A Computer-Aided-Diagnosis System for Hallux Valgus

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Abstract

We proposed for measuring Hallux Valgus (HV) and the First-fifth intermetatarsal (M_1M_5) angles on X-ray images. The method consisted of two procedures, shape recognition and finding direction. In the former procedure, shapes of the proximal phalanx and metatarsals were recognized by using the Segment Anything. A principal component analysis was sequentially applied to the coordinates of pixels in each shape in the latter. The HV and M_1M_5 angles were calculated as the differences between the directions of the first principal components of them. Experiments using actual 14 X-ray images showed that the angles processed by the proposed method well agreed with those independently measured by two doctors.

Keywords: hallux valgus, X-ray measurement, segment anything, principal component analysis.

1. Introduction

Hallux valgus is a foot condition characterized by the outward tilting and displacement of the big toe. When diagnosing hallux valgus, doctors must measure the HV and M_1M_5 angles[1] on X-ray images. They first identify specific landmarks, for example, on the metatarsal, and obtain the centerline based on their positional relationships[2]. The angles are calculated as the difference between the directions of the centerlines. Since the shape and condition of bones vary from patient to patient, identifying landmarks not only includes some positional errors but also takes much time. Those cause instability in resultant angles and a decrease in the number of treatable patients. In order to get stable results and to increase the number of treated patients, a computer-aided diagnosis system has been required.

Here, we propose a method for measuring the HV and the M_1M_5 angles with high stability, high accuracy, and high reproducibility. The method is based on the fact that the proximal phalanx and metatarsals are elongated and have straight shapes. Actually, a principal component analysis applied to the coordinates of the pixel in those bones gives us almost the perfect centerlines less susceptible to variation in shape from patient to patient by averaging over the entire shape. Since the bones are overlapped in X-ray images, it is not easy to recognize bone edges, so we adopt the Segment Anything[3] to extract the entire bone.

2. Methodology

Figure 1 shows an example of the X-ray image to be processed. The HV angle α is defined as the difference between centerlines representing both the 1st proximal phalanx P_1 and the first metatarsal M_1 as shown in Figure 1. The M_1M_5 angle β is also defined as the direction difference between centerlines of M_1 and M_5. The accuracy of these angles depends on how to determine the centerline of the proximal phalanx, the 1st metatarsal, and the 5th metatarsal.

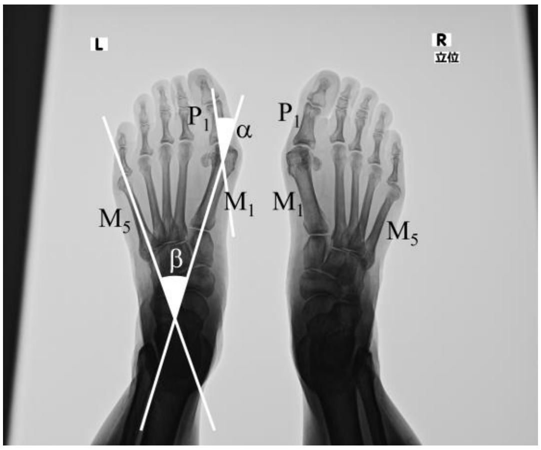


Figure 1: Bones and angles.

2.1. Shape recognition

Since an X-ray image has a bright background, feet are easily recognized and separated from each other by using contour detection. For each foot, we first apply a prompt setting process as the preprocessing for the Segment Anything. The prompt means the initial the segmentation. Scanning the foot image vertically, we find the tip of the big toe and use it as a key point A. An edge detection algorithm such as Canny gives us the edges of all bones in the image. Harris corner detection is applied to the region where coordinates are greater than 40% of the total foot length, calculated from Key point A. The process identifies the smallest y-coordinate, which is then designated as Key point B for both left and right feet. At this time, it is also noted that the 1st metatarsal (M1) has smooth edges, meaning there are no detectable corners that can be identified as such for detection purposes. Segment Anything works well when we use two prompts; one of them is set inside the bone area and the other outside it. We regard the vertical distance between A and B as the base length L for the

*PS&MC: Podiatric Surgery & Medicine Clinic prompt setting as shown in Figure 2 and Table 1. Horizontal positions are determined by considering the bone edges obtained above. Some of these prompts are placed within the bone area to be recognized, i.e. P_1, M_1, and M_5, and the others somewhere else in another bone or the background.

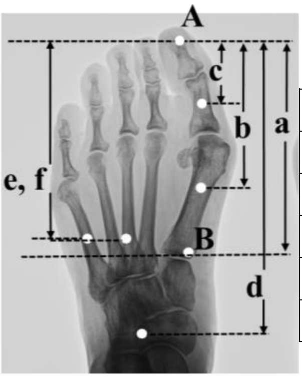


Figure 2: Key points and prompts.

Table 1: Vertical position of prompts.

Distance	Value
a	L
b	0.7 L
c	0.3 L
d	1.4 L
e, f	0.9 L

2.2. Finding direction

After applying the Segment Anything, we obtain bone areas of P_1, M_1, and M_5. For those areas, we apply a principal component analysis. When pixel P_i (i=1,…,n) in a bone region S has coordinates x_i and y_i, the center of gravity (x_m,y_m) of the region is described as

$$x_m = \frac{1}{n}\sum_{i\in S} x_i, \quad y_m = \frac{1}{n}\sum_{i\in S} y_i, \tag{1}$$

and their covariance matrix Σ as

$$\Sigma = \frac{1}{n-1} X' X, \tag{2}$$

where,

$$X = \begin{bmatrix} x_1 - x_m & y_1 - y_m \\ x_2 - x_m & y_2 - y_m \\ \vdots & \vdots \\ x_n - x_m & y_n - y_m \end{bmatrix}. \tag{3}$$

Let E_i (i=1,2) be the eigenvalues ($E_1 > E_2$) of Σ, and V_i (i=1,2) be the eigenvectors corresponding to the eigenvalues. The bone region S's centerline is the first eigenvector through its center of gravity, used to calculate HV and M1M5 angles.

$$\begin{cases} \alpha = \cos^{-1}\left\{V_1(P_1)\cdot V_1(M_1)\right\} \\ \beta = \cos^{-1}\left\{V_1(M_1)\cdot V_1(M_5)\right\} \end{cases}. \tag{4}$$

When we tried the calculation in Eq.(4), the centerline L_1 and the M_1M_5 angle β were slightly off, as shown in Figure 3, due to asymmetry of the root of the 5th metatarsal. So, we improved the algorithm. We measure width of M_1 along the original centerline L_1 from the gravity center to left and right, and find the maximum width positions. The distance H between those positions is divided in the ratio of 0.3:0.4:0.4. The new centerline L_2 is the line through the midpoints of two segments, as shown in Fig.3. The bone shapes of P_1 and M_1 are nearly symmetrical, so there was no need to correct the centerline.

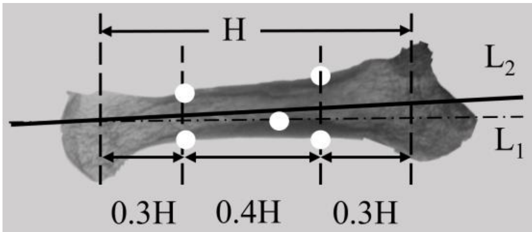


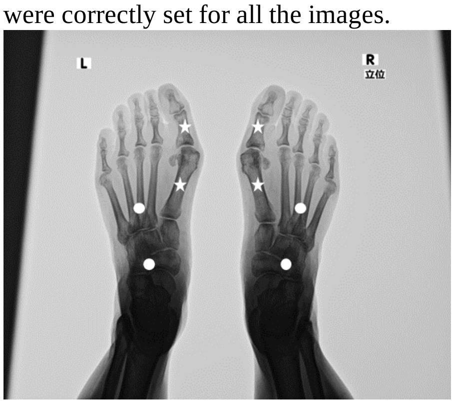
Figure 3: Centerline improvement.

3. Experiments

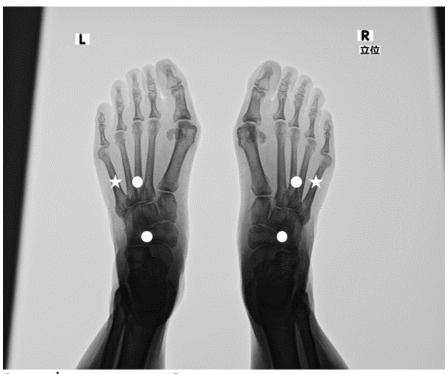
The dataset we used included 14 X-ray images of both feet for 10 male and 4 female hospital technicians. They were not actual patients but volunteers who consented to the use of their data. The data, in DICOM format, had personal information removed for anonymity and privacy. We compared HV and M1M5 angles measured by the method with those evaluated by two doctors.

3.1. Experimental results

Figure 4 shows an example of the results for setting prompts for the Segment Anything. The positions of the prompts were correctly set for all the images.



(a) for the 1st proximal phalanx and the 1st metatarsal



(b) for the 5th metatarsal

Figure 4: Prompts setting.
(Circle: background prompt, Star: target prompt)

Then the Segment Anything was applied, and we obtained the shapes of the target bones as shown in Figure 5. The HV angle and the M_1M_5 angle were obtained by crossing of centerlines shown in Figure 6. Tables 2 and 3 indicate the numerical results of all the X-ray images. Figures 7 and 8 show scattergrams among the three measurements.

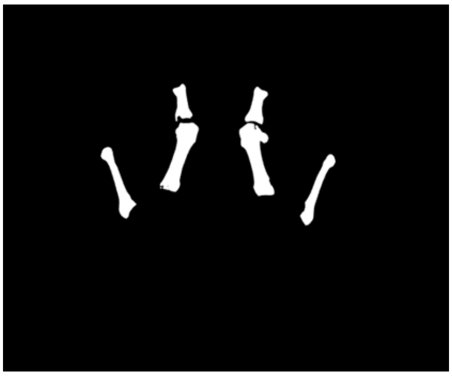


Figure 5: Bone regions extracted by the Segment Anything.

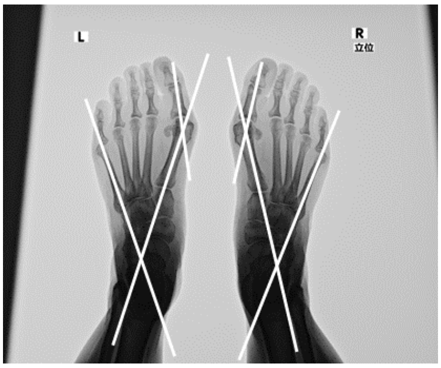


Figure 6: Centerlines for the 1st proximal phalanx (P_1), and the 1st and the 5th metatarsals (M_1 and M_5).

Table 2: Left (_L) and Right (_R) feet HV angles measured by Doctor1 (Dr1), Doctor2 (Dr2) and the proposed method (Pr).

No	Dr1_L	Dr1_R	Dr2_L	Dr2_R	Pr_L	Pr_R
1	4.5	4.2	2.4	4.1	0.2	1.3
2	29.6	29.5	29.5	28.0	26.3	25.8
3	18.0	20.1	15.3	17.2	16.5	18.4
4	12.8	11.5	9.8	8.4	9.1	7.0
5	14.3	9.2	13.1	5.7	11.9	5.1
6	15.7	18.9	16.0	16.3	12.2	14.9
7	6.1	9.5	6.9	6.7	6.6	7.2
8	11.5	9.7	11.5	10.9	11.2	9.9
9	14.2	15.0	13.7	14.9	10.6	11.6
10	18.1	22.3	18.1	19.8	17.6	20.2
11	12.5	13.0	14.2	11.7	13.7	11.4
12	16.8	18.8	13.0	15.7	12.9	14.7
13	17.8	12.0	18.2	10.5	18.9	12.7
14	5.5	8.7	7.6	12.1	10.3	9.0

Table 3: Left (_L) and Right (_R) feet M_1M_5 angles measured by Doctor1 (Dr1), Doctor2 (Dr2) and the proposed method (Pr).

No	Dr1_L	Dr1_R	Dr2_L	Dr2_R	Pr_L	Pr_R
1	26.2	26.5	21.4	24.0	21.1	22.5
2	40.8	37.7	40.6	38.2	36.8	34.1
3	26.4	28.9	23.8	28.7	24.0	26.5
4	29.5	28.5	24.5	26.3	20.0	22.8
5	30.6	30.3	28.1	28.8	25.6	26.1
6	28.3	27.9	25.8	27.0	23.2	23.3
7	29.6	27.4	31.5	31.3	29.2	30.7
8	29.7	29.6	29.8	31.0	27.7	27.9
9	28.2	28.2	28.2	29.3	25.5	26.5
10	32.3	31.3	31.0	30.4	28.9	30.3
11	30.5	30.8	29.1	29.5	26.6	27.0
12	34.9	32.8	31.6	30.2	29.9	28.6
13	35.2	36.3	33.5	34.1	29.6	33.3
14	26.6	27.3	29.1	28.1	17.0	23.7

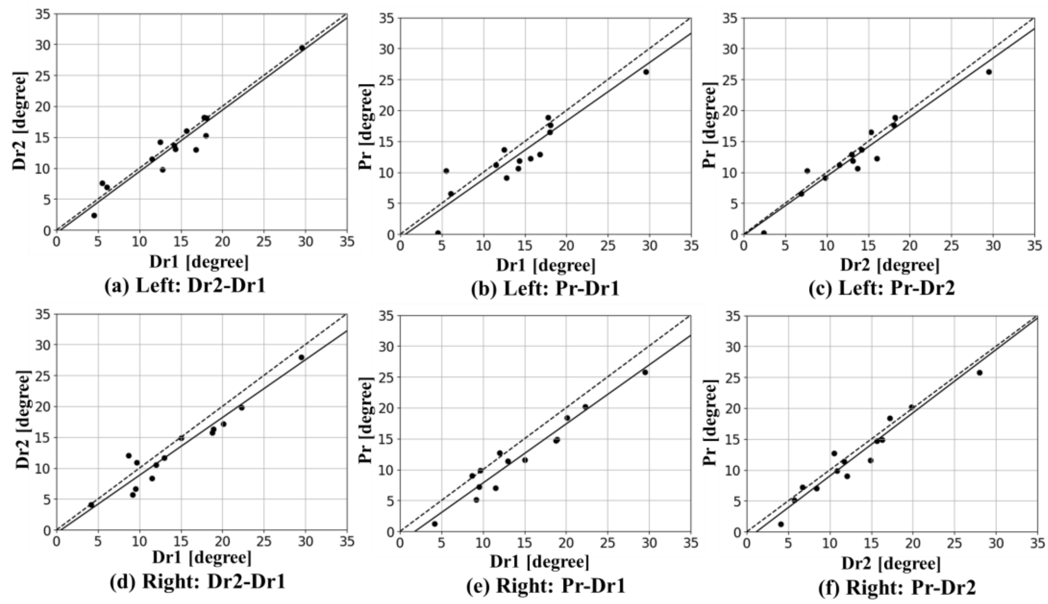


Figure 7: Scattergram among HV angle measurements by Doctor1 (Dr1), Doctor2 (Dr2), and the proposed method (Pr).

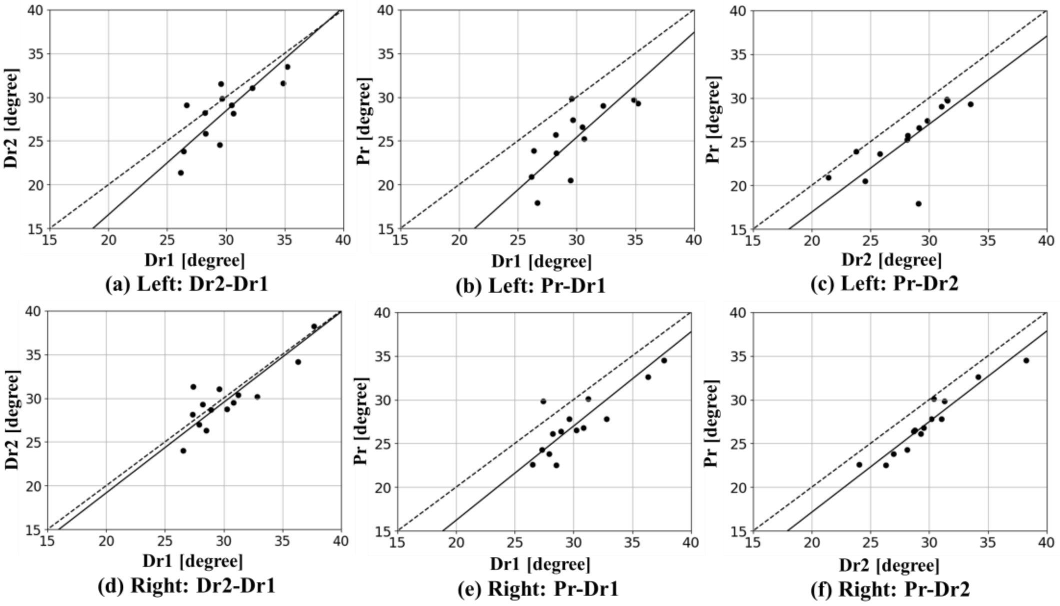


Figure 8: Scattergram among M_1M_5 angle measurements by Doctor1 (Dr1), Doctor2 (Dr2), and the proposed method (Pr).

Since the scatter diagrams of Dr1 and Dr2 were not on a straight line, i.e. there are some errors in their measurements, a structural analysis was performed. In Figures 7 and 8, the broken line represents where the quantities on the horizontal and vertical axes match, and the straight line is the direction of the first principal component of the scattergram. We used a note PC (CPU: i7 - 12700H, Clock:2.70 GHz, Memory:32GB, GPU: RTX3070Ti Laptop, OS: Windows11) for the processing. Doctors used to take about 1.5 minutes to measure the HV and M1M5 angles on an image, the method reduced the time to 8 seconds.

3.2. Discussion

Comparing the results in Figure 7 with those in Figure 8, the straight line is closer to the broken one. This indicates that the proposed method yields values similar to the doctors' measurements in the HV angle measurement, with correlation coefficients of 0.93 and 0.96 with Dr1 and Dr2, respectively. In the M_1M_5 angle measurement, the proposed method also gave us well-correlated results with the doctors' measurements. The correlation coefficients were 0.81 and 0.93 for Dr1 and Dr2, respectively. Here, we see that the straight line was slightly separated from the broken one. This indicates the presence of a certain bias component. The discrepancy seems to be due to doctors' tendency to measure angles larger. We also see that the dispersion of the points was greater than that in the HV angle measurement, and there was also greater dispersion among doctors (see Figure 8 (a) and (d)). This suggests that each doctor may focus on different landmarks in the M_1M_5 angle measurement. Since the proposed method stably gives the angle determined by the algorithm, the method is useful as a reference. In both angle measurements, the angle dispersions in Pr-Dr1 and Pr-Dr2 compatible with those in Dr1-Dr2, so the proposed method is useful in terms of accuracy.

4. Conclusions

We proposed a automated method to reduce the time for a doctor to measure the HV and the M_1M_5 angles from a patient's feet X-ray image and to see more patients. The method was based on the fact that bones in the foot were elongated. We measured the HV angle by finding the centerlines for the 1st proximal phalanx and the 1st metatarsal. We also measured the M_1M_5 angle by finding those for the 1st and the 5th metatarsals. The centerlines were determined by applying a principal component analysis to the coordinates of pixels in the target bone region. The target bone region was recognized by the Segment Anything. The method was characterized by its stability in angle measurements. The HV and M_1M_5 angles were compared with those independently measured by two doctors. The resultant angles were well agreed with those by doctors. Applying the method to actual patients' X-ray images is a subject for future work.

References

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