Foot & Ankle International

DOI: 10.3113/FAI.2012.0772

# Effect of Heating on the Mechanical Properties of Insole Materials

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## ABSTRACT

***Background:*** **The most common method of customizing shoe insoles to the shape and surface of the foot is to heat and then mold the materials. The effect of heating on the mechanical properties of these materials is unknown. *Methods:* The properties of individual and common combinations of insole materials were tested before and after heating. Individual materials tested were soft Plastazote (SP), medium Plastazote (MP), Puff (F), and Nickelplast (N); combinations of materials that were tested were SP + F and MP + F, each with and without Poron (P). Three samples of each were tested five times. Materials were heated and then compressed with an MTS servohydraulic device. Load transmission and percent compression at maximal load were measured on single materials and their combinations. Stress–strain curves were measured. *Results:* Compared to unheated material, the heated material transmitted higher forces. After heating, the combinations transmitted maximal load at a lower percentage of compression (i.e., became stiffer). Heating also changed the stress–strain curves of the three-material combinations, causing them to transmit maximal pressure at a lower strain. *Conclusion:* Heating insole materials changed their mechanical properties. The materials became stiffer and less effective in the attenuation of applied forces. *Clinical Relevance:* The common practice of heating insole materials to improve their contact with the foot reduced the pressure-reducing properties of the materials, which may decrease their clinical effectiveness.**

**Key Words: Insole Materials; Mechanical Properties; Plantar Pressure; Metatarsalgia; Neuropathic Disorders**

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No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

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## INTRODUCTION

Insoles are widely used and highly promoted in sports as well as in the treatment of neuropathic conditions of the foot. Multiple authors have noted that in the current clinical climate the science of insole design and insole function appears to be somewhat obscured at times by unproven assumptions for their widespread prescription, especially in sports and other common conditions of the foot.[2,9,11,19] The clinical use of insoles is indeed considered fundamental to the treatment of patients with diabetes and other peripheral neuropathies with a risk for, or a history of, plantar ulcerations.[1,2,6,7,15] The purpose of insoles is to reduce force transmission to the plantar foot and lower limb and to protect the foot and reduce the occurrence or recurrence of plantar ulcers in the diabetic populations.[3]

The presumed mechanism by which insoles function is reducing the transmission of elevated plantar loads (force and pressure) from plantar bony prominences.[1,2,12,14] Soft, moldable insoles are believed to accommodate bony prominences and distribute plantar pressures over a wider surface area, to reduce peak loading pressures in regions of high pressure, thus reducing the risk of ulceration.[1,6,7,10,12,14]

There is limited information regarding the mechanical properties of insole materials and the commonly utilized combinations of materials.[2,8,13] With the exception of two studies,[3,8] previous investigations have tested insole materials individually. In clinical practice, the majority of insoles are made of combinations of materials, both prefabricated and custom-made prescription insoles.[9]

Insoles are usually made of materials that are conceived to act as shock absorbers, (i.e., load distributors) to reduce plantar pressures. Two qualities have been described in the analysis of insoles, and different authors have used varied terminologies to describe these. The two qualities are (1) the mechanical properties of the material as it deforms under applied loads and (2) force dissipation or the ratio of input versus output force (i.e., the proportion of force not transmitted to the plantar surface of the foot).[7]

Previous studies have analyzed insole materials both by compressing the materials against a flat surface[4,5] and also in models of plantar bony prominences.[2,3] Because pain in sensate, or ulceration in insensate patients occurs under plantar bony prominences such as the metatarsal heads, it is common practice to create molding of the materials by first heating them.

The purpose of the study was to investigate the functional properties of insole materials in clinically relevant conditions in order to better understand and thus to improve their function. The hypothesis of this study was that the heating of individual or combined insole materials adversely affects their mechanical properties and ability to reduce load transmission.

## MATERIALS AND METHODS

### Individual and combinations of orthotic materials

This study tested four individual materials and four clinically prescribed combinations of orthotic insole materials for their properties of load transmission, strain under compressive load, and elastic deformation in their native forms before heating and again after heating. The materials and the material combinations that were tested are listed in Tables 1 and 2, respectively. The moldable materials were closed-cell foams. One of the materials used in the combinations, Poron, was not heated, because it is a nonmoldable, open-cell foam that is frequently added to insoles for its extreme durability and shock-absorbing qualities.[2,3]

### Heating protocol

For replicating clinical practices of creating custom insoles, the materials were heated at 300 F for 3 minutes in a convection oven of which the temperature was monitored by an oven thermometer. After heating, the materials were removed from the oven and allowed to cool for 15 minutes before testing.

Testing of the combinations of materials was also done to simulate clinical practice. The soft Plastazote or medium Plastazote was glued to the Puff, allowed to set, and then heated. For the three-material combinations, the Poron was glued to the Puff surface of the combined materials once the combinations were cooled. After 3 minutes in the convection oven, the combination was immediately placed on the MTS machine where 233-kg load/283 kPa of pressure was applied for 10 seconds to mimic a patient standing on the materials to create a custom molding. Following the molding, the material was removed from the MTS machine and allow to fully cool before testing.

**Table 2:** Material Combinations Tested

| |
|---|
| SP + Puff |
| MP + Puff |
| SP + Puff + Poron |
| MP + Puff + Poron |

### Testing apparatus

To test the insole materials, an Alliance RT/5 material testing system (MTS Systems Corporation, Cary, NC) and a digital load cell (Imada DSP-440, Imada, Inc., Northbrook, IL) were attached to a custom-made stainless steel testing jig (Figure 1). A previously published testing jig[2] was utilized as a model of a plantar bony prominence to evaluate the efficacy of the materials in load attenuation. The jig consisted of a stainless steel cylinder with a 10.16-cm-diameter tray (81.07-$cm^2$ area) in which the orthotic materials were placed. In the center of the tray, a 1.5-cm-diameter steel cylinder was raised 3.0 mm above the tray surface to simulate a plantar bony prominence (Figure 1). The prominence was connected to the digital load cell to measure the load transmitted through the jig. The materials were sharply cut to fit the area of the material tray on the testing jig, using a scalpel because scissors create material compression at the edges of the cut materials.

The materials were tested with the first-listed material of the combination oriented toward the bony prominence model, and the second-listed material in the middle, and the third material oriented toward the MTS load applicator, to simulate clinical insole use. Materials were placed in the order that is used clinically, the softest molded material next to the skin (jig) and the poron furthest, or most "plantar," (i.e., closest to the source of pressure ("floor" = MTS). The combinations were glued together using a very thin layer of contact cement,

**Table 1:** Individual Insole Materials

| Material | Description | Manufacturer |
|---|---|---|
| Soft Plastazote | Closed-cell, cross-linked polyethylene foam | Zotefoam PLC (Croydon, UK) |
| Medium Plastazote | Closed-cell, cross-linked polyethylene foam | Zotefoam PLC (Croydon, UK) |
| Puff | Ethylene vinyl acetate (EVA) foam; Closed-cell foam make from ethylene vinyl | Acor (Cleveland, OH) |
| Nickleplast | Acetate (EVA) and polyethylene | Alimed (Dedham, MA) |
| Poron | Open-cell urethane foam | Rogers Corporation (Rogers, CT) |


**Fig. 1:** A MTS load applicator and a digital load cell were attached to a custom-made stainlees steel testing jig to test the insole materials.

as is utilized in construction of clinical insoles. Pretest trial runs were used to establish the testing protocol.

The MTS machine cycling parameters were controlled with commercial software (TestWorks 4, MTS Systems Corporation, Eden Prairie, MN). The MTS apparatus has a built-in load cell in the actuator, which is used to apply the external loads for the testing. This provides verification of the applied load, which is then compared to the measured load transmitted to the load cell in the jig beneath the materials. The MTS apparatus was used to calculate compression thicknesses between the load applicator and the surface of the jig (i.e. the thickness of the material being tested).

**Testing protocol**

A peak pressure of 283 kPa (2.88 kg/cm$^2$) was applied to the insole materials using the MTS apparatus. The pressure was determined by the ratio of applied force over the area of the material tray on the testing jig. The compression test speed was set at 2.5 mm/min to minimize the MTS machine overshooting the desired load. Data were sampled at 100 Hz. Sampling was performed from a preload of 10 kPa, simulating the pressure of putting the foot into the shoe, to the peak pressure (283 kPa).[4,5] Three unheated and three heated samples of each of the eight materials or combination of materials were tested, and each sample was tested five times. Three parameters were measured for each of the 48 tested samples: percent compression at maximum loads, strain under compressive load, and load transmission.

The parameters during the testing session were defined on the basis of previously published studies. Plantar pressures between 2.8 and 3.6 kg/cm$^2$ have been utilized in prior studies of insole materials.[1,6,10,11,16] Percent compression was determined by measuring the thicknesses of the samples before and after heating with a fine caliper. The percentage of compression required to reach maximal load was compared for the native and heated individual materials and combinations. The compressible zone was defined as the difference in thickness between preload and peak pressure (i.e., the amount the material combination compressed during one cycle).

The difference in the position of the crosshead from the established 10-kPa preloads to the maximal load, 283 kPa, was calculated and divided by the material's thickness. To reveal the accurate percentage of compression for the heated samples, the material's thickness was measured both in the original, unheated materials and following heating and molding, but before the compression testing because the material thickness changed as a result of heating. Percent compression was normalized to the precompression thickness of the materials, both unheated and heated.

Strain under compressive load is comprised of the change in thickness of the materials in compression at the maximal load. Insole thickness was measured by the MTS system, using the known position of the MTS crosshead. The MTS crosshead position resolution was 0.002 mm. Measurements were taken at peak pressure.

To determine the ability of the materials to reduce load transmission, measurements were made of the applied load that was transmitted through the individual material and combinations, both unheated and heated, to the bony prominence model.

**Data analysis**

The data from compression testing were normalized to express the changes as a percentage of the thickness of the virgin material combination. Force transmission data were presented as a percentage of the applied load. Statistical analysis was done using an analysis of variance with post-hoc Tukey's test when differences were demonstrated. Statistical significance was set at $p < 0.05$.

## RESULTS

**Percent compression**

Figure 2 depicts the percent compression of materials at maximal compressive loads both in the original, unheated materials and material combinations and in the materials and material combinations after heating. Figure 2A shows the percent compression to reach the maximal load for the individual materials. Following heating, the Nickelplast demonstrated the largest shrinkage of all the individual materials at 15% (0.76/5.08 mm). In its native form, Nickelplast compressed 62% (3.15/5.08 mm) to reach the maximal load. Once heated, however, the Nickelplast compressed 68.9% (2.97/4.32 mm) in order to achieve the desired maximal load. Similar to Nickelplast, the soft Plastazote required greater compression to reach the maximal load following heating: 66.8% (4.00/5.97 mm) heated compared to 64.1% native (4.40/6.86 mm). By contrast, Puff required 70.8% (3.60/5.08 mm) compression of the native material to reach the maximal load; however, the heated material required only

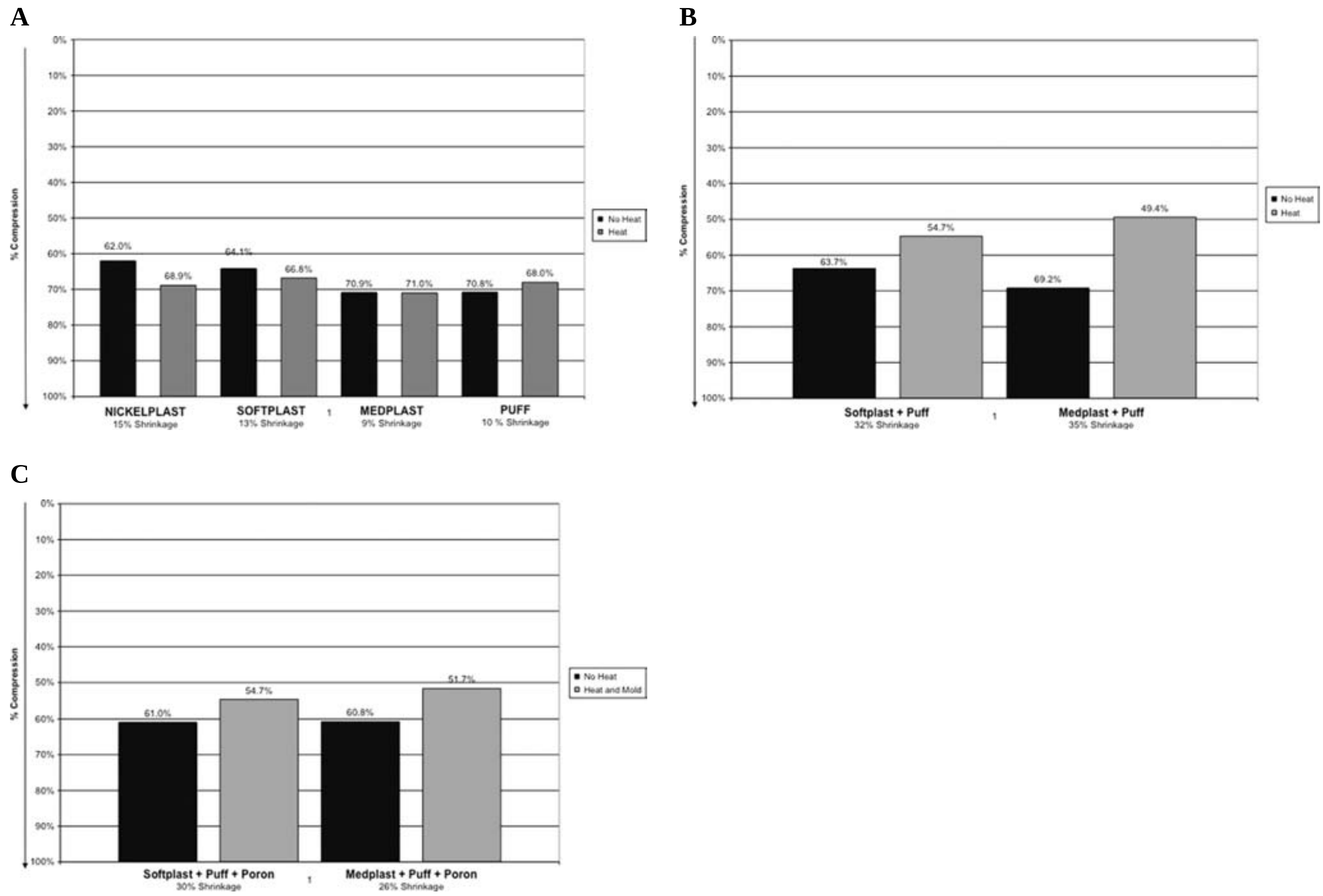


**Fig. 2:** Percent compression: (**A**) individual materials, nonheated versus heated; (**B**) two-material combinations, nonheated versus heated; (**C**) three-material combinations, nonheated versus heated.

68% (3.10/4.57 mm) compression to reach the same load. Once heated, the Puff shrunk only 10% (0.51/5.08 mm).

Figure 2B displays the two material combinations. In both the soft and medium Plastazote with Puff samples, the heated trials required less compression to reach the maximal load than the native forms. Unlike the individual materials that were only heated, the combination of materials were both heated and molded, which likely accounts for the greater shrinkage of both the soft and medium Plastazote/Puff samples, 32% (4.20/11.58 mm) and 35% (3.81/10.92 mm), respectively. The medium Plastazote and Puff sample showed the greater difference in percent compression required to achieve the maximum load: 69.2% (7.56/10.92 mm) compression was required for the native sample, while the heated and molded sample required only 49.4% (3.52/7.11 mm) compression to achieve its maximum load.

Similar to the results from the two-material combinations, the three-material combination tests, represented in Figure 2C, revealed that heating and molding the material resulted in a decrease of a percent compression to reach the maximal load when compared with the native sample. In its native form, the soft Plastazote/Puff/Poron sample required 61.0% (8.87/14.55 mm) compression to reach 283 kPa; however, once heated and molded, the combination of materials required only 54.7% (5.56/10.16 mm) compression to attain the same maximal load. Similarly, the native medium Plastazote/Puff/Poron sample required 60.8% (8.49/13.97 mm) compression to reach the maximum load and only 51.7% (5.35/10.34 mm) compression following heating and molding.

### Strain under compressive load

Figure 3 reveals the dynamic changes of the three-material combinations (soft Plastazote/Puff/Poron and medium Plastazote/Puff/Poron) throughout the trial. The slope of the dynamic strain curve represents the modulus of elasticity of the material. Early and late in the trial, the slope was great, indicating the material was stiffer, and the flatter central portion of the curve represents less stiff behavior of the viscoelastic material.

The heated and molded curves of the soft Plastazote/Puff/Poron sample remain similar in slope and percent strain until roughly120-kilogram-force (kgf) load is reached, upon which the curves of the two different trials diverge

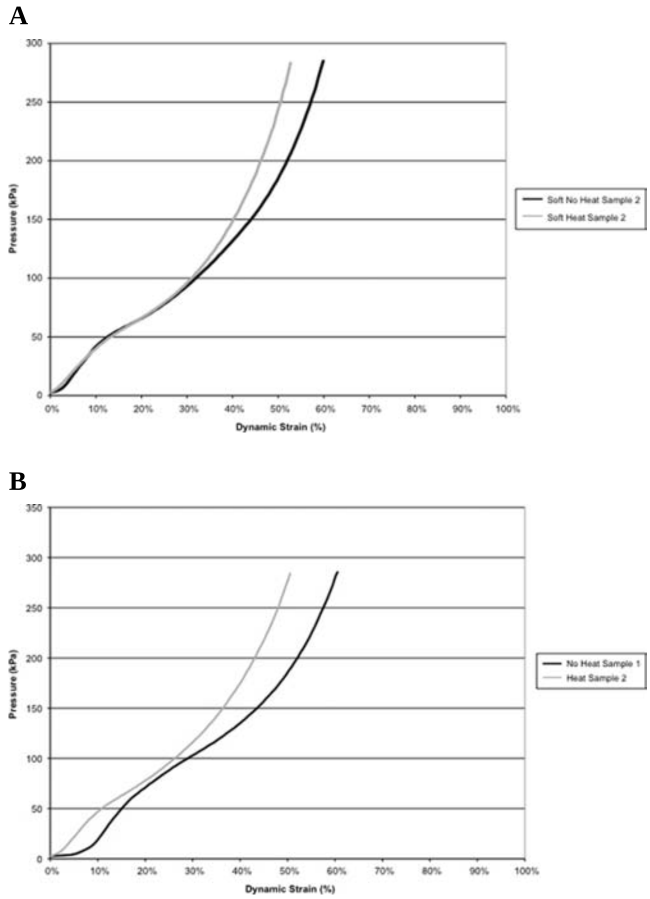


**Fig. 3:** Stress−curve: (**A**) soft Plastazote + Puff + Poron; (**B**) medium Plastazote + Puff + Poron.

with the heated and molded samples reaching the maximum pressure of 283 kPa at a lower strain than the native samples.

In contrast, the beginning portion of the stress−strain curves for the medium Plastazote/Puff/Poron samples are quite different. Immediately, there is a disparity between the curves of native samples and the heated and molded samples. At a pressure from 0 until 60 kPa, the curves diverge with the heated samples reaching a higher pressure under a lower strain. At 60 kPa, the two trials converge, and it is not until a 120-kPa pressure that the trials diverge once again in similar fashion to the soft Plastazote/Puff/Poron sample.

#### Load transmission

Figure 4 depicts the load transmitted across a bony plantar surface at the peak load of 283 kPa. Each material sample is compared in its native nonheated form against a heated sample. In all cases, the heated material transmits a statistically significant greater force across the bony surface than the native unheated material. When the results of the first series of tests are compared with the fifth, there is no difference in the data obtained with each of the materials or combinations.

Individually, Puff had the least difference in transmitted force from the native material to the heated material (22.5 kgf). In contrast, heated Nickelpast revealed the greatest disparity between the heated and nonheated samples: the native Nickelplast transmitted 41.3 kgf, while the heated Nickelplast transmitted 198.9 kgf—a difference of 157.6 kgf.

In Figure 4B, the two-material combinations revealed the same trend of an increase in load transmitted following heating the materials. While the individual materials were only heated, these two-material combinations were heated and molded. The medium Plastazote/Poron transmitted a lesser force, 22.5 kgf, than the soft Plastazote/Poron, 25.1 kgf. Once heated, however, the medium Plastazote sample transmitted 11.4 kgf greater force across the bony surface than the heated soft Plastazote/Poron sample. Once heated and molded, the soft Plastazote sample transmitted a 44% (20.4/45.5 kgf) greater force than its native sample. Even greater, the medium Plastazote/Puff sample transmitted 56% (28.9/51.4 kgf) more force after it had been heated and molded when compared to the force transmitted by the native sample.

Figure 4C represents common clinical orthoses material combinations. Consistent with the data from the two previous sample pools, the heated and molded samples transmitted a statistically significant higher force across the bony prominence. Unlike the two-material combinations, the heated and molded medium Plastazote/Puff/Poron sample transmitted a lesser force than the soft Plastazote sample: 24.5 kgf and 30.5, respectively. The soft and medium Plastazote combinations transmitted a 30% (9.1/30.6 kgf) and 18% (4.4/24.5 kgf) greater force across the bony prominence, respectively.

### DISCUSSION

The results from this study reveal that heating individual and combinations of orthotic material altered their mechanical properties and their mechanical effectiveness. In all cases, the individual material samples transmitted a higher force across the model of a bony prominence. Although all the individual materials demonstrated a significant increase in load transmission following heating, Nickelplast had the highest increase in transmitted load after heating, compared with its native state.

Because custom orthoses are typically constructed of more than one material, usually applied in layers, the testing on the combinations of orthotic materials added greater clinical relevance than the testing of individual materials alone. As demonstrated in Figure 4, B and C, the combination of multiple materials reduced the overall force transmitted over the bony prominence model. However, despite the addition of Poron, which is not a heat-moldable material, the heated combination of soft or medium Plastazote with Puff still transmitted a significantly higher force across the bony prominence, compared with the unheated sample.

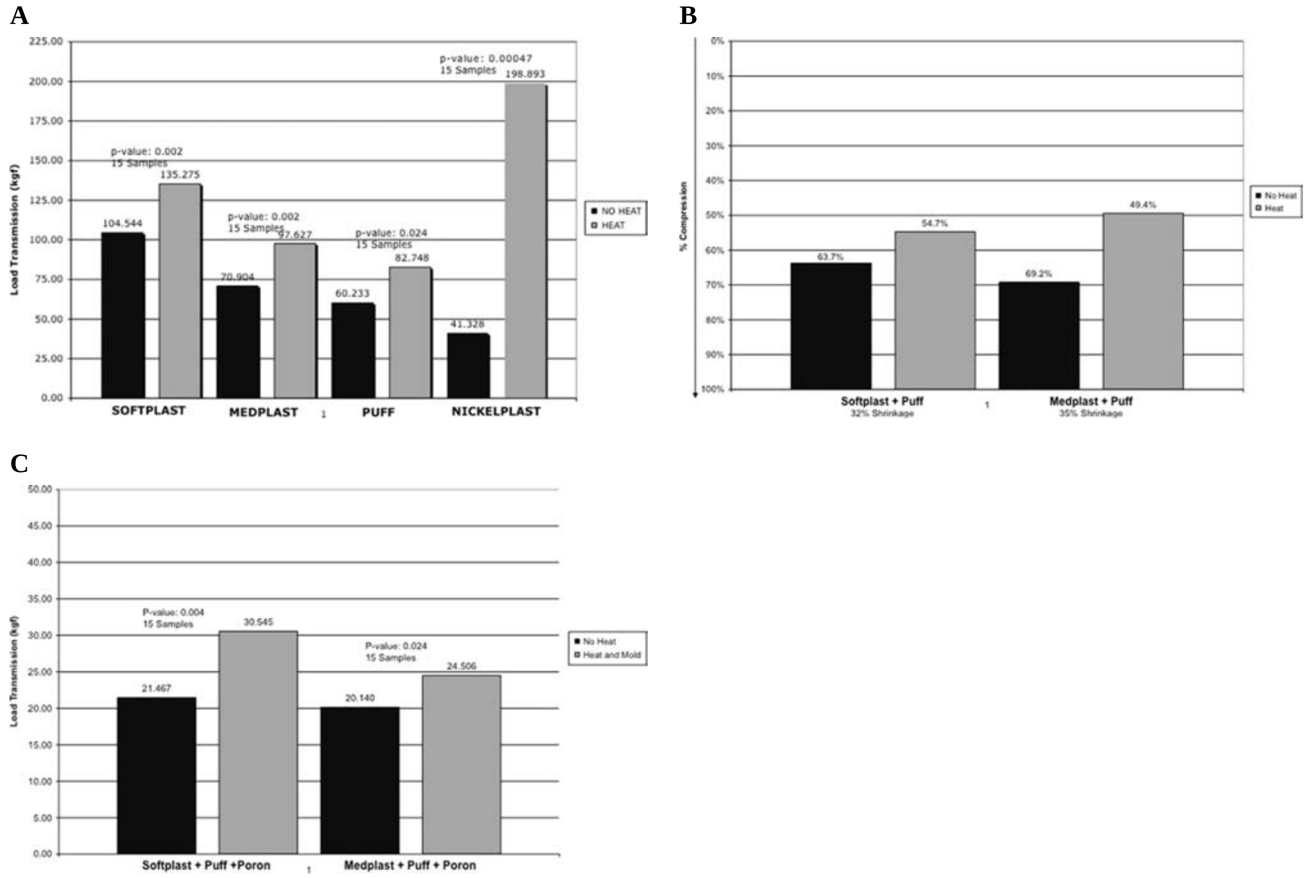


**Fig. 4:** Load transmission: (**A**) individual materials; (**B**) two-material combinations; (**C**) three-material combinations.

The decrease in percent compression to reach the maximal load in all material combinations demonstrates the immediate effects of heating on the material's compressibility. Because heating altered the material's mechanical properties and a lower percentage of compression was required to reach the maximal load, the orthotic material lost some of its ability to reduce the transmission of peak plantar loads away from bony prominences.

The stress−strain curves of the three-material combinations demonstrate the effect of heating on the dynamic function of the material as shown by the decrease in elastic deformation. In particular, the effect of heating on the medium Plastazote/Puff/Poron samples was evident within the first 60 kPa of pressure.

These results can have direct clinical significance in a clinician's expectations for reducing elevated plantar loads and transmitting pressures away from bony plantar prominences. As indicated by multiple previous studies, elevated plantar loads can lead to plantar lesions and ulcerations in patients with diabetes or Hansen's disease suffering from peripheral neuropathy.[1,8,11,12,15−18,20] The necessary heating protocols used to create custom orthoses for diabetic patients and athletes reduce the material's ability to reduce the loads transmitted to the plantar bony prominence model.

## CONCLUSION

In conclusion, this study examined the effects of heating on the mechanical properties of common orthotic materials. Despite the customary wisdom that molding of insole materials is a valuable component of the manufacture of custom insoles whose purpose is to decrease pressure under the foot of diabetic, other neuropathic, or even athletic patients, these data show that heating the materials resulted in an increase in load transmission, when compared with unheated material. Perhaps future alternatives will include the development of new materials that are moldable and have enhanced function in the attenuation of pressure on the foot. The unanswered question is whether there is a compensatory benefit in load reduction at the actual bony prominence in patients, as a result of the molding, that would offset the increase attributable to the change in the properties of the materials themselves. This is difficult to test because of the artifact introduced by measuring materials placed in the interface between the insoles and the foot.[17]

The combination of material samples should continue to be evaluated in a cyclic testing protocol to establish the long-term effect of heating. However, this study demonstrated that common heating techniques used to construct custom orthoses altered the mechanical structure of the orthotic material and decreased its ability to disperse peak plantar loads.

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