiffness) of Shoes A, B, and C.
control shoe, the order was labeled as C1-A-C2-B and C1-B-C2-A. Half of the 20 participants in each experiment rated the shoes in the order C-A-C-B and the other half rated them in the order C-B-C-A. For any one participant, the presentation order was the same in both trials. A 7-point Likert scale (1 = very poor, 7 = very good) was used.

In each experiment, the participants were informed that the experiment concerned the perception of cushioning and that they would be asked to wear and rate a total of eight pairs of shoes (i.e., two trials of four pairs, with C being repeated within a trial). Note that in reality there were only three pairs of shoes.

**Experiment 1: Standing**

The participants first wore the assigned pair of shoes while seated. They then evaluated the level of cushioning in the shoes while standing. During the test they were allowed to change their lower extremity limb positions without stepping (walking). Standing, bouncing on heels or toes, wriggling, and leaning fore and aft were all permitted. The participants were also asked to take at least 30 s prior to making a response. No maximum time limit was set. Each participant rated the PLC in the left and right shoe separately for the eight pairs of shoes (C1-A-C2-B-C1-A-C2-B or C1-B-C2-A-C1-B-C2-A).

**Experiment 2: Walking**

The test procedure was identical to that of Experiment 1 except that PLC was rated during walking. Participants walked at 3 miles/h (4.8 km/h) for a minimum of 30 s prior to rating each shoe.

**Experiment 3: Running**

The test procedure and the rating order were identical to those in Experiment 1. The only difference was that the rating was performed after the participants had run for a minimum of 30 s at 7.5 miles/h (12 km/h). All participants were experienced runners who run 20 to 50 miles (32 to 80 km) per week on a regular basis.

At the end of each experiment, verbal protocols of each participant were recorded. The protocols addressed the “perceptual meaning of cushioning.” Hence these protocols are indicative of cushioning. In addition, it is hoped that they may be used to explain the mechanisms by which cushioning is perceived.

**RESULTS**

A battery of statistical tests were performed using the SAS statistical package. Wilcoxon rank sum tests were performed to identify significant ($p < .05$) differences. The statistically important results for each experiment are summarized in the following paragraphs. Note that all comparisons among shoes were among respective sides (i.e., left of one shoe vs. left of another shoe or right of one shoe vs. right of another shoe). Because any imbalance could cause uneven loading between the left and right feet, comparisons between the two sides were performed only within a pair of shoes. Because the loading levels are different among the three activities of standing, walking, and running, no cross-comparisons were performed.

**Standing**

The participants’ descriptions of cushioning and the PLC values are given in the Appendix and Table 1, respectively. Some participants’ responses were the same or similar. The Wilcoxon rank sum tests showed the following:

1. No statistically significant ($p < .05$) difference exists between the left and right shoes for both Shoe A and Shoe B in either trial.
2. No statistically significant ($p < .05$) difference exists between Trial 1 and Trial 2 for either side of Shoe A or B.
3. No statistically significant ($p < .05$) differences exist between Shoe A and Shoe B for either trial and pooled trials for the left and right sides.
4. The PLC value for Shoe C was significantly higher ($p < .001$) than that of Shoe A.
5. The PLC value for Shoe C was significantly higher ($p < .001$) than that of Shoe B.

To understand the relationship between perceived cushioning and the material properties, we performed a correlation analysis using the mean PLC score of all participants. The correlation coefficients and their significance levels are shown in Table 2.
Walking

For walking, the PLC values (Table 1) from best to worst for each shoe were as follows: C (Left) 4.850, C (Right) 4.725, A (Left) 4.465, A (Right) 4.265, B (Right) 4.065, and B (Left) 3.940. The Wilcoxon rank sum tests showed the following:

1. No statistically significant ($p < .05$) difference exists between the left and right shoes for both test shoes (Shoe A and Shoe B) in either trial.
2. No statistically significant ($p < .05$) difference exists between Trial 1 and Trial 2 for either side of Shoe A or B.
3. When the two trials were pooled, the comparison between Left Shoe A and Left Shoe B shows a trend ($p < .06$) with a higher PLC rating for A.
4. No statistically significant ($p < .05$) differences exist between Shoes A and C in either trial or either side. However, with pooled trials, the right C2 (second presentation of Shoe C) was significantly ($p < .05$) better than Shoe A (right).
5. In Trial 2, the left of Shoe C was significantly better ($p < .05$) than the left of Shoe B. In Trial 1, Shoe C2 was significantly better ($p < .05$) than Shoe B (for both feet). When the trials were pooled, Shoe C was significantly better than Shoe B for both left and right sides.

The correlation coefficients and their significance values are shown in Table 3. The significant correlations between the mean PLC values and the material properties were as follows: (a) maximum deceleration: correlation coefficient = −.997, $R^2 = .99$, $p < .0001$; (b) stiffness: correlation coefficient = −.917, $R^2 = .84$, $p < .05$.

Participant descriptions of cushioning are given in the Appendix. Here again, some responses were the same or similar.

Running

The PLCs and the correlation analysis are given in Tables 1 and 4, respectively. The Wilcoxon rank sum tests showed the following:

1. No statistically significant ($p < .05$) difference exists between the left and right shoes for both Shoe A and Shoe B in either trial.
2. No statistically significant ($p < .05$) difference exists between Trial 1 and Trial 2 for either side of Shoe A or B.
3. No statistically significant ($p < .05$) differences exist between Shoe A and Shoe B for either trial and pooled trials for the left and right sides.

4. Shoe C was significantly better than Shoe A in Trial 1. However, no statistically significant difference ($p < .05$) exists between Shoe A and Shoe C in Trial 2. When the trials were pooled, Shoe C was significantly better than Shoe A.

5. Shoe C was significantly better than Shoe B in Trial 1. However, no statistically significant difference ($p < .05$) exists between Shoe B and Shoe C in Trial 2. When the trials were pooled, Shoe C was significantly better than Shoe B.

The participants’ responses are given in the Appendix.

**DISCUSSION**

The participants’ responses appear to be similar and do not seem to reveal any differential effects among the three activities. However, the participants’ responses justify the physical measures that were used in this study, given that the physical attributes that are quantified by these measures are perceived (or resemble those that are perceived) by people in relation to cushioning. In this sense, it is certain that all relevant measures have been considered in the objective measures. It is also clear that all participants understood the task and the term cushioning and rated PLC appropriately. Hence, a better understanding of cushioning may be obtained through the relationship between the subjective and the objective measures.

The significant differences in the PLC values are not easy to interpret. However, with a few reasonable assumptions, cushioning can be better understood. The three assumptions are as follows:

1. The significant differences in the PLC values are dependent on one or more of the five physical properties measured by the impact tester: maximum deceleration, time to maximum deceleration, maximum compression, percentage energy loss, and stiffness calculated from the load-displacement curve (Figure 4).

**TABLE 2: Correlation Analysis between Mean PLC during Standing and the Measured Physical Property Values**

<table>
<thead>
<tr>
<th>Physical Property</th>
<th>Correlation Coefficient</th>
<th>$R^2$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum deceleration (g)</td>
<td>-.856</td>
<td>.733</td>
<td>.0296*</td>
</tr>
<tr>
<td>Time to max. deceleration (ms)</td>
<td>.941</td>
<td>.885</td>
<td>.0052*</td>
</tr>
<tr>
<td>Compression (mm)</td>
<td>.971</td>
<td>.942</td>
<td>.0013*</td>
</tr>
<tr>
<td>% energy loss</td>
<td>-.352</td>
<td>.124</td>
<td>.4941</td>
</tr>
<tr>
<td>Stiffness (kN/m)</td>
<td>-.993</td>
<td>.986</td>
<td>.0001*</td>
</tr>
</tbody>
</table>

*Significant at $p < .05$.

**TABLE 3: Correlation Analysis between Mean PLC during Walking and the Measured Physical Property Values**

<table>
<thead>
<tr>
<th>Physical Property</th>
<th>Correlation Coefficient</th>
<th>$R^2$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum deceleration (g)</td>
<td>-.997</td>
<td>.994</td>
<td>.0001*</td>
</tr>
<tr>
<td>Time to max. deceleration (ms)</td>
<td>.697</td>
<td>.485</td>
<td>.1240</td>
</tr>
<tr>
<td>Max. compression (mm)</td>
<td>.783</td>
<td>.614</td>
<td>.0653</td>
</tr>
<tr>
<td>% energy loss</td>
<td>.108</td>
<td>.012</td>
<td>.8393</td>
</tr>
<tr>
<td>Stiffness (kN/m)</td>
<td>-.917</td>
<td>.841</td>
<td>.0101*</td>
</tr>
</tbody>
</table>

*Significant at $p < .05$. 

---

Downloaded from hfs.sagepub.com at HFES-Human Factors and Ergonomics Society on December 14, 2014
words, the perception of cushioning is physical property dependent.

2. Differences in the PLC values are attributable solely to the magnitude of the physical property; that is, perception of cushioning is physical property magnitude dependent. In other words, variations in the magnitude of the physical property will affect PLC.

3. Humans perceive positive differences (i.e., an increase from one shoe to another) and negative differences (i.e., a decrease from one shoe to another) in physical properties the same way; that is, perception of cushioning is sign independent.

The differences in the material properties and the significant difference in the PLC scores are useful in further exploring and analyzing possible causal factors. The differences in the physical properties among the shoes are shown in Table 5.

The results obtained for both standing and running are similar, and both these will be discussed together.

### Standing and Running

No statistically significant differences were found between Shoes A and B at the \( p < .05 \) level. Using the three assumptions just mentioned and the results obtained for the PLC values, it is evident that energy loss or maximum deceleration cannot be a possible cause for the other perceived differences. The reason is clear. For example, the differences in the maximum deceleration between shoes can be ranked from high to low as follows: B-C Left (2.14 g) > B-C Right (1.44 g) > B-A Left (1.37 g) > A-C Right (1.09 g) > A-C Left (0.77 g) > B-A Right (0.35 g).

If Assumption 2 is true, then any significant difference between Shoes A and C has to result in a difference between Shoe A (Left) and Shoe B (Left). However, no significant \( (p < .05) \) difference exists in the PLC. Hence it is unlikely that the PLC depends on maximum deceleration.

In contrast, consider the stiffness (or time to maximum deceleration or maximum compression) values and the statistically significant

<table>
<thead>
<tr>
<th>Physical Property</th>
<th>Correlation Coefficient</th>
<th>( R^2 )</th>
<th>( p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum deceleration (g)</td>
<td>−.886</td>
<td>.784</td>
<td>.0189*</td>
</tr>
<tr>
<td>Time to max. deceleration (ms)</td>
<td>.887</td>
<td>.787</td>
<td>.0183*</td>
</tr>
<tr>
<td>Max. compression (mm)</td>
<td>.926</td>
<td>.857</td>
<td>.0081*</td>
</tr>
<tr>
<td>% energy loss</td>
<td>−.263</td>
<td>.069</td>
<td>.6148</td>
</tr>
<tr>
<td>Stiffness (kN/m)</td>
<td>−.979</td>
<td>.959</td>
<td>.0006*</td>
</tr>
</tbody>
</table>

*Significant at \( p < .05 \).
differences that exist in the PLC. The highest stiffness differences (absolute) are between Shoes A and C and Shoes B and C. The lowest stiffness difference is between Shoe A and Shoe B. The data match the significant differences seen in the PLC values.

Hence it is reasonable to conclude that during both standing and running, a lower stiffness (or higher compression, or higher time to maximum deceleration) value will provide a higher level of perceived cushioning. The two dependencies of stiffness and compression and their possible influence on PLC is not surprising considering that stiffness (or spring constant) $K = F/X$. The use of compression measures in standing evaluations (Redfern & Chaffin, 1988, 1995; Rys & Konz, 1989, 1990) and the importance of the shock absorption property (Hong Kong Trade Development Council, 1993), measured using deceleration time, is thus justified.

**Walking**

No statistically significant differences were found between Shoes A and B at the $p < .05$ level. Hence it is evident that during walking, an approximate difference of 25% energy loss in the heel region was not perceived by the participants. (The exact values were 26% between Shoe A [left] and Shoe B [left], and 21.2% between Shoe A [right] and Shoe B [right]). In contrast, consider the stiffness values and the statistically significant differences that exist in the PLC:

1. A significant difference exists between Shoe A (left) and Shoe B (left) when the trials are combined. The difference in stiffness between these two pairs is only 4.7 kN/m.
2. A significant difference exists between Shoe C2 (right) and Shoe A (right) when the trials are combined. The difference in stiffness between these two pairs is 24 kN/m.

Based on the magnitude dependency assumption (Assumption 2), it is reasonable to assume that a “high” stiffness difference of approximately 26 kN/m between Shoe A (left) and Shoe C (left) should have shown a statistically significant difference in the PLC (see point 4 in the walking results section). However, no such difference was found. A possible explanation is that material stiffness is not a good predictor or indicator of PLC during walking. However, differences in the maximum deceleration values seem to be a better predictor for the differences in the PLC values. A difference of 2.14 g between Shoe B (left) and Shoe C (left) shows significant differences (point 5 in the walking results section). A difference of 1.37 g between Shoe A (left) and Shoe B (left) shows a trend when the two trials are combined (point 5 in the walking results section). A difference of 1.44 g between Shoe B (right) and Shoe C (right) shows significant differences (point 5 in the walking results section). A difference of 1.09 g between Shoe A (right) and Shoe C (right) appears to have significant differences (point 4 in the walking results section) at times.

In addition to the low correlation coefficients, similar arguments show that the differences in the other three properties (time to maximum deceleration, maximum compression, percentage energy loss) do not support the significant differences in the PLC values that exist among the shoes.

Hence, it is reasonable to hypothesize that during walking, (a) a lower deceleration value will provide a higher level of perceived cushioning and (b) a minimum difference in deceleration of approximately 1.4 g is needed to adequately differentiate the cushioning between shoes by adult men.

**CONCLUSIONS**

The results and the outcome of the three experiments are clear. Impact characterizations can reveal important differences between materials and how they are perceived during activity. The combinatorial nature of the midsole materials allowed a thorough analysis of the “independent” properties related to PLC with three basic assumptions. The assumptions are reasonable, considering human perception and sensation. During standing and running, the PLC appears to be linked to material stiffness (or compression) and time to peak deceleration. Higher PLC values are observed with lower material stiffness. During walking, however, the magnitude of the deceleration seems to be a good predictor of PLC. Interestingly, the PLC values are independent of the property
of “energy loss,” which is really an indicator of the shock dissipation.

The similarities between standing and running are not surprising. If the dynamic stiffness is adequate for running, it can be assumed that the static stiffness, which is generally perceived during standing, is similar. However, the reverse may not be true – that is, the stiffness property appropriate for standing may not be desirable for running because of the high-impact loading resulting in more dynamic conditions. It is not clear why the PLC results for walking differed from the results for standing or running, even though, biomechanically, the heel loading is in between that of standing and running.

Comfort (Basford & Smith, 1988; Rys & Konz, 1989, 1990), discomfort (Godfrey et al., 1967; Silvino et al., 1980; Zhang et al., 1991), and tiredness (Redfern & Chaffin, 1995) have traditionally been used to quantify subjective perceptions. Such psychophysical parameters are whole-body dependent if not whole-body oriented. Measures such as PLC can give a more independent measure related to materials while helping one to understand the cause-effect relationships involved in the perception and sensation of footwear feel, as shown in Figure 2.

The ideal material will have the desired deceleration as well as the stiffness property. It is hoped that this will not only improve PLC but also reduce injury, pain, and discomfort. It should be noted that cushioning cannot be increased infinitely, considering its interaction with perceived stability. Hence, achieving the optimal level of cushioning without sacrificing stability is of utmost importance.

The conclusions drawn in this study are based on the impact tester parameters used. It would be good to perform more investigations with different settings if the dynamic properties of the materials are to be better evaluated.

APPENDIX: PARTICIPANTS’ CUSHIONING DESCRIPTORS

Standing

“Ability of a material to provide shock absorbance, comfort, softness [and] bounce.”
“Softness under the foot.”

“How my foot feels in relation to the ground…. If I can feel the ground underneath my foot, then…cushioning is not well.”

“Softness of the shoe and [the amount] the foot sinks.”

“Give of an object in response to my weight.”

“Something…that protects my feet on impact. Absorbing the shock.”

[Ability to] “provide shock absorption.”

“Shoe’s ability to absorb force…and protect the foot from impact shock. [Should] not absorb too much energy.”

“The ability to absorb shock….Feels good on your foot.”

“Amount of stability provided.”

“Basically the comfort when I put my foot on the ground…. With my socks, I can feel the floor is hard, and it's less hard” [with the shoes].

“Protection the shoe can offer….Part of the thing you look at when you are buying the shoes.”

“Something like softness…. It’s the degree of not feeling your body weight on the heels of your feet.”

“Ability to prevent the feeling of your weight under the foot.”

“Degree of not feeling your body weight on the heels of your feet.”

“The response to a subject’s weight or impact.”

“Something that feels soft and comfortable under my feet.”

“Amount of bounce the material provides.”

“Kind of shock absorbing.”

“…Comfort.”

Walking

“Cushioning helps absorb the shock, while still giving you a firm stable contact with the ground.”

“…Comfort.”

“…Amount of absorption of shock that my shoes have taken off the bottom of my foot. It takes away the pounding.”

“The softness…. How far your foot goes down in, or presses.”

“When I push down and… feel my weight sink down.”

“How your heel strikes the surface. How hard or soft it feels.”

“…A comfortable amount of deceleration.”

“…Soft enough for you not to feel the ground too much, but still prevents your feet from rolling side to side.”

“…Something that’s flexible and soft but still gives you support.”

“Very good cushioning is something that has a lot of squish to it.”

“…Feeling that there is something there on the bottom of the shoe, not too much. Not to where you feel you’re going to roll over.”

“…Comfort.”
“...Ability to absorb the shock during a striding motion...walking or running.”

“...Method by which shock is absorbed or at least reduced...the pounding [is] absorbed through whatever system you've got. Really, it's a slowing of the rate of descent...when the foot comes crashing down. So I think the key thing is slowing that rate.”

“The ability of the shoe to absorb the shock from the impact with the ground.”

“Something that gives adequate absorption of the shock and pressure without being too mushy or flexible....”

“It keeps you from feeling the hard ground under your foot, but at the same time is very smooth.”

“...Feel of the heel...whether it's mushy or a little bit more rigid. What kind of protection it affords...the bottom of your feet. Something could be so mushy, you know its not going to protect anything.”

“...The lack of [sensation] or the non-sensation of having your heel...strike anything. The shoes that seemed most comfortable to me were the ones that as I put my heel down..., I didn't feel like I was hitting anything. It was almost as if I was being gently absorbed into the step as I walked into it.”

“...Not too soft, but still stable. At least for walking, it doesn't have to absorb a lot of shock.”

“...In a short-term sense such as this, it is the impact you can really feel on your bottom bone, your ankle [heel] bone and kind of like in your ankle. But cushioning over the long term is for your joints, but in this instance, definitely how your foot hits the floor, the hardness you feel when you hit. The amount that takes away that stiff feeling.”

Running

“Shock absorption...I mean eliminating the jarring motion of my body against the road.”

“The...softness.”

“...Is reducing the impact when my heel hits the ground, so that I don't have a lot of shock going into my foot and legs.”

“...The ability to stop jarring in my body when I run.”

“...Ability to absorb the impact...”

“The combination of shock attenuation and it's a comfort factor as well.”

“Good support, good shock absorbency.”

“A reduction of impact forces on the heel, in my mind, in the heel area of the foot so it’s less intense.”

“The ability of a shoe to slow down and soften the impact of each step.”

“The impact between your leg and the road.”

“The ability of the shoes to deflect a person’s force or impact with the ground as they hit the ground, and the ability to absorb a person’s weight.”

“It’s the perceived amount of absorption of the impact. Possibly...how it spreads out or rebounds back.”

“...Protection of the shoe that keeps your foot from striking the ground hard...If it's too cushy, it feels very soft, but your heel still hits the ground and that's not adequate cushioning. So I'd say the deceleration of your heel, so that it hits the ground and provides support.”

“...Detour the shock from the surface...”

“...Is a soft but stable landing of the foot with equal response...when you land on the surface,...it springs you off the ground.”

“...The bottom of my foot...cannot feel the ground. I don't feel any shock...or the least amount of shock going from my shin bones all the way down to my heels.”

“...Protection of your foot, or of your whole leg from the shock of hitting the ground. But it's also increasing comfort over the long term. It should be firm, because if it's soft and it bottoms out, it doesn’t do any good.”

“Something that would cushion the heels as I run, but still give me a feel for the surface that I’m running on...take a lot of the impact away from the heels to keep me from getting shin splints since that’s a common occurrence for me. So, I’d say cushioning of the heels is pretty important.”

“The ability to attenuate shock or shock absorption. The best cushioning is somewhere in between totally absorbing shock, but then having enough memory that it comes back so that you’re not just sinking down and fighting it...like a marshmallow.”

“...Property in a shoe that cushions your body or regulates or governs the amount of shock your legs feel, but needs to do so in a way that doesn’t cause energy loss. In other words, shoes that can really absorb a lot of shock can get to be too soft, a shoe that's too hard can give you too much shock, so its somewhere in the middle for me.”

Acknowledgments

The author would like to thank Nike, Inc. for its support for this study. In addition, thanks are due to Jennifer Himmelsbach for conducting the experiments at the Nike Sport Research Laboratory in Beaverton, Oregon. The author would also like to gratefully acknowledge the support of the Research Grants Council in Hong Kong for making this paper possible.
REFERENCES


Athletic shoe cushioning. (1988, September/October). Nike Sport Research Review. [whole issue]


Cavanagh, P. R., Williams, R., & Clarke, T. E. (1979, October). Sophisticated testing procedures give runners significant new data. Runner’s World, 14, 48–75.


Physical tests. (1990, January/February). Nike Sport Research Review. [whole issue]


Ravindra S. Goonetilleke is an assistant professor in the Department of Industrial Engineering and Engineering Management at the Hong Kong University of Science and Technology. He received his Ph.D. in human factors engineering in 1990 from the State University of New York at Buffalo.

Date received: October 14, 1997
Date accepted: July 16, 1998.