THE MYTH OF RUNNING SHOE CUSHIONING[1]

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INTRODUCTION

The advent of the “Running Boom” in the late 1970’s coincided with the introduction of the first “technical” running shoe products incorporating cushioned soles and features intended to stabilize the foot during ground contact. The sensation of comfort provided by cushioned running shoes appears to have facilitated the participation of many “joggers” who would otherwise not have taken up the sport.

The Running Boom also precipitated rapid growth in related scientific research. In both university and corporate laboratories, studies of the physiology of exercise, the biomechanics of running and the mechanics of running shoes became common. Numerous investigators sought to determine a link between running shoe cushioning and the impact loads experienced by the runner. The results of these experiments were generally inconclusive, however. Many researchers reported no differences in peak impact force among different cushioning systems and, in some instances, more compliant cushioning was found to <u>increase</u> impact force.

These equivocal results have lead others to hypothesise that running shoe cushioning offers little benefit to athletes. Very compliant cushioning may increase injury risk in some instances, since there is a correlation between cushioning compliance and excessive subtalar joint motion, which has been linked with common running injuries (Clement et al, 1981). Some (e.g. Robbins and Waked (1997)) have interpreted the available data less equivocally, stating bluntly that cushioned athletic shoes are dangerous and that shoe companies offering cushioning as a benefit are guilty of deception.

The purpose of this paper is to briefly summarise some of what is known about the mechanics of running shoe cushioning, in an attempt to determine why the expensively engineered shock attenuating systems built into athletic shoe soles apparently fail to attenuate shock.

THEORETICAL EFFECTS OF SHOE CUSHIONING

In theory, more compliant cushioning system can be expected to reduce peak impact forces. For a mass, $\boldsymbol{m}$, falling onto a spring of stiffness, $\boldsymbol{k}$, with initial velocity $\boldsymbol{v_0}$, the peak impact force, $\boldsymbol{F_{max}}$, is given by

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$$F_{max} = mg\left(1+\sqrt{1+\frac{k}{m}\left(\frac{v_0}{g}\right)^2}\right) \qquad (1)$$

predicting that peak impact force will decrease roughly in proportion to the square root of the cushioning system stiffness.

Hertzian contact theory (e.g. Johnson, 1985) also raises the expectation that shoe cushioning within an appropriate range of material properties will reduce impact forces. Assuming that both the foot's fat pad and the cushioned shoe behave like elastic half spaces with elastic moduli of λ_{foot} and λ_{shoe} respectively,

$$F_{\max} \propto \left(\lambda\sqrt{R}\right)^{\frac{3}{2}} \qquad \text{with} \qquad \lambda = \left[\lambda_{foot}^{-1} + \lambda_{shoe}^{-1}\right]^{-1} \qquad (2)$$

where R is the uncompressed radius of the fat pad. Hertz theory also predicts that the peak pressure on the plantar surface, P_0, with decrease with more compliant cushioning ($P_0 \propto (\lambda / R)^{2/3}$). Finite element models also predict lower impact forces and lower peak pressures at the plantar surface when the cushioning system is more compliant (e.g. Shorten, 1993; 1994).

IN-VITRO TESTS OF CUSHIONING

In vitro mechanical tests of shoe cushioning generally confirm the predictions of mathematical models. Figure 1 compares the force-time curves from standard impact tests (ASTM F1976) of shoes with relatively firm and relatively soft cushioning systems. Consistent with simple elastic collision models, the more compliant sole attenuated the peak force of impact, extended the contact time of the collision and reduced both the peak and average rates of loading.

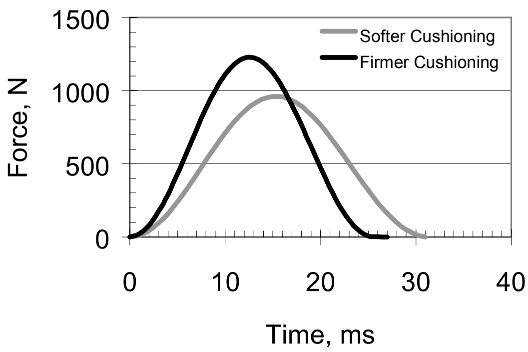

Fig 1. Shoe Cushioning Impact Tests

IN-VIVO GROUND REACTION FORCE COMPONENTS

The ground reaction forces recorded during running have a characteristic pattern that scales with body mass and running speed (Cavanagh & Lafortune,1980; Munro *et al* ,1987). Figure 2 shows an example of the vertical component of force during a running step. Nigg (1983) first described the two distinct peaks as "passive" and "active" phases. The passive phase reflects the initial impact between the body and the ground and is determined by the initial conditions of impact. The active phase reflects the propulsive forces applied by the musculo-skeletal system.

The first studies of running shoe cushioning were conducted using the "passive" peak in the vertical component of the ground reaction force (***F_{z1}***) as an index of impact shock; hypothesizing that more compliant cushioning would reduce impact loads and, by extension, impact-related over-use injuries. The hypothesis has never been confirmed however. In contrast to theory and the results of *in vitro* tests, running shoes do not appear to reduce impacts forces during running. While some studies found that cushioning decreased peak impact forces, many researchers have reported no differences among different cushioning systems (e.g. Clarke, et al, 1983). In some cases, researchers have reported that softer shoes <u>increased</u> impact force (e.g. Nigg et al, 1981). As noted earlier, the of experimental evidence for a significant effect of cushioning on *in-vivo* impact force has lead some to believe that shoe cushioning effects are illusory.

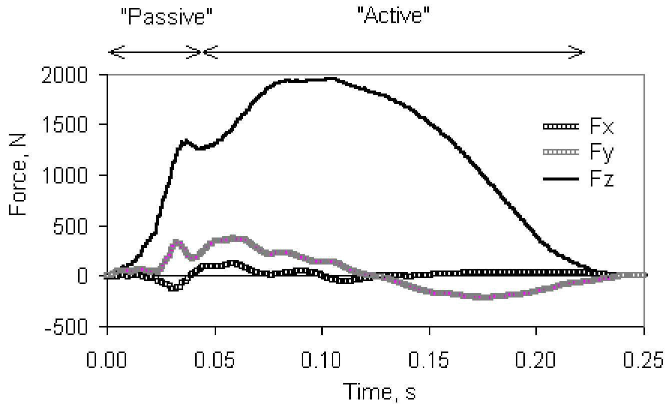

Fig 2. Orthogonal components of the ground reaction force during running, with phases marked according to Nigg (1983).

PLANTAR PRESSURE DISTRIBUTION

The reaction forces acting on the runner are not applied at a single point, but are distributed over the plantar surface of the foot. Figure 3 shows the peak pressures experienced by different regions of the foot while running in shoes with different degrees of cushioning. The "minimal", "average" and "firm" cushioning conditions approximate the 5th, 50th and 90th percentiles of cushioning stiffness found in commercially available running shoes. With increasingly compliant cushioning, in-shoe pressure measurements show a redistribution of plantar surface loads away from bony prominences to more peripheral regions, with a consequent reduction in peak pressure. The rate of pressure increase during impact is also much less pronounced in more cushioned shoes. These findings are qualitatively consistent with models of contact between non-conforming elastic bodies and, in contrast to ground reaction force measures, appear to suggest that shoe cushioning does influence the way in which the body is loaded.

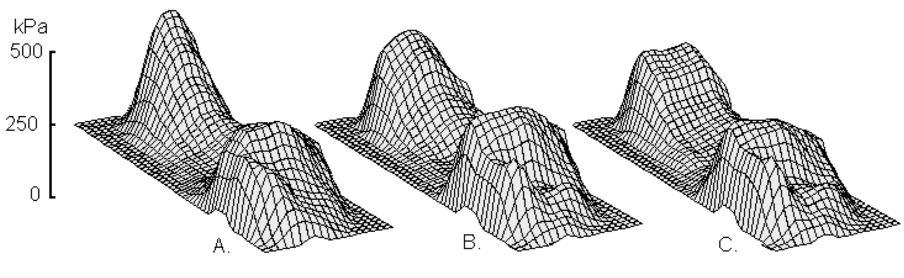

Fig 3: Peak pressure on the plantar surface during a running step.
(A) "Minimal" Cushioning (B) "Average" Cushioning (C) "Firm" Cushioning
(5.0 m s^{-1}, mean of 5 steps from each of 12 subjects)

OTHER MEASURES OF LOAD

While measurements of ground reaction force and in-shoe plantar pressure offer direct means of evaluating the effects of cushioning on the loads transmitted to the body, there are other approaches. These include the measurement of shock-related decelerations in the lower extremity and at the head, both in the time and frequency domains (e.g. Shorten and Winslow, 1992). Physiological studies of oxygen uptake and mechanically induced haemolysis have also shown significant cushioning effects (e.g. Dressendoefer et al, 1992), consistent with reduced load. While ethical standards do not permit controlled studies of injury mechanisms in humans studies, there is indirect evidence of cushioning effects from experiments showing reduced rates of lower extremity injury and reduced low back pain when cushioned inserts are added to footwear (e.g. Milgrom et al, 1992).

One of the more sensitive cushioning detection tools is the human brain. People are sensitive to differences in cushioning and can detect heel stiffness differences greater than about 10-15 kN m^{-1} in magnitude. Psychophysical studies have found that a runner's subjective perception of impact in different shoes is highly correlated with the shoes' scores on a standardized impact test, but not with the magnitude of the impact peak in the ground reaction force.

GROUND REACTION FORCES REVISITED

A brief survey of research into the effects of running shoe cushioning on the loads transmitted to the body suggests a degree of consistency among different approaches to the problem. Mathematical models predict that more compliant cushioning will reduce peak impact forces, peak plantar pressures and peak rates of loading. *In vitro* mechanical tests are consistent with these predictions. *In-vivo* measurements of plantar pressure distribution and leg shock also show effects that are qualitatively consistent with theories describing low velocity collisions between elastic bodies. However, the body of research showing that running shoe cushioning has no effect on impact forces is not consistent with theory, *in vitro* tests or other *in-vivo* measures. Clearly, this discrepancy must be resolved if we are to determine whether athletic shoe cushioning is a useful ergogenic aid, simply a myth promoted by shoe companies, or even harmful to athletes.

A closer examination of the ground reaction force reveals factors that may limit it's value as a measure of cushioning.

Firstly, the measurement and analysis of ground reaction forces assumes that the body is acted on by single force vector accelerating the center of mass. However, the reaction force actually reflects the vector sum of the accelerations of many segmental masses, each accelerating with a unique direction and rate. Consequently, the assumption that the passive force peak reflects loads in the lower extremity may not be a safe one. The analysis of Bobbert *et al* (1991), for example, has shown that while the passive peak has its origin in the accelerations of the lower extremity, the peak's magnitude is largely determined by accelerations of the rest of the body.

Secondly, the ground reaction force is distributed spatially, temporally and in the frequency domain. The effects of cushioning on impact force in the heel may be masked by superimposition of low frequency "active" components and forces acting on other parts of the foot. A similar superimposition has been found in leg shock measurements (Shorten and Winslow, 1993)

Figure 4 shows ground reaction forces from running in three shoes with different cushioning characteristics, decomposed in to spatial and frequency domain components. In the first case (Figure 4A), simultaneous pressure distribution measurements were used to distinguish force components acting on the heel from the forces acting on other regions of the foot. In the second case (Figure 4B), spectral analysis was used to isolate and reconstruct low (<= 8 Hz) and high (> =12Hz) frequency components.

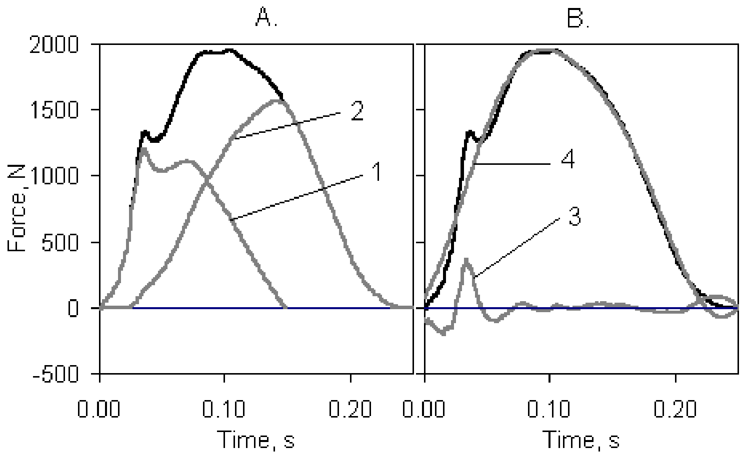

Fig 4. Components of the ground reaction force during running (1) heel (2) forefoot (3) high frequency (4) low frequency.

These data demonstrate that the magnitude of the passive impact peak is not uniquely determined by the high frequency heel impact components that are the target of shock attenuating shoe soles. Both the low frequency motions of the body's center of mass and loads applied to other regions of the foot contribute to the peak. In this typical example, the superimposed signals contribute more than half the peak's magnitude.

DISCUSSION

The observation that the passive peak of the ground reaction force does not reliably reflect the magnitude of high frequency impact loads to the heel may explain the inconsistencies between cushioning studies relying on ground reaction force data and those using other means of determining cushioning effects, including simulation models, *in vitro* mechanical tests, *in-vivo* pressure and shock measurements and psychophysical measurements of perceived shock attenuation.

Other factors may have contributed to the mythology of cushioning, too. Cushioning materials are typically non-linear and very soft shoes will bottom out when loaded, producing higher impact forces than firmer shoes that do not bottom out (Nigg et al, 1981). Other significant variables include the various accommodations that the musculo-skeletal system makes in response to different levels of impact load.

In future studies, there is a clear need for more thorough characterisation of the cushioning properties of experimental conditions and careful choice of appropriate indicators of cushioning performance. As research in this area continues, greater attention to "The Mythology of Ground Reaction Force Measurements" and more detailed study of neurological, biological and psychological factors should lead to a better understanding of athletic shoe cushioning mechanics.

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