Estimation of calcaneal deformation while standing from the boolean operation between 3D and footprint image and its comparison with lateral x-ray

Dwi Basuki Wibowo^{1,}, Agus Suprihanto¹, Achmad Widodo¹ and Gunawan Dwi Haryadi¹*

¹Mechanical Engineering Department, Diponegoro University, Tembalang, 50275 Semarang, Indonesia

Abstract. Load and deformation in the calcaneal/heel region are often studied because of their potential for pain. Research conducted before proved that the calcaneal region receives large loads, both standing and walking, mainly due to excessive body weight. While heel pad deformation is not always associated with body weight, but its influenced by the mechanical properties of plantar soft tissues. In the older person the deformation of the calcaneal region while standing is lower than the adult person, which indicates the loss of the elasticity of the heel pad in aged adults. The aim of this study is estimating deformation of calcaneal area while standing from the Boolean Operation between 3D and footprint image of foot which is a novelty. Thirteen patients who feel pain due to calcanea spur were asked to volunteer research (3 males and 10 females, age 56 ± 10 years old, and BMI 25.53 ± 3.74 kg/m²). The 3D image is obtained from 3D scanner for foot orthotics, while the 2D footprint image is obtained from the digital footprint scanner. To determine the accuracy of this method compared with the deformation result of lateral x-rays due to its own weight.

1 Introduction

The calcaneal/heel is the most important area that is often studied by researchers because it receives the greatest burden that can trigger pain in the foot. Load distribution on the foot depends on body mass index (BMI) [1], gender [2], foot area contact (FAC) [3], and daily activities [4]. Research conducted by Wunderlich et al. proves that the higher the BMI the higher the FAC and FAC of male is larger than female [5]. Chia et al. noted that the heel area support about 69% of body weight (BW) while standing [6]. During walking Giddings et al. proves that there are peak loads for the achilles tendon of 3.9 BW, the plantar fascia and the plantar ligaments of 1.8 BW [7].

Deformation of the foot is caused by a compressive load that is primarily influenced by the mechanical properties of plantar soft tissues which different for adults and elderly. In the heel area the older person gets lower deformation, which indicates less energy absorbed in the foot in elderly than adult [8]. To obtain the heel deformation is still done statically as

* Corresponding author: rmt.bowo@gmail.com

shown in Figure 1. Hsu et al. obtain heel deformation by increasing the load gradually through the push-pull scale A4 and the deformation of the heel was measured by an ultrasound transducer A6 (Fig. 1a) [9]. Nass et al. found a relationship between the heel deformation and the load which increased gradually through the scale-loaded plate and deformed heel was measured by an ultrasound transducer on a plexiglass platform (Figure 1b) [10]. Similar to previous research, Rome et al. obtained a deformation of the heel as well as from an ultrasound transducer, the difference was to adjust the position of the patient's legs to the right of the ultrasound window (Figure 1c) [11].

Fig. 1. Measurement of heel deformation using ultrasound transducer.

The aim of this study is estimating deformation of calcaneal area while standing from the intersection of 3D and footprint image of foot (commonly named Boolean Operation). To determine the accuracy of this method compared with the deformation result of lateral x-rays due to its own weight.

2 Methods

This research to determine the heel deformation from the Boolean Operation between 3D and 2D footprint image is a novelty. The 3D image is obtained from 3D scanner for foot orthotics made by Vismach Technology (Figure 2) [12], while the 2D footprint image is obtained from the digital footprint scanner (Figure 3) [13]. In order to intersect between the two images can produce deformation of the foot required parameters to be equated with the 3D image i.e.: foot length (FL, Figure 3c), foot width (FW, Figure 3d), and foot area contact (FAC). FL is the direct distance from pterion point to the most anterior point of the longest toe measured parallel to the heel center line [14], which is a line drawn from the center of the heel to the tip of the second toe [15]. While FW or foot breadth horizontal is the horizontal distance between metatarsal tibial to metatarsal fibular measured perpendicular to the heel center line [14] and FAC is the area of the foot that is in contact with the platform of the digital footprint scanner (Figure 3b) [13]. Overall FL, FW, and FAC are calculated using MATLAB software.

Fig. 2. 3D foot image from 3D scan for foot orthotic.

Fig. 3. 2D footprint image from the digital footprint scanner.
(a) scanning result, (b) after the ucontacted part is removed, (c) foot length, (d) foot width

The procedure for determining heel deformation are as follows. Initially detecting the edge of white image footprint (Figure 3b, around the foot area contact) using MATLAB *bwboundaries* function and read the 3D scan coordinates output file (extension .dxf) by using Microsoft Excel which integrated in AutoCAD software. The output structure of the data sheet (Figure 4a) are:

1. the default reference axis of the 3D scanner output file is shown in Figure 5
2. generally the line numbers for adult subjects are more than 4000 numbers, depending on the subject's FL
3. the first line is the tip of the toe and the last line is the tip of the heel
4. rows of data with the same *y*-coordinate indicate the location of the *x*-coordinates along the width of the foot (Figure 4a) with the distance between the node is $\Delta x = 2\text{ mm}$ (Figure 4b)
5. the next row of data with a different *y*-coordinate of $\Delta y = 2\text{ mm}$ (Figure 4b) indicate the next location of the *x*-coordinates along the appropriate width of the foot.

Fig. 4. Generating xyz-coordinates of 3D foot image.

Fig. 5. 3D scanner output default reference axis.

To obtain the footprint depth, scale the boundaries of outer area of foot with the boundaries of 3D scanner coordinates and adjust the position of outer area of foot; inner area of foot; and 3D scanner coordinates to make sure that they are in a row. Next remove the area outside the boundaries and find the coordinates from 3D Scanner which the x and y value match with the boundaries of inner area. Two dimensional foot area of this intersection (FAC_{3D}) can be calculated by MATLAB *bwarea* function. While the foot length (FL_{3D}) is calculated from the y -coordinate subtraction in the first row with the last row and the foot width (FW_{3D}) is calculated from the largest x -coordinate subtraction in the first column with the last column of Microsoft Excel data sheet (Figure 4a).

Heel pad deformation can also be determined from lateral x-rays, as shown in Figure 6 [16]. The subject is instructed to stand on a flat bench which is 50 cm in height by crossing the legs (the right leg is in the first front and the left leg is behind) and distance from YU to YL indicates the amount of heel pad deformation due to own weight.

Fig. 6. Schematic illustration of heel pad deformation, YU-YL.

Thirteen patients with calcanea spur (the growth of the pointed bone on the inferior side of the calcaneum bone) were selected by an orthopedic specialist to be the subject of the study. Characteristics of the subjects are: 3 males and 10 females, age 56 ± 10 years old, weight 61.3 ± 9.0 kg, and BMI 25.53 ± 3.74 kg/m². Each patient was asked to do x-ray, footprint and 3D scanning.

3 Results and Discussion

Commonly foot length (FL_{3D}), foot width (FW_{3D}), and foot area contact (FAC_{3D}) the 3D scanning results are greater than the footprint results (Table 1). This is due to the curved edge of the sole of the foot read by 3D scan (Figure 7) and the coordinates are generated in Microsoft Excel (Figure 4a). The same thing is seen from the heel deformation of Boolean Operation which is also larger than x-ray. Calcaneal deformation mean and SD of Boolean Operation is 7.5 ± 2.6 mm and x-ray is 7.3 ± 2.7 mm.

Table 1. Comparison of foot length, foot width, and foot area contact between footprint with 3D scanning results (mean ± SD)

Scanning Method	Foot Length (mm)	Foot Width (mm)	Foot Area Contact (mm ²)
Footprint	251.2±15.1	100.2±7.4	11172.8±2201.0
3D Scanner	253.2±15.1	102.2±7.4	15083.3±2971.4

Fig. 7. Differences in evaluation of dimensions parameters of footprint and 3D scanner results.

The correlation between BMI and FAC can be presented by orde 2 polynomial regression with correlation coefficient 0.78 (Figure 8) and FAC of male is greater than female [5]. FAC mean and SD of male is 12518±987 mm² and female is 10769±2336 mm². While the correlation between age and calcaneal deformation can be presented by orde 2 polynomial regression with correlation coefficient 0.78 too (Figure 9).

Fig. 8. The correlation between BMI and FAC.

Fig. 9. The correlation between age and calcaneal deformation.

In contrast to the research of Nass et al., in this study there is no relationship between BMI and calcaneal deformation (correlation coefficient 0.24). In the Nass study the correlation is in the form of a hyperbolic curve between calcaneal deformation and calcaneal loading, which shows the greater of the load the smaller of calcaneal deformation, obtained by increasing the heel pressure gradually through the scale-loaded plate and deformed heel was measured by an ultrasound transducer on a plexiglass platform of one subject (Figure 1b) [10]. On the contrary in this study the absence of an association between BMI and calcaneal deformation is due to differences in mechanical properties of the plantar soft tissues which are different in each subject [8]. Therefore, knowing the

mechanical properties of plantar soft tissues in relation to calcaneal deformation is important to do in subsequent studies.

4 Conclusion

Calcaneal deformation while standing can be estimated from the intersection of 3D and footprint image of foot (called Boolean Operation) with high accuracy, compared to the measurement of x-ray result. This method facilitate the researchers in determining the deformation in the calcaneal region while standing simply by scanning the loaded and unloaded feet instead of measurement using x-ray.

References

1. Asanka S. Rodrigo, Ravindra S. Goonetilleke and Shuping Xiong, *Ergonomics*, **56** (2013)
2. R. Periyasamy, A. Mishra, Sneh Anand, et al., *The Foot* **21** (2011)
3. Bavornrit Chuckpaiwong, James A.Nunley, Nathan A.Mall, et al., *Gait & Posture* **28** (2008)
4. Mary M. Rodgers, *Physical Therapy* **68** (1988)
5. Roshna E. Wunderlich and Peter R. Cavnagh, *Med. Sci. Sports Exer.*, **33** (2001)
6. Jason KK Chia, Sanjay Suresh, Angeline Kuah, Jean LJ Ong, Jessie MT Phua and Ai Ling Seah, *Ann Acad Med Singapore*, **38** (2009)
7. Giddings, Virginia L., Beaupre, Gary S., Whalen, Robert T., and Carter, Dennis R., *Medicine & Science in Sport & Exercise, American College of Sports Medicine* (2000)
8. Kinoshita H., Francio P.R., Murase T., et al., *European Journal of Applied Physiology*. **73** (1996)
9. Tsz-Ching Hsu, Chung-Li Wang, Wen-Chung Tsai, et al., *Arch Phys Med Rehabil* **79** (1998)
10. D. Nass, Hennig and Van Treek, (2000)
11. Keith Rome, Robert Campbell, Allison Flint, Ian Haslock, *Foot & Ankle International*, **23** (2002)
12. ScanPod3D, (2013)
13. Dwi Basuki W., Gunawan DH., Achmad W., Sri Puji R, *MATEC Web of Conferences* **135** (2017)
14. Lee, Yu-Chi, Lin, Gloria and J Wang, Mao-Jiun, *Journal of Foot and Ankle Research* (2014)
15. Peter R. Cavanagh and Mary M. Rodgers, *J. Biomechanics* **20** (1987)
16. Somchai Prichasuk. *J Bone Joint Surg [Br]*, **76-B** (1994)