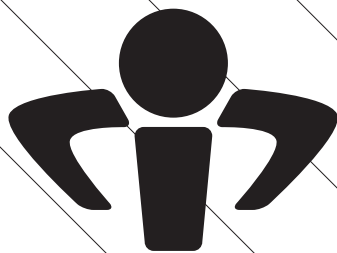


The Use Of Viscoelastic Materials In Shoes and Insoles

A Review

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The use of viscoelastic materials in shoes and insoles: a review

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ABSTRACT

Viscoelastic materials are commonly used in the construction of running shoes, and may be used as an insole in other types of shoe. Like other elastic materials, viscoelastic materials are effective in redistributing the pressure beneath the foot, thereby reducing local pressures and the stresses on foot structures. By absorbing energy, viscoelastic materials reduce the heelstrike transient, which originates beneath the foot at initial ground contact, and is transmitted up the skeleton as a "shock wave". This shock wave appears to damage soft tissues, and the use of viscoelastic materials in footwear has been shown to reduce the incidence and severity of a variety of overuse injuries of the foot, leg and low back, including the painful heel syndrome, femoral, tibial and metatarsals stress fractures. It is also probable that excessive levels of shock can overstress the joints, resulting in osteoarthritis. The heelstrike transient may also accelerate the loosening of prosthetic joints. In healthy individuals, the fat pad beneath the foot acts as a viscoelastic shock absorber. If this function is degraded by age or disease, viscoelastic footwear materials may be used to replace or augment it. Many different polymers have been used for these purposes, as either elastomers or foams. While most are effective when new, the softer foam materials tend to deteriorate rapidly with use. Very compliant foams tend to "bottom out" at moderate loads, unless a considerable thickness is used, which is seldom practical. Insoles combining two or more materials appear to offer the best overall performance.

INTRODUCTION

Viscoelastic materials came into widespread clinical use during the 1980's, for two primary purposes - to reduce the effects on the hands of damaging vibrations in industry, and for use in footwear. The present review is devoted to the latter application. Viscoelastic materials have been promoted for the relief or prevention of a large number of conditions, including degenerative joint disease, headaches, prosthetic joint loosening, plantar fasciitis,

Achilles tendinitis, muscle tears and stress fractures (Pratt, 1989). Transient skeletal forces have been suggested as the primary etiological agent in many of these conditions, and it has been demonstrated that these forces can be reduced through the incorporation of viscoelastic materials into the footwear, either in the construction of the shoes, or as additions to shoes, such as insoles or orthotics.

Many materials are viscoelastic to a greater or lesser extent. Those which have been used clinically fall into seven groups: 1) polyurethane elastomers (e.g., Cambion, Sorbothane, Viscolas); 2) polyurethane foams (e.g., Cleron, Poron, PPT); 3) polyethylene foams (e.g., Evazote, Frelon, Pelite, Plastazote); 4) polyvinyl chloride foams (e.g., Implus); 5) ethylene vinyl acetate (EVA); 6) synthetic rubber foams (e.g., Neoprene, Noene, Spenco, Ucolite, Zdel), and 7) silicone rubber. The main viscoelastic materials used for footwear and insoles were reviewed by Rome (1990). The foams are cellular materials, which may be either open or closed cell. Open cell materials resemble a sponge, where the bubble walls are incomplete, allowing free exchange of air in and out of the material. In closed cell materials, air or some other gas (usually nitrogen) is trapped within minute bubbles, which become pressurized when the material is stressed, the gas pressure aiding in the elastic recovery. In contrast to the various foams, polyurethane elastomer is a soft, non-porous rubbery material.

An undesirable property of many foams is "compression set", in which repeated loading causes the walls of the cells to collapse, leading to a loss of material thickness, elasticity and energy absorption capacity. Foam materials differ in their resistance to compression set, due to their chemical makeup and their initial stiffness. Polyurethane foams were found to be more resistant to compression set than polyethylene foams of similar density (Brodsky et al., 1988). Closed-cell foams tend to resist compression set better than open-cell foams. Foam materials are usually only immune to compression set if they are relatively stiff, such as the materials which are used in midsole construction for sports shoes. Materials as stiff as this are unlikely to provide useful pressure redistribution beneath a painful foot. Polyurethane elastomer is much less susceptible to compression set than foam materials (Edwards & Rome, 1992).

This review will first consider the mechanical properties of these materials, and then go on to examine their clinical uses. Publications on this topic have appeared in a wide variety of places, including presentations at scientific conferences, book chapters, dissertations, theses, articles in

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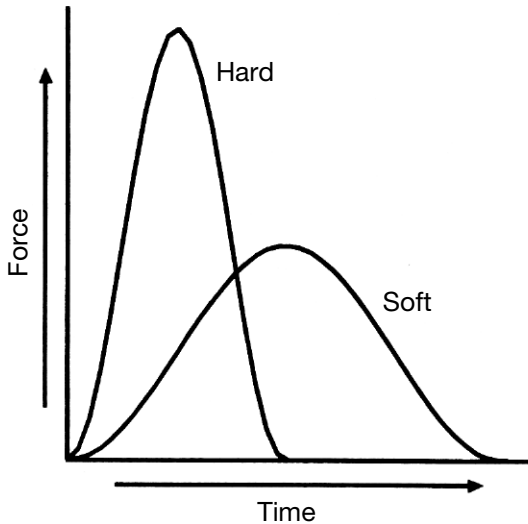


Figure 1: A higher force occurs, over a shorter period of time, when impact takes place with a hard surface, rather than a soft one. The momentum exchanged, represented by the area under the curve, is the same in each case.

trade journals, magazines and newsletters. However, the present review is based almost entirely on studies which have been published in peer-reviewed scientific journals.

MECHANICAL PROPERTIES OF VISCOELASTIC MATERIALS

Viscoelastic materials, as their name suggests, combine two different physical properties. The term "viscous" implies that they deform slowly when exposed to an external force. The term 'elastic' implies that once a deforming force has been removed, they return to their original configuration, in contrast to viscous fluids, such as oil or syrup, in which deformation involves a permanent rearrangement of the fluid molecules. Viscoelastic materials are often characterized in the literature by an engineering measurement known as the 'tan delta', or 'loss tangent' which is the ratio of the viscosity of a material to its elasticity.

From a clinical standpoint, one of the most important properties of viscoelastic materials is their ability to reduce the magnitude of impact forces, which they achieve in two different ways: by extending the time course of the, impact event, and by absorbing energy. This will be illustrated with respect to the impact force which occurs at heelstrike (the 'heelstrike transient'), when the heel contacts the ground at the beginning of the stance phase of gait. Any moving object, such as the foot during the swing phase of gait, possesses momentum, which is the product of its mass and its velocity. Following the heelstrike transient, the foot comes to rest on the ground, so that its velocity, and hence its momentum, becomes zero. Since momentum cannot be created or destroyed, the

momentum of the moving foot must be transferred to the ground, by means of a force between the heel and the ground, which results in a (very small!) acceleration of the whole earth.

As well as possessing momentum, the moving foot also possesses kinetic energy, given by the formula $1/2mv^2$ (where m is the mass and v the velocity). Energy must be conserved following an impact event, but it may be converted into a number of different forms. In the case of the heelstrike, some of the energy goes into accelerating the earth (dictated by the need to conserve momentum), some is stored as elastic potential energy, and the remainder is dissipated as heat and sound.

The magnitude of the force between the heel and the ground depends on two things: the amount of momentum transferred, and the time it takes to transfer it. Momentum is equal to the product of force and time, so that the same amount of momentum may be transferred by a large force in a shorter time, or by a smaller force in a longer time (Fig. 1). Any elastic materials, including viscoelastic ones, are able to lengthen the time taken to transfer the momentum, and hence to reduce the magnitude of the peak force. However, if the heel is decelerated over a longer period of time, it must necessarily travel further. Thus, reducing the peak force in this way requires the presence of a finite thickness of compressible material. Where the thickness of material is inadequate, the phenomenon of 'bottoming-out' occurs, the stiffness of the material increasing abruptly once it has been compressed through most of its thickness. Very soft, compliant materials are often used for insoles sold "over the counter", but they give little protection to the feet, because they bottom out too readily when

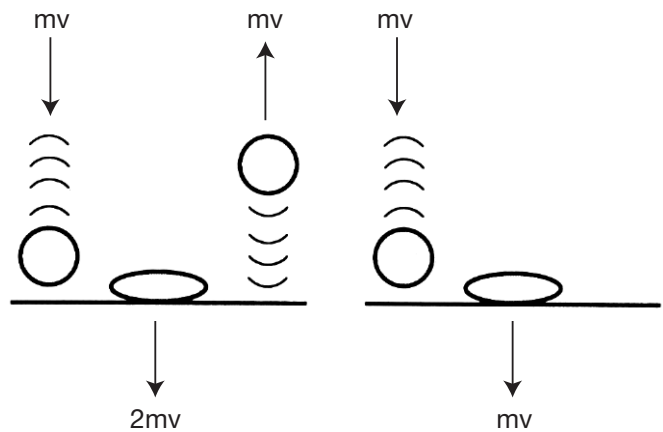


Figure 2: When a falling object bounces (left) its downward momentum (mv , where m is mass and v velocity) is replaced by upward momentum, making the total momentum transferred to the supporting surface $2mv$. An object which does not bounce (right) only undergoes a momentum transfer of mv .

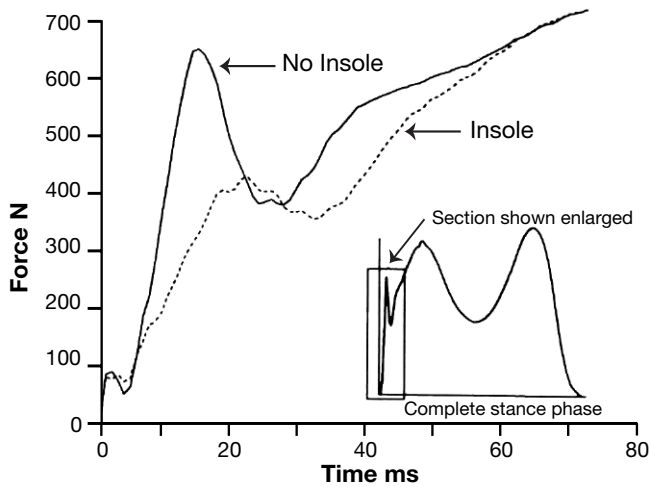


Figure 3: Vertical ground reaction force from two walks by the same individual in the same shoes, with and without a viscoelastic insole (see text). The main graph is an enlargement of the area indicated in the insert.

everyday walking loads are applied to them.

An important difference between elastic and viscoelastic materials beneath the heel is that purely elastic materials return most of the momentum to the foot, whereas viscoelastic materials return little or none, through the absorption of energy. If an elastic material was able to store and return all of the energy, the change in momentum would be from mv downwards (where m is mass and v velocity) to mv upwards, a change in momentum of $2mv$ (Fig. 2). In contrast, with a viscous material capable of dissipating all of the energy, the change in momentum would be only half as much (mv). This difference in the change in momentum is mirrored by the magnitude of the ground reaction force. With viscoelastic materials, the material recovers from deformation over a period of time, and the energy which was used to deform it is largely converted to heat. The time course of this recovery depends on the formulation of the viscoelastic material; to be effective in the heel of a shoe, most of the recovery needs to occur before the next step is taken. Fig. 3 shows the vertical ground reaction force following initial contact by the same individual wearing the same hard-heeled shoes, both without an insole and with an insole consisting of an upper layer of open-cell polyurethane foam and a lower layer of polyurethane elastomer (Cambion; Magister Corporation, Chattanooga, Tennessee). The magnitude of the heelstrike transient is markedly diminished by the insole, and its time course is extended. Since the area beneath each curve represents the change in momentum, the difference between the two curves demonstrates the difference between the two conditions in the amount of momentum exchanged.

The mechanical properties of materials are usually examined by means of a stress/strain (or load/deformation) graph (Fig. 4). For purely elastic materials, the lines representing loading and unloading

are superimposed; for viscoelastic ones they form a 'hysteresis' loop, the area within the loop representing the energy lost. This energy absorption explains why viscoelastic materials are better than purely elastic ones at reducing the peak force at heelstrike: an elastic material returns both momentum and energy to the heel, by means of an increased and prolonged ground reaction force, whereas a viscoelastic material transfers momentum to the ground, and converts the associated energy into heat.

A further important property of viscoelastic materials is that their mechanical properties depend on the rate at which they are deformed, the stiffness increasing with the loading rate. There is thus not just one stress/strain curve, but a whole family of curves, representing different deformation rates (Fig.4). In selecting materials for clinical application, it is important to examine the material properties at an appropriate loading rate. An excellent review of the requirements for the realistic testing of insole materials was given by Garcia et al. (1994). The properties of many of these materials vary considerably with both temperature and humidity, and it is important that testing is carried out under conditions similar to those which exist beneath the foot (Pratt, 1989a).

TRANSIENT TRANSMISSION FORCE GENERATION AND TRANSMISSION

Much of the research on the use of viscoelastic materials in footwear has been directed toward the generation of transient forces, and their transmission up the skeleton. As a result of the heelstrike, an acceleration 'wave' passes up the skeleton, which (in accordance with Newton's second law) must necessarily be associated with a force. In the literature, this transient

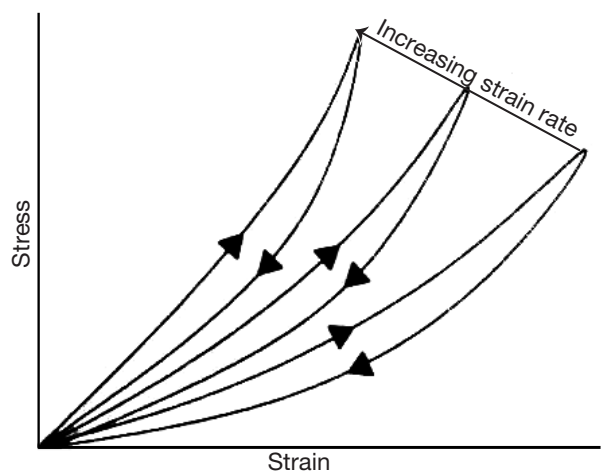


Figure 4: Typical features of the stress/strain relationship in a viscoelastic material: a) the curves are not straight lines, indicating non-linear elasticity; b) different rates of performing the test (strain rates) produce different curves; c) the ascending and descending portions follow different paths (hysteresis), the area within the curve indicating the absorption of energy.

acceleration and its associated force - have generally been referred to as a 'shock wave' or 'stress wave'. There is a wealth of evidence, reviewed below, that these transients exist, and that their amplitudes may be decreased by using viscoelastic materials either in the construction of the footwear, or as an insole. However, although it seems reasonable to suppose that these transient forces are harmful, there is only indirect evidence for this, in the relief of symptoms which often follows the attenuation of these forces by the use of viscoelastic materials. There is little direct evidence that the forces are harmful under physiological conditions in humans, mainly because the damage occurs over a long period of time, making it difficult to perform adequate prospective studies. The way in which the heelstrike transient is generated, and how it can be measured, was reviewed by Collins & Whittle (1989).

The "gold standard" for research on the heelstrike transient has involved the mounting one or more accelerometers on pins, inserted into the tibia of a volunteer (Light & McLellan, 1977; Light et al., 1980; Lafortune & Hennig, 1992), although for obvious reasons this invasive procedure has only been used occasionally. Much of the early work using this method was performed by Light and co-workers, who showed that during normal walking, the heelstrike generates an acceleration of up to 80ms^{-2} (8g) in the tibia, but much less in the skull, since passage through successive joints attenuates and delays the acceleration wave, and removes high frequency components (Light & McLellan, 1977). The same authors showed that the transient acceleration in the tibia was reduced when wearing shoes incorporating a viscoelastic polymer in the heel (Light et al., 1980). More recently, Latortune & Hennig (1992) used bone-mounted accelerometers in five subjects, and showed differences in the magnitude of the heelstrike transient between the barefoot and shod conditions, and confirmed the attenuation of the acceleration wave by the joints, as it passes up the body.

Although the use of bone-mounted accelerometers represents the optimum method for studying the heelstrike transient, useful data can also be obtained non-invasively using skin-mounted accelerometers, providing careful attention is paid to the method of mounting (Wosk & Voloshin, 1981; Voloshin & Wosk, 1982; Johnson, 1986; Pratt, 1988). Early studies were made using an accelerometer mounted on a plate which was glued and strapped to the skin on the front of the tibia (Light & McLellan, 1977), but it has subsequently been suggested that this method of mounting might not have given valid results (Latortune et al., 1995). An instrument for in vivo testing of footwear and insoles, based on the spectral analysis of the output of an accelerometer firmly mounted over the lateral malleolus, was developed by Johnson (1990).

Valuable information on the heelstrike transient can also be obtained using a force platform, providing it has a high enough natural frequency, and providing the data are not low-pass filtered prior to analysis (Simon et al., 1981). Using a force platform, Simon et al. showed that the magnitude of the heelstrike transient depends on the velocity and angle at which the foot meets the ground, and on the compliance of the two materials coming into contact.

The body has two natural defenses against potential damage from the heelstrike transient: appropriate joint alignment (such as knee flexion), and viscoelastic materials in both the heel pad and the joints (Pratt, 1989b). Footwear, particularly if it incorporates viscoelastic materials, may provide an additional line of defense.

HEEL PAD PROPERTIES

There already exists in the body a mechanism in which a viscoelastic material reduces the force of the heelstrike transient: the heel pad. The majority of body tissues are viscoelastic, and the heel pad particularly so. However, estimates of energy absorption by the natural heel pad of up to 99% (Valiant, 1990) have subsequently been revised downward, since the results of some of the earlier in vivo testing included the energy-absorbing properties of the lower leg. A more realistic estimate for the energy absorption by the heel pad itself is between 47 and 66% (Aerts et al., 1995). The use of a Viscoelastic material in a shoe or insole thus augments a function the body already possesses (Jorgensen & Bojsen-Moller, 1989), and replaces lost function when the natural heel pad becomes degraded. The normal heel pad is between 10 and 20 mm thick (Jorgensen & Bojsen-Moller, 1989; Ker et al., 1989; Valiant, 1990; Noe et al., 1993). Estimates for the compression of the heel pad during the heelstrike transient have ranged from about 3mm (Light et al., 1980) to about 8mm (Valiant, 1990). Realistic values for the mechanical properties of the heel pad, for use in mathematical models of the heelstrike, were given by Ker et al. (1989).

A number of studies have stressed the idea that viscoelastic materials in footwear do not act in isolation, but interact with the natural heel pad. The shock absorption of the natural heel pad depends to a large extent on the extent to which it can be confined and prevented from spreading sideways upon impact loading. Jorgensen & Ekstrand (1988) modified shoes so that the material directly below the heel was retained, but the surrounding area, known as the 'heel counter', was removed. This decreased the shock absorption of the heel pad by an average of 9%, both in gait and in a test where the subject was dropped from a height of 100 mm, landing on the heel of one foot. Lafortune & Hennig (1992) went so far as to suggest that the main effect of

shoes is to confine the heel fat pad, although they did suggest that the compliance of the shoe itself also provides impact attenuation. In cadaver studies, Noe et al. (1993) showed that viscoelastic insoles are able to augment the shock absorption of the natural heel pad.

LOSS OF NATURAL VISCOELASTICITY WITH AGE AND DISEASE

A clinically important use of viscoelastic materials beneath the heel is in individuals whose natural heel pads have lost some or all of their shock-absorbing function. With age and overuse, or following trauma, changes may occur in the structure of the heel pad, including a reduction in thickness, rendering it 'dysvascular and senescent' (Jahss et al., 1992). This results in a loss of shock absorbing capacity (Jorgensen & Bojsen-Moller, 1989), which may lead to diffuse heel pain, plantar fasciitis and Achilles tendinitis (Valiant, 1990).

In addition to changes in the shock absorption of the heel pad, other types of pathology may also reduce the shock absorbing capacity of the lower limb. Voloshin & Wosk (1983) showed that the ability of the knee to attenuate impulsive loads is decreased following meniscectomy or degenerative joint disease.

LABORATORY MATERIALS TESTING OF VISCOELASTIC

Much of the laboratory testing which has been performed on viscoelastic materials is beyond the scope of the present review. However, some of the more pertinent studies will be mentioned. They indicate that most viscoelastic materials provide useful shock absorption under physiological conditions, but that foam materials deteriorate much more rapidly with use than elastomeric materials.

Cinats et al. (1987) made careful measurements of the energy-absorbing properties of a viscoelastic polymer under physiological conditions, and suggested that other authors had been optimistic as to the energy absorption; they thought that only about 10% of the heelstrike energy was likely to be absorbed.

Lewis et al. (1991) suggested a 'performance index' for shoe insert materials, based on both shock absorption and energy return. They regarded energy absorption as harmful (without producing any evidence for this unusual point of view), and as a result the performance index was highest for elastic materials with low viscosity. This approach appears to contradict most of the other published work on this subject.

Garcia et al. (1994) introduced a more 'physiological' laboratory test method than had been used previously, and found that a 'micro-air elastomer' provided the highest energy absorption, followed by a polyurethane

elastomer. They suggested that materials which are too stiff, when tested at realistic strain rates, would not provide good pressure redistribution beneath the foot. They also found wide variations in material properties between different thickness samples of the same material.

A particular problem with foam materials is 'compression set', described above. In a series of long-term wear tests on a variety of insole materials, Pratt and co-workers found that when new, polyurethane elastomers and polyurethane foams were similar to each other in shock-absorbing performance, and were better than other materials. After prolonged use, however, the elastomers retained most of their shock absorption, whereas the foams deteriorated (Pratt et al., 1986; Pratt, 1988, 1989b, 1990). Edwards & Rome (1992) similarly found that a polyurethane elastomer provided better shock absorption following 40 hours of wear than a variety of cellular materials. They suggested that solid materials generally (which in this context would include polyurethane elastomer and silicone rubber) are to be preferred to cellular materials of whatever type, since they are essentially immune to compression set.

VISCOELASTIC MATERIALS IN WALKING

There is abundant evidence that viscoelastic materials are capable of reducing the magnitude of the heelstrike transient during walking. This has been demonstrated using accelerometers mounted directly to bone, skin-mounted accelerometers, force platforms, and in-shoe pressure-measurement devices.

Only a few studies on heelstrike attenuation have been performed using bone-mounted accelerometers. Light et al. (1980) showed that the use of resilient crepe shoe heels reduced the heelstrike transient, and that inclusion of a polyurethane elastomer in the heel reduced reverberation immediately following heelstrike. Lafortune & Hennig (1992), using bone-mounted accelerometers, showed that leather-soled street shoes attenuated the heelstrike transient by 36%, compared with the barefoot condition, and athletic shoes (incorporating viscoelastic materials) attenuated it by 46%. However, they did not examine the effects of insoles.

A large number of studies on the effects of viscoelastic materials on the heelstrike transient have been performed by Voloshin and co-workers, using lightweight accelerometers firmly fixed to the skin over the tibia. Voloshin & Wosk (1981) used this technique to quantify the effect on the heelstrike transient of a viscoelastic arch support, finding a mean reduction of 42% in the peak acceleration. This group also showed that the use of high-heeled shoes caused an increase in the dynamic loading on the musculoskeletal system, and that viscoelastic shock absorbing devices can reduce such loading (Voloshin & Loy, 1994).

Johnson (1986) showed that spectral analysis of the output of skin-mounted accelerometers could be used to examine insole material performance. Using this method, he compared the performance of nine different viscoelastic polymer insoles (Johnson, 1988). He stated that 'statistically significant shock reductions can be achieved by insoles', but also pointed out that both the fit and the mechanical properties of the shoe affected the ability of the insole to absorb shock. Valiant (1990) showed that during walking, viscoelastic insoles can reduce the peak acceleration at the tibia by 50%.

Shiba et al. (1995) used a force platform to measure the heelstrike attenuation provided by three viscoelastic insole materials. All three reduced the magnitude of the heelstrike transient and prolonged the time taken to reach peak force. Laboratory determinations of energy absorption showed general agreement with the walking trials, regarding the relative performance of the three materials.

As well as studies on insoles, Voloshin (1988) showed that athletic shoes reduced impact forces by between 10 and 45%, and the use of 6mm thick viscoelastic insoles further reduced skeletal forces by 20-30%. There were considerable differences between the insoles, but the author used trade names without material descriptions, so that it is impossible to make generalizations about the different types of material.

VISCOELASTIC MATERIALS IN RUNNING, JUMPING AND CLIMBING STAIRS

Research on transient forces in running has suffered from technical problems, which are outlined below. However, allowing for these difficulties, it is apparent that viscoelastic materials in the region beneath the heel provide useful peak force reduction in rearfoot striking runners. In running with midfoot striking, and in jumping and stair climbing, viscoelastic materials used as the midsole in shoe construction provide significant peak force attenuation, but there is generally insufficient space within a shoe to add a shock-absorbing insole thick enough to be useful.

Two characteristics of running have caused difficulties with research on the effects of viscoelastic materials - the existence of two distinct running styles, and the relatively high speed with which the events of running occur. Cavanagh & Lafortune (1980) described the two different running styles: rearfoot and midfoot striking. Since midfoot strikers make initial contact with the forefoot, it could be anticipated that viscoelastic materials in the heels of their running shoes would provide little shock absorption, but much of the research in this area has neglected this factor. The speed of events in running may also lead to errors, for example when force platforms with

an inadequate frequency response are used to study running. Lafortune et al (1995) reported problems due to the speed of events in running, which cause surface-mounted accelerometers to give inconsistent results, when compared with bone-mounted devices.

MacLellan & Vyvyan (1981) conducted a prospective study in which viscoelastic inserts were prescribed for 14 runners with Achilles tendinitis; 12 reported complete relief of symptoms within three months, one was improved and the other unchanged. Dickinson et al. (1985) demonstrated that barefoot-running, with rearfoot striking, resulted in a large heelstrike transient, which was entirely eliminated by the use of running shoes. Voloshin (1988) showed that skeletal shock is between three and four times higher in running than in walking. Oakley & Pratt (1988) found that a variety of materials were able to reduce skeletal transients in heelstrike running, but that only one (polyurethane foam) reduced transients in toestrike running. Geiringer (1995) stated that running on hard surfaces probably produces stress fractures of the metatarsals through direct impact forces, and recommended the use of viscoelastic insole materials, both in prevention and treatment.

In a computer simulation, Gerritsen et al. (1995) showed that the viscoelasticity of the foot-ground interface absorbs most of the energy in running, and that both the elasticity and the viscosity influence peak forces.

In contrast to most other studies, Nigg et al. (1988) reported that the addition of viscoelastic insoles to running shoes did not modify the 'vertical impact force' in running by rearfoot strikers. However, they reported the impact peak as occurring 20-30 ms after initial contact, whereas Dickinson et al. (1985) stated that in barefoot running the transient occurs around 5 ms after initial contact. The implication is that the heelstrike transient was attenuated by viscoelastic materials in the shoes (which were not described) to such an extent that the addition of viscoelastic insoles made little or no difference.

Most of the studies on the ability of viscoelastic materials to attenuate shock have been concerned with the heelstrike, in either walking or running. However, Loy & Voloshin (1991) pointed out that in going up and down stairs, and in landing from a jump, the initial contact of the foot with the ground is by the metatarsals, rather than the heel. This area of the foot is less well protected than the heel, and useful shock attenuation could be provided by insoles based on polyurethane elastomers. There are, however, practical problems imposed by the lack of space for insoles in this area, in the majority of shoes.

ENDOPROSTHESIS LOOSENING

A number of authors (e.g., Pratt, 1989b) have suggested that prosthetic joint components may be loosened by transient forces, such as that generated by the

heelstrike, and that the use of viscoelastic materials in footwear may be able to retard or prevent this process. However, to date this remains simply an attractive theory, since no prospective studies have been conducted to test it.

Bergmann et al. (1995) suggested that prosthesis loosening depends on both the magnitude and direction of applied forces. They measured the forces in the prosthetic hip joint of an 82-year-old man, and found that the lowest forces were encountered in barefoot walking and jogging. They failed to show a benefit from walking with 'softer' shoes, but did not test viscoelastic insoles as such. They found that the peak joint force was largely uninfluenced by the heelstrike transient, which is presumably attenuated by its passage up the leg.

Rooser et al. (1988) studied tibial acceleration in patients who had received a total knee joint replacement for rheumatoid arthritis. They found no significant attenuation of the heelstrike transient by a number of different commercial viscoelastic insoles, but shoes with thick viscoelastic heels did provide significant attenuation. They suggested that their results may have differed from others in the literature because these individuals walked very slowly. They concluded that 'footwear with shock-absorbing soles could probably reduce the peakloads [sic] at the cement-bone interface...'

DEGENERATIVE JOINT DISEASE

Research on the use of viscoelastic footwear materials in relation to degenerative joint disease has centered around two areas: prevention and treatment. The theory (described below) that the heelstrike transient is a major etiological factor in degenerative joint disease remains simply a theory, despite some persuasive animal studies, because to date there have been no prospective studies on the subject in humans. There is evidence, however, that the use of shock-absorbing materials in the footwear provides useful symptomatic relief in those already suffering from the condition.

Much of the interest surrounding the heelstrike transient has centered on the theory put forward by Radin and co-workers, in a series of papers (e.g., Radin et al., 1982), that it is a major etiological factor in the development of degenerative joint disease, which these authors call osteoarthritis, but which is more generally known as osteoarthritis. This theory was well described by Voloshin (1988) in the following description: '...the cyclic loading of a joint brings about the gradual fracture of the subchondral bone trabeculae. The first stages of the healing of fractures, when abundant calluses are present, cause thickening and stiffening of the subchondral bed, thereby decreasing its efficiency as a shock absorber. The no longer protected joint cartilage is, thus, subjected to increasing dynamic stresses resulting from everyday

physical activities and suffers from gradual fatigue-failure, which ultimately leads to the destruction of the tissue.' The evidence used to support this theory includes the development of degenerative joint disease in the knees of guinea pigs (Simon et al., 1972) and rabbits (Radin et al., 1973; 1978), subjected to impact loading of the limb. Sheep forced to walk on a hard surface developed degenerative joint disease of the knee, whereas sheep walking on a soft surface did not (Radin et al., 1982). However, since almost all the evidence for this theory comes from animal studies, it must at present be regarded as "not proven". Collins & Whittle (1989) reviewed the evidence that the heelstrike is an etiologic factor in degenerative joint disease and chronic low back pain.

Folman et al. (1986) suggested that the body's natural shock absorption system is relatively ineffective at withstanding sudden impulsive loads. Not only have impulsive loads been suggested as a cause of joint disease, but joint disease has been implicated as a cause of increased joint loading. As mentioned above, the ability of the knee to attenuate impulsive loads is decreased following meniscectomy or degenerative joint disease (Voloshin & Wosk, 1983). There thus exists the possibility of a vicious circle, in which the early stages of degenerative joint disease impair a protective mechanism, thereby leading to further, more rapid degeneration. Wosk & Voloshin (1981) noted that apparently healthy people could be divided into two groups, about two thirds having 'normal' attenuation of the acceleration wave and one third having "impaired" attenuation; they predicted that the latter group would later develop degenerative joint disease.

Evidence for the effectiveness of viscoelastic materials in providing symptomatic relief was obtained by Voloshin & Wosk (1981), who used viscoelastic insoles in the conservative treatment of 60 individuals suffering from degenerative joint disease, 80% reporting 'good improvement' and 17% 'satisfactory improvement' at the end of 18 months.

REDUCTION OF BACKACHE

Low back pain is a symptom, not a diagnosis, and it may result from a range of pathological processes. Nonetheless, in many patients, the underlying pathology appears to involve chronic inflammation, in response to overuse and repetitive strain. Such patients often report a reduction in their symptoms following the use of viscoelastic materials in their footwear.

Voloshin & Wosk (1982) suggested that chronic low back pain may follow a loss of the body's natural ability to attenuate the heelstrike shock waves. Tooms et al. (1987) randomly assigned nursing students to two groups, a control group who wore their normal shoes, and a test group who wore their normal shoes with

polyurethane elastomer insoles, for a period of five weeks. The test group showed a significant decrease in the incidence of backache, and significant reductions in both the frequency and duration of back and leg pain. Basford & Smith (1988) showed that the use of viscoelastic polyurethane insoles reduced back, leg and foot pain in adults who stand for most of the day. Wosk & Voloshin (1985) used light flexible shoes and viscoelastic shoe inserts in the conservative treatment of chronic backache in the L4-L5-S1 region. They found that "rapid and surprisingly significant improvement of pain syndrome and patient mobility occurred in about 80% of the patients".

PRESSURE REDISTRIBUTION

Many insole materials possess the ability to redistribute the force beneath the foot, thereby reducing the pressure in some areas. This is clearly a desirable characteristic in an insole material, since it results in an improvement in comfort and it reduces the stresses in some of the structures beneath the foot. A number of authors have reported good results (described in the next section) from the use of polyurethane elastomers in patients with heel spurs. At first sight this is surprising, since if a material is used purely for pressure redistribution, it should not matter whether it is viscoelastic or simply elastic. One possible reason for the difference is that when an open cell foam is compressed, the cells become smaller, and the volume of the material decreases, with little transfer of pressure laterally to other areas. In contrast, elastomers act like a fluid, so that material displaced from one area moves to adjacent, less pressurized areas, thereby giving a better redistribution of the applied load. Closed cell foams are intermediate in their properties between open cell foams and elastomers. A further advantage of elastomers is not their viscoelasticity as such, but their resistance to compression set. In conditions such as diabetic neuropathy, in which sensation is lost from the sole of the foot, the shock attenuation provided by viscoelastic materials may be additionally valuable if the gait includes an element of 'stamping'.

Since foam materials lose volume when compressed, it may be anticipated that a greater initial thickness of the material would be necessary for adequate pressure relief. This is of particular importance beneath the metatarsals, where most shoes provide very little space for an insole.

Boulton et al. (1984) showed that 5 mm thick polyurethane elastomer insoles significantly reduced the pressure beneath the foot in patients with diabetic neuropathy. They reported a reduction in the mean peak pressure in walking from 19.9 kg/cm² (1952 kPa) to 10.3 kg/cm² (1010 kPa) in subjects with a history of ulceration. Subjects without a history of ulceration showed a reduction in mean peak pressure from 8.95

kg/cm² (878 kPa) to 3.9 kg/cm² (383 kPa). For comparison, normal subjects have a peak pressure beneath the foot in walking of 200-500 kPa (Whittle, 1996).

Brodsky et al. (1988) compared five different insole materials used for diabetic footwear, in laboratory tests. They found that soft foam materials gave the best pressure redistribution initially, but they suffered from compression set with cyclical testing. The material which best combined pressure relief and durability was polyurethane foam.

Insoles constructed entirely of polyurethane elastomer tend to be firmer than foam insoles. For this reason, many patients have bought (or been prescribed) very soft foam insoles, which, are more comfortable initially, but which provide poor shock-attenuation and have a short useful life, due to compression set. Insoles are now available which consist of a base layer of polyurethane elastomer, covered by a layer of polyurethane foam. The elastomer provides good shock attenuation and pressure redistribution, but does not feel soft; the foam provides some shock attenuation, gives good pressure redistribution, feels soft to the touch, and is reasonably resistant to compression set.

PAINFUL HEEL SYNDROME

According to Davis et al. (1994), the painful heel syndrome is the commonest problem seen in foot clinics. The commonest cause is inflammation of the plantar fascia at its insertion on the calcaneus, other causes being stress fracture and entrapment of the first branch of the lateral plantar nerve. In a number of studies, viscoelastic insoles have been successful in providing partial or total resolution of the condition.

In a prospective study, nine runners with pain beneath the heel were treated using viscoelastic inserts. Eight reported complete resolution of their symptoms within three months, and the remaining one was much improved (MacLellan & Vyvyan, 1981). Levitz & Dykyj (1990) described very good clinical results from the use of a heel orthosis in patients with pain beneath the medial calcaneal tubercle (mostly associated with x-ray evidence of a heel spur). The orthosis consisted of two densities of polyurethane elastomer, the softer one being located beneath the painful area. Seventy three percent of the patients reported reduction or absence of pain after one month of use. Davis et al. (1994) found that viscoelastic heel cushions (in addition to other non-operative measures) provided symptomatic relief in approximately 90% of subjects with this condition. They stated that 'the viscoelastic polymer heel cushion provided symptomatic relief of pain by cushioning the heel and providing a small heel lift to relieve tension in the tight Achilles tendon and plantar fascia'.

OVERUSE INJURIES

A large number of studies have provided evidence that viscoelastic materials, either as insoles or used in shoe construction, provide useful protection against a range of pathologies, grouped together as 'overuse injuries of the foot and leg'. Many of these studies have been performed on recruits in the military and similar organizations, who typically undergo a program of vigorous training whilst wearing 'army boots' - one of the least compliant forms of footwear ever devised!

Stacy & Hungerford (1984) reported a significantly reduced incidence of both overuse and traumatic injuries in military recruit training, when the wearing of boots was introduced gradually, and running and physical training were performed in 'approved running shoes', which presumably included viscoelastic materials in their construction. They blamed the high injury rate when running and exercising in boots on 'recurrent stress'. In a similar study on US Coast Guard recruits (Smith et al., 1985), the incidence of foot and leg injuries was reduced from 63% in control subjects to 26% using an open-cell Polyurethane foam insole, and to 14% using a closed-cell synthetic rubber foam insole. However, the latter insoles showed a greater wear rate. Milgrom et al. (1985) performed a prospective study on military recruits, half of whom used a semi-rigid orthotic insole, covered with a thin layer of polyurethane foam, with additional polyurethane foam beneath the heel. Thirty one percent of the total subject population developed stress fractures (14% femoral, 20% tibial, 4% metatarsal, some developing more than one). Those using the orthotic insoles had a lower incidence of stress fractures in all three categories, but only the reduction in femoral fractures was statistically significant. In interpreting these results, it is difficult to distinguish between the two possible effects of the orthosis: bony realignment and shock absorption. It is also quite likely that the thickness of polyurethane foam was inadequate to provide effective shock absorption. In a subsequent study, Milgrom et al. (1992) showed that wearing basketball boots with an EVA midsole, rather than military boots, produced only a minor reduction in stress fractures of the tibia and femur, but statistically significant reductions were seen in metatarsal stress fractures, metatarsalgia, arch and heel pain. Simkin et al. (1989) found a relationship between the incidence of femoral and metatarsal stress fractures in military recruits and the height of the arches of the foot. They suggested that high-arched feet provide inadequate shock absorption for the tibia and femur, and that low arched feet protect the tibia and femur, but in doing so overstress the metatarsals. They found that a semirigid orthosis, incorporating viscoelastic materials, reduced the

incidence of stress fracture in the femur, tibia and metatarsals. In a prospective study, Schwelinus et al. (1990) reported a reduction in overuse injuries when using neoprene insoles, in military recruits during basic training.

In contrast to these other studies, Gardner et al. (1988) found no statistically significant reduction in stress fractures of the lower extremities, in a controlled trial in which marine recruits used viscoelastic insoles. The reason for this discrepancy in findings is not obvious.

Another group of individuals with a high incidence of overuse injuries, particularly stress fractures, are dancers. Clark et al. (1989) showed that aerobic dancers using viscoelastic insoles had fewer injuries than control subjects using foam insoles (the insoles were not described in detail). However, the number of injuries in both groups was low, and the differences observed were not statistically significant. Voloshin et al. (1989) suggested that viscoelastic insole materials might reduce the incidence of foot and leg problems in flamenco dancers, although the urogenital problems from which they also suffer probably relate more to trunk motion in the dance than to floor impact.

In an animal experiment related to stress fractures, Milgrom et al. (1990) described an experiment in which a mechanical apparatus (the so-called 'bunny-banger') applied cyclic loading to rabbit tibias in vivo. Interpolation of 3mm of a polyurethane elastomer between the apparatus and the animal failed to reduce the incidence of tibial stress fractures. However, the authors pointed out that such fractures are generally thought to be due to bending stress, which would not have been significantly reduced by the elastomer.

Dyer (1983) found that symptoms of fatigue and stiffness following long distance walking were reduced by the use of energy-absorbing insoles. Geiringer (1995) stated that shock absorbing shoe inserts were useful in rehabilitation following stress fractures of the lower limbs.

SUMMARY

Viscoelastic materials, used either as insoles or incorporated in shoe construction, provide redistribution of pressure beneath the foot and attenuate the impact load at the heelstrike transient. They are able to provide symptomatic relief, often leading to resolution, in a variety of conditions affecting the back, lower limbs and feet, particularly those related to overuse. It is possible that these materials could also reduce the incidence of osteoarthritis, and retard the loosening of joint prostheses. Optimal results would probably result from insoles which combine materials with different properties, such as a foam and an elastomer.

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