The Effect of Environmental Temperature on the Properties of Running Shoes

Hiroshi Kinoshita and Barry T. Bates

The purpose of this study was to investigate the effects of environmental temperature conditions and running duration on the mechanical properties changes of shoes having ethylene vinyl acetate (EVA) midsoles. Midsole temperature changes were obtained for a series of 40-min runs (2 subjects, 7 runs) under various seasonal environmental temperature conditions (winter 5–15 °C, summer 45–55 °C) for a normal shoe (35 durometers, Shore A). Midsole temperatures increased an average of 8 °C during the initial 15–20 min of running and were followed by relatively constant temperatures. Subsequently, the mechanical properties of soft (25 durometers), moderate (35 durometers), and firm (41 durometers) midsole shoes were evaluated using an impact tester over similar temperature ranges. With increasing temperature, peak deceleration and energy absorption decreased, and the times to peak deceleration and peak deformation increased. The results suggest that ordinary running shoes with moderate midsole hardness probably provide inadequate cushioning in cold environments and inadequate rearfoot control in hot environments.

One major cause of overuse injuries in runners is repetitive application of impulsive forces at ground contact. In response to a growing awareness of the need for protection from such injuries, manufacturers have designed running shoes with a relatively thick midsole cushion to protect runners. The most commonly used sponge material for the midsole is ethylene vinyl acetate (EVA), one kind of elastomer. It is well known that the mechanical properties of most polymers are highly temperature dependent (Ferry, 1960; Nielsen, 1975); the lower the temperature, the less elastic the material. Consequently, it would seem reasonable to expect different cushioning characteristics for the same shoe under different environmental temperature conditions. In addition, heat can also be developed inside the material due to repetitive compression and stretching of the material, since the shoe is subjected to substantial forces at every heelstrike during running. This heat also has the potential to change the mechanical properties of the midsole material.

Biomechanists and sports medicine physicians also emphasize the importance of adequate midsole firmness, since poor rearfoot control has been associated with shoes having soft midsoles (Bates, Ostermig, Mason, & James, 1978; Brody, 1986; Clarke, Frederick, & Cooper, 1983b; James, Bates, & Ostermig, 1978; Kinoshita, Ikuta, & Okada, 1990; Stacoff & Kaelin, 1983). Environmental heat as well as internally generated heat could result in a functional softening of the midsole material, resulting in less stability.

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Although there is a strong possibility that the properties of the shoe midsole will change as a result of changing environmental temperature as well as internally generated heat, no studies have investigated this hypothesis. Indeed, runners generally seem to use the same or similar shoes throughout the year regardless of environmental temperature.

The purpose of this study was to investigate the effects of environmental temperature conditions and running duration on the mechanical property changes of EVA midsoles, within the range of temperatures under which the shoes are commonly used.

**Methods**

*Midsole Temperature During Running*

The purpose of the first phase of the study was to determine the range of EVA temperatures during running for different environmental temperature conditions. Midsole temperature was measured using a digital electrothermometer (Takara Ltd., D-611) in conjunction with a small and flexible thermosensor (Takara Ltd., SXK-67). The sensor was inserted beneath the heel of the right shoe through a small hole drilled from the medial side of the midsole. The sensor location was 4.0 cm from the back of the heel, 3.5 cm from the medial side, and 1.8 cm above the surface of the outer sole. The test shoe was constructed with the same dimensions and materials as commercially available running/jogging shoes. The hardness of the midsole EVA foam at 20 °C was 35 durometers on a Shore A scale. The thicknesses of the heel and forefoot portions of the midsole were 25 and 11 mm, respectively. The outer sole was composed of a 5.0 mm thick carbon rubber material, and the sockliner was made of soft rubber sponge 2.0–3.0 mm thick. The upper portion of the shoe was nylon.

The test shoes were worn by 2 male runners, age 25 years (Runner 1) and 49 years (Runner 2), whose weight and height were 66.5 and 67.1 kg and 176 and 166 cm, respectively. Each runner wore the test shoes about 10 min prior to being tested. During this 10-min period, each subject performed light warm-up exercises on the test surface. Subjects then ran on a flat asphalt road for 40 min at a running speed of about 200 m/min under different environmental temperature conditions according to the season of the year, as shown in Table 1. The same running course was used for all measurements. The midsole

<table>
<thead>
<tr>
<th>Condition</th>
<th>Season</th>
<th>Time</th>
<th>Environmental temperature</th>
<th>Road surface temperature</th>
<th>Midsole temperature</th>
<th>Min.</th>
<th>Max.</th>
<th>Diff.</th>
</tr>
</thead>
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<tr>
<td>C1</td>
<td>Summer</td>
<td>13:30</td>
<td>35.0</td>
<td>44.5</td>
<td>43.6</td>
<td>54.3</td>
<td>11.2</td>
<td></td>
</tr>
<tr>
<td>C2</td>
<td>Summer</td>
<td>12:30</td>
<td>35.4</td>
<td>43.7</td>
<td>43.3</td>
<td>52.8</td>
<td>9.5</td>
<td></td>
</tr>
<tr>
<td>C3</td>
<td>Summer</td>
<td>8:30</td>
<td>29.2</td>
<td>29.2</td>
<td>31.9</td>
<td>40.6</td>
<td>8.7</td>
<td></td>
</tr>
<tr>
<td>C4</td>
<td>Spring</td>
<td>13:15</td>
<td>20.8</td>
<td>21.8</td>
<td>25.5</td>
<td>33.0</td>
<td>7.5</td>
<td></td>
</tr>
<tr>
<td>C5</td>
<td>Spring</td>
<td>14:05</td>
<td>21.1</td>
<td>21.0</td>
<td>25.5</td>
<td>31.9</td>
<td>6.4</td>
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</tr>
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<td>C6</td>
<td>Winter</td>
<td>10:00</td>
<td>4.3</td>
<td>2.3</td>
<td>3.8</td>
<td>13.2</td>
<td>9.4</td>
<td></td>
</tr>
<tr>
<td>C7</td>
<td>Winter</td>
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<td>0.3</td>
<td>-1.8</td>
<td>2.1</td>
<td>6.3</td>
<td>4.2</td>
<td></td>
</tr>
</tbody>
</table>

*Note.* Environmental and road surface temperatures were measured prior to running.
temperature was monitored on-line using a 10-m connecting cable attached to the electrothermometer carried in a car driven behind the runner. Midsole temperature was recorded each minute from the beginning of the run for the entire 40-min period. Minimum and maximum values were identified for the test period.

Impact Tests

The effects of temperature variation on the cushioning properties of running shoes with EVA midsoles were investigated using mechanical impact tester procedures developed in Japan. These procedures are similar but not identical to those used by other investigators (Denoth, 1986; Misevich & Cavanagh, 1984; Valiant, 1990). The differences in equipment and procedures could result in absolute differences between our results and previously published results but do not change the comparative results presented. The impact tester was a conventional free-fall type impactor, which consisted of a weighted stainless steel impact shaft (mass 7.5 kg), a lightweight uniaxial accelerometer (Kyowa Ltd., Type AS50B), and a position transducer (Kyowa Ltd., DLT 50A). The impact shaft consisted of a steel contact head with a flat lower surface (diameter 40 mm) and was dropped from a height of 5 cm onto the heel region of the shoe. The running shoes tested during this phase of the experiment were constructed with midsole hardnesses of 25, 35, and 41 durometers for the soft, moderate, and firm shoes, respectively. The moderate shoe was the same model as that used to measure midsole temperature during running. The soft and firm shoes were constructed using the same design, structure, and materials as the moderate shoe except for the midsole hardness. The sockliner was left in place during all impact tests to more closely approximate the running condition.

Shoe temperature was controlled at seven levels (−5, 0, 10, 20, 30, 40, 50, and 55 °C) using a temperature control chamber (Iuchi Ltd., Type 11-3093-04). Impact data were obtained for five drops at each temperature level and stored for subsequent analysis. Before we began to collect actual impact test data, three to four pre-impacts were performed. In an ordinary shoe impact test, 20 to 30 pre-impacts are commonly used. However, in the present experiment, this number of pre-impacts was not possible because shortly after the shoe was removed from the temperature control chamber, the midsole temperature began to change. The small number of pre-impacts might have systematically influenced the results slightly.

Output signals from both the accelerometer and the position transducer of the impact tester were filtered at 300 Hz prior to analog to digital (A/D) conversion. The sampling frequency for the A/D converter was 1 kHz. Output signals from the position transducer and accelerometer provided displacement and deceleration curves, respectively, as a function of time. From each data trial, peak deceleration (P1 in Figure 1A) and time to peak deceleration (T1) were determined from the deceleration curve, and peak deformation (P2) and time to peak deformation (T2) were evaluated from the displacement curve. The force–deformation relationship was also examined for each trial. The force of impact was calculated as the product of the mass of the impact shaft times deceleration. The deformation of the shoe sole was obtained directly from the displacement–time curve. The force–deformation relationship curve was obtained for the time interval between the instant of impact and zero deceleration (Figure 1B). The area under the loading curve (upper curve) from zero to maximum deformation (dotted area + filled area) represents the input energy during compression of the shoe sole, while the area under the unloading curve (lower curve – filled area) represents the energy returned during decompression of the sole. The dotted area is the difference between the input and returned energies and therefore represents the energy absorbed during impact. The areas under
Figure 1 — A: Representative deceleration and displacement curves obtained in a single trial with the moderate shoe at 20 °C in the mechanical impact test. The parameters evaluated are also identified. Dotted line indicates the moment of impact, dashed line the moment of zero deceleration. Deformation of the shoe sole is obtained from displacement data after subtracting the impact moment displacement value. B: Force deformation relationship curve. Dotted area indicates the energy absorbed during impact.

Figure 2 — Midsole temperature during running under varied environmental temperature conditions. Filled circles indicate the results for Runner 1 and empty circles the results for Runner 2.

The curve were estimated by a numerical integration based upon the trapezoidal rule. The energy absorbed is expressed as a percentage: Energy absorbed = ([Energy input – Energy returned]/Energy input) × 100. Mean values for five impacts were calculated for all parameters.
Results

Midsole Temperature During Running

Changes in midsole temperature during running for the two runners under different environmental temperature conditions are presented in Figure 2. The midsole temperatures at the beginning of the run were substantially influenced by the road surface temperature during the warm-up period. As running commenced, midsole temperatures increased gradually for the initial 15–20 min, followed by a nearly constant temperature for the remainder of the run. Minimum and maximum midsole temperatures along with the differences are given in Table 1 for each environmental temperature condition. The average increase in temperature was 8.1 ± 2.3 °C. The minimum temperature of 2.1 °C was recorded at the start of an early morning run in winter, while the maximum temperature of 54.3 °C was recorded during the second half of a sunny midday summer run.

Slight differences were noted in the midsole temperature curves between the two runners. The temperature curves for Runner 2 always increased faster and peaked earlier than those for Runner 1. Runner 2 also had slightly greater peak and steady-state temperatures than Runner 1.

Mechanical Properties of the Shoes at Various Temperatures

Selected impact test results for the three test shoes for all temperatures are presented in Figure 3. The best fit polynomial curve for each data set is also shown. Peak deceleration exhibited a curvilinear decrease for all shoes as temperature increased (Figure 3A). The time to peak deceleration (Figure 3B), peak deformation (Figure 3C), and the time to peak deformation all displayed nearly linear trends as temperature increased. Comparisons among the three shoes within the range of temperatures examined indicated the same relationships with greater peak decelerations, shorter times to peak deceleration, lesser peak deformations, and shorter times to peak deformation associated with the firm shoe compared to the moderate shoe followed by the soft shoe.

The amount of energy absorbed by the shoe for each temperature condition was computed from the individual trial data (Figure 4B). Representative force-deformation curves at 0, 30, and 50 °C for the moderate shoe are also shown (Figure 4A). For all three shoes, energy loss was greatest and nearly equal at the coldest temperature. As the temperature increased, energy loss decreased for all shoes but at different rates so that the energy lost was always greatest for the firm shoe. For example, as temperature was increased from −5 °C to 55 °C, the energy absorbed by the moderate shoe decreased from 64% to 35%.

Discussion

Midsole Temperature and Mechanical Property Changes During Running

Midsole temperatures increased during the initial 15–20 min of the run followed by a relatively constant temperature period as heat exchange due to absorption and radiation became balanced. The average increase in midsole temperature was about 8 °C with a maximum value of 13 °C. This increase was believed to be due to the effect of internally generated heat resulting from repetitive compression of the air cells inside the EVA sponge, friction between the sponge material and the sensor, and heat transferred from the runner’s foot. To identify the proportion of heat due solely to the effect of repetitive compression,
the shoe used to generate the running temperature data was further evaluated. Additional midsole temperature measurements were obtained using the mechanical impact tester to impact the shoe repetitively at 1.4 and 1.45 Hz for 20 min at an environmental temperature of 20 °C. These impact frequencies were selected based upon the average step frequencies observed for Runners 1 and 2, respectively, during their runs. These tests resulted in midsole temperature increases of 13 and 14 °C by 15 min for the 1.4- and 1.45-Hz rates, respectively (Figure 5). These results indicate that repetitive impacts with a steel impact head had a similar or even slightly greater effect on midsole temperature than running. The midsole temperature for the 1.45-Hz condition increased at a greater rate than for the 1.4-Hz condition. These later results support the observed differences between the midsole temperatures for the two runners; that is, Runner 2, who had the faster step frequency, produced slightly greater rate increases and temperatures during running than did Runner 1.
A limitation of the study was our inability to determine the heat developed due to friction of the thermosensor and the EVA material. We attempted to reduce this effect by using a relatively small sensor tip (<2 mm). However, the effect of friction between the sensor tip and surrounding sponge material on the heat developed is unknown, and there is a possibility that a portion of the observed temperature changes during running were due to this effect.

Changes in foot temperatures for 3 runners during a 40-min, 10-km run were reported by Nagai, Fujita, Sekioka, Maekawa, and Yoshimura (1982), who measured temperature at the heel–shoe interface using thermography. No information regarding envi-
rnonmental temperature was reported except that the measurements were conducted in the spring. The average foot temperature recorded was 28 °C before the start of running, 30 °C at 10 and 20 min after the start, and 31 °C at the end of the run. These results suggest that the heat internally generated by repetitive impacts is the major factor for midsole temperature changes during running and that the contribution of heat transfer from the foot is relatively small.

The extent to which the mechanical properties of the midsole change within one running session may be assessed from the polynomial equation fitted to the moderate shoe data. Temperature changes of 8 °C under hot (around 50 °C) and cold (around 5 °C) environmental conditions resulted in peak deceleration differences of about 1 and 3 g, respectively. The corresponding values for the time to peak deceleration were about 2 ms for both conditions with maximum deformations of 1.5 mm. The change in the percentage of energy loss for the hot and cold environments was about 5 and 7%, respectively. These results indicate greater mechanical property changes in winter compared to summer.

**Seasonal Effects on Midsole Temperature**

Midsole temperatures at the start of the run ranged from 2.1 to 43.3 °C. Midsole temperatures stabilized after approximately 20 min at values ranging from 6.2 to 54.3 °C. It is apparent that this wide range of results was due largely to the effect of seasonal temperature differences and the effect of the temperature of the running surface. These results indicate that in winter (C6 and C7 in Figure 2) the midsole temperatures remained within a range of 5 to 15 °C, whereas on hot summer days (C1 and C2 in Figure 2) the range was mostly between 45 and 55 °C but was never below 40 °C.

The impact test results clearly demonstrated that the mechanical properties of the shoes changed markedly as a function of temperature. The lower the temperature, the greater the peak deceleration and the shorter the time to peak deceleration. In addition, lower temperatures resulted in lesser deformations and greater amounts of energy absorbed. Using the polynomial equation for the moderate shoe, peak deceleration and time of occurrence were estimated for the extreme temperatures recorded during running. At 2.1 °C, peak deceleration and time to peak deceleration were 17.0 g and 9.4 ms, respectively, while at 54.3 °C, the corresponding values were 11.3 g and 17.9 ms, respectively. These results indicate that runners who use the same shoes during both winter and summer could be subjected to 1.5 times greater impact forces at twice the frequency during winter compared to summer if they do not modify their running technique. Corresponding peak deformation values were 6.4 and 12.0 mm, with percentage of energy loss values of 59.4 and 32.8%. During winter running, therefore, the shoe is 1.8 times stiffer and returns only half of the stored energy compared to summer running. These findings suggest that functional changes in running shoes due to seasonal temperature variations are substantial and can alter the stress placed on the body if running kinematics are not altered.

**Implications for Running Injuries and Running Economy**

In the discussion of running injuries and running economy, at least two functions of running shoes must be considered: shock attenuation and rearfoot control.

Animal studies as well as clinical observations of injured runners suggest that muscles, bones, and joints can be damaged as a result of repetitive impact forces at ground contact (Detmer, 1986; MacLellan & Vyvyan, 1981; Radin, Paul, & Rose, 1972; Sterink, Nachemson, & Hansson, 1977; Voloshin & Wosk, 1982). It has also been reported that repeated impacts increase the rate of red blood cell breakdown and can contribute to de-
pressed iron status in runners (Miller, Pate, & Burgess, 1988). The findings of the present study clearly indicate that the shock attenuation capacity of running shoes with EVA midsoles declines with decreasing temperature. Suppose a runner uses moderately firm EVA shoes, which are probably the most common type on the market. The peak deceleration that the runner will experience at every heelstrike can be 1.3-1.4 times greater during a winter run (0-5 °C) compared to a typical spring or fall daytime run (25-35 °C). The time to peak deceleration also occurs 1.6 times (7 ms) faster in the cold temperature than in the warm temperature.

The worst combination would undoubtedly be a firm shoe used in a cold environment. The peak deceleration would be around 20 g, 1.5 times greater than that expected for the soft shoe used under the same temperature condition. Therefore, potentially deleterious effects due to poor shock attenuation can be countered by the selection of an appropriate shoe.

Controlling excessive rearfoot motion, which can lead to overpronation injuries, is also an important function of running shoes. Clinical observations suggest that an excessive amount of pronation in the subtalar joint is linked with many lower extremity problems in runners (Brody, 1986; Clement, Taunton, Smart, & McNicol, 1981; James, Bates, & Ostering, 1978). Clarke et al. (1983b), who measured the kinematics of rearfoot movement, found that shoes having a soft EVA midsole (less than 35 durometers) allowed significantly greater pronation and total rearfoot movement. However, Nigg, Bahlsen, Denoth, Luethi, and Stacoff (1986) presented a result that contradicted Clarke et al.’s study. They reported that shoes with a firmer midsole increased initial pronation angle and its angular velocity. The total pronation angle also increased when midsole firmness changed from 25 to 35 durometers, and it then decreased from 35 to 45 durometers. Although there were discrepancies between results of the two studies, they both suggest that adequate midsole firmness is important in rearfoot control.

The present results indicate that the midsole becomes softer and more easily deformable as temperature increases. The moderately firm shoe during summer temperatures was functionally softer than the soft shoe (with 25-durometer midsole) at 20 °C, which can cause instability of the foot. The EVA midsole became fairly firm as temperature decreased, which can lead to a greater initial pronation angle. Accordingly, ordinary shoes when used at high or low temperatures appear to lack adequate rearfoot control and can expose runners to a greater risk of injury due to excessive pronation. To maintain stiffness properties of the midsole in a hot environment (above 45 °C) similar to those obtained from a 35-durometer midsole under normal temperatures, a midsole having a durometer value of 45 or greater may be required. In a cold environment (0-5 °C), softer midsoles are recommended.

The relationship between running economy and shoe design has been investigated by several researchers (Frederick, Howley, & Powers, 1986; Kinoshita, Ikuta, Hirakawa, & Okada, 1992). Frederick et al. (1986) compared the oxygen demand for runners wearing shoes having a small air-mattress-like cushion inside the midsole to shoes with an EVA foam midsole. They found that the shock attenuation capacity of the air-soled shoe was only 78% of that of the EVA-soled shoe and that the subjects used an average of 2.8% (maximum = 6.4%) less oxygen with the air-soled shoes. Kinoshita et al. (1992) compared the effect on oxygen demand of a soft EVA-soled shoe with that of a firm EVA-soled shoe at running speeds of 200 m/min and 270 m/min. Average oxygen consumption was 2 and 4.5% less with the soft shoes for the slow and fast speeds, respectively. The firm shoes weighed about 180 g more than the soft shoes. Some researchers have reported a 0.6 to 1.2% increase in energy cost per 100 g increase in shoe weight per pair (Caltin &
Dressendorfer, 1979; Frederick, Daniels, & Hayes, 1984; Martin, 1985;). Kinoshita et al., therefore, suggested that the difference in oxygen consumption due to shoe firmness was probably about 1 to 2% less than the actual measured values.

Several factors could be related to these findings. First, during running with firm shoes, additional muscular effort may be necessary to reduce the greater impact forces. Indeed, Clarke et al. (1983a) observed greater knee flexion while subjects ran in firm shoes compared to soft shoes. Kinoshita, Fujii, and Fukuda (1988) reported greater activity in the leg and thigh muscles prior to landing during barefoot running compared with shod running. Second, extra physiological energy may be required to regain the greater kinetic energy loss resulting from a firm shoe. Hardening of the midsole due to temperature, therefore, seems to be a disadvantage in terms of running economy.

In summary, both to prevent injuries and facilitate running economy, shoes with appropriate midsole hardness should be selected based upon the environmental temperature. Common running/jogging shoes, which include an EVA foam of moderate hardness, can be appropriate at moderate environmental temperatures but appear to be inappropriate for cold and hot environments. For temperatures ranging between 5 and 15 °C, a common winter midsole temperature range, soft shoes (around 25 durometers at 20 °C) can provide an adequate level of shock attenuation with better rearfoot control than moderately firm shoes. At 45 to 55 °C, a common summer temperature range, firmer shoes (45 durometers at 20 °C) should be used to provide sufficient rearfoot control. Although only EVA midsoles were investigated in this study, it is reasonable to assume that other types of midsoles could be similarly influenced; these midsoles should be tested using a similar protocol to determine the exact effects.

References


Acknowledgments

We are grateful for the technical assistance of T. Murase and R. Torigoe, Osaka University. This study was supported by a grant from the Descente and the Ishimoto Memorial Foundation for the Promotion of Sports Sciences.