Mechanical Properties Testing of Running Shoes

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Abstract
Mechanical properties testing of running shoes was performed. Stress relaxation tests and energy absorbing tests were performed on excised samples and on unmodified shoes. The stress relaxation moduli for running shoe midsole materials ranged from 19 psi to 114 psi.

Keywords: Running Shoes, Stress Relaxation

1. Introduction

Running shoes are an important part of the athletic-shoe industry, that has annual sales in excess of $7B[1]. Running shoes continue to develop, to address runners' requirements and concerns. Some of the criteria that runners use when purchasing shoes are based on osteomechanical effectiveness, comfort, expected shoe lifetime and cost. Materials used in the shoes, particularly in the soles, affect the shoe properties and it was upon these considerations that this study was based.

Running midsole materials may include polyvinyl acetate (PVA), polyurethane (PU), ethylene vinyl acetate (EVA), isoprene, neoprene or combinations of these polymers. The materials are examples of elastomers (isoprene and neoprene) or thermoplastic elastomers (PVA, PU and EVA). One of the primary functions of the midsole is to absorb energy during running. Running shoe designs incorporate varying combinations of these materials, resulting in shoes with different energy absorbing qualities. Specific polymer formulations are not published, as these are proprietary data. A given formulation is based on mechanical requirements of the shoe design and the available injectable materials at a given shoe manufacturing plant.

Many mid- to high-end running shoes today have midsoles comprised of EVA, PU or a combination of the two. Through different molds and forms, shoe manufacturers use EVA, PU and other polymers in different combinations to achieve the desired properties required by different shoe styles.

2. Procedure

2.1 Stress Relaxation Tests

Stress relaxation tests were performed on samples excised from the heel and forefoot of the shoe midsole. Stress relaxation testing is based on applying an initial load to a sample (tensile or compressive), and holding that strain at a fixed level while monitoring the decrease in load. Stress is calculated by dividing the force (which is relaxing with time) by initial sample area. The output of the tests is force (or stress) as a function of time. A stress relaxation modulus can be calculated if the stress (at a given point in time) for several tests (at different strains) is plotted as a function of strain. The slope of the stress (at time t_o) as a function of strain gives the relaxation modulus (for data taken at t_o).

Figure 1 shows an example of stress as a function of time for a typical compressive trial. The data shown is for a 12.7 mm (0.5 inch) diameter specimens from a running shoe midsole. The intial (fixed) strain applied for the test shown in Figure 1 is 40%.

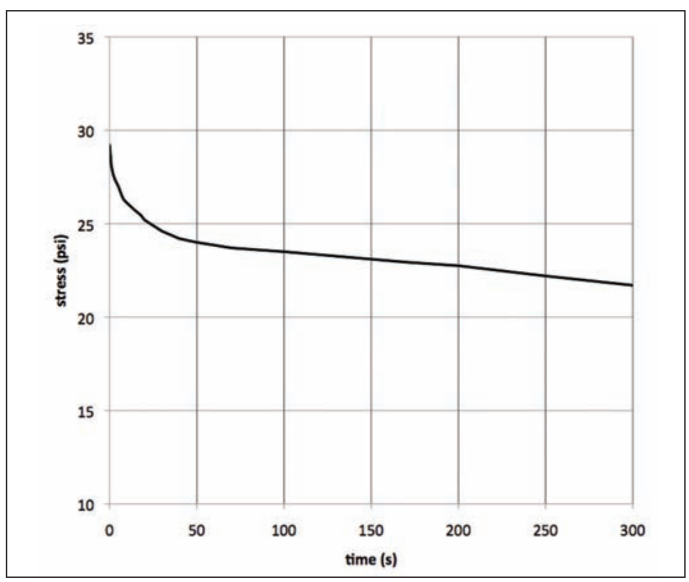

Figure 1. Stress as a function of time for a typical load relaxation test. The data shown is for a 12.7 mm diameter specimen from a Saucony shoe with an initial compressive strain of 40%.

The data shown in Figure 1 is from a Saucony shoe excised sample with a diameter of 12.7 mm. By comparison, other sample sizes that were tested included 7.6 cm diameter samples from from shoe midsoles. Samples were hand ground with coarse sandpaper to have flat, parallel sides. The thicknesses of the samples ranged from 5 to 35mm. The relatively large range of sample thicknesses was a result of whether samples were from the forefoot or the heel of the midsole. Figures 2a and 2b show samples from a heel (Figure 2a) and and a side by side comparison of forefoot and heel samples (Figure 2b).

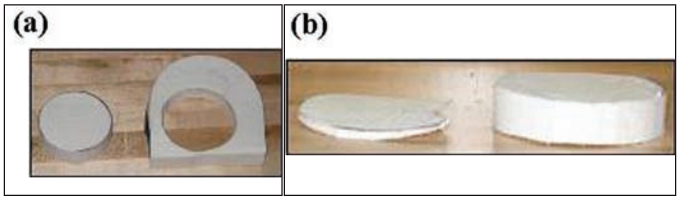

Figure 2 (a) Photo of stress relaxation sample from a midsole heel. **(b)** Photo of stress relaxation samples from forefoot and heel samples. The heel sample is the thicker sample shown on the right. After removing the samples from the midsole, the flat sides were sanded until parallel.

Stress relaxation tests were carried out on a MTS 858 tensile tester using a 2.5N load cell. The samples were placed between two flat metal surfaces (platens), and the samples were given an initial known strain. Initial strains ranged between 10 and 60%. Caliper measurements were taken to measure the distance between the platens before and after the load was applied, to determine the compressive strain on the sample.

In the stress relaxation tests that were performed, two approaches were used to define the time at which stress would be calculated. Some of the data were taken when the load was sixty percent of the initial load. Another group of data were taken after a fixed time of thirty five seconds into the test, regardless of the percent that the load had relaxed.

The types of shoes that were tested included competitive running shoes made by Adidas, Brooks, Saucony, New Balance and Athletic Works as well as other non-running shoe samples. Table 1 shows examples of the types of shoes that were tested.

Table 1. Examples of Shoes that were Stress Relaxation Tested.

Type of Shoe	Cost $	Midsole Material
Saucony Progrid OMNI 7	100	EVA Polymer
New Balance 550	60	EVA Polymer
Athletic Works Journey MW	20	EVA Polymer

2.2 Energy Return Percent Tests

In addition to stress relaxation testing on excised samples, an additional test on intact shoes was performed. Cyclic tests were performed in a tensile tester to calculate a parameter called 'Energy Return Percent' or 'ERP'. The work was based on a previously published standard[2]. One objective of the work was to determine if New Balance's 'Zip' material was significantly different than EVA from other manufacturers, including Asics and Brooks. To conduct the test, a ram of a machined dimension (known as a 'tup') was pressed into the sole of the shoe at the inside heel. Force, time and displacement were monitored to determine the energy into the shoe and the energy returned for each heel strike. Figure 3 shows a schematic diagram of force as a function of displacement for a loading and unloading cycle. The area between the two curves is the energy absorbed by the shoe.

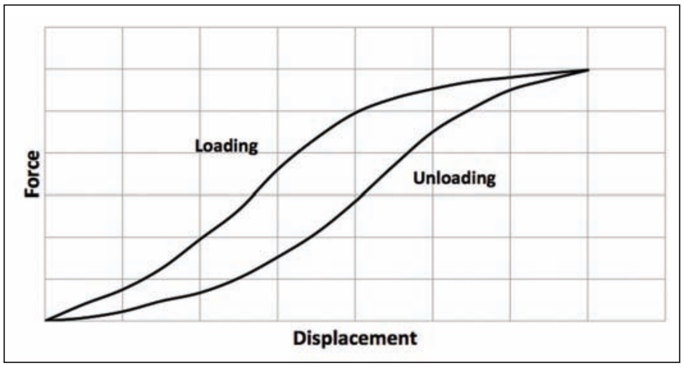

Figure 3. Example of load as function of diplacement during the Energy Return Percent (ERP) tests. The area between the 'loading' and 'unloading' curves represents the energy absorbed. The energy returned is the complement of the ratio of energy out to energy[2].

An ASTM standard[3] requires that the specimen response must be a half sine curve. To achieve a half sine curve response, a pause in the drive is necessary in between cycles due to the viscoelastic effect of the material. The shoe material's inherent viscoelasticity causes the insole to take time in getting back to the 'starting position'. In experimental practice, a two second pause in between full cycles was used.

A constraint on testing was that the initial force into the shoe on each cycle had to be nominally 5 ± 0.5 J. This reference energy is a constraint of the ASTM standard and is measured by taking the product of maximum force and maximum displacement for the hysteresis curve[3].

The shoes that were tested had midsoles made of EVA, neoprene, and Zip. The Zip material was chosen since it was a relatively new shoe material on the market, and extensive claims had been made about its performance[4].

The variability in shoe design is addressed in ASTM F1614-99 standard. According to that standard, a flat span of 45 millimeter diameter is required in the inside heel region of the sole, to allow for the contact surface to be parallel with the bottom platen upon which the shoe sits during testing. The standard also requires that the thickness of the sole must fall within the range of 5 to 35 millimeters in thickness from the top of the insole to the bottom of the outsole[3].

The performance metric for testing energy into and out of the shoe is a hysteresis energy curve. The values for energy are obtained from the displacement and force through a numerical integration where the energy into the specimen is represented by the top curve of the plot and the energy out of the specimen is the lower curve. The energy lost is the area between the curves, which is the value of interest for the specimen. Energy Return Percent (ERP) is calculated by taking the complement of the difference between the energy applied and the energy returned.

An MTS 858 tensile tester was used to test three shoe samples. Shoe samples were conditioned by running 25 cycles of the displacement function before data was recorded. The 26th through 30th cycles served as data in the analysis. The conditioning helped mitigate the possible effects of initial stiffness[2].

3. Results

Table 2 summarizes stress relaxation moduli for samples from running shoes (Adidas and Brooks) and other non-running shoe samples. For each individual stress relaxation test, the stress was determined when the stress was at 60% of the initial stress. The data shows that the running shoes have a lower stress relaxation modulus than non-running shoe samples.

Table 2. Examples of Shoes that were Stress Relaxation Tested.

Type of Shoe	Cost	Midsole Material
Saucony ProGrid OMNI 7	$100	EVA Polymer
New Balance 550	$60	EVA Polymer
Athletic Works Journey MW	$20	EVA Polymer

Table 3 gives the load relaxation moduli for samples for which stress was determined 35 seconds after the initial application of the load. The data shows that the Saucony ProGrid shoes had the lowest relaxation modulus, and that Athletic Works Journey model had the highest relaxation modulus of the shoes tested. The data suggests that relaxation modulus and cost are inversely related. The data in Table 3 are generally higher than that in Table 2, possibly as a result of a different time used after the start of each experiment for obtaining stress measurements

Table 3. Stress Relaxation Moduli (at time τ = 60% of max).

	Adidas	Boot	Brooks	Old	Sandal	Pink Sandal
E_r (psi)	22.4 ± 0.7	67.6 ± 2.0	18.5 ± 1.2	25.9 ± 0.7	32.7 ± 0.8	25.7 ± 0.5

Table 4. Stress Relaxation Moduli (at time to = 35 s after loading).

	Saucony Progrid OMNI 7	New Balance 550	Athletic Works Journey MW
E_r (35s) (psi)	66 ± 13	83 ± 22	114 ± 28
Cost $	100	60	20

Figures 4 and 5 are example plots of stress (at 35 s) as a function of applied strain. The slopes of the best fit lines shown in each Figure give the relaxation moduli provided in Table 3. Figure 5 is a plot of relaxation moduli as a function of shoe cost, showing an inverse correlation. The purpose of plotting relaxation modulus as a function of cost was to determine if performance (as approximated by shoe cost) cost was a function of stress relaxation modulus. Since cost and relaxation modulus are inversely related, Figure 6 preliminarily suggests that low relaxation modulus correlates with higher performance running shoe midsole materials.

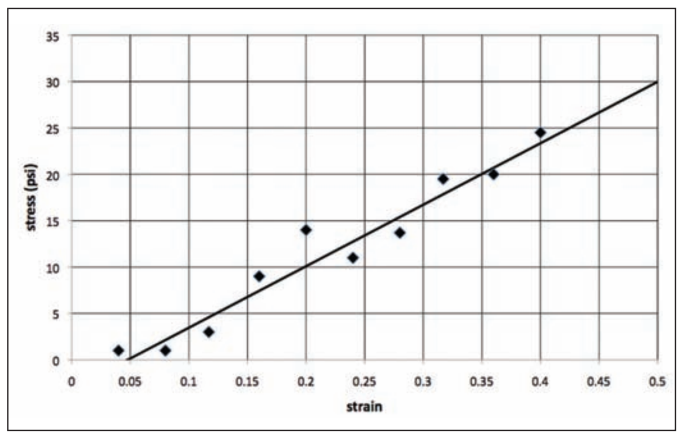

Figure 4. Stress (at 35 seconds) as a function of strain for Saucony shoes. The modulus is 66 psi for the data shown.

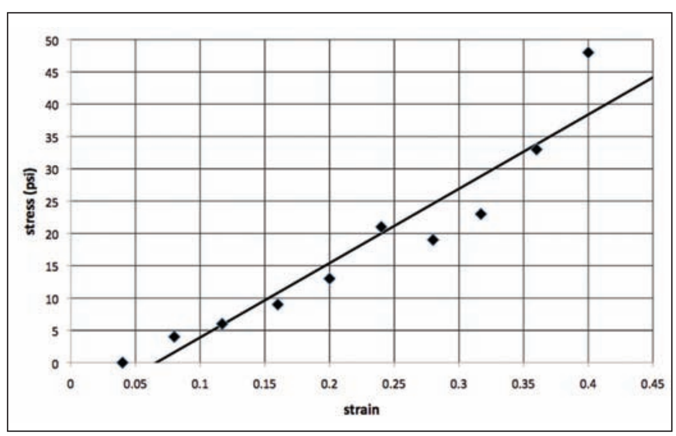

Figure 5. Stress (at 35 seconds) as a function of strain for Athletics Works Journey shoes. A stress relaxation modulus of 114 psi was calculated for this shoe.

Figure 7 shows programmed displacement as a function of time. The relatively small displacement, in the relatively short period of time (~20 ms) ensures that the 5 J energy input requirement is met. An advantage of controlling displacement is that displacement can be programmed as a sine function, a ramp, or any combination. The impact (sine function input) is completed in 30 ms. The actual displacement is different because the tensile tester does not perfectly follow the input function. Displacement can be adjusted to alter both maximum force and total energy applied over a given time period.

Figure 8 shows when the measured force is plotted as a function of displacement for a single impact. The data shown is representative of all of the impacts that were measured. The ASTM standard requires that the impact loading time has to be 15 ± 5 ms[3]. The time between the 10% of the maximum force and the maximum defines the loading time.

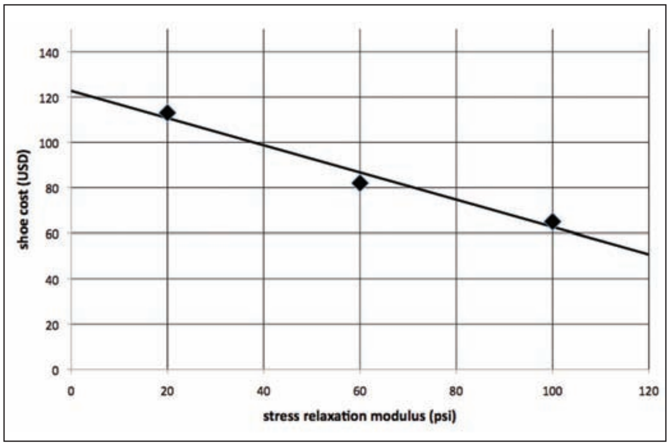

Figure 6. Relaxation modulus (for stresses calculated at 35 seconds after loading) as a function of shoe cost. A linear relationship between modulus and shoe cost is suggested.

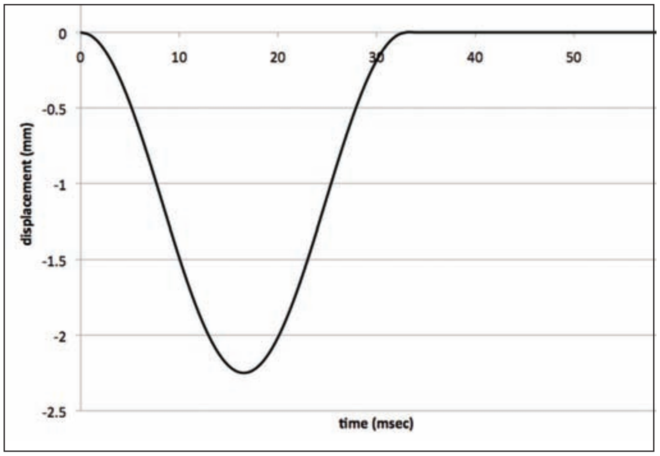

Figure 7. Example of test data, showing programmed displacement as a function of time.

Table 5 gives Energy Return Percent values for the three shoes that were tested. The reference energy input is shown to be within the specification of 5 ± 0.5 J.

Table 5. Energy Return Percent Values for the Three Shoes.

	ERP	Max Reference Energy Input (J)
EVA (Asics)	71.9 ± 1.8 2.5% of value, 95% C.I.	5.07
Neoprene (Puma)	80.6 ± 1.8 2.3% of value, 95% C.I.	4.76
New Balance Zip	72.1 ± 1.8 2.5% of value, 95% C.I.	5.17

4. Discussion

One of the general conclusions that can be made from examining the data in Table 2 is that lower relaxation moduli, for running shoe midsole materials, is correlated with better quality running shoes. For example, the relatively moduli values for Adidas and Brooks shoes are lower than that of work boots and sandals. Another example is seen by correlating the moduli with cost. If cost is an indicator of running shoe quality, then the data shown in Table 3 indicate that a low midsole relaxation modulus is correlated.

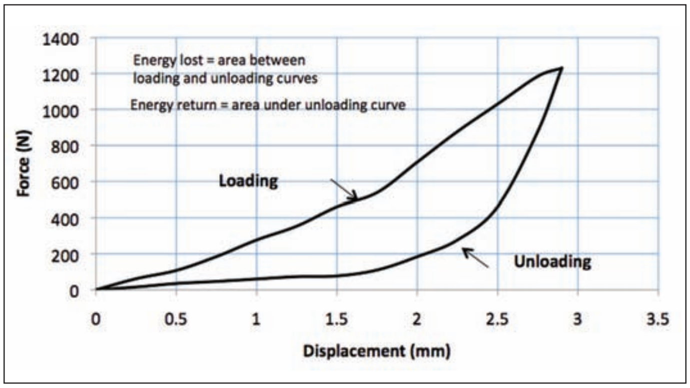

Figure 8. Representative plot of loading and unloading force as a function of displacement. The ERP parameter is the complement of the ratio of energy returned to energy applied.

The Energy Return Percent work showed that neoprene material in the Puma shoe has a higher energy return percentage than the New Balance Zip material, as well as that from the EVA material found in the Asics shoe. Possible future tests can determine if this is a result of the material itself or another factor inherent to the shoe design. Other running shoes can be tested, and more data may suggest whether the preliminary results reported are due to material or shoe design. Another future study may focus on the possible effects of higher energy return percentage. It may not be known whether a higher energy return percentage is always associated with higher performance for running shoes. Rather, an optimum energy return percentage may be possible and could be determined by further testing.

5. Conclusion

Compressive stress relaxation modulus was determined for running shoe midsole materials. Lower modulus appears to correlate with higher performance running shoes. Energy Return Percentage experiments were performed on three types of running shoes. Three brands were tested, and preliminary results indicate that a specific Puma shoe had a higher energy return percentage than the other two shoes tested (New Balance and Asics).

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