Original Article

IN VIVO AND *IN VITRO* TESTING OF SHOE HEEL INSERT PROPERTIES; A COMPARATIVE STUDY

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Abstract

Shoe heel inserts (SHI) are a common method of conservative treatment for various painful disorders like degenerative joint diseases (DJD) and overuse injuries. They are also used to enhance exercise performance in athletes. There is little in the literature to guide orthopaedic practitioners in relation to optimum material for these SHI. The current study examines properties of three different kinds of off-the-shelf SHI in terms of their performance, endurance and cost. The material properties of inserts were tested on a universal material testing machine (UTM) before and after mechanical degradation (MD) that was performed by a purpose built repetitive loading machine (RLM) under compression and shearing forces. The results of material tests were augmented through subject tests by a pressure sensitive insole system, Pedar®. The data provided evidence that MD, simulating a normal walking distance of 100 to 130 Km, deteriorated the performance of all inserts tested in the current study. There were significant changes in the stiffness and elastic hysteresis of inserts and they were less efficient in cushioning heel areas. The SHI were responsible for putting more pressure under the lateral metatarsal heads. The SHI may be effective in symptomatic relief of painful DJD and overuse injuries but should be used cautiously in diabetic patients.

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Keywords: Endurance; Mechanical degradation; Cost; Stiffness; Hysteresis.

Introduction

The SHI are commonly used for the symptomatic relief of DJD, overuse injuries, enhancing exercise performance and plantar pressure distribution in diabetic patients. Due to increasing interest in exercise, now more than ever people are involved in exercise, aerobics and sports resulting in overuse injuries. It has been suggested that osteoarthritis of the knee joints might be due to vertical loading of joints responsible for micro fractures of subchondral bone. The healing of these micro fractures results in stiffness of the bone leading to wear and tear of joint cartilage and osteoarthritis.[1] Subsequently it has been claimed that shock-

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waves transmitted on heel strike are responsible for backache by producing fatigue fractures in the vertebral bodies and facet joints. These transient forces are thought to be responsible for overuse injuries and prosthesis loosening.[2] The effect of forces generated on walking was studied and it was proposed that these forces are responsible for stress fractures in femur, tibia and metatarsals in military recruits.[3] However, the human body has natural defences against these transient shockwaves. The static shock absorbers are heel pads, foot joints, joint cartilages, cancellous bone, meniscus and intervertebral discs. Dynamic shock absorption is provided by the changes in the positions of body parts mediated through joint movements and muscle contractions. Any problem with these shock attenuating structures results in transfer of greater forces to the skeleton. It has been proposed that the shock attenuating capacity of subjects with a healthy musculoskeletal system is 30% greater than the subjects with joint diseases.[4] Later on it was claimed that viscoelastic inserts attenuate the magnitude of shockwaves by 42% and are very effective artificial shock absorbers. In a study conducted on 60 subjects having DJD, symptomatic relief was found in 78% of patients when viscoelastic SHI were used for 18 months.[4]

Most of the work on this subject has been done to study shock attenuation properties but little attention is given to the cushioning effect of inserts (plantar pressure distribution). It is important to study material characteristics of inserts when they are new and later when they are MD after cyclic loading impacts simulating normal gait. The material changes which appear after MD of inserts are increase in the stiffness of the material and decrease in its hysteresis. It is important to see whether this affects distribution of peak plantar pressure generated on heel strike. Different brands of SHI are available on the market at various prices. There is no scientific study available which guides prescribing doctors and patients to identify which one is best for individuals. Most SHI are sold on the basis of their availability on the market and personal choices. For this current study, a test was designed to evaluate these SHI both by material and by subject tests based on the criteria of their availability on the market over the full size range. A universal material testing machine (Zwick/Roell® z050) was used to test material characteristics and Pedar®–x to test pedobarograghy. Furthermore, the results of this study will help selection of SHI which are more appropriate in cushioning of heels when inserts are new as well as after prolonged use.

Methods and Materials

This study was conducted in the Institute of Motion Analysis (TORT Centre) in Ninewells Hospital, Dundee. The study was conducted in the period October, 2010 to February, 2011. Ethical approval for the study was granted by the University of Dundee Research Ethical Committee. Eighteen asymptomatic, healthy participants were recruited for the study. The exclusion criteria were that participants did not have previous foot and ankle injuries, foot disorders, limb length inequality and / or needed walking aids for leg movement. Three different brands of SHI were selected and purchased from the local retail outlets purely on the basis of their availability over full size range. These are:

1. Profoot® £ 9.99.
2. Zanni® £ 6.98.
3. Minigrip® £ 9.70.

Material Property Tests

The experimental setup used a right heel cast made of hard resin, with a smooth surface (men's size 8) being mounted on a UTM (Zwick/Roell® Z050). The applied force was increased from 0 to 1050N and decreesed from 1050N to 0 with a load control mode over twenty cycles. Load displacement curves were produced. A RLM is a purpose – built machine in which force of loading, number of strikes and angle of impact can be controlled. The machine mechanism was set to deliver 100 strikes per minute and a compression force of 700N which is equal to the ground reaction forces that an individual of average body weight of 70 kg experiences on normal walking. A downward angle of 15° was created in the foot cast to simulate shear.

Tests with Human Subjects

Pedar-x® system was used to measure plantar pressure distribution during the normal gait cycle which consists of different sizes of insoles having 99 sensors to measure plantar pressure. The Pedar® double insole has a cable for the attachment of insoles to a synchronisation box (blue tooth dongle). During walking, information of pressure changes under various areas of foot was transferred to Pedar-x® software. The soft ware interpreted and displaced pressure in different colours ranging from pink and red (high pressure areas) to blue and black (low pressure areas). The volunteers walked five times with each of the three types of SHI and once without any insert on a 10 meter walkway of foot laboratory. The foot pressure readings recorded in the computer software for analysis and later on transported to SPSS for statistical analysis.

Results

These SHI were subjected to material tests and then subject tests. The physical changes were more prominent in the SHI Zanni® as it developed a full thickness tear after 40,000 cycles. Therefore, SHI, Zanni®, was excluded from further study. The change in stiffness of material was one of the criteria to test material properties of SHI. These are shown in Tables 1 and 2. Hysteresis reflects the energy dissipated when a viscoelastic material underwent cyclical loading and unloading. It is shown in figure 1. For the purpose of simplification, three different points were selected at equal distance on this non-linear load – displacement curve at 200N, 500N and 1000N. Ten readings of load and displacement were taken around these points for twenty cycles. The stiffness of the SHI was calculated by taking a gradient of force and displacement of inserts. The hysteresis was calculated by subtracting area under loading curve from area under unloading curve.

The data obtained from Pedar® was analysed with the help of Pedar-x® software. The following seven parameters were used for analysis:

1. Maximum force (N).
2. Peak pressure (Kpa).
3. Contact time (%ROP).
4. Contact area (cm^2).
5. Pressure time integral (Kpas).
6. Force time integral (Ns).
7. Instant of peak pressure (%ROP).

The data obtained from Pedar® for SHI, Minigrip®, was analysed before and after its MD. The results indicated that the performance of the SHI to absorb the transient force deteriorated after the MD. There was more pressure on lateral heel area and second and third metatarsal heads (Table 3). The results of peak pressure (PP) measurements from Pedar® showed that Profoot® was also affected by MD as total PP increased significantly (Table 4). The results of pressure-time integral (PTI) of Minigrip® obtained from subject tests indicated that it increased quite markedly at all areas of the foot after MD. The PTI of Profoot® remained the same or decreased a little on all the areas of the foot except the lateral heel area where it increased.

Discussion

One of the aims of the current study was to examine the material properties of off-the-shelf SHI after wear and tear produced by prolonged use. Another aim of the study was to see if the marketing price of the inserts was reflected by their endurance.

The material tests followed by subject tests were the best recommended model to frame such a study.[5] The stiffness and hysteresis were two important parameters to be considered in the analysis of material properties by material tests.[6] The UTM was adjusted to apply a load from zero to 1050N. This wide range of forces covered all the forces experienced during walking and running, as the forces may reach 1.5 times the

Table 1:
Stiffness of Minigrip®.

Stiffness	Force 200N	Force 500N	Force 1000N	P-value
New insert	79.44 N/mm	165 N/mm	299.65 N/mm	0.00
Degradation 10,000 times	177.1 N/mm	298.93 N/mm	453.52 N/mm	
Degradation 40,000 times	123.73 N/mm	231.55 N/mm	350N/mm	

Table 2:
Stiffness of Profoot®.

Stiffness	Force 200N	Force 500N	Force 1000 N	P-value
New insert	228.72 N/mm	352.75 N/mm	562.809 N/mm	0.00
Degradation 10,000 times	78.17 N/mm	163.66 N/mm	292.99 N/mm	
Degradation 40,000 times	75.30 N/mm	160 N/mm	288.558 N/mm	

Figure 1:
Hysteresis of Minigrip® and Profoot®

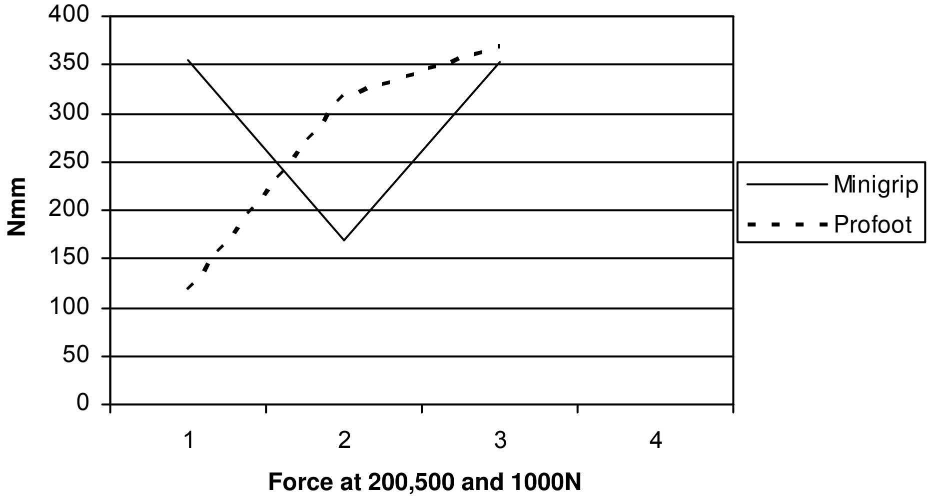

Table 3:
Peak pressure of Minigrip®.

Peak Pressure in Kilopascals	Mean	Standard Deviation	Maximum	Minimum	P-value
Total peak pressure	296.61	60.092	514	188	0.011
	316.85	76.907	480	148	
Area no.1 medial heel area	186.78	46.131	303	93	0.334
	192.91	42.042	314	111	
Area no.2 lateral heel area	196.01	55.61	345	106	0.125
	187.80	46.311	355	113	
Area no.3 medial metatarsal head	225.95	46.80	355	45	0.633
	224.09	68.038	425	69	
Area no.4 metatarsals (2nd and 3rd)	234.24	50.609	353	79	0.025
	223.62	56.807	378	66	
Area no.5 metatarsals (4th and 5th)	139.57	52.779	275	40	0.348
	133.33	62.33	313	33	
Area no.6 (first toe)	258.17	78.69	514	64	0.877
	262.70	93.028	480	75	
Area no.7 (2nd and 3rd toe)	209.68	72.479	365	41	0.114
	200.13	72.207	403	41	
Area no.8 (4th and 5th)	87.44	41.187	230	21	0.435
	85.85	39.149	160	0	

body weight during running.[7] The UTM provided a load – displacement curve. The MD, simulating normal walking, was done by a purpose built RLM. The RLM was utilized for the MD of SHI because the speed of the machine could be adjusted according to the need of the experiment. The speed of RLM was fixed to 100 cycles per minute because on an average, an adult individual walks at the speed of 90 to 120 steps

Table 4:
Peak pressure values of Profoot®.

Peak Pressure in Kilopascals	Mean	Standard Deviation	Maximum	Minimum	P-value
Total peak pressure	296.58	76.77	560	139	0.010
	318.08	81.943	478	176	
Area no.1 medial heel area	222.97	48.507	333	120	0.258
	218.66	47.138	333	119	
Area no.2 lateral heel area	202	38.559	288	113	0.061
	210.92	43.327	310	109	
Area no.3 medial metatarsal head	223	74.969	463	60	0.633
	219.38	70.751	450	129	
Area no.4 metatarsals (2nd and 3rd)	230.37	58.968	360	81	0.721
	233.28	77.767	450	120	
Area no.5 metatarsals (4th and 5th)	149.64	57.268	284	34	0.286
	143.60	54.074	328	33	
Area no.6 (first toe)	238.66	86.454	560	68	0.00
	270.33	93.073	478	75	
Area no.7 (2nd and 3rd toe)	192.04	65.354	353	58	0.477
	197.28	66.638	453	53	
Area no.8 (4th and 5th)	87.75	36.189	165	25	0.890
	87.59	33.802	179	29	

per minute.[8,9] The loading force of RLM was set to 700N for the MD of inserts. Because an average adult individual of 70 Kg body weight experiences a transient force to one's own body weight during walking.[7] It was decided to subject each insert to a cyclic compressive and shearing force of 700 N for 10,000, 40,000 and 60,000 times. From evidence reported in the literature; it was assumed that the maximum changes in the material properties of inserts occurred when they were degraded by compressive forces from zero to 10,000 cycles. Thereafter, minimal changes were observed in material properties when compression forces were continually applied for 40,000 cycles and no changes were noticed from 40,000 to 60,000 cycles.[10] In the current study, the SHI underwent cyclic loading in both compressive and shearing loading forces. The angle of shear was 15° created by making adjustment in the platform of the RLM. This is the angle that our foot makes with the ground at the time of heel strike.[8] After cyclic loading to 40,000 times, two of the SHI were damaged considerably for further use. One of the insert (Zanni®), developed a full thickness tear and other (Profoot®) had superficial longitudinal cracks on its surface. For this reason further MD was stopped. The Pedar® pressure sensitive insole system was used in the current study for subject tests. The repeatability of results of Pedar® had been demonstrated in previous studies.[11-13] This system could measure dynamic pressure at the foot – shoe interface as this system consisted of pressure sensitive insoles which were placed in the subject shoes. The system provided discrete pressure data over the selected areas of the foot plantar surface which was not possible with any other method, for example a force plate.

The results obtained from material tests showed that two of the inserts were badly worn out when they were degraded by RLM under compression and shearing forces for 40,000 cycles (100 km). The results were quite in contrast to previous studies in which the inserts showed wear and tear when they were degraded to more than 60,000 times (250 km) under compressive forces. This showed that the compression forces along with shearing forces might be more damaging than compression forces alone. In the current study, the deterioration in material properties continued progressively when degraded from zero to 40,000 cycles. One of the inserts, Minigrip®, became stiffer when MD from zero to 10,000 cycles but later on became little more compliant when degradation continued to 40,000 times. This may be due to some structural damage of the material of the insert. The SHI Profoot® became progressively less stiff on increasing MD from zero to 40,000 cycles and developed superficial cracks. It indicated that some structural damage may have occurred in the substance of the insert. Another important observation was that the stiffness of all the inserts increased when they were loaded by UTM from 0 to 1050 N even when they were new or MD. During running, an individual of average body mass of 70 kg experiences transient forces which may reach 1.5 times the body weight.[7] This indicated that a SHI that would be effective in dampening shock waves while walking might not be as effective during running. This is due to the fact that the transient forces increase many fold during running, resulting in increased stiffness and a decrease in hysteresis of the SHI.[14] An important aspect of the study was to examine the hysteresis properties of SHI.[6] The hysteresis represented the energy lost and not transmitted to the skeletal system. In the current study, one of the insert Minigrip® showed a decrease in hysteresis when its stiffness increased after repeated MD from zero to 10,000 cycles. Thereafter it became more compliant than before on continued MD from 10,000 to 40,000 loading cycles resulting in increased hysteresis. The other SHI, Profoot®, showed a progressive increase in its compliance and hysteresis on MD from 0 to 40,000 loading cycles. This increased could be due to the structural damage and loss of elasticity of the insert. It has been reported that more compliant materials have inferior performance when compared to stiffer materials used in the manufacture of SHI.[5] The more compliant materials dissipate too much energy and return very little energy to the musculoskeletal system. This energy is important for efficient forward propulsion. The muscles of the leg have to do extra work to overcome this increase in hysteresis and may become fatigued sooner. Counter intuitively low stiffness may actually lead to higher transmission of impact forces to the forehead. This effect can be due to decrease impact proprioception which leads to a lower activation of natural shock absorbing mechanisms such as knee flexion and muscle stress changes.[6] The analysis of data of PP, PTI and instant of peak pressure (IOPP) of both SHI showed that both the inserts responded differently to loading forces. The data of PP of Minigrip® showed decreased cushioning of all areas of the foot after the MD when compared to the unused condition. The change was quite significant on the lateral part of heel and over lateral metatarsal heads. The SHI, Profoot®, also showed an overall decrease in cushioning against PP after the MD. The two types of inserts were compared to the no insert condition in respect to their ability to attenuate PP. It was observed that both types of inserts were better than the no insert condition in cushioning the heel areas of the foot against PP. Both types of inserts were exposing the lateral metatarsal heads to more PP than the no inserts condition which increased after MD. This might be due to a rise in heel contact area between the foot and insert as the change was quite marked for Minigrip® which was thicker than Profoot®. The PTI increased significantly under all areas of the foot, particularly, on the lateral metatarsal heads after the degradation. When Minigrip® was new; PTI was lower than Profoot® and the no insert condition and remained so even after degradation. After MD, PTI decreased on the medial heel area and increased over the lateral metatarsal heads. This increase in PTI was more than the no insert condition. The PTI did not change much for the Profoot® insert after degradation when compared to an unused insert. The values of PTI were greater over the lateral metatarsal heads than any of the other two conditions even when Profoot® was new and it increased further especially on the lateral metatarsal heads and lateral heel area after the degradation. The IOPP did not change significantly after degradation when compared to a new Minigrip® SHI. The IOPP was more on all areas of foot except the heel area before and after MD when compared to the no insert condition. The IOPP also did not change noticeably for Profoot® after degradation. When the insert was new, IOPP was lower on all areas of foot except the heel area when compared to Minigrip® and the no insert condition. After MD, IOPP increased markedly on lateral metatarsal heads and lateral heel area even more than the no insert condition. Overall there was no difference of contact time for both the inserts before and after the MD. The contact area decreased for both the inserts but change was not significant. The force time integral increased significantly (0.011) for Minigrip® while it did not change for Profoot® after MD. The maximum force values increased for Minigrip® and decreased for Profoot® but the change was not significant. The current study followed the best possible model available to design such a project.

The MD was performed by a purpose built RLM. The machine applied MD to the inserts between two hard surfaces. The real life situation is entirely different from a laboratory condition in which no individual walks continuously for 100 km without any break. The SHI are laid in boots between the foot heel and shoe which are not as rigid as metal surfaces. The real life conditions cannot be fully imitated in a laboratory control trial. In the current study, the SHI used were of different thickness. In the subject tests, the participants were requested to walk with their normal walking speed but still there was a great difference in individual walking style and speed. Viscoelastic materials behave differently when they are subjected to different loading frequencies. A very slow application of force will result in little resistance, whereas a rapidly applied force is more fully resisted by the viscous material.[13]

Conclusion

All the three inserts studied in the current project deteriorated in their capacity to dampen transient shock waves after MD. The SHI, Minigrip®, was better than Profoot® and Zanni®. The diabetic patients should use off-the-shelf SHI cautiously because they put more pressure on lateral metatarsal heads of feet. SHI with very low retail price may not be as effective in performance as more expensive options. The thickness of the SHI should be kept minimal by manufacturers as it may be responsible for putting more pressure on forefoot. The individuals who are using SHI for the treatment of DJD or overuse injuries or enhancing exercise performance should change the insert on appearance of signs of wear and tear.

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