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Brief Reports

Development of a method to assess alignment of the foot and lower leg

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ABSTRACT

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Purpose: Three-dimensional analyses of the foot and lower leg have been restricted to large-scale research facilities, since such analyses require a large experimental area and expensive measurement systems. Therefore, we developed a new three-dimensional method of analyzing still pictures using commercially available digital cameras, and applied it to clinical use.

Methods: We used three digital cameras. One was set 6 m behind the subject, while the other two were placed at 45 degrees to the right and left sides of the first camera, each the same distance from the subject. We used a plaster model of a lower leg and foot, on which several markers were mounted. The positions of the three-dimensional coordinates of the markers were computed by triangulation from the pictures taken with the three cameras, and the accuracy was verified.

Results: The average reading error was 0.6 mm, and the average and maximum repetition errors were 1.3 mm and 1.6 mm, respectively. Comparison with direct evaluation was found to be 2.3% at maximum. These results showed that the method is highly reliable.

Conclusion: Although a three-dimensional analysis using this method has the limitation of still picture analysis, it may be useful in many clinical applications because it requires only inexpensive apparatus and a small experimental area.

Key words: foot-lower leg alignment, three-dimensional analysis, digital camera, accuracy

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Introduction

Some studies concerning kinematic analysis involving foot arch ratio [1, 2], fluctuation of center of gravity, foot pressure distribution [3, 4], motion capture [5, 6], X-ray pictures [7], and CT [8] pictures have been reported. Although the foot has been analyzed in previous studies of foot arch ratio or foot pressure distribution, there have been few analyses of the relationship between the foot and lower leg. Although there have been reports on the effect of the alignment of the foot on the rotation angle of the lower leg, these studies used motion capture systems, which require expensive equipment and a large experimental area [5, 6]. In order to measure the alignment of the ankle joint and lower leg, a motion capture system is usually required [10]; however, such a system is expensive and requires a large experimental space. Therefore, we developed an alternative three-dimensional measurement method based on trigonometry, using commercially available digital cameras.

In this study, we propose an inexpensive and simple method. Measurement of the alignment of the lower leg and foot is shown as an example application of this method.

Theory and method

Our method is based on the principles of trigonometry [11]. All three cameras used were an Optio RZ18 (PENTAX; 3465×4608 pixels; focal length: 60.3 mm, 35 mm equivalent of 335 mm; stop: F5.4; shutter speed: 1/6−1/4 seconds, ISO: 100). The cameras were placed as shown in Fig. 1; Camera P was placed 6 m behind the subject, and Camera R and

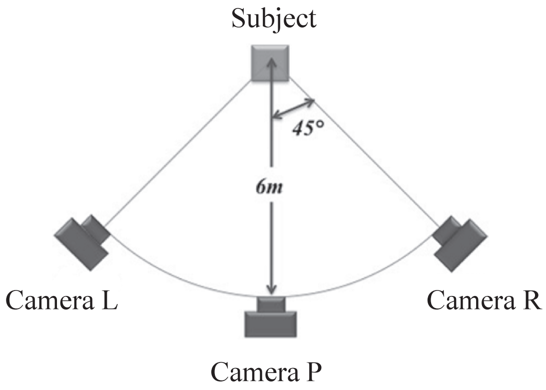

Figure 1. Camera arrangement.

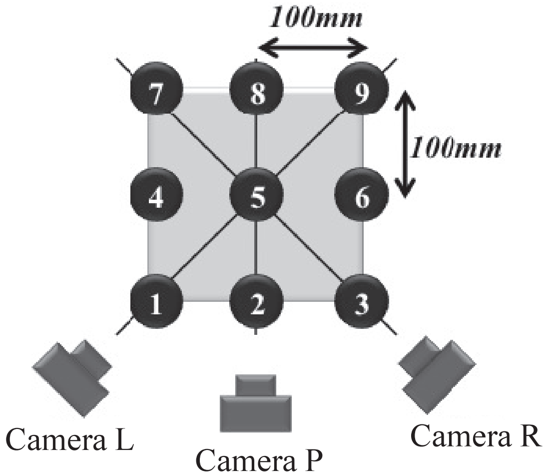

Figure 2. Calibration frame.

Camera L were placed at 45 degrees to the right and left sides of Camera P.

Nine spherical markers with a diameter of 5 mm were placed at lattice points (3×3) 100 mm apart from each other, and used as a calibration frame as shown in Fig. 2. Markers 1 to 9 shown in the figure are hereinafter referred to as P1 to P9.

First, the calibration frame was observed on the liquid crystal display monitor of Camera P to confirm that the three markers P2, P5 and P8 overlapped. The calibration frame was then observed on the monitors of Camera R and Camera L to confirm that P3, P5 and P7, and P1, P5 and P9 overlapped, respectively. The origin of the coordinate system was set to P5. The X and Y axes were defined as the horizontal and vertical perpendicular lines passing through point P5 going respectively from left to right and from bottom to top of the page. The Z axis, perpendicular to the X and Y axes, was defined as positive coming out of the page and negative going out the back of the page.

It was confirmed from Camera P that all the markers were observable, from Camera R that markers on the right-hand side were observable, and from Camera L that markers on the left-hand side were observable.

The two-dimensional coordinates acquired from the photos were expressed as (u_i, v_i) (horizontal direction, vertical direction), and i denotes one of the cameras (R, P, or L), and the three-dimensional coordinates after computation were expressed as (x, y, z). As two or more cameras are indispensable in three-dimensional analysis, at least two pictures of each marker were taken. We then read the two-dimensional coordinates (u_i, v_i) from the two pictures, and computed three-dimensional coordinates (x, y, z) based on each two-dimensional coordinate.

The images from each camera were saved in JPEG format using the LabVIEW (National Instruments) program. The program was written such that the user had to visually scan the image. Upon clicking on a point of the image, the coordinates of that point were displayed by the program.

The (x, y, z) coordinates were obtained by the following equations based on geometric optics, from the two-dimensional coordinates acquired by the abovementioned process.

To obtain (x, y, z) from Camera L and Camera P, using coordinate x', which denotes the x coordinate before compensation, we used the equation:

$$\begin{bmatrix} x' \\ y \\ z \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 \\ -\sqrt{2} & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} u_L \\ v_L \\ u_P \\ v_P \\ u_R \\ v_R \end{bmatrix}$$

To obtain (x, y, z) from Camera R and Camera P, using coordinate x', which denotes the x coordinate before compensation, we used the equation:

$$\begin{bmatrix} x' \\ y \\ z \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & \sqrt{2} & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} u_L \\ v_L \\ u_P \\ v_P \\ u_R \\ v_R \end{bmatrix}$$

To obtain x from x' we used the equation:

$$x=x'(1+y/6000)$$

To calibrate the distance and the angle, P5 was set as the origin, the distance between P4 and P6 was set at 200 mm, and the line segment of P4 and P6 was set horizontal. We remotely controlled the three cameras to take pictures simultaneously.

For verification of accuracy, 10 markers were mounted on the plaster model of the lower leg and foot: medial side of the calcaneus, lateral side of the calcaneus, navicular, fifth metatarsal base, first head of metatarsal, fifth metatarsal head, medial malleolus, lateral malleolus, tibia proximity (the posterior border of the medial collateral ligament attachment), and fibula head. The coordinates of the 10 markers were computed by the abovementioned method, and reading reliability and repeating accuracy were evaluated.

To evaluate reading reliability, we read the coordinates of the 10 markers from a picture 10 times repeatedly. Since the average reading fluctuation was important for evaluating reading reliability, we computed the mean square error of 10 repeated readings.

To evaluate reproducibility, we replaced the plaster model at random so that the position and angle differed for each trial to make it a comparable change to the case when a subject replaces his leg. The position of Camera P was arranged such that it could take pictures of all markers.

Coordinates were computed from 10 sets of pictures, the distance between markers was computed from the coordinates, and the distance was evaluated as an index of accuracy.

To evaluate distance accuracy, long distances of each coordinate were used: the distance between the medial and lateral sides of the calcaneus and the distance between the first and fifth metatarsal heads on the X axis, the distance between the medial side of the calcaneus and the first metatarsal head on the Y axis, and the distance between the medial malleolus and tibia proximity and the distance between the lateral malleolus and fibula head on the Z axis.

The above-mentioned distances were also directly measured by tape measure or Vernier calipers and compared with the distances computed by three-dimensional analysis.

Results

The coordinates of the same marker were measured 10 times with the computer cursor. The mean square errors of reading reliability are shown in Table 1. The average was 0.6 mm.

The plaster model, on which the markers were mounted, was replaced 10 times, and the error distances between markers were measured. The results are shown in Table 2. The largest repeating accuracy (1.6 mm) was found in the distance between the medial side of the calcaneus and the first metatarsal head, and in the distance between the lateral side of the calcaneus and the fifth metatarsal head. The error rate by direct measurement was 2.3% at maximum.

Discussion

From the verification experiment of reading reliability, it was shown that the accuracy of the cursor setting position was around 0.6 mm, which was sufficiently accurate. In the repeating accuracy experiment, the plaster model was replaced 10 times, and the accuracy was about the same order. The error rate of measurement by Vernier calipers or tape measure was 2.3% at maximum. Thus, the reliability of this system appeared to be excellent. Compared to conventional three-dimensional measurement equipment, such as Kinema Tracer, the reading error was around 5

Table 1. Reading reliability. (mm)

	x (Horizontal)	*y* (Depth)	*z* (Vertical)
Calcaneus (medial)	0.5	0.7	0.7
Calcaneus (lateral)	0.6	1.0	0.7
Navicular	0.5	0.7	0.7
5th metatarsal base	0.5	0.6	0.4
1st metatarsal head	0.3	0.7	0.4
5th metatarsal head	0.4	0.8	0.5
Medial malleolus	0.5	0.7	0.7
Lateral malleolus	0.4	0.5	0.4
Tibia proximity	0.6	0.7	0.4
Fibula head	0.7	0.7	0.5

Table 2. Repeating accuracy. (mm)

	Present	Direct measurement	Error ratio (%)
Calcaneus (m) − Calcaneus (l) *	44.9±0.8	45.3±0.8	−0.9
1st met head − 5th met head **	101.9±0.8	102.7±0.7	−0.8
Calcaneus (m) − 1st met head	170.9±1.6	166.9±1.0	2.3
Calcaneus (l) − 5th met head	165.8±1.6	163.3±1.1	1.5
Medial mal − Tibia proximity ***	295.9±1.3	296.4±1.2	−0.2
Lateral mal − Fibula head	311.9±1.3	312.6±1.0	−0.2

*(m), medial; (l), lateral; ** met, metatarsal; ***mal, malleolus.

mm when a 500-mm long object was used, giving an accuracy of about 1%. Although neither the reading accuracy of VICON nor the error rate is published, it is thought that the accuracy is comparable.

The purpose of developing our system is to enable anyone to perform measurements anywhere. The total cost of all the equipment is about 36,000 yen (approx. US$380, on March 12, 2013). Furthermore, the cost was reduced by coding our own image-analysis program. The equipment is portable and can be used anywhere, such as a general hospital or nursing institution for elderly people. Since the system is inexpensive and requires minimal experimental area, as well as being sufficiently accurate, it is expected to be widely used for clinical applications, and may become a practical measurement means, including for analysis along a horizontal plane, such as rotation of the lower leg. To carry out measurements, a total time of 1 minute and 15 seconds was required: 1 minute to mount the markers while the subject was sitting on a chair, 10 seconds to adjust the standing position, and 5 seconds to take pictures.

The present method is limited to the analysis of still pictures and evaluation of alignment; it cannot analyze chronological data such as joint movements.

Conclusion

Although the method is limited to the analysis of still pictures, it is suitable for assessing the alignment of the foot and lower leg. In institutions not fully equipped with measurement equipment, such as general hospitals and nursing institutions for elderly people, alignment is subjectively evaluated by sight. The present study showed that by using commercially available digital cameras, our method enables objective evaluations with high reliability.

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