Classification and mass production technique for three-quarter shoe insoles using non-weight-bearing plantar shapes

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A B S T R A C T
We have developed a technique for the mass production and classification of three-quarter shoe insoles via a 3D anthropometric measurement of full-size non-weight-bearing plantar shapes. The plantar shapes of fifty 40–60-year-old adults from Taiwan were categorized and, in conjunction with commercially available flat or leisure shoe models, three-quarter shoe-insole models were generated using a CAD system. Applying a rapid prototype system, these models were then used to provide the parameters for manufacturing the shoe insoles. The insoles developed in this study have been classified into S, M and L types that offer user-friendly options for foot-care providers. We concluded that these insoles can mate tightly with the foot arch and disperse the pressure in the heel and forefoot over the foot arch. Thus, practically, the pressure difference over the plantar region can be minimised, and the user can experience comfort when wearing flat or leisure shoes.

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1. Introduction

Feet are indispensable for walking—an important mode of transportation for humans. Further, foot protection certainly aids foot care (Nordin and Farnkel, 2001). Hence, suitable shoe insoles are required for the general public, more importantly for patients with foot diseases or abnormal plantar shapes. A pair of suitable shoe insoles can absorb the impact or pressure exerted on the foot. A decade ago, Kogler et al. (1996) designed an arch support to help relieve the pressure exerted on the foot arch during weight bearing. Apparently, through skeletal support, the tension in plantar aponeuroses can be decreased. Lee et al. (2004) found that a metatarsal pad reduced the forefoot pressure and transferred the weight onto longitudinal and metatarsal arches. In addition, a total contact insert (TCI) provides pressure relief in heel and forefoot regions (Lord and Hosein, 1994; Chen et al., 2003). A reduction in the difference between the maximum and minimum pressure values indicates that shoe insoles can really disperse the pressure (Chuang et al., 1999; Jahss et al., 1992; Boulton et al., 1984), and this indicates the significance of shoe insoles in human foot care. As for the traditional shoe insoles, trial and error would be required to amend the shoe-insole models to suite patients (Lee et al., 2004; Jorgensen and Ekstrand, 1988; Kogler et al., 1996).

In this study, we utilized a non-weight-bearing 3D scanner system to acquire the foot shapes of 50 adults of 40–60-year-old in Taiwan, with statistical analysis, to produce optimum foot profiles as a basis for mass production of 3/4 health-care shoes’ insole, such as flat or leisure shoes.

During the course of this study, we determined whether the use of various types of shoe insoles would result in changes in the foot-pressure distribution and provide comfort during walking. Furthermore, various types of shoe inserts, including heel cups and arch supports, closely resembling plantar shapes were reviewed. Specifically, we selected the three-quarter foot-care shoe-insole system, classified as S, M and L types, with parameters derived from the various commercially available shoe models.

2. Materials and method

In this study, a 3D scanning system was used to acquire the non-weight-bearing plantar shapes from random sampling of healthy and active people in Taiwan (Fig. 1). The characteristics of the plantar-shape data are as follows: 50 adults with the mean age of 40–60 years, mean height of 155–170 cm and mean weight of 45–65 kg.

The plantar shape plays an important role in the manufacturing of the three-quarter shoe insoles. The closer the resemblance between the plantar profile and the shoe insole, the more appropriate are the three-quarter shoe insoles. The detailed procedure to acquire a plantar shape is outlined as follows:

The three highest (or the deepest, if viewing from top to bottom) points—near the bottom of the toe, far side of the forefoot, and top of the heel on the sole contour area—were identified and assigned...
as M, T and C, respectively, on the plantar shape to obtain an intersection plane, and a 3D image editing system was applied to create an intersection region of the plantar shape with the arch height “h” (Fig. 2). The other elements of the plantar shape were eliminated, and the plantar shape was completed. The 3D image editing system was then used to edit the plantar shapes for obtaining statistics and classifying the plantar profiles. The parameters used to define a three-quarter plantar shape—W1, the forefoot width; W2, the width of the heel; D, three-quarters of the length of the foot; and h, the arch height—are all illustrated in Fig. 2. The parameter D of a commercially available shoe model was determined first. In this study, the sizes of the shoe models were classified into three categories, i.e. S, M and L types, based on their central tendencies. By calculating the mean value of D, i.e., the central tendency for each category, the parameter D was then assigned the S-, M- or L-type category. Subsequently, the parameters W1, W2 and h were also defined and classified into S-, M- and L-type categories by means of a statistical analysis (Fig. 3). The end users would only be required to select the foot-care shoe insoles that match their own shoe patterns (Fig. 5).

The manufacturing process of the three-quarter shoe insoles presented in this paper can be divided into three major modules: first, obtaining the 3D full-size image models of the non-weight-bearing plantar shapes using a computer; second, editing the full-size image models wherein the non-weight-bearing plantar shapes are edited by using the rapid prototyping system to obtain three-quarter shoe-insole profiles (Fig. 4); and third, classifying the image models as S, M and L types using the commercially available shoe models. A subsequent requirement would be an analysis of the foot pressures in the case of the three-quarter shoe insoles. Each module can be described as follows.

### 2.1 Capturing non-weight-bearing plantar images

The 3D scanning system was used in this study for rapidly scanning the full-size non-weight-bearing plantar shapes in an objective manner. A foot support designed for this study conforms to human factor engineering under non-weight-bearing and neutral conditions. It was designed and manufactured by the Computer Assisted Surgery Lab at I-Shou University, Taiwan (Fig. 1). Under the non-weight-bearing condition, a plantar image was obtained by using the 3D scanner to scan the foot placed on the support. Subsequently, the 3D image editing system was employed, followed by the application of a reverse-engineering software system to generate plantar images for further studies. The plantar images were acquired as follows:

1. Placing the foot of the user, seated on an adjustable chair, on the foot support. After adjusting to an appropriate height, the ball and socket joints of the foot support’s bipod were adjusted to provide good support to the user’s calf and the underside of the knee joint. Consequently, the foot was in a state of total relaxation. Thus, a natural and non-weight-bearing state was achieved.
2. Setting up the 3D scanner to scan and obtain the 3D image data of the entirety of the foot.
3. Using a 3D data collective software to process the 3D image data of the entire foot and generate a 3D plantar image.
4. Using the 3D image editing system to generate a three-quarter plantar image after obtaining the full-size 3D plantar image.
2.2. Mass production module for three-quarter shoe insoles

By editing the non-weight-bearing plantar shapes using the 3D image editing system, physical models suitable for the three-quarter shoe insoles were established. Further, these models were used in conjunction with the commercially available shoe models to develop a mass production module for manufacturing the three-quarter shoe insoles as follows:

1. The computer-generated image models were fed into the 3D image editing system whereby the non-weight-bearing plantar shapes were edited for obtaining the statistics and classifying the plantar shapes. These image models in conjunction with the commercially available shoe models were then used to generate the shoe-insole image models. Next, the rapid prototyping (RP) system was used to manufacture the three-quarter shoe-insole physical models.
2. The 3D shoe-insole molds were fabricated from the RP models, and then, the three-quarter shoe insoles were manufactured.
3. The foot-pressure distribution over the three-quarter shoe-insole prototype was measured.
4. The shoes’ outfit effect of the three-quarter shoe insoles was analyzed.

2.3. Measurement and analysis of foot pressure for three-quarter shoe insoles

The shoe insoles have been designed specifically for the purpose of foot care. The experimental results indicate that the three-quarter shoe insoles mate tightly with the foot arch and disperse the pressure exerted on the heel and toes region into the foot arch region (i.e., increase the stress region), thus minimising the difference between the maximum and minimum foot pressure. RS SCAN was used to measure the foot pressure (Barnett et al., 2001; Chen et al., 1994) (normal foot-pressure percentage distribution, shown in Fig. 6) in the following manner.

1. Measure the dynamic foot pressure without a three-quarter shoe insole as shown in Fig. 7.
2. Measure the dynamic foot pressure with a three-quarter shoe insole as shown in Fig. 8.
3. Analyze the difference between these two measured values.

The hardware and software integrated in this study are mature and commercially available products. These make the project quite significant since the measurements and calculations performed in this study can be verified readily. The major equipments and facilities employed for capturing the full-size 3D plantar image and the subsequent analysis conducted in this study are listed in Table 1. An outline of the manufacturing process of the three-quarter shoe insoles is presented in Table 2. End users are strongly urged to select the three-quarter shoe insoles matching their own shoe patterns (Fig. 5).

This study offers a unique concept as well as a practical system for designing and manufacturing the three-quarter shoe insoles that improve the foot-pressure distribution without changing the gravity distribution during walking (red lines in Figs. 7 and 8) (For interpretation of the references to color in these figures, the reader is referred to the web version of this article.) The shoes’ insole would withstand the same pressure during normal walking, so the bigger the stress area, the smaller the specific stress would be dispersed to the mean stress area. Clearly, the foot pressure can be dispersed evenly with a reduction in pressure per unit area, as shown in Figs. 9 and 10 (Mueller and Strube, 1996; Lin and Chen, 1999; Liou and Lin, 2001; Anthony et al., 2000; Alexander et al., 1990).

3. Results

In this study, we developed physical models of non-weight-bearing plantar shapes by using a foot support designed by applying human factor engineering. The support helps minimise the deformation of the foot and maintain a natural shape. During
the scanning procedure, it might be required to swing the foot around to acquire an accurate image of the entirety of the foot. However, it is required that the foot be returned to the exact starting position to complete the data scanning. The non-weight-bearing plantar images can be generated conveniently, precisely and reliably. Specifically, this study employs a 3D full-size plantar-shape scanning system for scanning a foot under a non-weight-bearing condition, without resorting to radiation methodologies. Furthermore, this study can offer a reliable scheme to set up design modules for ankle-foot orthotics (such as shoe insoles) under a non-weight-bearing condition. The plantar shape was analyzed to provide the basis for creating a mass production module for the three-quarter shoe insoles. By integrating clinical and engineering knowledge, this research has helped define a three-quarter plantar shape with the help of a high-efficiency measurement of relative parameters by obtaining 3D full-size non-weight-bearing plantar images for analysis and classification. Consequently, the plantar shape can be integrated to generate shoe-insole mass production modules.

The experimental results indicate that the three-quarter shoe insoles mate tightly with the foot arch and disperse the pressure in the heel and toes over the foot arch (i.e., increase the stress region), thus redistributing the pressure difference between the maximum and minimum foot pressure. The foot pressure was measured and analyzed as shown in Figs. 9 and 10 wherein the longitudinal axis represents the peak pressure (N/cm²) and the horizontal axis represents the forefoot, midfoot and heel regions (Corrigan et al., 1993). The three-quarter shoe insoles can efficiently reduce the maximum pressure exerted on the left heel by 19.2%, right heel by 32.2%, left metatarsal by 15.5% and right metatarsal by 17.6% and also increase the maximum pressure exerted on the left midfoot by 98.1% and right midfoot by 100%, as compared to the case when no insoles are used. Notably, the three-quarter shoe insoles can vary the foot-pressure distribution by extending the stress region to the foot arch, i.e., by redistributing the pressure in the heel and forefoot region for gaining an optimum and uniform pressure distribution.

The plantar shapes of 40–60 years old people in Taiwan were classified as S, M and L types, and then in conjunction with the commercially available shoe models, the three-quarter shoe insoles were manufactured. By editing the 3D non-weight-bearing plantar shapes using the 3D image editing system, it should be possible in conjunction with the commercially available shoes models to establish certain physical plantar image models suitable for manufacturing the three-quarter shoe insoles; these shoe insoles will help bridge the gap between shoe-manufacturing and fitness-equipment-manufacturing industries.

4. Discussions

A computer-aided system is an advanced tool used in orthotics that helps incorporate computational environment, engineering technology and clinical knowledge for applications in orthotics fabrication. The computer-aided system applied in this study is a reverse-engineering technique that has been successfully applied in industrial usage. The foot support developed in this study can maintain the plantar shape in a non-weight-bearing condition and

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**Fig. 5.** Three-quarter 3D shoes’ insole integrated with commercial shoe mold.

**Fig. 6.** Normal foot-pressure percentage distribution (Alexander et al., 1990).

**Fig. 7.** Dynamic foot-pressure analysis without 3/4 3D shoes’ insole.
While capturing the non-weight-bearing plantar images, the support can surely affirm the plantar shape to be under the non-weight-bearing condition as it has been designed by applying human factor engineering. It can also help design better ankle-foot orthotics.

The three-quarter shoe insoles, including heel cups and arch supports, differentially altered the pressure distribution over various regions. As compared to the case where no insoles were used, the use of three-quarter shoe insoles effectively reduced the peak pressure in the heel region by 32% and that in the medial forefoot region by 18% and increased the pressure in the midfoot region by 100%. The three-quarter shoe insoles were manufactured according to the plantar geometry of the user’s foot in conjunction with accommodative arch-support and heel-cup mechanisms. This produced a high degree of conformity between the contact surface of the insole and the foot contours. The close fit of the insole resulted in a uniform distribution of the pressures in the heel, arch and forefoot regions with no significant local foci. The three-quarter shoe insoles were proved to maximise these confining effects. The insole was effective in improving footwear comfort when walking with flat shoes. The insoles can be mass produced in order for the users to select from.

There are several limitations to this study. First, a length difference in the two legs or a size difference in the right and left feet might be a confounding factor in determining the experimental conditions. In addition, the experiments were performed over a period of a couple of hours. In a realistic environment, however, the user might wear shoes for a considerably longer time of the day. An experiment performed over a longer duration might provide better insight into the behavioral and physical adaptations of each individual and reflect the effects in real life. Second, when examining pressures at the foot–shoe interface using an insert as a measuring device, the fact that the presence of the insert itself could influence these parameters must not be neglected. There is no direct method of measuring this. Therefore, the recorded pressure may include small errors that are inevitable. However, the user’s perceptions of changes in comfort produced by the insertion of the insole may provide some indication of the changes in the pressure distribution (Lee and Hong, 2005).

This study intends to discuss genetic transformation foot care, specifically that of plantar fascia, which is a portion of the fascia tissue of foot with the rear part attached to the calcaneus and the calcaneus.

Table 1
3D non-weight-bearing foot shape capture system.

<table>
<thead>
<tr>
<th>Equipment and facilities</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foot support</td>
<td>Maintaining non-weight-bearing plantar shape</td>
</tr>
<tr>
<td>3D Optics Scanner</td>
<td>Scanning full size 3D foot image (by generating 3D point-cloud data)</td>
</tr>
<tr>
<td>by 3D Digital Corp.</td>
<td>Creating three-quarter plantar image model and calculating related parameters of plantar image</td>
</tr>
<tr>
<td>Geomagic Studio (3D image editor)</td>
<td>Combining three-quarter plantar image models with the commercially available shoe models</td>
</tr>
<tr>
<td>Magics RP (3D solid model CAD system)</td>
<td>Rapid prototyping (RP) system, manufacturing physical models of three-quarter shoe insoles</td>
</tr>
<tr>
<td>Objet RP machine</td>
<td>Analyzing normal foot stress and in-shoe foot stress with and without shoe insole</td>
</tr>
<tr>
<td>RS SCAN (foot stress analysis system)</td>
<td></td>
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</tbody>
</table>

Table 2
Process for 3/4 shoe-insole production technology.

1. Acquire 3D non-weight bearing full-size image models (3D scanner and Geomagic Studio) to enable classification of profile image models.
2. Combine the profile image models with commercially available shoe models to generate 3D shoe-insole models (Magics RP), and manufacture 3/4 3D shoe-insole model using rapid prototyping machine (RP model).
3. Fabricate 3D shoes-insole molds from RP models, and then manufacture special shoe insoles.
4. Analyse dynamic and static stress for three-quarter 3D shoe insoles with commercially available shoes (RS scan).
5. Analyze the shoes outfit effect of three-quarter 3D shoe insoles.

Fig. 8. Dynamic foot-pressure analysis with 3/4 3D shoes’ insole.

Fig. 9. Left foot pressure analyzed with and without insole.
Plantar fasciitis patients. The shoe insoles are expected to provide desirable foot care to the mean value with a uniform foot-pressure distribution. Thus, three-quarter shoe insoles, the pressure in the forefoot and heel regions declined markedly and that in the midfoot region was close to the mean value with a uniform foot-pressure distribution. Thus, the shoe insoles are expected to provide desirable foot care to planar fasciitis patients.

In this study, the plantar shapes of 40–60-year-old people in Taiwan were classified as S, M and L types, and then the plantar shapes were used in conjunction with the commercially available shoe models to manufacture the three-quarter shoe insoles; S type includes male shoes with size numbers ranging between 3 and 6.5 and female shoes with size numbers ranging between 5 and 8.5, M type includes male shoes with size numbers ranging between 7 and 9.5 and female shoes with size numbers ranging between 8.5 and 11, and L type includes male shoes with size numbers ranging between 10–13 and female shoes with size numbers ranging between 11.5 and 14.5, as shown in Table 3. End users with such shoe insoles can walk comfortably since the maximum foot pressure is efficiently and uniformly dispersed, avoiding any injury to the fascia tissue of foot arising from the centralized pressure in the heel and forefoot regions.

5. Conclusions

The better the non-weight-bearing plantar profile, the more appropriate the three-quarter shoe insoles. Three-quarter shoe insoles for leisure shoes would be effective in the reduction of the pressure in the heel or forefoot regions and for an improvement in footwear comfort. In particular, the three-quarter shoe insoles manufactured in conjunction with the commercially available leisure shoe models provide a heel-cup and an arch-support mechanism that better resemble the plantar shape and can reduce the heel pressure by 5% and forefoot pressure by 5% and increase the foot arch pressure by 5% and that situated plantar stress under an equalized condition that offered better comfort for wearing the shoes. With more options and greater ease-of-use, the three-quarter shoe insoles can be mass produced and fulfill a majority of the customer needs. It is suggested that the three-quarter shoe insoles may contribute to relief from foot pressure and provide more comfort for users wearing flat or leisure shoes.

References