Effectiveness of Various Materials in Reducing Plantar Shear Forces

A Pilot Study

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Vertical plantar forces are known to be a major precipitating factor in the development of foot pathology. It is also postulated that shear forces are important in the pathogenesis of foot ulcers in patients with diabetes mellitus. Various materials are used in insoles designed to reduce forces on the foot. While many foam materials have been tested for their ability to dissipate vertical forces, few studies have tested the effect of these materials on shear forces. This study assessed the effectiveness of five different materials in reducing plantar shear forces and compared two new gel materials with three of the more conventional foam materials. Four subjects were tested while walking over a force platform with one of the five materials taped to the surface. Peak force, impulse, and resultant shear force data were analyzed. The gel materials were significantly better than the foam materials at reducing shear forces. Thus the use of gel materials in insoles may be indicated for the reduction of plantar shear forces on the diabetic foot. (J Am Podiatr Med Assoc 90(7): 346-353, 2000)

During walking, the sole of the foot is subjected to mechanical stresses. These stresses comprise two components: direct pressure perpendicular to the surface (vertical) and shear forces tangential to the surface (horizontal).[1] In the diabetic foot, it has been shown that high vertical pressures are associated with the presence of neuropathic ulceration.[2, 3] Shear forces, which are on average 30% of the value of vertical forces,[4] are also thought to be important in the pathogenesis of these ulcers.[5]

In tests using a strain gauge transducer on the palm, shear forces were shown to combine with direct pressure to cause blood flow occlusion over time.[6] Pollard and Le Quesne[7] showed that healed ulcer sites corresponded to the areas with greatest horizontal and vertical forces. This suggested that repetitive vertical and shearing forces are the most likely cause of foot ulceration among diabetic neuropathic patients.[8]

Devices that measure forces beneath the foot have been extensively reviewed.[9-15] Devices currently used for dynamic assessment of plantar forces can be broadly categorized into force-plate and in-shoe systems.[9] Force platforms are commonly used to measure plantar shear forces during human locomotion; however, they do not provide information regarding forces at the foot-shoe interface. In-shoe systems that measure shear forces are being developed as prototypes but are not yet commercially available.[16] Until these shear-sensing in-shoe systems are available, force-plate technology appears to be the best option for accurate measurement of shear force during gait.

Foot-care practitioners often use insoles or orthoses to redistribute the forces on the foot. Choice of material is based on personal experience, cost, and availability.[17] The insoles may be flat or molded, have excavations, have redistributive metatarsal pads, or have pads with U-shaped accommodations.[18-21] A cavity or U in the insole can be filled with

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use of such devices. All researchers should be humble and recognize that the perfect research project has yet to be performed.

4) Research must consider all aspects of the foot's function before taking a stand on one variable. For example, the claim that a pronated foot is a stable foot that can be a rigid lever may be true.[22, 23] Such a statement, however, is not consistent with facts about the need for supination of the arch in order for the toes to dorsiflex during propulsion.[24, 25]

5) All theories about what is normal must fit with known principles of mechanics. If they do not, then the theorist must explain why.

6) All theories about what is normal should be built for the lowest common denominator: that is, they should be based on the maximal stress that society may place on that person.

7) Theories about what is normal should try to optimize the sharing of stress by all elements. A theory may explain how to minimize stress on one portion of the foot, but that solution may maximize stress on another portion of the foot.

8) A theory explaining the normal positions and movements for any one individual should be applicable to all shapes and sizes of feet.

9) A universal theory of foot function should include both the static and the dynamic functions of the foot.

10) A theory of foot function should be based on a full understanding of the individual components of the foot, with the result that the sum of the components will equal the final outcomes. It is almost impossible for a final outcome to be measured and therapy to be directed to this final outcome without an understanding of the individual components. Such an attempt will only exacerbate the problems currently encountered in differentiating the normal from the abnormal. Such things as bunions and arch heights should be considered outcomes, not components.

11) Finally, care should be taken before criticizing the work of clinicians who are making honest attempts to fix the abnormal. As noted above, many definitions and criteria exist for the term "normal." People consult clinicians about conditions they view as abnormal. In making decisions about treatment options, clinicians must use the best research as well as their own experience and judgment and must also consider the goals of the patient. Most of the time, clinicians do not have the luxury of sitting on the sidelines, waiting for additional research to be performed, before making treatment decisions. Therefore, great tolerance and latitude must be provided in areas where differences of opinion still have room to exist.

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a "button" of a less dense material (eg, soft, open-cell foam or silicone gel). A molded insole with a U or cavity in the area of previous ulceration and a Plastazote (Zotefoams, Inc, Croydon, England) cover is often used to prevent recurrence of ulceration; however, clinical experience has shown that this approach is not always effective. An ulcer dressing called Conformagel (Kendal Co, Mansfield, Massachusetts) has been tried as a "button." Although Conformagel is not an insole material, it has been perceived as being clinically effective in reducing the incidence of ulceration in diabetic patients.

Several studies have assessed the ability of insole and footwear materials to reduce vertical forces.[19, 21-27] In shear force studies, the emphasis has been on developing instruments and protocols for measuring shear forces.[1, 4, 5, 22-26] Technology for shear force measurement has not reached the point where it is regularly used as a clinical research tool. The lack of systems that accurately and reliably measure shear force on the plantar surface of the foot during walking is probably the reason that few investigators have studied the effect of insole materials on shear forces.[4]

In the 1960s, the role of shear forces in the formation of decubitus ulcers was recognized, although these forces could not be measured. Researchers typically used silicone gel and neoprene to reduce plantar shear forces.[27-29] In 1983, Pollard et al[5] studied the effect of shoes, insoles, and plaster casts on shear forces by taping discrete transducers to the foot. It was found that Plastazote insoles reduced the peak longitudinal shear force by 30% to 50%. Rocker-bottom soles reduced shear forces by 30% to 70%, but did not significantly alter peak shear force under the first metatarsal head. The greatest reduction in shear forces on the forefoot was produced by a plaster of Paris walking cast, while the greatest reduction in heel shear forces was produced by a surgical shoe.

The current study aimed to address a gap in the literature by comparing different materials that could be used in a diabetic insole for their effectiveness in reducing plantar shear forces. This study also addressed the hypothesis that gel materials are more effective than foam materials for shear force reduction. To prevent ulceration in people with diabetes, the appropriate material could be incorporated into insoles at high shear points.

Subjects and Methods

Subjects

Four research subjects were selected from the staff of the Rehabilitation Centre (Ottawa, Ontario, Canada). Subject age ranged from 22 to 34 years (mean [±SD], 29.25 ± 5.25 years), and weight ranged from 565 to 784 N (mean [±SD], 661.25 ± 94.86 N). All subjects met the following selection criteria:

- Able to give informed consent to participate in the study
- Available to attend all five test sessions
- Body mass index less than 25 kg/m^2
- No history of traumatic injury to the foot or leg within 1 year preceding the start of the study
- No gross cutaneous, soft-tissue, or osseous abnormality of the foot or leg
- No foot symptoms
- No sensory, motor, or gait disorder.

The subjects consented to participate in the study and were informed that this was a noninvasive test with minimal risk. No personal information was recorded other than weight, height, and age.

Instrumentation and Materials

Data were collected with the use of the model OR6-3A Biomechanics Platform (AMTI, Watertown, Massachusetts), Ariel Performance Analysis System (APAS) software (Ariel Dynamics, Trabaco, California), and APAS A/D (analog-to-digital) hardware. All data were sampled at 200 Hz.

The materials used are described in Table 1. PPT (Langer Biomechanics Group, Deer Park, New York), Plastazote, and Spenco (Spenco Medical Corp, Waco, Texas) were chosen as the foam-type materials because they are regularly used in podiatry for insole manufacture.[1, 30] Two gel materials were included in the study so that the test could indicate whether gel materials reduce shearing stresses more effectively than foam materials. The two gel materials chosen were Soft Shear (Silipos, New York, New York) and Conformagel because they are available in sheet form. These materials were affixed to the top of the force plate with two-sided carpet tape.

Carpet Tape Evaluation. All materials were affixed to the force platform by completely covering the underside of the materials with strips of 2-inch-wide double-sided carpet tape (Tape Specialties, Concord, Ontario, Canada). To ensure that the carpet tape was not altering shear forces, a single subject from the main subject group was recruited to walk barefoot ten times over the plate only, then ten times over the plate with an 8-mm-thick aluminum sheet affixed to the surface with the carpet tape. Anteroposterior shear, lateral shear, and vertical forces and impulses were compared for the two test conditions by means of a two-tailed *t*-test. This test showed that there was no significant difference ($P < .05$) between

Table 1. Information on Materials Used in the Study

Material	Manufacturer	Description	Approximate Thickness	Orientation
Plastazote (pink, soft)	Zotefoams, Inc, Croydon, England	Expanded closed-cell polyethylene foam	4 mm	Reversible
Spenco	Spenco Medical Corp, Waco, TX	Neoprene rubber foam with nylon cover	4 mm	Nylon cover side up
PPT (blue, single abraded)	Langer Biomechanics Group, Deer Park, NY	Open-cell urethane foam	4 mm	Abraded side down
Soft Shear (fabric cover both sides)	Silipos, New York, NY	Medical grade silicone gel	4 mm	Reversible, nylon both sides
Conformagel	Kendal Co, Mansfield, MA	Hydrogel wound dressing	4 mm	Nylon cover side up

the two test conditions. Hence the authors concluded that the tape did not have a significant effect on ground-reaction forces.

Data Collection

The material and force-plate-only tests were performed on five occasions over a 2-week period. For each material, all four subjects walked barefoot across the same piece of material. A new piece of each material was used on each of the 5 test days. All materials were tested on each test day (ie, each material was tested five times). The material and subject testing orders were randomized.

During testing, each subject was asked to first step with the left foot, then step onto the platform with the right foot.[31,32] Data were collected for ten acceptable trials. When all four subjects had completed the data collection for the plate-only condition, the first material was affixed to the force plate, and data were collected for all four subjects. This process was repeated for all five materials. The same protocol was used on all data-collection days.

Data Analysis

Data for anteroposterior (y), lateral (x), and vertical (z) forces were digitally filtered at 12 Hz with the use of the APAS software and exported as a computer text file. This text file was imported into a QuattroPro (Corel Corp, Ottawa, Ontario, Canada) spreadsheet for normalization, ensemble averaging, and calculation of peak forces. A custom analysis program was used to calculate impulse.

All raw data for the materials comparison were analyzed to produce peak forces and impulse for the following: F_y (braking); F_y (propulsive); F_z; resultant shear forces (braking), and resultant shear forces (propulsive). To standardize the results between subjects, all forces were normalized to body weight. The mean forces and impulses for each subject and each test condition were calculated to reduce the data for analysis. While this study focused on the effect of the test materials on anteroposterior shear forces, vertical forces and resultant shear forces were also analyzed.

Repeated measures analysis of variance (ANOVA) with Tukey's Honestly Significant Difference *post hoc* analysis was performed to identify any significant differences among the materials ($P < .05$). To show the order of effectiveness of materials, the mean values for the five materials were presented as percent differences from the force-plate-only results.

Results

The repeated measures ANOVA showed a significant difference between materials and a significant difference between subjects ($P < .05$), but no significant interaction. No significant differences in stance times ($P < .34$) were found between test sessions.

Impulse Values

Percent differences for impulse values from the force-plate-only trials are shown in Figure 1. All of the materials consistently reduced the horizontal impulse values. In most cases, the two gel materials showed the greatest percent differences.

Vertical impulses were reduced, though not significantly, by Conformagel, Spenco, and Soft Shear, but were not reduced by PPT and Plastazote. Plastazote showed a very slight increase in vertical impulse. F_y (braking) impulses and resultant shear (braking) impulses were significantly reduced by Conformagel, Soft Shear, and Spenco, as compared with the force

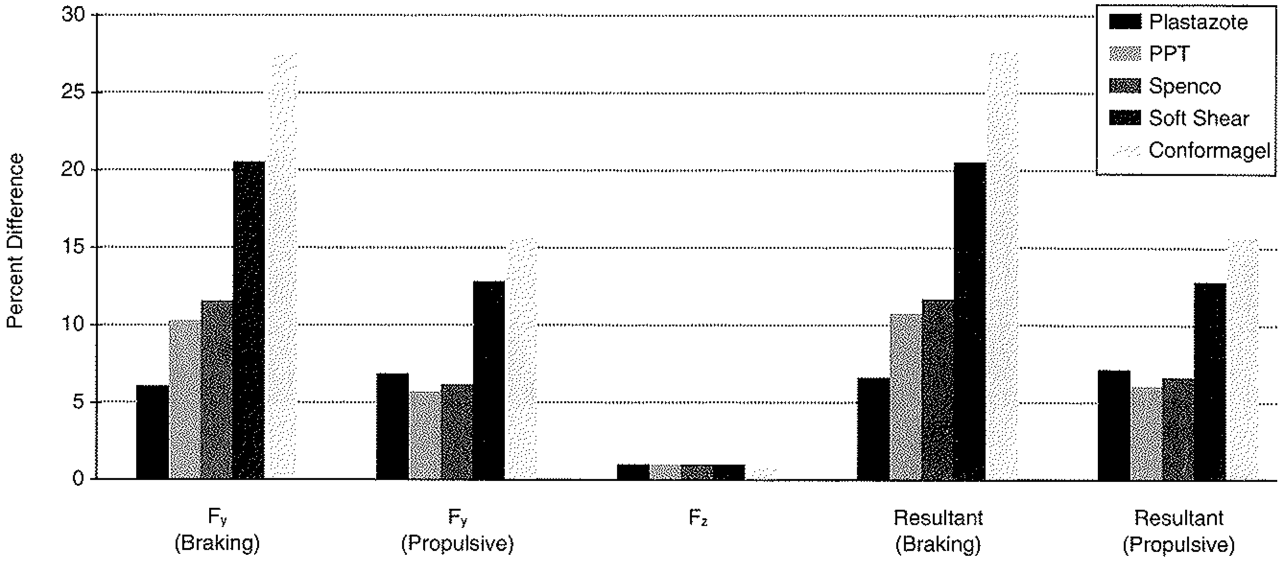

Figure 1. Percent differences between normalized impulses from the force-plate-only trials and normalized impulses for the five materials.

plate only and Plastazote. Conformagel alone showed significant differences from the force plate only for F_y (propulsive) impulse. There were no significant differences for resultant shear (propulsive) impulses with any of the materials. Table 2 displays the mean impulse results for all materials.

Peak Forces

All of the test materials consistently reduced peak plantar forces. The percent differences are shown in Figure 2. The two gel materials, Conformagel and Soft Shear, showed the greatest percent differences from the force-plate-only condition. The shear forces were all reduced to a greater degree than the vertical forces, and the braking shear forces were reduced to a greater degree than the propulsive shear forces (except in the case of Plastazote). Plastazote reduced propulsive forces to a greater degree than it did braking forces.

For peak vertical forces (F_z), there were no significant differences with any materials. For F_y (braking) and resultant shear (braking) peak forces, Conformagel and Soft Shear were associated with significantly lower forces than the force plate only, Plastazote, and PPT. For F_y (propulsive) and resultant shear (propulsive), Conformagel and Soft Shear had significantly lower forces than the force plate only. Table 3 displays the mean peak force values for all materials.

Discussion

This study tested five materials for their effectiveness in reducing forces on the plantar surface of the foot. The values analyzed were peak forces and im-

Table 2. Mean (SD) Impulses as a Percentage of Body Weight for Each Material

	F_y		F_z	Resultant	
Material	Braking	Propulsive		Braking	Propulsive
Conformagel	−3.87 (0.63)	4.39 (0.64)	72.07 (11.16)	−4.14 (0.58)	4.64 (0.59)
Force plate	−3.72 (0.59)	4.09 (0.62)	64.82 (8.73)	−3.87 (0.66)	4.21 (0.64)
PPT	−3.71 (1.20)	3.68 (1.01)	57.35 (15.42)	−3.87 (1.23)	3.75 (1.03)
Plastazote	−3.22 (0.54)	2.72 (0.35)	46.17 (6.15)	−3.33 (0.54)	2.77 (0.35)
Spenco	−2.91 (0.58)	2.78 (0.51)	49.74 (6.52)	−3.12 (0.57)	2.86 (0.53)
Soft Shear	−2.65 (0.30)	2.93 (0.37)	54.53 (5.71)	−2.95 (0.34)	3.03 (0.38)

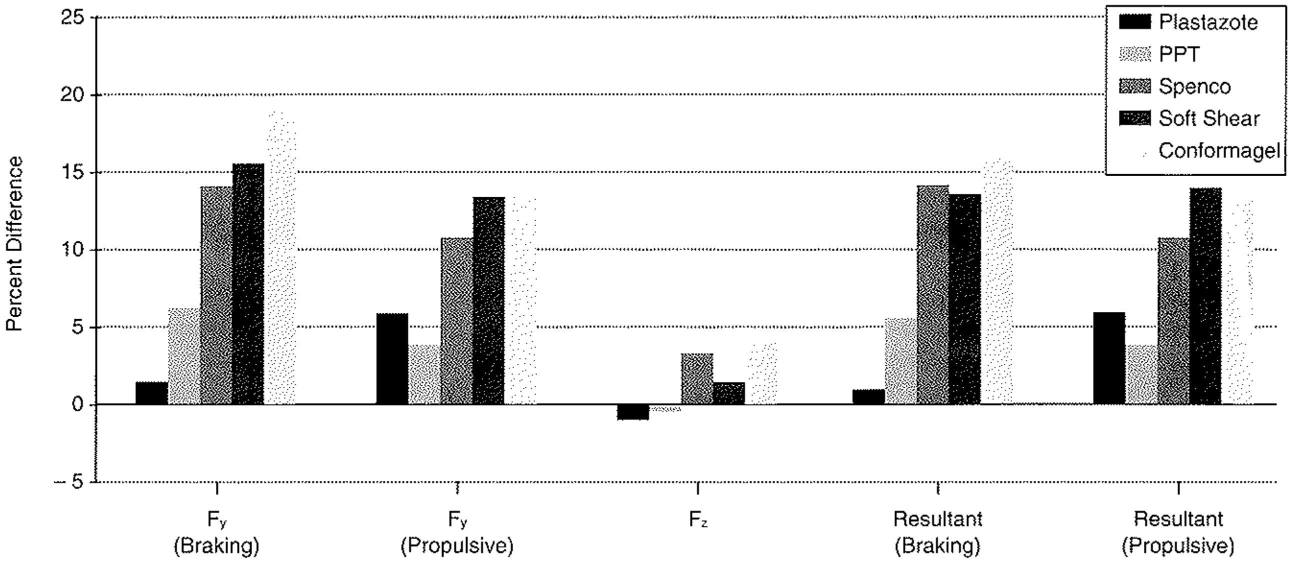

Figure 2. Percent differences between normalized peak forces from the force-plate-only trials and normalized peak forces for the five materials.

pulses. Most studies focus on peak forces; however, it is now well recognized that not only the amount of force is important, but also the amount of time the force is applied. Thus the integral of the force-time graph, also known as the impulse, is useful because it examines both the peak force and the amount of time the foot is loaded.[33] Impulse is also equal to the sum of all forces applied to a body.[34] Since diabetic foot problems are directly related to plantar loads, examination of the sum of these forces is important when evaluating insole materials.

While the percent differences in the current study were small, they did show that the gel materials are significantly better at reducing resultant shear (braking) forces on the plantar surface of the foot than no material, Plastazote, or PPT. It is probable that, in the current study, the softer gel materials allowed the foot to sink further into the material, thus increasing the force-bearing area of the foot.[35, 36] As Bauman et al[36] postulated, a soft, resilient insole lowers peak pressures by distributing them in space and time.

The gel materials may also perform well because the top layer, which the foot contacts, can glide over the gel beneath. Spence and Shields[27] describe this effect seen in a closed-cell neoprene material (such as Spenco) as a ball-bearing effect; it is not seen in open-cell foams (such as PPT). One can also speculate that the physical consistencies of gel materials are similar to human fat and therefore function as a layer of "artificial fat" to protect bony prominences.[28]

The material top covers may also play a part in the reduction of shearing stresses, as the three most effective materials in the current study were also the three materials with nylon covering. The multistretch

Table 3. Mean (SD) Peak Forces as a Percentage of Body Weight for Each Material

	F_y		F_z	Resultant	
Material	Maximum	Minimum	(Maximum)	Maximum	Minimum
Conformagel	20.25 (3.98)	−15.18 (3.99)	112.82 (7.94)	20.35 (4.01)	−15.32 (3.95)
Force plate	24.02 (2.92)	−21.02 (3.54)	117.47 (8.65)	24.13 (2.92)	−21.27 (3.54)
PPT	22.61 (1.99)	−18.85 (3.66)	115.22 (7.48)	22.70 (1.97)	−19.06 (3.68)
Plastazote	22.41 (1.92)	−19.71 (3.71)	115.92 (8.52)	22.50 (1.90)	−19.90 (3.67)
Spenco	22.51 (2.11)	−18.59 (4.00)	116.22 (9.01)	22.59 (2.10)	−18.72 (3.96)
Soft Shear	20.90 (3.28)	−16.76 (4.34)	114.30 (8.09)	20.99 (3.30)	−16.94 (4.29)

nature of a nylon cover is reported to result in a low coefficient of friction, which may be essential in allowing the material to move sideways without being inhibited by its top membrane.[27]

The ball-bearing effect may explain why the gel materials and Spenco were more effective than PPT. Plastazote, being closed cell, would have been expected to perform as well as the gels and Spenco, but it did not. This may give further indication that the nylon top covering plays an important role in shear force reduction.

For all materials except Plastazote, braking forces were reduced to a greater degree than propulsive forces. While comparing Plastazote insoles with plaster casts, Pollard et al[5] found that Plastazote was better at reducing forces under the heel than under the forefoot. The findings of Pollard et al would seem contrary to those of the current study; however, studies that used shear transducers have found that there is no clear distinction between braking and propulsive forces.[4, 5] Thus it is not clear if any conclusions can be drawn from Plastazote's acting differently from the other materials in this study.

Vertical impulses were reduced by Conformagel, Spenco, and Soft Shear, although not significantly. PPT and Plastazote show a very slight increase in vertical impulse. As cadence was not controlled in the study, this increase may be due to stride variations that lead to a longer time spent on the material. The increased impulse values could also be due to the foot's sinking into the material and thereby slowing down the footstep.[37] This would increase the time of application of the force and increase the vertical impulse.

The present study found, as did Pollard et al,[5] that shearing forces can be affected by interventions to a greater extent than vertical forces; however, the range of percent differences is much smaller in this study. This could be a result of the different technology used, the differing units in which the forces are recorded,[9, 14] or the positioning of the measuring device relative to the foot. The studies by Pollard et al[5] and Leber and Evanski[30] placed the measuring device at the interface of the foot and the test material or footwear. In the current study, the material is next to the foot, and the measuring device is below the material. Thus the percent differences from the present study may be lower because they do not measure the forces at the shoe-foot interface.

Because the subjects in the present study were all asymptomatic, they probably did not have areas of high peak plantar forces; therefore, large plantar force reductions were not seen. This is consistent with other investigations that tested subjects with "normal" load distributions.[3] As Holmes and Timmerman[38] suggest, there may be a threshold of plantar pressure below which an intervention may be ineffective in lowering plantar pressures.

The present study investigated the forces under the whole foot and could not look at the heel and metatarsal areas separately. When the net resultant of all forces applied to the foot is considered, the dissipation of forces may appear less dramatic; previous studies reported these two areas separately and record the greatest differences under the metatarsal heads. It is also likely that each region of the foot has a different threshold of pressure above which an injury can occur.[9]

Speculation on the Ideal Insole Material

Campbell et al[17] describe the ideal insole material as one that would progressively deform throughout the full range of load to accommodate the shape of the bony prominence and to transfer a portion of the load to other less prominent regions of the foot. However, a highly deformable material will rapidly become deformed to its limit ("bottoming out"), thus limiting the material's life span. Brodsky et al[35] reasoned that this easy compression, or bottoming out, is advantageous for the insensate foot since the force of walking will dissipate through the compression of the material rather than through the breaking down of the plantar skin.

The current study, though limited by a small subject group and a small group of sample materials, suggests that Conformagel or Soft Shear could be an ideal insole material according to the description given by Campbell et al.[17] In practice, however, the ideal insole for the insensate foot may be a combination of materials because Conformagel is likely to bottom out quickly. Longevity was not tested in the current study; durability testing is indicated. The two-sided nylon cover and firmer consistency of Soft Shear may make such a material durable enough to be clinically useful while still having the ball-bearing effect and a multistretch covering with a low coefficient of friction.

Conclusion

Within the limitations of the current study, the findings indicate that the gel materials tested are more effective at reducing anteroposterior and resultant shear forces than foam materials tested in the study. Conformagel consistently reduced the mean ground-reaction forces and impulses studied to a greater degree than any other material tested. However, the reduction in forces was not significant for vertical impulse or vertical peak force values. The second most effective material was Soft Shear, the other gel material, and the most effective of the foam materials was Spenco. Plastazote appeared to be the least effective of the materials tested.

Pending more thorough investigation, the clinical implications of the current study are that the effectiveness of materials used in the standard "diabetic insole" should be further evaluated. A Spenco insole with Conformagel buttons may prove more effective in preventing ulcer formation or recurrence than a standard PPT insole with a U or sponge buttons and a Plastazote cover. In clinical observation, when Conformagel was used as a button in an insole and covered with Plastazote, it appeared to stay viable for the life of the Plastazote cover. This is estimated to be 9.25 hours of continuous walking, or a maximum of 2 months for a relatively inactive person.[35]

While this pilot study has provided useful information, a larger trial is indicated to obtain a full understanding of the effects of materials on plantar forces. It is also acknowledged that the two-step method of data collection used has been validated only for pressure measurements and not force or impulse. Testing of subjects with abnormally high body weights to determine if the materials have a threshold vertical force at which they bottom out may also be of value. Examining data from symptomatic subjects is also warranted. Material-related tests could include evaluating different material thicknesses, other commonly used materials, how the materials perform when bonded to different materials, and the long-term effect of wear on the materials. Should an in-shoe shear-measuring device become commercially available, testing of the materials in the shoe would yield valuable information. The manufacturer of Conformagel has recently stopped making the product. A similar material, Elasto-Gel, is available from South West Technologies, Inc (North Kansas City, Missouri).

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The Biomechanics, Etiology, and Treatment of Cycling Injuries

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The authors review the biomechanics of cycling and discuss the ideal cyclist's morphology. Examination of the cyclist when resting and when cycling is described. A variety of overuse injuries commonly sustained by cyclists are reviewed, and strategies for altering the cyclist's mechanics to relieve the pain are described. Because the bicycle and the cyclist must be considered as a unit, this article offers instruction for adjusting the bicycle as well as the cyclist. (J Am Podiatr Med Assoc 90(7): 354-376, 2000)

The bicycle invented in the early 1800s was merely one wheel set in front of another with the two wheels connected by a piece of wood. The cyclist sat on the wood and propelled the bicycle forward by pushing on the ground. In the late 1800s, the Penny Farthing bicycle was invented. The Penny Farthing bicycle was much like today's tricycle, with the pedals on the front wheel directly turning the front wheel, propelling the cyclist forward. The height of the front wheel varied considerably. Around the turn of the nineteenth century, the chain-driven bicycle became popular. It has matured over the last 100 years, but the bicycle of today is basically the same as the bicycle of 80 years ago (Fig. 1).

During the last 60 years, the injuries sustained by cyclists have also remained much the same. Knee problems are the most common and most serious of cycling-related overuse injuries. Because the incidence of overuse injuries in cycling is low compared with those from running or soccer, they have generally been overlooked in the past. In the last 30 years, cycling has enjoyed increased popularity and interest. Research has concentrated on how to make a cyclist go faster, but little attention has been directed toward the care and prevention of overuse injuries in cycling.

This article provides basic information about the biomechanics and etiology of overuse cycling injuries so that the sports specialist can increase the enjoyment of cyclists and prolong their participation in the sport. The information is specifically related to cyclists who experience pain as a result of their cycling. The improvement of cycling efficiency or speed is not the primary concern here, but those benefits may follow.

Biomechanics of Cycling

Pedal Cycle

While seated or standing, the cyclist produces the power to move the bicycle forward by pushing its pedals. The pedals move in a circle as they rotate around the bottom bracket. One complete circular motion is called a pedal cycle and is divided into two phases. In the power phase, the cyclist pushes down on the pedal and makes the greatest contribution toward moving the bicycle and the cyclist forward. The power phase begins at top dead center and ends at bottom dead center. While seated, the cyclist can apply the force of approximately half of his or her body weight to the pedal during the power phase. When standing, the cyclist can apply the force of up to three times body weight to the pedal because the cyclist pulls up on the handlebars while pushing down on the pedal (Fig. 2).[1]

The power phase of the pedal cycle is followed by the recovery phase, which progresses from bottom dead center to top dead center. Some cyclists actively

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