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Fully automated determination of arch angle on weight-bearing foot radiograph

E-Fong Kao[a,*], Chiao-Yi Lu[b], Chi-Yuan Wang[b], Wei-Chen Yeh[c], Pang-Kai Hsia[c]

[a] Department of Medical Imaging and Radiological Sciences, Kaohsiung Medical University, Kaohsiung, Taiwan
[b] Department of Radiology, Zuoying Branch of Kaohsiung Armed Forces General Hospital, Kaohsiung, Taiwan
[c] Department of Medical Imaging, Nantou Hospital of Ministry of Health and Welfare, Nantou, Taiwan

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A B S T R A C T

Background and Objective: Flatfeet can be evaluated by measuring the calcaneal-fifth metatarsal angle on a weight-bearing lateral foot radiograph. This study aimed to develop an automated method for determining the calcaneal-fifth metatarsal angle on weight-bearing lateral foot radiograph.

Method: The proposed method comprises four processing steps: (1) identification of the regions including the calcaneus and fifth metatarsal bones in a foot image; (2) delineation of the contours of the calcaneus and the fifth metatarsal; (3) determination of the tangential lines of the two bones from the contours; and (4) determination of the calcaneal-fifth metatarsal angle between the two tangential lines as arch angle.

Results: The proposed method was evaluated using 300 weight-bearing lateral foot radiographs. The arch angles determined by the proposed method were compared with those measured by a radiologist, and the errors between the automatically and manually determined angles were used to evaluate the precision of the method. The average error in the proposed method was found to be $1.12° \pm 1.57°$ In the study, in 73.33% of the cases, the arch angles could be determined automatically without redrawing any tangential lines; in 23.00% of the cases, the angles would be correctly determined by redrawing one of the tangential lines; further, in only 3.67% of the cases, both the calcaneal and fifth metatarsal tangential lines needed to be redrawn to determine the arch angles.

Conclusion: The results revealed that the proposed method has potential for assisting doctors in measuring the arch angles on weight-bearing lateral foot radiographs more efficiently.

1. Introduction

A flatfoot is a condition characterized by partial or complete loss (collapse) of longitudinal arch of the foot and is frequently encountered pathology in pediatric and adult population. The causes of flatfoot can be divided mainly into two categories: congenital flatfoot and acquired flatfoot. In the former, the most common form is pediatric flexible flatfoot [1,2], which is characterized by a normal arch during non-weightbearing and a flattening of the arch on standing. Most flexible flatfeet are physiological, asymptomatic, and require no treatment [3]. Adult acquired flatfoot is defined as a foot condition that persists or develops after skeletal maturity. Adult flatfoot encompasses a wide variety of pathological etiologies that may include a benign process reflecting continuation of a congenital problem, trauma, or a condition associated with systemic pathology. The most common acquired flatfoot in adults is due to posterior tibial tendon dysfunction [4].

Weight-bearing radiographic examination of foot [5], which shows the longitudinal arch under full weight of the body, is the standard method for evaluating flatfoot. Multiple radiographic measurements are determined from weight-bearing foot radiographs to assess the extent of flatfoot [6–9], such as the calcaneal pitch angle, calcaneal-first metatarsal angle, calcaneal-fifth metatarsal angle, talar-first metatarsal angle, and talocalcaneal angle. In Taiwan, military conscripts undergo a flatfoot examination wherein flatfoot is evaluated by measuring the calcaneal-fifth metatarsal angle on a weight-bearing lateral radiograph of the foot [10]. The calcaneal-fifth metatarsal angle [11,12] is an obtuse angle formed by a line constructed along the inferior border of the calcaneus and a line through the inferior cortex of the fifth metatarsal. For determining the calcaneal-fifth metatarsal angle, radiologists need to carefully annotate the tangential lines for the calcaneus and fifth metatarsal on foot radiographs. Measuring the calcaneal-fifth metatarsal angle by annotating the tangential lines for the

* Corresponding author.
E-mail address: tonykao@kmu.edu.tw (E.-F. Kao).

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calcaneus and fifth metatarsal on a foot radiograph is a time-consuming task. How to aid radiologists in measuring the arch angle efficiently is an issue that warrants attention.

Although computer-aided diagnosis/detection has been applied to many kinds of medical images [13–15], the methods for automated analysis of weight-bearing foot radiograph seem to have received little attention. A relevant method has been proposed by Yang et al [16]. The method used mutual information (MI) to register the images in order to calculate the calcaneal-fifth metatarsal angles. In the method, the reference and template images for the calcaneus and the fifth metatarsal bone were manually isolated before automatic measurement. The images directly isolated from the radiographic images were used as the reference of the calcaneus and the fifth metatarsal bone. The calcaneal template image was created by using a representative image and rotating until its calcaneal inclination was horizontal, and the template image of the fifth metatarsal was generated by rotating a representative image be horizontal. Image registration was achieved after repeated calculation until the MI between the template and the reference images was maximized. The rotation angles of the template images represented the calcaneal inclination or the fifth metatarsal inclination to the horizontal line. The angles then were used to calculate the calcaneal-fifth metatarsal angle.

In this study, a fully automated method for determining the calcaneal-fifth metatarsal angle on weight-bearing lateral foot radiograph was proposed. The potential usefulness of the method for assisting radiologists in measuring the arch angle more efficiently was also demonstrated.

2. Materials and methods

2.1. Image database

The proposed method was evaluated using 300 weight-bearing lateral foot radiographs, which included 150 images of the right feet and 150 images of the left feet. The images were obtained from the Zuoying Branch of Kaohsiung Armed Forces General Hospital and the Nantou Hospital of Ministry of Health and Welfare in Taiwan. Institutional review board approval was given for this study. The radiographs of foot were taken with the patients in standing position with full weight bearing of the body. All foot radiographs were obtained using a computed radiography system (REGIUS MODEL 110; Konica Minolta Inc., Tokyo, Japan) and a digital radiography system (CXDI; Canon Inc., Tokyo, Japan). The images obtained by REGIUS MODEL 110 were digitized with a pixel size of 0.175 mm and a gray scale of 12 bits. The images obtained by CXDI were digitized with a pixel size of 0.16 mm and a gray scale of 12 bits. Herein, the Photometric Interpretation attribute of the images was MONOCHROME2, and the regions of greater X-ray attenuation corresponded to higher pixel values in the images.

2.2. Overall scheme of the proposed method

The proposed method for automatically determining arch angle comprises four main steps, and the overall scheme is illustrated in Fig. 1. The four main steps: identification of the regions of interest, delineation of the contours, determination of the tangential lines, and determination of the calcaneal-fifth metatarsal angle are described in detail as follows.

2.3. Identification of the regions of interest (ROIs)

The main purpose of the method is to determine the angle formed between the tangential lines of the fifth metatarsal and calcaneus. The first problem encountered by us was with identifying two small regions in a foot radiograph, which include the fifth metatarsal and calcaneus. There are two advantages of analysis by the ROIs instead of the whole image: (1) reducing the computation time and (2) reducing the complexity of the searching algorithm (a local maximum/minimum point will become global maximum/minimum in the ROI). To locate the ROIs for the fifth metatarsal and calcaneus, six reference positions were determined from a lateral foot radiograph in advance. Each of the position is described in sequence as follows:

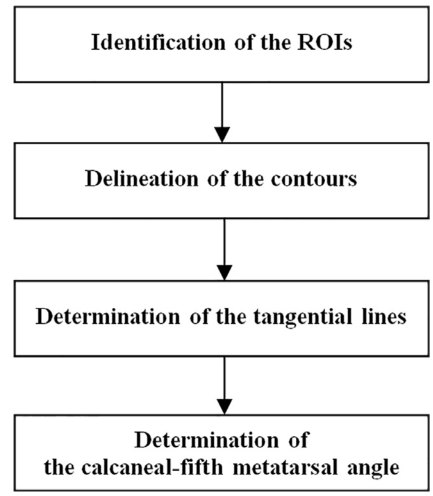

Fig. 1. Overall scheme of the proposed method.

2.3.1. Position for the leg (X_{leg})

The position for the leg on the X-coordinate was first determined, as shown in Fig. 2(a). For determining the position, a projection profile, $P_{leg}(x)$, was obtained by summing the pixel values of the foot image along the Y-coordinate. $P_{leg}(x)$ is defined as follows

$$P_{leg}(x) = \sum_{y=1}^{H} I(x, y)/H \quad (1)$$

where $I(x, y)$ is the foot image, H is the height of the image and W is the width of the image. The position for the leg, X_{leg}, can be determined by searching a global maximum from the projection profile, as shown in Fig. 2(b). X_{leg} could be used to identify the image as a right or left foot image. If X_{leg} is larger than $W/2$, $I(x, y)$ is identified as a right foot image; otherwise, $I(x, y)$ is a left foot image. In this study, all methods are described using right foot images and are extrapolatable to left foot images.

2.3.2. Position for the base (Y_{base})

Following the determination of X_{leg}, the base of the foot (Y_{base}) was further determined, as shown in Fig. 3(a). To determine the position for the base, another projection profile, $V_{base}(y)$, was obtained by summing the pixel values of the foot image along the X-coordinate from X_{leg} *to* W. $V_{base}(y)$ is defined by Eq. (2):

$$V_{base}(y) = \sum_{x=x_{leg}}^{W} I(x, y)/\left(W - x_{leg}\right) \quad (2)$$

As shown in Fig. 3(a), the projection path corresponding to the foot base contains soft tissue pixels and more background pixels. Due to small pixel values of the soft tissue and background, the projection value corresponding to the foot base would have smaller value than those of the other projection paths. Hence, the position for the base, Y_{base}, can be determined by searching a global minimum from the projection profile between $H/2$ and H, as shown in Fig. 3(b).