Heel-shoe interactions and the durability of EVA foam running-shoe midsoles

R. Verdejo, N. J. Mills

Metallurgy and Materials, University of Birmingham, Birmingham B15 2TT, U.K.
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Abstract

A Finite Element Analysis (FEA) was made of the stress distribution in the heelpad and a running shoe midsole, using heelpad properties deduced from published force-deflection data, and measured foam properties. The heelpad has a lower initial shear modulus than the foam (100 vs. 1050 kPa), but a higher bulk modulus. The heelpad is more non-linear, with a higher Ogden strain energy function exponent than the foam (30 vs. 4). Measurements of plantar pressure distribution in running shoes confirmed the FEA. The peak plantar pressure increased on average by 100% after 500 km run. Scanning Electron Microscopy shows that structural damage (wrinkling of faces and some holes) occurred in the foam after 750 km run. Fatigue of the foam reduces heelstrike cushioning, and is a possible cause of running injuries.

Keywords: FEA, foam, heelpad, running, plantar pressure distribution.

1. Introduction

Running involves a series of heel-strikes on the ground. The midsole foams of running shoes, by absorbing energy, limit the peak impact force in the heel-strike. Shorten (2000) showed that soft cushioning systems increased the duration of footstrike impacts and spread the load across a larger area of the plantar surface. Plantar surface pressure distributions were measured for running in various shoe types by Chen, Nigg et al. (1994), Henning & Milani (1995) and (2000), and Shiang (1997). However, there is no published information on how the pressure distribution changes with shoe use.

The impact response of a heel on a flat rigid surface was shown to be non-linear, with energy absorption on unloading, by Cavanagh et al. (1984). In these experiments the heelpad deformation is overestimated, since the lower leg and knee deform to some extent. Aerts et al. (1995), (1996) measured the impact response of the isolated lower half of the foot, giving a better indication of the heelpad response. However, no one has simultaneously measured the heelpad response and the pressure distribution at the foot/floor interface. Miller-Young et al. (2002) characterised the fat pad, taken from cadavers of the elderly, in compression, to generate data for Finite Element Analysis (FEA). However the magnitudes (0.01 to 0.1 Pa) of the moduli reported, appear unrealistically small. Aerts and De Clercq (1993) performed pendulum impact tests on shod heels, and showed that the heelpad compression was smaller with a harder shoe midsole; they reasoned that the heelpad response was rate dependent, and that the shoe heel counter constrained the heelpad. Gefen et al. (2001) measured the heelpad thickness of two 30 year old subjects as 11 and 13 mm. They found that the non-linearly elastic heelpad had an initial compressive modulus of $105 \pm 11$ kPa.

The only detailed FEA of a foot-shoe interaction (Lemmon et al., 1996) was a 2-dimensional analysis of the forefoot region for walking. Shiang (1997) performed FEA of polyurethane foam midsoles in the heel region, but gave no material parameters. Rather than model the heelpad, he used in-shoe pressure data as vertical loads for the upper surface of the midsole; this ignores shear stresses at the interface. He predicted a greater (mean) vertical strain in the centre of the heel contact area than elsewhere in the foam. Most running shoe midsoles are made from the foamed copolymer of ethylene and vinyl acetate (EVA), of density in the range 150 to 250 kg m$^{-3}$. Footstrokes, repeated at approximately 1.5 Hz, may cause fatigue damage to the foam, hence may lead to the foam bottoming out,
causing injuries. Prior research has used laboratory fatigue tests, which only provides indirect evidence of performance deterioration in running. Misevich and Cavanagh (1984) used repeated, rapid, uniaxial compression tests on EVA foam, to show that the midsole force-deflection response changed with cycle number. No details of the EVA foam densities were given. Cook et al. (1985) used a prosthetic foot, tilted back by 15°, to load the heel of the shoe from 0 to 1.5 kN at 2.5 Hz. After the equivalent of 500 miles running, the shoes had 55 ±10% of their initial energy absorption. Barlett (1995) discussed the cell geometry in sectioned EVA midsoles, claiming that cells next to the outsole became flattened after 3200 km of running. Mills and Rodriguez-Perez (2001) studied diffusion in EVA foam under creep loading, concluding that the air content of the foam cells decreased, reducing the cushioning.

One objective was to study the mechanical interaction of the heelpad with running shoe midsoles, and to estimate the magnitude of internal heelpad stresses. Another was to clarify the mechanism of shoe midsole degradation, and to investigate the resulting changes in the peak plantar pressures.

The approach taken was to use FEA of the heelpad and shoe to predict the pressure distribution at the heel/shoe interface, then use the pressure distribution experiments on runners to validate the analysis, and to follow changes in shoe cushioning.

2. Methods

2.1 Plantar pressure distribution

Three healthy male long distance runners (Table 1) ran at 2.61 m/s for 10 min on a Quinton Instrument Co. 640 treadmill; this short experiment avoided fatigue, hence possible changes in foot loading (Edington et al., 1990). The treadmill provides a standard running speed and running surface. They were all rearfoot strikers, did not use orthotics, and reported no lower extremity injury for the past year. The University ethical committee approved the study and informed consent was obtained from the runners. They wore Reebok Aztrek DMX shoes that were new at the start of the experiment.

Their plantar pressure distribution was recorded using the Tekscan ‘F-Scan’ system - a flexible, 0.18 mm thick, plastic sole-shape having 960 pressure sensors with spatial resolution of 5 mm. The resistance of pressure-sensitive ink, contained between 2 polymer-film substrates, decreases as the pressure, applied normal to the substrate, increases. Ahroni et al. (1998) and Mueller & Strube (1996) reviewed studies on F-scan sensors; some researchers reported good reliability and reproducibility, while others reported a decrease of sensor output with time at fixed pressure. Woodburn & Helliwell (1996) concluded that they were not suitable for accurate, repeatable measurements. However, peak pressure measurements in this paper were similar to those reported previously, allowing for differences in running speeds (Gross & Bunch, 1989).

To check the sensor linearity, an area of 0.0079 m² in the forefoot region was sandwiched between two 6 mm layers of soft, closed-cell ‘Airex 5230’ PVC foam, then loaded in uniaxial compression between metal plates using an Instron machine. Constant pressures of 31, 36, 39, 155, 225, 329, 398 kPa were applied for 20 s, while data was recorded for 2 sec. The loading cycle was repeated 5 times, on 5 new and 3 used sensors. Values were taken from 15 different frames of each 300 frames ‘movie’. The manufacturer suggested using the ‘weighted averaging’ function to reduce cell-to-cell variation. There is a linear relationship between pressures measured by the F-scan sensor and those applied by the Instron (Fig. 1). Table 2 gives the values of the intercept $a$, the slope $b$ and the correlation coefficient $R^2$. Calibrations using ‘weighted averaging’ and ‘non-weighted averaging’ are not significantly different. However when sensors were recalibrated, at the end of their use, the slope was 11% larger than that for new sensors.
Table 2. Tekscan sensor calibration

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Data treatment</th>
<th>Intercept ( a ) (kPa)</th>
<th>Slope ( b )</th>
<th>Correlation ( r^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>New</td>
<td>Non-Average</td>
<td>1.876</td>
<td>1.023</td>
<td>0.998</td>
</tr>
<tr>
<td>New</td>
<td>Average</td>
<td>1.894</td>
<td>1.028</td>
<td>0.998</td>
</tr>
<tr>
<td>Used</td>
<td>Non-Average</td>
<td>2.591</td>
<td>1.136</td>
<td>0.996</td>
</tr>
</tbody>
</table>

Average values for 5 new and 3 used sensors.

The subjects were asked to run on hard surfaces (track or roads), and to keep a running distance diary. Every 15 days the plantar pressure distribution was measured, after a standardised 24 hour recovery time since the last run. The insole was trimmed to fit the subjects’ right shoe. The sensors were calibrated every session by the known weight of the test subject, standing on one foot. Data were recorded, at the beginning (once they had acquired their gait) middle and end of the 10 minute run, at 150 Hz for 4 sec, which gave an average of 5 strikes per movie. The peak pressures from each frame were corrected to an ‘Instron’ pressure value using the new ‘non-averaged’ calibration of Fig. 1.

2.2 Shoe midsole foam characterisation

The midsole of Reebok Aztrek DMX shoes was 20 mm thick and contained two foams: a section of area 20 mm by 40 mm on the lateral side of the heel was coloured grey, and the rest white. The densities were measured using a hydrostatic balance. Differential Scanning Calorimetry (DSC) was carried out using a Mettler DSC 30. The melting point and crystallinity were taken from the second heating run; this eliminates the effect of thermal ageing. The melting point was taken as the peak of the heat flow vs temperature curve; the degree of crystallinity was calculated by dividing the melting peak area by the 286.8 J/g enthalpy of fusion for polyethylene crystals (Brandrup, 1975).

Cross-sections of the midsoles, from new and used trainers, were fractured after immersion in liquid Nitrogen, then vacuum coated with gold. They were examined using a JEOL JSM 5410 scanning electron microscopy (SEM).

3.FEA

3.1 Geometry and boundary conditions

ABAQUS Standard FEA version 6.3 (HKS) was used with the large deformation option. The calcaneus geometry was simplified to have a vertical axis of rotational symmetry. The geometry of its lower projection was simplified as a hemisphere of radius 15 mm, attached to the end of a 20 mm long vertical cylinder of radius 15 mm (fig. 8a). The heel pad geometry was taken to be a vertical cylinder of radius 30 mm; the lower surface was spherical with a radius of curvature of 40 mm, typical of a foot; a smooth blend was made between this surface and the vertical cylindrical surface. The minimum heel pad thickness was taken as 12 mm, the mean of the values given by Gefen et al. (2001). The lower ends of the tibia and fibula are approximated as an annular projection on the upper part of the calcaneus. When a EVA midsole foam was present, it was taken as vertical cylinder of radius 35 mm and height 22 mm, with initially flat upper and lower faces. Its lower surface (or that of the heel pad when no foam was present) rested on a flat rigid support table.

The support table was fixed, while the upper calcaneus boundary was ramped down by 20 mm (12 mm when no foam was present). The heel pad is assumed to expand freely at the sides; it is assumed that a shoe heel counter and upper would have no confining effect. The heel pad is assumed to be bonded to the calcaneus surface, which allows load transfer by shear stresses at the interface. The coefficient of friction between the heel pad and the foam or support table was taken as 1.0. Meshing was chosen to maximise the computation stability.

3.2 Material models

Ideally, energy losses in the heel pad and shoe should be considered. Linear viscoelasticity can be incorporated in Explicit FEA, but the heel pad and the foam are non-linear viscoelastic materials. Initially a hyperelastic model was used, allowing the use of the more-stable Implicit FEA. The hyperfoam model in ABAQUS uses the Ogden strain energy function

\[
U = \sum_{i=1}^{N} \frac{2\mu_i}{\alpha_i^2} \left[ \lambda_1^{\alpha_i} + \lambda_2^{\alpha_i} + \lambda_3^{\alpha_i} - 3 \right] + \frac{1}{\beta_i} \left( J^{\beta_i} - 1 \right) \quad (1)
\]

where \( \lambda_i \) are the principal extension ratios, \( J = \lambda_1 \lambda_2 \lambda_3 \) is a measure of the relative volume, the \( \mu_i \) are shear moduli, \( N \) is an integer, and \( \alpha_i \) and \( \beta_i \) non-integral exponents. The latter are related to Poisson’s ratio \( \nu \) by

\[
\beta_i = \frac{\nu_i}{1 - 2\nu_i} \quad (2)
\]

The initial shear modulus is given by

\[
\mu = \sum_{i=1,N} \mu_i \quad (3)
\]

One of the hyperelastic models in ABAQUS is the Ogden strain energy function

\[
U = \sum_{i=1}^{N} \frac{2\mu_i}{\alpha_i^2} \left[ \lambda_1^{\alpha_i} + \lambda_2^{\alpha_i} + \lambda_3^{\alpha_i} - 3 \right] + \frac{1}{D_i} (J - 1)^{2\beta_i} \quad (4)
\]
where the bulk modulus $K$ is given by

$$K = \frac{1}{D_i}$$

Lemmon et al. (1996) used a $N = 3$ hyperfoam model to fit compressive data for an EVA foam (‘Cloud’ from Soletech); the initial shear modulus was 479 kPa, while their parameters predict that the Young’s modulus in tension is much higher than that in compression. Soletech says the Cloud’s density is between 150 to 200 kg m$^{-3}$ (personal communication).

The heelpad was simulated using the Ogden hyperelastic material, with initial compressive modulus close to that found by Gefen et al. (2001), and bulk modulus that of water (2 GPa). The non-linearity parameters were found by matching the force-deflection response of the isolated heel of a 24 year old male (‘Foot II’ of Aerts et al. (1996)). The response of the EVA foam from the Reebok shoes was measured in both uniaxial compression and in tension. Since the response alters with cycle number, for the first few cycles of deformation, data was taken after 10 cycles. Fig. 2 shows the combined response for tension and compression, on loading and unloading for the 10$^{th}$ cycle. The EVA foam response was modelled using the Ogden hyperfoam material, with $N = 2$ and shear modulus $\mu_1 = 1000$ kPa, $\alpha_1 = 10$, Poisson’s ratio $\nu_1 = 0$, $\mu_2 = 50$ kPa, $\alpha_1 = -4$, $\nu_1 = 0.4$. Fig. 2 shows that this provides a reasonable match to both the tensile and compressive response.

4. Results

4.1 Plantar pressure distribution

The Tekscan measurements of pressure distributions (Fig. 3) are for the time in the footstrike when the peak pressure is a maximum in the heel region. This local peak almost has the axial symmetry assumed in the FEA, although the centre of this peak is offset to the medial side of the foot for runner 3. The peak pressures are lower than some reported values (Henning & Milani (1995) and (2000)), due to the running speed being low, and the surface being more compliant than a running track.

The peak pressures in the heel region increased with running time (in the 10 minute experiment), with a greater increase in the second and subsequent sessions, when the trainers had been used for several 100 km. There is an average 100 % increase in peak pressure over the total run distance for all three runners (Fig. 4).

4.2 Foam characterisation

The density and DSC results (Table 3) are approximately the same for both white and grey foam samples, suggesting that they only differ in colour. The
degree of crystallinity suggests a 18% VA content in the copolymer (Dupont, 1997).

The elastic moduli of EVA foams increases with their density. Larger shoe sizes may have higher foam densities, to give extra support to the assumed heavier wearers. Samples were cut from the arch region of each used running shoe, a region that suffers little damage. The size 11 shoe has increased foam density (Table 4), but sizes 8 and 9 the same density, allowing for density variation from the manufacturing process.

Table 3 Characterisation of EVA foams in Reebok midsole.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Density (kg/m³)</th>
<th>Melting Point (ºC)</th>
<th>Melting Enthalpy (J/g)</th>
<th>Crystallinity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>White</td>
<td>170</td>
<td>82.2</td>
<td>56.7</td>
<td>19.8</td>
</tr>
<tr>
<td>Grey</td>
<td>173</td>
<td>82.0</td>
<td>53.6</td>
<td>18.7</td>
</tr>
</tbody>
</table>

Table 4. EVA foam density in used trainers

<table>
<thead>
<tr>
<th>Runner</th>
<th>Shoe Size</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Runner 1</td>
<td>11</td>
<td>190 ± 3</td>
</tr>
<tr>
<td>Runner 2</td>
<td>9</td>
<td>168 ± 5</td>
</tr>
<tr>
<td>Runner 3</td>
<td>8</td>
<td>164 ± 4</td>
</tr>
<tr>
<td>Unused</td>
<td>8</td>
<td>170 ± 3</td>
</tr>
</tbody>
</table>

Micrographs of the midsole foam from the new trainers (Fig. 5) contain flattened cells close to the lower (outsole) and upper (insole) surfaces; they result from moulding the midsole into its final shape. The cells are slightly elongated along the shoe length direction. Hence Bartlett (1985) may have incorrectly interpreted flattened, near-surface cells as evidence of foam fatigue.

All the trainers at the end of the experiment (Fig. 6) contain some cell faces that are wrinkled. More severe damage, such as cell-face fractures, is present in the trainers of runners 1 and 2. Fractures in cut cell faces may be due to sample preparation; consequently only fractures in complete cell faces are considered to be due to trainer use.

4.3. FEA Results

The best fit to Aerts et al. (1996) data for a heel pad impacted by a flat rigid surface was obtained (Fig. 7) using shear moduli $\mu_1 = \mu_2 = 50$ kPa, with exponents $\alpha_1 = 30$ and $\alpha_2 = -4$. Although the material model cannot simulate hysteresis on unloading, it predicts the shape of the loading curve.

Fig. 8b and c show the vertical compressive stress $\sigma_{22}$ contours, respectively for the bare heel on flat anvil and the heel on shoe, at total deformations of 4 and 10 mm respectively, when the force is close to 0.5 kN. The total force on the foot will be higher, since other parts of the foot also transit force to the ground (Fig. 3). The main
peak force during the footstrike of runner 3 was typically 1.0 kN, with an initial peak of 0.8 kN. These compares with values of 2.3 and 1.7 kN respectively for running at 3.6 m/s on a rigid surface (Gross and Bunch, 1989). Their peak heel pressures increased from 300 to 420 kPa, when the running speed increased from 3.0 to 4.5 m/s.

For a heel force close to 0.5 kN, the predicted maximum compressive stress on the heelpad/foam interface is approximately 0.7 MPa, while in the bare heel test (fig 8b), it is 2.0 MPa. The maximum stress at the bone-heelpad interface is 1.0 MPa for the shod foot.

In the foot/shoe simulation, for forces less than 200 N, the majority of the deformation occurs by the flattening of the lower surface of the heelpad, and the increase of the contact area with the foam. However, at higher forces, the deformed heelpad does not decrease much in thickness, while the midsole upper surface becomes increasingly concave. Although the heelpad has spread laterally, the side of the EVA foam hardly bulges. The maximum foam stress occurs at the centre of the contact area on the foam upper surface (Fig. 8c). This confirms the Tekscan data for the pressure map on the upper surface of the shoe midsole— with a 300 kPa stress area of diameter approximately 20 mm.

The energy of the footstrike was calculated as the integral of the force vs. deflection graph, for the heel plus midsole simulation. Fig 9 shows the force is a nearly-linear function of the footstrike energy; the result of the force increasing nearly exponentially with the deflection, but not as rapidly as for the bare heel in Fig. 7. The maximum vertical compressive stress in the foam, which occurs at the centre of the heel/foam interface, is a

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**Fig. 7.** Force versus displacement, for impacts on an isolated human heel, redrawn from Aerts et al, (1996). FEA prediction for heel model (dashed curve)

**Fig. 8.** a) undeformed mesh. Contours of vertical compressive stress (kPa) for heel on flat surface: b) no shoe; 424 N force, 4.0 mm deflection, b) EVA foam shoe, 502 N force, 10.2 mm deflection.

**Fig. 9.** Predicted force (and peak compressive stress on heelpad surface) vs energy input for heelpad on an EVA midsole, compared with force vs energy graph without a shoe.
roughly linear function of the footstrike energy. Hence a footstrike of a given kinetic energy will produce a much lower peak force for the shod foot rather than the bare heel.

5. Discussion

Both the heelpad and the running shoe EVA foam act as shock-absorbing non-linear spring-dashpot structures, reducing the peak force in a heelstrike. There is a synergy in their responses; the foam, by indenting on its upper surface, increases the load spreading to the plantar surface, which reduces the force on the heel area. The indentation also probably stabilises the angular position of the calcaneus, affecting foot pronation. The properties of EVA foam can be measured more easily than those of the human heelpad; the modelling of their interaction is also a method of comparing their relative mechanical properties.

FEA has successfully analysed the non-linear, large deformation, problem of heel/shoe interaction. The predicted lack of bulging of the shoe foam sides is consistent with experimental observations; however such bulging is predicted for softer, low-density EVA foams. The EVA foam is more compliant than the heelpad, since it has a much lower bulk modulus, in spite of its shear modulus being higher. The initial foam shear modulus used here is double that used by Lemmon et al. (1996), for an EVA foam density inside the range estimated for their Soletech foam. Their Ogden strain energy function exponent $\alpha_2 = 3.9$ is smaller than the $\alpha_1 = 10$ used here, but both values provide significant hardening in compression. The heelpad initial shear modulus used here is 100 kPa, the same order of magnitude as their value used for forefoot soft tissue, and equal to the value given by Gefen et al (2001). Hence the data of Miller-Young et al. (2002) must be in error by orders of magnitude. The uncertainty in the moduli is probably an order of two, since the exact dimensions of the heel tested by Aerts et al (1996) is unknown, and since viscoelasticity was ignored in the modelling. It appears that heelpad is highly hyperelastic, with a Ogden strain energy function exponent close to 30. This is higher than the value of 17 used to model the thigh tissue (Setyabudhy et al, 1997). The predicted pressure distribution at the skin/midsole interface is confirmed qualitatively by the F-scan data. In an ideal experiment, the interface pressure, and the deformation of the heelpad and foam, would be simultaneously measured for a runner; however this is impossible at present.

FEA predicts a significantly higher peak heelpad pressure in a bare heel strike, compared with a shod heel strike with the same force; however barefoot and shod runners run differently. The pressure distribution on the midsole upper surface is non-uniform, with peak values near the centre of the heel contact area. The impacts cause fatigue damage to the EVA foam. Although air compression provides a major shock cushioning mechanism in the foam, other experiments (Verdejo and Mills, 2003) suggest that air loss is negligible in running. Instead, weakening of the EVA structure causes softening of the foam. The wrinkling of some cell faces is evidence of the foam fatigue. The consequent increase in peak plantar pressures is a real effect, since it is an order of magnitude larger than the sensitivity change of Tekscan F-scan sensors.

One limitation of the plantar pressure measurements is that they were made on a treadmill. The biomechanics of treadmill running differ from those of overground running (Nigg et al, 1995), and the peak footstrike force will be lower on the more-compliant treadmill surface. This means that the peak plantar pressures will be higher for running on a road than those measured for running on a treadmill.

Modelling of EVA foam midsoles, with a region weakened by the heel-strike stress field, has not yet been attempted; further FEA will consider a weakened region in upper centre of the midsole. Recent research (Taunton et al, 2003) suggests that running shoe age contributes to running injuries. The deterioration of running shoe cushioning may be an important explanatory factor for such an effect.

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