Application of 3-D Scanner to Analysis of Functional Instability of the Ankle

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Abstract: This paper describes a technique, which analyzes the functional instability of the ankle using three-dimensional scanner. The technique is based on the structured light pattern projection method, which is performed by using one digital still camera and one LCD projector. This system can be easily realized with the low cost. The measuring result has high accuracy. The measuring error is about 0.2 mm or less. Using this technique the three-dimensional posture of the leg and foot of the target person are measured and analyzed.

Keywords: structured light, shape measurement and reconstruction, image processing, functional instability and ankle sprain.

1. INTRODUCTION

Ankle sprain is a kind of diseases those can be often found on the ankle of sports players. Functional instability of the ankle is recognized as one of the most common residual disability after an acute ankle sprain. Due to this functional instability of the ankle, recurrent ankle sprains are reported. Several causes for this functional instability have been proposed: mechanical instability, personal muscle weakness, and an improper sense of joint angle. In order to analyze the individual sense of the joint angel, a technique to use 3-D scanner is proposed. The technique is based on the structured light pattern projection method, which is performed by using one digital still camera and one liquid crystal display projector. Using this technique the three-dimensional posture of the leg and foot of the target person are measured and analyzed.

An experiment to analyze functional instabilities of the ankle is executed as follows. Target persons are requested to stand with his left foot on an inclined table and the right foot on the other table with bare foot (Fig.1). The inclination of left table is adjusted to some pre-specified angles. The right table has two-degree of freedom. And the target person can move the table to any posture by his right foot. The target person is requested to adjust the inclination angle of the right table. There exists some deviation between the right and the left table. In case the target person has experiences of ankle sprains, the difference of the table is admitted as an index to represent the functional instabilities. It is also important to consider the posture of the leg and foot as well as table.

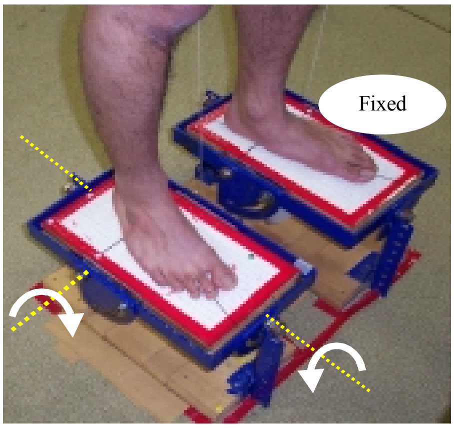

Fig.1 Foot on the inclined table

Therefore, the three-dimensional features of the legs, feet and tables are measured using a three-dimensional scanner, which is developed in this study. A feature of the three-dimensional scanner is that it can measure the three-dimensional surface with high resolution and high accuracy without any mechanical contact. This feature that it can measure without any mechanical contact is important to obtain the functional instability of the ankle, since the mechanical contact often disturbs the accuracy of the measurement. In addition to the analysis of the functional instability, three-dimensional data of the leg can be stored to diagnose the physical situation.

The system is composed of one digital still camera, one LCD projector and computer, which execute the image processing and obtains three-dimensional data. In order to simplify the measuring, some target marks are attached on the target body. Every mark is a white round plate, which is easy to recognize on the target. Detection of the target position on the images is executed automatically or manually.

In this patter, a calibration technique and measuring procedure are explained.

2. OVERVIEW OF MEASURING SYSTEM

For the measurement of the 3-D posture of the target person, the following measuring system is used (Fig.2).

Fig.2 Overview of the measuring system

The LCD projector of EPSON ELP-70/50 and the digital still camera of CANNON PowerShotG3 was connected to the DELL note PC of Pentium Ⅲ 866Mhz. The 3-D scanner is composed of these three devices. The features of this 3-D scanner is as follows:

1) The projector and camera are settled at the appropriate distance in order to carry out the shape measurement based on the triangulation method.
2) The structured light pattern generated by PC is projected on the measurement space based on the 1024*768 resolution by projector.
3) Camera acquired its illuminated pattern based on 1600*1200 resolution, and transferred through the USB port in PC.
4) Finally, the three-dimensional data are calculated by our developed program, which is based on image processing and triangulation method in PC.

In this structured light pattern we employed the gray code pattern considering the robustness [4]. Furthermore, we used the inverse pattern method [9] for more stabilized binary processing. Therefore, the gray code pattern is 8 sheets, and actual measurement used 18 sheets including the full white and black. As a result, the trade-off problem was generated between the measuring accuracy and the measurement time. The system can measure the static three-dimensional shape.

3. NUMERICAL MODEL AND SYSTEM CALIBRATION

3.1 Camera model

To determine the properties of the camera system, we need the geometrical relation between the camera and the world coordinate. In 3-D scanner, the geometrical relationship is determined using four steps calibration model [5,6,7].

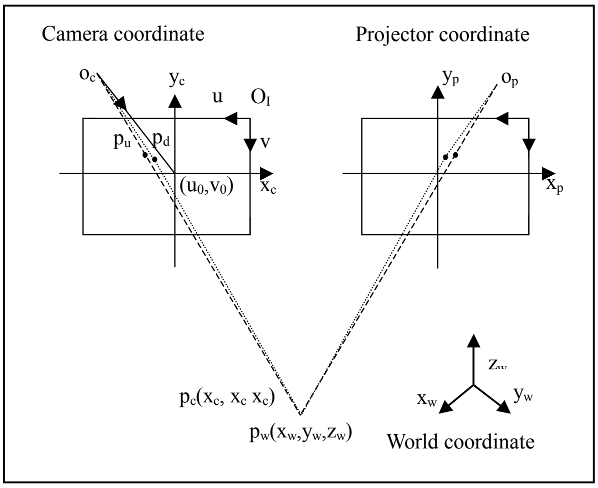

Fig.3 Geometric relation between 3D point and its 2D projection

1) The relation between the world coordinate system and the camera coordinate system:
This transformation is modeled using a translation vector and a rotation matrix, as shown in the following equation,

$$\begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} = R \cdot \begin{bmatrix} x_w \\ y_w \\ z_w \end{bmatrix} + \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix} \qquad (1)$$

where the rotation matrix R is represented using roll, pitch, yaw angles. Therefore, using the Eq. (1), the camera coordinate p_c (x_c,y_c,z_c) is obtained from the world coordinate point p_w (x_w,y_w,z_w).

2) The projection of the 3D point on the image plane:
From the point p_c (x_c,y_c,z_c) in the camera coordinate we used the pinhole camera model to obtain the un-distortion point p_u (x_u,y_u) in the image plane by the following equation,

$$x_u = f \cdot \frac{x_c}{z_c} \;,\; y_u = f \cdot \frac{y_c}{z_c} \qquad (2)$$

where the f is a focal length of the optical lens. In our experiment, the focal length is fixed.

3) The lens distortion:
In order to obtain more accurate model, both radial and tangential lens distortion components should be considered. With radial distortion, image coordinates are radial shifted from the principal point, while the tangential distortion accounts for the component that is perpendicular to the radial direction. We only consider radial distortion since the tangential distortion is often negligible with respect to the radial one. Furthermore, the radio distortion is calculated with only the first coefficient k1. The conversion relations of the coordinate p_d (x_d,y_d) and the coordinate p_u (x_u,y_u) are shown in the following equation.

$$x_u = x_d + x_d \cdot k_1 \cdot (x_d^2 + y_d^2),$$
$$y_u = y_d + y_d \cdot k_1 \cdot (x_d^2 + y_d^2) \qquad (3)$$

4) The relations between the camera image plane and the computer pixels system:
The conversion relations of the computer coordinate (u_c,v_c) and the camera image coordinate p_u (x_u,y_u) are shown in the following equation.

$$u = -k_u \cdot x_d + u_0$$
$$v = -k_v \cdot y_d + v_0 \qquad (4)$$

where the k_u, k_v are scaling factor (pixel/mm). The u_0, v_0 are the pixel coordinates of the principle point. In our experiment, the shear coefficient (pixel/mm) defined zero.

Using Eqs. (1)~(4) the camera properties in world coordinates are defined. In this experiment, the following vector with the eleven elements specifies the camera system parameters.

$$C_n = [\alpha, \beta, \gamma, t_{cx}, t_{cy}, t_{cz}, u_{c0}, v_{c0}, k_{uc}, k_{vc}, k_{1c}]^T \quad (5)$$

where the α is a roll angle, the β is a pitch angle, the γ is a yaw angle. So as to obtain the camera system parameters (5), we used the two-steps method. In this method, the initial parameter values are computed linearly. And, the final parameter values are obtained with non-linear least square optimization method.

3.2 Camera calibration

At the beginning of the experiment, the geometrical relation of the camera system needs to be calibrated. As a practical calibration, we put a square box inside the visible region and acquire an image from the camera. The world coordinates of the reference control point on the square box are known. Therefore, from the acquired image the raster coordinates of the control points are obtained. Finally, from the obtained raster coordinates and its world reference coordinates, we can get the geometrical relationship by Eqs. (1)～(4).

3.3 Projector calibration

The geometrical relationship of the projector can be modeled similarly to the camera. In this three-dimensional scanner, we used only the vertical gray code pattern. In fact, projector is a one-dimensional device. Therefore, the projector system parameters are reduced. In this case, the following vector with the nine elements specifies the projector system parameters.

$$P_n = [\alpha, \beta, \gamma, t_{px}, t_{py}, t_{pz}, u_{p0}, k_{up}, k_{1p}]^T \quad (6)$$

where the α is a roll angle, the β is a pitch angle., the γ is a yaw angle. We also use the non-linear least square optimization technique to estimate the projector system parameters (6). The calibration is performed as follows. First, we projected the spotlight on the world reference control points of the square box by the manual operator. Secondly, we get the projector coordinate points from screen that's projector raster. Finally, using the projector coordinates and its world reference coordinates, the geometrical relationship is obtained.

4. DEFINITION OF POSTURE PARAMETERS

In Fig.4 the leg of the target person and the mark position are shown. The seven mark points can be recognized. The three of those points ⑤,⑥,⑦ are allocated on the inclined table; ② is at the front side of the ankle; ④ is at the right-hand side of the ankle. ① is allocated at the front side of the knee and, ③ is allocated at the right-hand side of the knee.

To simplify the analysis, we modeled the leg and foot of the target person (Fig.5). From the 3-D coordinates of these seven points, posture of the leg and foot is represented by the angle Θ_1-Inv (inversion angle) which is defined as inclination angle of projected line of a straight line to connect point ① and ② onto x-z plane. The other angle to represent the posture is Θ_2- plate (planter flexion) which is defined as inclination angle of projected line of a straight line to connect point ③ and ④ onto y-z plane.

In this experiment, the seven target marks are obtained from the reconstructed 3-D points model. Furthermore, the 3-D posture of the target person is obtained by using these target marks position in the world coordinates.

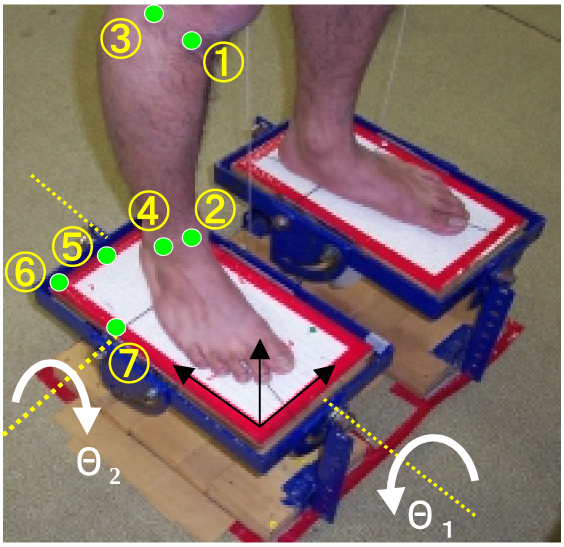

Fig.4 Target marks on the leg and table

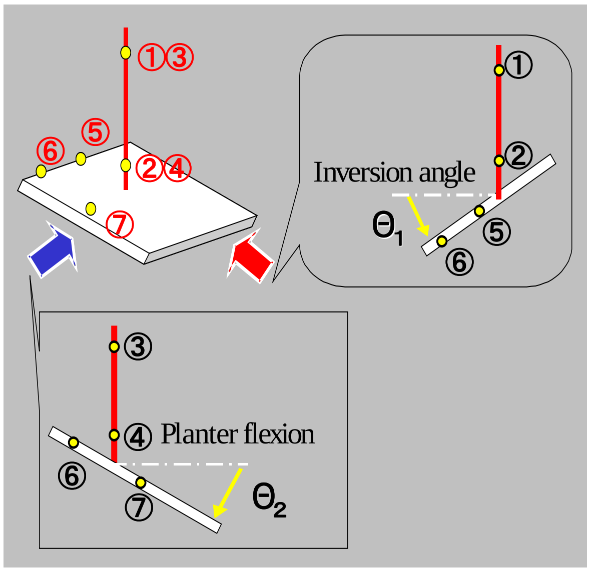

Fig.5 Definition of parameters

5. EXPERIMENTS AND RESULTS

5.1 Experiments

In the experiment, two group of the subject are examined. Members of the first grout have experiences of ankle sprain at least twice in the last six months. And members of the second group have no such experiences. Both groups have four members. Target person is requested to stand on plate with his foot on an inclined table and the right foot on the other table. The inclination angle of the left table is settled to various specified values in advance. The right table had 2DOF as shown in Fig.1. The target person is requested to incline his right table to the inclination angle of the left table.

In Fig.6 and Fig.7 varying posture of the leg are shown. In Fig.8 and Fig.9 the reconstructed 3-D points models of the leg are represented.

To analyze the three-dimensional posture of the leg, we need to get three-dimensional coordinate of a mark in world coordinate. But, the mouse coordinate is a two-dimensional coordinate in a screen. Therefore, we are using the Depth-Buffer of the OpenGL to convert a world coordinate. The conversion procedure is performed as follows. First, we can get the 2D mouse coordinates in a screen by manual operator. Secondly, we can read the Depth-Buffer value in its coordinate. At the same time, we acquire the perspective matrix, the model view matrix and the view port matrix, which are set up to the CG hardware at present. Finally, using the mouse coordinate, the Depth-Buffer value and the inversed its matrix, the mouse coordinate in the world coordinates is calculated. In fact, it is a world coordinate of a target mark.

The 3-D coordinates of the target marks can be obtained by specifying the raster coordinates of the marks using the computer mouse operation. From these 3-D coordinates every posture parameters can be obtained by vector analysis.

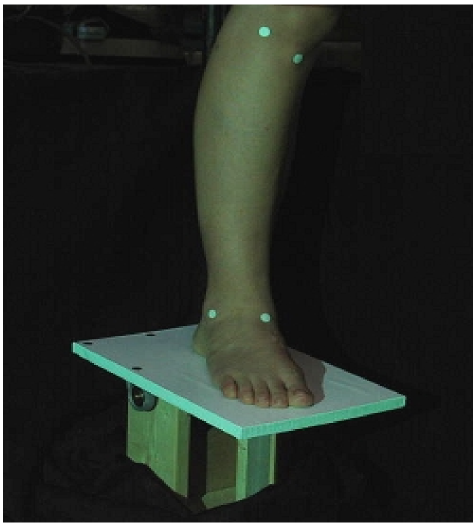

Fig.6 Initial posture of the leg

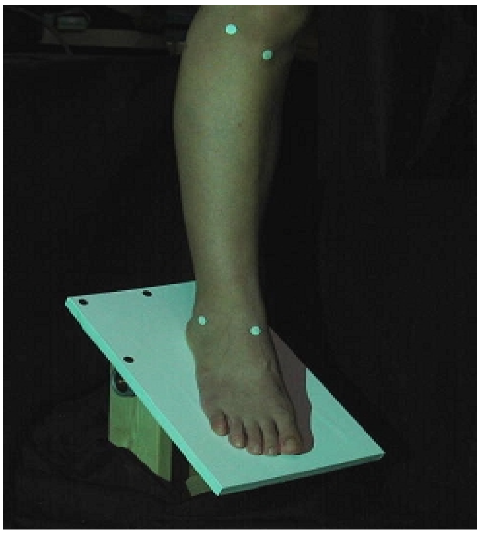

Fig.7 Rotated posture of the leg

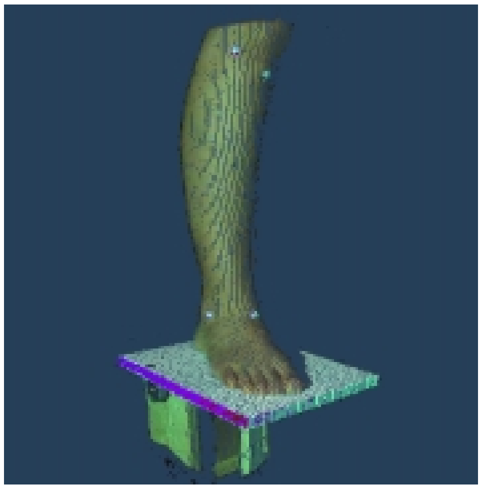

Fig.8 Reconstructed 3-D points model of the leg

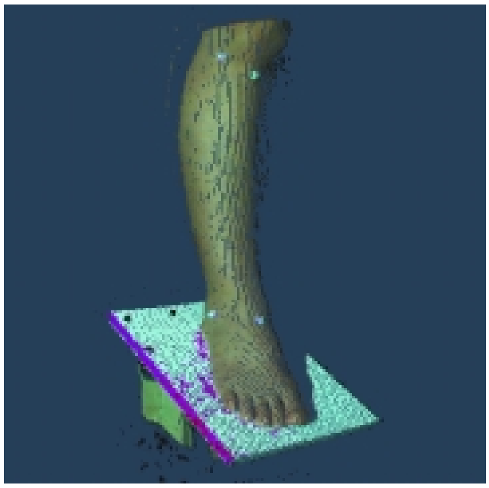

Fig.9 Another reconstructed 3-D points model of the leg

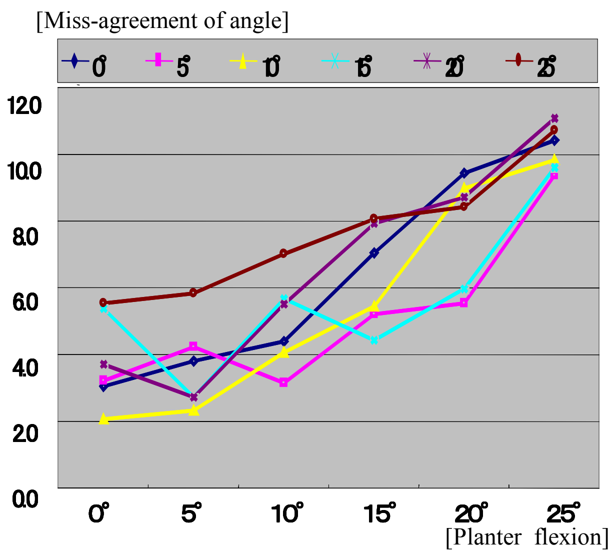

Fig.10 Result of the miss-agreement of the angle in the different inversion angle

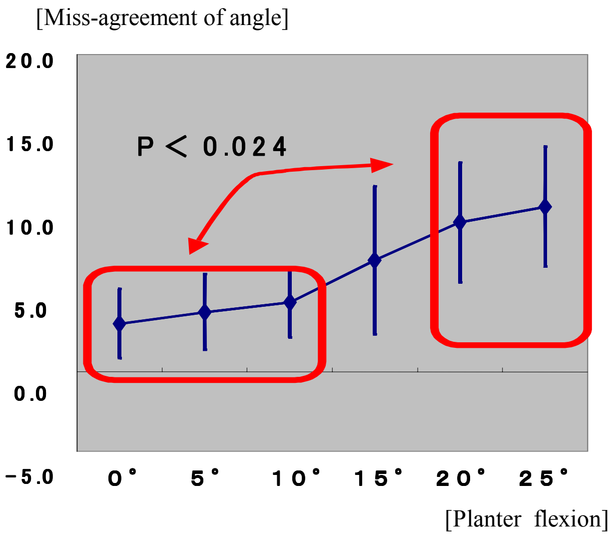

Fig.11 error range of the miss-agreement of the angle (Case of 0-degree inversion angle)

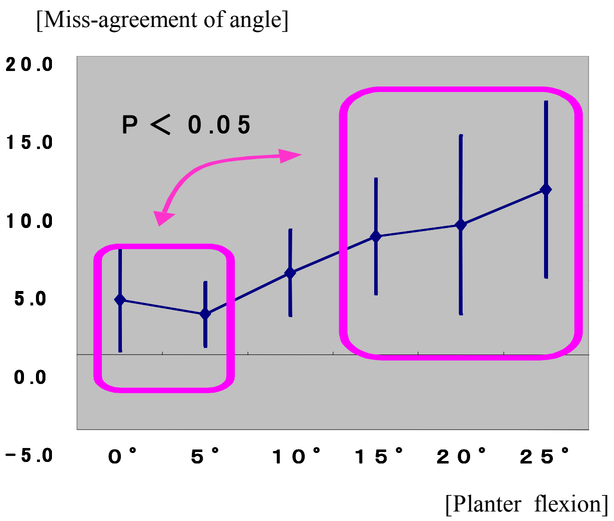

Fig.12 error range of the miss-agreement of the angle (Case of 20-degree inversion angle)

5.2 Results

In fig.10 the transformation relation between the planter flexion and miss-agreement of the angle in the different inversion angle is represented. In Fig.11 and Fig.12 the error range of the miss-agreement of the angle is shown.

In the experiment, two group of the subject are examined. One group is with the experience of ankle sprain, and another group is without the experience. As results, we understand group with experience of ankle sprain have wide miss-sensing between their both legs. This means if you have an experience of ankle sprain, your sense of ankle joint may have some deviations. From another experience to compare the group of the barefoot and wear shoes, the group wearing shoes have better sensing ability of the joint angle on their.

6. CONCLUSION

A technique to analyze functional instabilities of the ankle by using one digital still cameras and a LCD projector is proposed. Due to the high accuracy of the digital camera, accurate 3-D data of foots, legs and tables could be obtained. Analyzing the 3-D data, functional instability of the ankle could be discussed quantitatively. The technique presented can be readily applicable to other kinds of diagnosis of the legs and feet.

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