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On the use of auxetics in footwear: Investigating the effect of padding and padding material on forefoot pressure in high heels. Lisa Ann Stojmanovski Mercieca[1], Cynthia Formosa[1], Joseph N. Grima[2,3], Nachiappan Chockalingam[4], Ruben Gatt[2,*], Alfred Gatt[1,*]

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Abstract

Although, high heels are known to affect the biomechanics of human movement, most notably by increasing forefoot plantar pressure it is commonly used worn due to the influence of fashion. To deal with resulting clinical issues some prescriptions include the use of cushioning pads to redistribute the plantar loads and increase comfort. This preliminary study has sought to investigate whether auxetic foam would be a good candidate for the redistribution of plantar loafing in the forefoot when compared to a more traditional material. From the results obtained, it was shown that auxetic foam demonstrated a decrease in forefoot peak plantar pressure while a commercial product, a material traditionally used for plantar cover paddings, increased pressure in the region of the 2nd – 4th MPJ. This demonstrates the potential for auxetic materials to become a material of choice for such applications, especially since it can be further remodeled until its properties can produce a significant forefoot pressure reduction.

Keywords: auxetic foam; negative Poisson's ratio; high heels; forefoot pressure; inshore pressure measurement;

Auxetic materials, i.e. materials with a negative Poisson's ratio[1], have been gaining a significant amount of attention in the last few decades since they can allow for the development of new and improved products due to enhanced materials properties such as increased indentation resistance and the ability to form dome shaped structures when subjected to a bending load. This rapid growth in the field, prompted by the pioneering work of Wojciechowski [2], Evans [3] and Lakes [4] has led to the discovery of a auxetics at various size scales, ranging from the nano-level to the macro-level. Some examples of materials with a negative Poisson's ratio include α-cristobalite [5-8], zeolites such as natrolite [9], and micro-structured polymers [10]. Mechanisms which lead to auxetic behaviour include the ones involving re-entrancy [11-13], hard spheres [14-17] and rotating rigid units [18-20]. A broad spectrum of applications has been predicted for auxetic materials, ranging from the biomedical industry to aviation [21- 25].

This work will look at a potentially new application of auxetics within the footwear industry in the form of plantar cover paddings for use with increased heel height. Wearing of high heel shoes has become a sign of fashion for many who habitually wear this type of shoes for various reasons. Fashion shoes have a very different shape and design from other shoes which are meant to optimize comfort or performance and typically have smaller toe boxes, with heels becoming higher and steeper [26]. This design results in what is considered as a very elegant shoes, where unfortunately, for the sake of elegance, the wearing of these shoes is habitually preferred over physical comfort, with appearance and design taking precedence over comfort [27]. Unfortunately, society constraints often still necessitates the wearing of high heels for long periods of time during working hours on a regular basis for work and the user may often feel unable to opt for more comfortable shoes despite knowing that wearing shoes with high heels will be a painful experience, a sensation which is backed by biomechanics. High heels are known to cause difficulty during gait by changing the natural position of the foot and ankle complex and thus creating a series of reactions which can have an influence on the lower limb and spine [28]. These shoes alter gait kinematics and kinetics, such as walking speed and mobility [29], with an increase in forefoot pressure [30-32] and a decrease in rear foot pressure [33,34]. Muscles and ligaments fatigue more easily and can lead to metatarsal head pathology [30]. Prolonged usage may cause ankle joint sprains and excessive plantar bending as a result of an increase in vertical shock loading that may create postural changes by concentrating the weight distribution on the forefoot [32,35,36]. The higher the heel, the greater the pressure transferred to the forefoot [31, 37]. It is reported that high heeled shoes create a shift in plantar pressures, from the third, fourth and fifth metatarsal head onto the first and second metatarsal heads [38].

Studies also demonstrated that habitual use of high-heeled shoes increases plantar flexion, resulting in restricted gastrocnemius and soleus extensibility, as well as changing their activation pattern [34,39,40]. This in turn leads to augmented metabolic cost and muscle loading, and can accelerate muscle fatigue [28]. It is common practice for high heel wearers to place some kind of foam as a pad underneath the forefoot in order to increase cushioning so as to reduce pressure underneath the metatarsophalangeal joint area, thus increasing comfort and lessening possible pain. A diversity of forefoot pad designs and materials exist [41, 42], however studies report inconsistent results when assessing the effectiveness of these pads for decreasing plantar pressures [43, 44]. These pads are thought to act through the relocation of force over a larger area of the plantar surface of the foot [44-46].

A common type of padding used in order to reduce forefoot pressure when wearing high heels and to provide comfort during walking is the ‘Plantar Cover’. This type of pad stretches from the styloid process of the fifth metatarsal to the web space to cover the whole plantar metatarsal area. It is normally produced from foam or felt of different thickness according to the space available in the shoe. The borders of the pad are beveled so as to improve and provide comfort and adhesion. Since it is utilized to provide cushioning to the metatarsal heads, it is also helpful in older people who have atrophy of the plantar soft tissue [42]. This could also be beneficial for those who regularly wear high heels. The padding can be directly adhered onto the plantar aspect of the foot, to the inner sole of the shoe or made into a replaceable device.

Unfortunately, there is a lack of research on the effectiveness of padding materials that are usually prescribed by medical professionals as an intervention material, more specifically when applied to persons using high heeled shoes. There is a paucity of research on the effect of plantar covers made from different material when worn in these shoes, especially whether materials which particular properties, such as auxeticity, can perform better than others in such applications. In view of the above, this study will assess the suitability of utilization of auxetic foam in the form of a padding in order to provide better forefoot pressure relief. More specifically, the aim of this study is to determine whether a plantar cover padding made from auxetic foam does in fact reduce peak plantar pressure and pressure time integral under the forefoot when worn in high-heeled footwear when compared to similar padding using a professional grade commercial product.

Method

The study investigated the effect of padding fabricated from two different materials on forefoot pressure and pressure time integral during high heeled walking. A Plantar Cover which covered the whole metatarsal forefoot area was applied to the same foot of each participant in all trials. The paddings applied were (i) custom–made plantar cover made from a professional grade commercial product, having a Poisson’s ratio of circa 0, measured under compression. The transverse and axial lengths of the commercial product were measured upon deformation using an appropriately calibrated MessPhysik Video-Extensometer, whilst it was being compressed in a Testometric universal loading machine at a constant strain rate of 5 mm min^{-1}, as detailed in [46]. ; and (ii) custom–made plantar cover made from auxetic foam produced using the well known 'thermo-mechanical' method [4, 47] from conventional polyurethane foam with a nominal ppi of 90 supplied by Articoli Resine Espanse, Italy. More specifically, the manufacturing process of the auxetic foams requited that the foams as supplied to be cut in a cuboid shape and subjected to a tri-axial compression of 20% in a lubricated mould having the same shape. The compressed foam was then heated for 10 min at 200℃. The foams were left to cool to room temperature while still in the mould and then stretched out so as to ensure that no ribs stick to each other. The foam was then inserted back into the mould, and the heating-cooling-stretching cycle was repeated twice more, once heating again to 200℃ for 10 min and once heating to100℃ for an hour during the last cycle [49]. This method produced auxetic foams having an initial Poisson's ratio of circa -0.2, measured as described above for the commercial product. After this process, strips of auxetic foams having a thickness of 5mm were produced by cutting the foam blocks using a hot wire cutter which were then used to make the Plantar Covers. Note that both the commercial and auxetic paddings were shaped according to each participant's metatarsal area prior to starting data collection which was carried out on healthy individuals who habitually wear high heels on a regular basis.

Ethical permission for this study was sought and obtained from the University Ethics Research Committee. All subjects signed informed consent prior to participation. Participants who habitually wore high heels at least 4 times a week and were able to walk confidently with high heeled shoes, were invited to participate in this study. Participants presenting circulatory, neurological, musculoskeletal and endocrine disorders, had some kind of lower limb injury in the past year, had surgery performed in the foot and/or ankle, had hallux abducto valgus, any type of lesser digit deformities, Tailor's bunion and impaired gait that could affect forefoot pressures or had prominent metatarsophalangeal joints which could affect the investigated variables, or otherwise required assistance to walk, were excluded from the study.

Participants were provided with a pair of shoes with a heel height of 10cm which were identical to all except for size. Participants were also requested to bring along running shoes on the day for the purpose of in-shoe system sensors calibration. A cardboard insole template was prepared for every participant according to shoe size in order to adhere the forefoot pad and to avoid slippage and movement of the forefoot padding used. An F-Scan in-shoe system (Tekscan Inc., South Boston, MA, USA) was employed to collect plantar pressure data. Prior to starting data collection, the F-Scan in-shoe sensors were trimmed according to the participants shoe size. The sensors used were resistive (Tekscan Medical Sensor 3000E), having a sensel density of 3.9 sensels / cm^2 and a pitch of 5.080 mm. Following sensor calibration in the participants' own running shoes according to the manufacturer instructions, each participant performed a practice trial that consisted of wearing the in-shoe device inside their running shoes, walking along a seven meter walkway. This trial was performed in order to familiarize the participant with the equipment and to ascertain that the same equipment was not causing any kind of restrictions [50].

Following this, the participants walked in high heels only, together with the shoe size template and the in-shoe sensors but without any forefoot padding in order to acquire baseline plantar pressure measurements to which padding plantar pressure data could later be compared. The sensor was placed between the participant's foot and the cardboard template by an experienced researcher in a consistent manner across all participants After all the three trials with high heels were completed, in order to maintain a random selection, the raffle method was used to randomly choose with which type of padding to commence with.

The marked cardboard templates obtained prior to commencing data collection were used to attach each forefoot padding in turn. Participants were asked to walk again to perform their three trials, with the first type of plantar cover (either commercial or auxetic), then repeating the same procedure with the other material.

The pressure readings obtained for the foot were divided into six regions as per Queen et al. (2007) [51]; however for the purpose of this study, only the peak plantar pressure and pressure time integral readings of the forefoot (Medial Forefoot – 1st metatarsophalangeal joint region; Mid-Forefoot – 2nd, 3rd and 4th metatarsophalangeal joint region, and Lateral Forefoot – 5th metatarsophalangeal joint region) were taken into consideration (Figure 1).

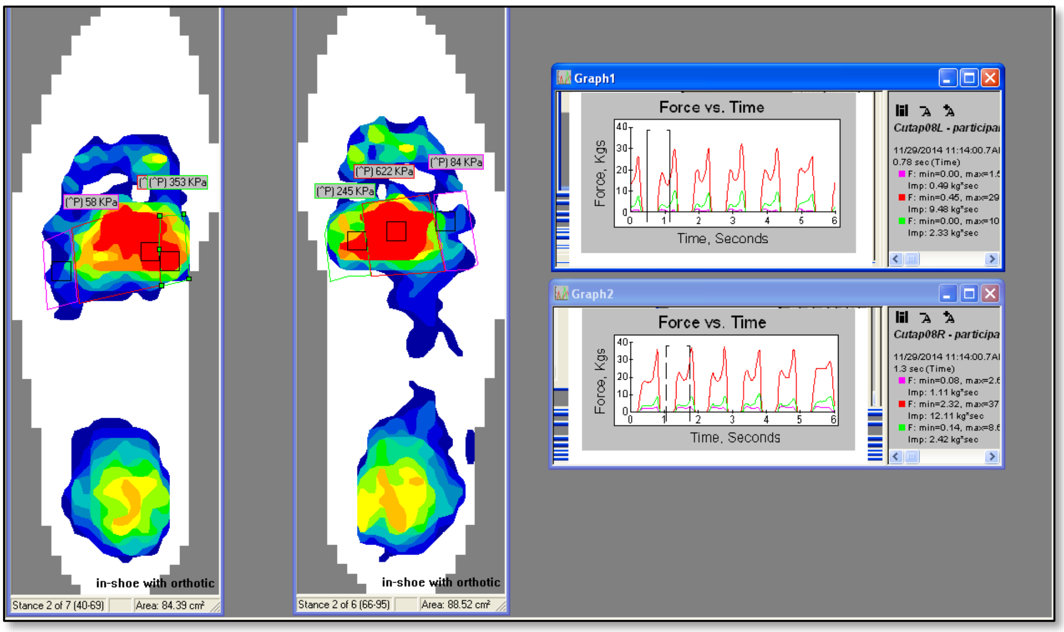

Figure 1: FScan image. The forefoot was divided into 3 regions by drawing polygons.

Results and discussion

Fourteen participants, all female, with a mean age of 29.2years (SD 9.1yrs), mean weight 55.7kg (SD 6.9kg), mean height 159.2cm (SD 4.6cm), mean shoe size 38, consented to participate in the study. As indicated in Figure 2, under the 1st Metatarsophalangeal Joint (MTPJ) region, the auxetic foam exhibited a greater reduction in the mean peak plantar pressure than the commercial product. Also, as shown in Figure 3, there was a very significant difference in the pressure time-integral between the two materials something that indicates that the auxetic foam may be performing to a better extent when compared to the commercial product in this region.

Under the 2nd – 4th MTPJ, the commercial product showed an increase in peak plantar pressure when compared to the no-insert condition. On the other hand, auxetic foam once again produced a slight decrease in peak plantar pressure. This pattern was also followed for the pressure-time integral. Under the 5th MTPJ, results demonstrate a decrease in peak plantar pressure from the auxetic foam, whilst peak plantar pressure remained practically constant with both paddings slightly increasing pressure-time integral. Here it should be noted that although there was improvement in the reduction of forefoot pressure when using the auxetic foam, such reduction was not as large as one may have anticipated. This merits further study which may require superior quality auxetic foams to be used as the particular auxetic foams used in the current preliminary study tend to show a sharp increase in the Poisson's ratio for rising compressive strain, reaching positive values for high compressive strains as also shown in [52]. In other words, the effectiveness of pressure reduction due to the auxetic behavior of the foam would be expected to be much higher if the auxetic foam used would have retained its negative Poisson's ratio at high strain so that the experienced benefits would not remain highly dependent on the compressive strain experienced by the foam itself. In the case of the commercially available product, the Poisson's ratio was measured to be circa 0, even for high compressions (up to 50% strain).

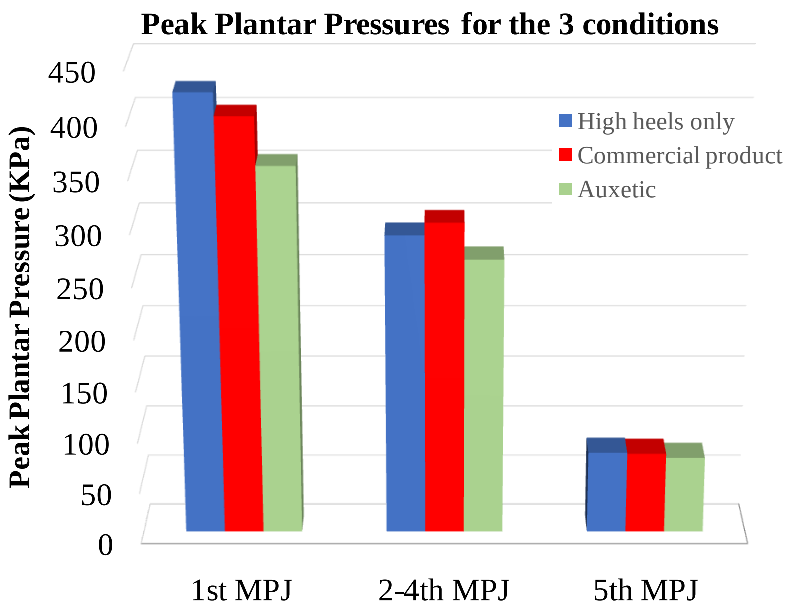

Figure 2: Peak Plantar Pressure for the 3 Conditions: high heels only, high heels with the commercial product and high heels with auxetic foam. Note that a statistical comparison using paired samples t-test, indicates that there is a significant difference between the peak plantar pressures obtained for the commercially available product and the auxetic foam for the region between the 2-4 MPJ (p-value 0.020). On the other hand, the difference between the commercially available product and the auxetic foam in the 1st and 5th MPJ regions is not significant with p-values of 0.087 and 0.641 respectively.

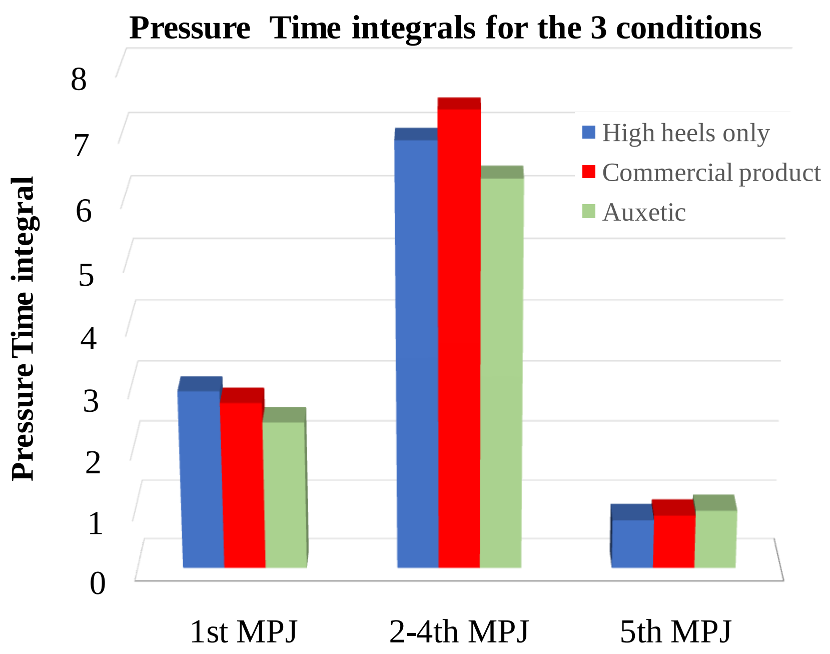

Figure 3: Pressure time integral for the 3 Conditions: high heels only, high heels with the commercial product and high heels with auxetic foam. Note that a statistical comparison using paired samples t-test, indicates that there is no statistical significance between the results obtained for the commercially available product and the auxetic foam with p-values of 0.085, 0.057 and 0.584 for the 1st MPJ region, 2-4 MPJ region and 5th MPJ region respectively.

The results in this study have some important practical implications on the use of padding in high heeled shoes. For example, the results suggest that the commercial product actually increases forefoot plantar pressure, notwithstanding that this type of padding has been widely accepted within podiatric practice for many years. On the other hand, the Plantar Cover fashioned out of auxetic foam provided better reduction of peak plantar pressure and pressure time integral when compared to the traditionally used material. In fact, although the sample size may have been too small to reach statistical significance, the work is able to clearly demonstrate a decrease in mean peak plantar pressures and pressure-time integrals underneath all metatarsophalangeal joints, except for pressure-time integral under the 5th MPJ. This means that auxetic foam, an innovative material in this field of forefoot offloading, could be an exciting new option that merits more remodeling and further investigation, especially when one considers that, notwithstanding the significant advances in material science, we are still utilizing the same traditional materials for offloading, with very little changes in material properties being made over the years.

It is suggested that a leap forward be made by exploring the use of alternative materials, such as auxetic materials or so-called ‘intelligent materials’ and moving away from traditional materials such as felt or normal foam whose effectiveness has not been scientifically proven. When one considers the high demands on such a material during gait in a high-heeled shoe, one should also consider the possible effect that this material might have on reducing peak plantar pressure in other situations, such the prevention of foot ulcers, for example, or the management of the rheumatoid forefoot, which is regularly subjected to high plantar pressures because of significant deformities.

The results from this study highlights that further studies are needed and until then one should be cautious when using commercial covers since their effectiveness in reducing plantar pressures is doubtful, when used with high heel shoes. This could be detrimental to high heel shoes users who present with forefoot pathologies such as Morton’s neuromas, inter-metatarsal bursitis, Freiberg’s infraction, capsulitis, and so forth; indeed common orthopaedic conditions in persons who frequently wear footwear of this type.

An obvious limitation of this study is small sample size recruited. Therefore one may consider this study as a pilot study which has highlighted the need for a larger study to be conducted in order to further evaluate the effectiveness of such material in reducing pressures in the forefoot.

In this case, factors such as difference in body type, weight, walking abnormalities and any conditions that might affect the foot should be taken into consideration. Also, these studies should also be done on other types of shoes. Further studies are also needed to study how different parameters in the production of the auxetic foams may affect the pressure reduction. For example, it would be interesting to explore the role played by the compression ratio when producing the auxetic foams as well as the role of the stiffness of the foam.

Conclusion

Although shoe inserts have been extensively applied in footwear to augment comfort and to diminish the frequency of movement-related injury, no study has attempted to investigate the effectiveness of a Plantar Cover in reducing pressure in high heels, especially targeting those fabricated from auxetic materials. This study has shown that care should be taken when using commercial plantar covers in order to relieve pressure onto the forefoot in high heeled footwear, since the use of an inappropriate material may actually cause an increase, rather than a decrease, in forefoot peak plantar pressure and pressure-time integral. In contrast, auxetic foam, shaped in the form of a plantar cover, produced a decrease in these pressure parameters. It is recommended that this type of material, which has previously never been utilized for this purpose, be further investigated and its material properties perhaps be further re-modelled until its properties perform as desired in order to reduce forefoot plantar pressure to accommodate the high pressures which persons endure when wearing high heel shoes.

Conflict of Interest

The authors declare no conflict of interest

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