Proceedings of the 28th IEEE
EMBS Annual International Conference
New York City, USA, Aug 30-Sept 3, 2006

Development of Measuring System to Measure Standing Pose of the Foot Using Distributed Triaxial Force Sensor

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***Abstract*—The bottom of a person's foot grips the floor for balance, and the action force and action moment work at the foot bottom when he maintains posture and when he moves. They are important indices in the evaluation and the medical attention of standing pose balance and gait disturbances. A lot of equipment to measure the floor reaction force have been researched. However, no floor reaction force meter exists that can measure distribution information force in three directions. This paper aims at the development of a system that can measure the standing pose of the foot that exists from a measuring instrument and that can measure the standing pose of foot distributed 6×4 three axis force sensors and software that displays and preserves the output of the sensor element. A time change of force that worked at the foot bottom is sought as a vector by outputting each sensor element. Moreover, an action vector is three dimensionally displayed whose data can be intuitively understood. The results of experiments show that the measuring system can measure the action force of the foot bottom as distribution information on force in three directions.**

I. Introduction

Recently, we are becoming more and more interested in medical treatment and rehabilitation in an aging society. An evaluation function that uses the latest movement analysis system and applications are noticed in the fields of medical treatment and rehabilitation, especially the development of clinical walking analysis research for persons who have troubles walking in daily life and so on [1], [2].

The bottom of a person's foot grips the floor for balance, and the action force and action moment work at the foot bottom when he maintains posture and when he moves. They are important indices in the evaluation and the medical attention of standing pose balance and gait disturbances [3]–[6]. Therefore, it is necessary to measure force not only in the vertical direction but also in the shear direction and also to measure the distribution information of the force in the three directions that act on the foot bottom when the force that acts on the foot bottom is measured by pattern analysis, etc. A lot of equipment and techniques to measure the floor reaction force have been researched and reported. Some have already been commercialized and used in the fields of rehabilitation and sports engineering, etc. [7]–[9]. However, no floor reaction force meter exists that can measure distribution information force in three directions.

In our research, we propose an instrument that can measure the distribution information force in three directions that work at the foot bottom of the bearing area by concentrating on the interaction of the foot bottom and the floor when a person stands and exercises. It aims to develop a measuring system that can measure the standing pose on the foot distributed by 6×4 three axis force sensors and software that displays and preserves the output of the sensor element. Each sensor element can measure the acting normal and shear forces by performing mutual interference correction, though mutual interference exists in the output of the sensor element for the structure. A time change of the force at the foot bottom is needed as a vector by outputting each sensor element. Moreover, the action vector is three-dimensionally displayed whose data can be intuitively understood three dimensionally a using the DLL function that is built in OpenGL [10].

II. Outline of System that Can Measure the Standing Pose of the Foot

A system that can measure the standing pose of the foot is composed of a measuring instrument part that can measure the standing pose of the foot and a PC part. The measuring instrument is composed of sensors where 24 three axis force sensors are arranged. A PC has software installed that displays and preserves the output from the three axis force sensors.

A. An Instrument that Can Measure the Standing Pose of the Foot

Fig. 1 shows a general view chart of a instrument that can measure the standing pose of the foot. It is 300 mm×560 mm×150 mm, and the sensor unit where 24 (6×4) three axis force sensors are arranged is buried in the top view, as shown in Fig. 2. Each sensor element is sequentially numbered from the upper left to the lower right. The width of the sensor unit is large enough to covered by the toes. Moreover, a load meter is installed both in front and in back of the unit so that

Manuscript received April 3, 2006. This work was partly supported by the Innovative Cluster Creation Project promoted by MECSST.

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the sensor unit can display the normal component of force. It is possible to measure the action force on the foot bottom as distribution information force from three directions when a person gets on the sensor unit. Various feet positions can be measured. The amplifier board and an analog to digital conversion device is build into the measuring instrument, and a LAN sends output to a personal computer. The unit includes a fan, so feat is prevented from influencing it. Fig. 3 shows its composition chart.

Fig. 1. Measuring Instrument

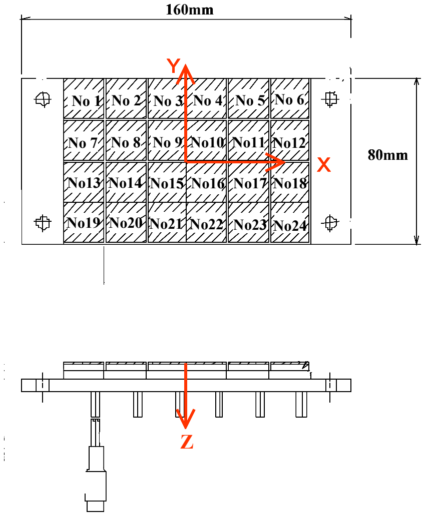

Fig. 2. Sensor Unit Measuring Instrument

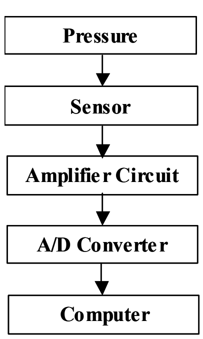

Fig. 3. Composition of Measuring Instrument

B. Triaxial Force Sensor

The shape of the three-axis force sensor that composes the measuring instrument is shown in Fig. 4, and its size is 20 mm×20 mm×5 mm. The three axis force sensor detects action force as electric resistance changes of the distortion gauge attached to the surface. The bridge circuit is united to the distortion gauge in each axis, and the action force is determined by measuring the differential motion voltage. Moreover, a pressure plate is fixed to the upper part of the sensor unit with screws, and rubber is glued to it. The Z axis action force is made to be a uniformly distributed load on the upper board.

The load rating of the three axis sense of the force sensor is the X, Y axis is ±250 [N], and the Z axis is 500 [N]. Under high-speed sampling frequency (400 kHz), and using a Data Recorder (DLR2000), we gave a light vibration to the top of the sensor head, and these characteristic frequencies obtain high values by the X and Y axes 700 [Hz] and the Z axis 3 [kHz]. Therefore, sensor vibration doesn't influence measurements.

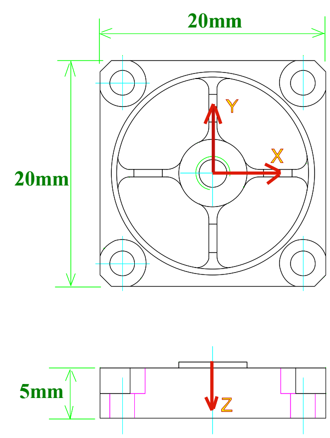

Fig. 4 Structure of Triaxial Force Sensor

C. Proofreading Method and Result of the Triaxial Force Sensor

1) Proofreading Method: Under three axis force action, we measure it to verify output value. The three direction force is given, as shown in Fig. 5, and each sensor element is put on the stand attached to the inclination, and the vertical load is put from the upper part. The vertical load, the direction of the sensor elements and the angle of gradient of the stand were changed and measured by various force combinations. And as a result, we found that the output of each sensor element caused an almost linear mutual interference in each axis for the action force. Then, the interference correction matrix shown in (1) is suggested.

$$\overline{\boldsymbol{F}} = \begin{pmatrix} \overline{F}_X \\ \overline{F}_Y \\ \overline{F}_Z \end{pmatrix} = \begin{pmatrix} a_{11} & -a_{12} & -a_{13} \\ -a_{21} & a_{22} & -a_{23} \\ -a_{31} & -a_{32} & a_{33} \end{pmatrix} \begin{pmatrix} F_X \\ F_Y \\ F_Z \end{pmatrix} = \boldsymbol{AF} \qquad (1)$$

Where $\boldsymbol{F}$ is a measurement value before correcting mutual interference, $\overline{\boldsymbol{F}}$ is a measurement value after correcting mutual interference, and A is transformation matrix. When the generalized inverse $\boldsymbol{F}^+$ of $\boldsymbol{F}$ is used, (2) is obtained from (1).

$$\boldsymbol{A} = \overline{\boldsymbol{F}}\boldsymbol{F}^+ \quad (2)$$

The direction of forces X, Y, and Z is a load and is removed from each sensor element, and transformation matrix $\boldsymbol{A}$ is obtained from (2), and mutual interference correction is done from the output at that time in (2).

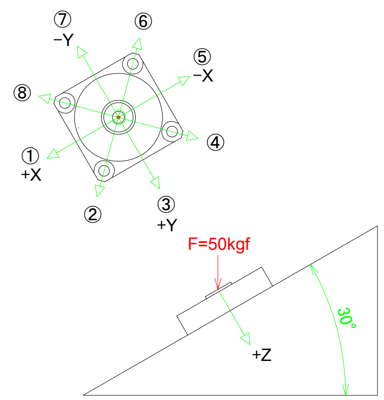

Fig. 5 Method of Experimenting on Proofreading

2) Proofreading Result: In this research, experiment results that was lower directions "1", "4" and "6", and an inclination corner 30 $^{\circ}$ were adopted as the calibration value that calculates the interference correction coefficient, as shown in Fig. 5 For example, TABLE I shows the output of the results of sensor element of No. 1 and direction "8" under mutual interference correction. Error that is the margin of the action force and a measurement value after correcting mutual interference is shown in TABLE I by percentage to load rating (X and Y axes ; ± 250 N, Z axis ; 500 N). Measurement value under mutual interference includes the nonlinearity and the hysteresis of the output value of the sensor element as error that cannot be corrected. Therefore, the accuracy of the sensor element became about 1% RO in the X and Y axes and about 3% RO in the Z axis. This value reflects good accuracy for the clinical engineering field.

TABLE I

PROOFREADING EXPERIMENT RESULTS

Load(N)	Component of Load (N)			Error(%RO)		
F	Fx	Fy	Fz	x	y	z
0.0	0.0	0.0	0.0	0.02	0.00	0.04
34.3	12.1	−12.1	29.7	0.03	0.04	0.15
230.5	81.5	−81.5	199.6	0.31	0.15	0.65
426.7	150.9	−150.9	369.6	0.66	0.16	0.94
490.5	173.4	−173.4	424.8	0.77	0.02	1.11
426.7	150.9	−150.9	369.6	0.58	0.03	1.08
230.5	81.5	−81.5	199.6	0.35	0.04	0.43
34.3	12.1	−12.1	29.7	0.13	0.08	0.14
0.0	0.0	0.0	0.0	0.10	0.09	0.06

D. Data Processing Software

The software developed in this research enabled output from a three axis force sensor to output to be preserved as a load. Moreover, the load was displayed as a 3D vector. We can see with a 360 $^{\circ}$ field of the vision if we change the point of the view by putting the bottom. Its details are described as follows:

Data from the measuring instrument is acquired by using the socket control of Microsoft Visual Basic, which also does the interference correction. It displays the data under the sampling time, updating the action force in the direction of three axes in 12 sensor elements: 72 channels of data. It displays the time change graph of the action force. The data of the action force can be preserved as csv files in arbitrary time. We made a Microsoft Visual C++ system including a DLL function, which is included in the Open GL. By using the picture box from the Visual Basic side, we can get display data as the vector of the action force in each sensor element and the vector of the action resultant force in a pressure center point of the sensor. How to get a pressure center point is shown in Section 3. By clicking on the box at the picture's bottom, we can enlarge or reduce, move left, right, up, or down data. We can see action force everywhere. Details are shown by the flow chart in Fig. 6. Moreover, the tool used for the program developed in this research is Visual Studio 6.0, and the OS is Windows 2000.

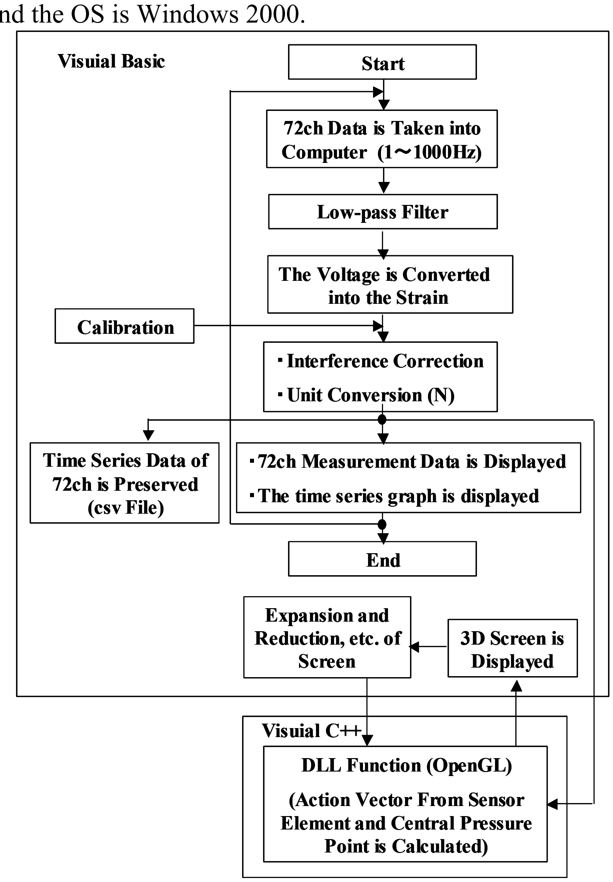

Fig. 6 Outline of Software

III. ALGORITHM

In this section, we indicate how to obtain the algorithm that can calculate the time change of the vector of the action force for each sensor element and the entire sensor unit.

A. Action Force of Sensor Source

The output of the sensor element of the measuring instrument is shown in (3), where n is 24 because this measuring instrument uses 24 sensor elements.

$$\boldsymbol{f}_i = {}^t\left(f_{xi} \quad f_{yi} \quad f_{zi}\right)\left(i = 1, \Lambda, n\right) \tag{3}$$

Moreover, change during that time is obtained (4) from (3).

$$\boldsymbol{f}_i(t) = {}^t\left(f_{xi}(t) \quad f_{yi}(t) \quad f_{zi}(t)\right)\left(i = 1, \Lambda, n\right) \tag{4}$$

The action force that works at the foot bottom can be measured as a time change in the output of each sensor element from (4).

B. Action Force of Sensor Unit

Now we calculate the action force obtained by the sensor as a central pressure point of the Z axis direction [11]. The action force that works in the entire sensor obtains (5) from (3).

$$F_x = \sum_{i=1}^{n} f_{xi},\ F_y = \sum_{i=1}^{n} f_{yi},\ F_z = \sum_{i=1}^{n} f_{zi} \tag{5}$$

Suppose that we define force moment vector $\boldsymbol{r}_i$ around the original point as a distance from the original point to each sensor unit, then we can obtain the value from (6).

$$\boldsymbol{M} = \sum_{i=1}^{n}\left(\boldsymbol{r}_i \times \boldsymbol{f}_i\right) = M_x\boldsymbol{i} + M_y\boldsymbol{j} + M_z\boldsymbol{k} \tag{6}$$

Next we define the pressure center point as

$$\left(x, y, z\right) = \left(X_G, Y_G, 0\right) \tag{7}$$

Using them, we calculate the center of the pressure moment around the point. A moment of force around a force center point becomes (8).

$$\begin{aligned}\boldsymbol{M}_G &= M_x\boldsymbol{i} + M_y\boldsymbol{j} + M_z\boldsymbol{k} \\ &- \left\{Y_G F_z\boldsymbol{i} - X_G F_z\boldsymbol{j} + \left(X_G F_y - Y_G F_x\right)\boldsymbol{k}\right\}\end{aligned} \tag{8}$$

Where the X and Y axes elements of $\boldsymbol{M}_G$ become zero, and the position of a force center point is obtained from (9).

$$\left(x, y, z\right) = \left(-\frac{M_y}{F_z}, \frac{M_x}{F_z}, 0\right) \tag{9}$$

If we regard the vector as a time change vector from (5) and (9), the time change in the action force that works in the entire sensor can be a vector.

IV. EXPERIMENT

Now we show the measuring system can measure the action force of the foot bottom as distribution information on force in three directions. This is verified by experiments.

In experimental conditions, the tester was one person: standard proportioned man in his twenties, sampling frequency was 50Hz, and low-pass filter was 5Hz. Experiment method are described as follows:

First, the right leg is put on the sensor unit of the measuring instrument, and the left leg is put on the stand. Second, we set the standard position that crosses the base of the big toe of the right leg with the sensor elements of position No.8, 9, 14, and 15. We set the foot if we have on opening 15 cm wide and see the front. Third, the hands are crossed over the chest and fixed. This state is posture 1. Fig. 7 shows posture 1. All weight is slowly moved to the right leg after posture 1. Next the left leg is affixed, we define the state as posture 2, which is maintained, and is then changed to standing on tiptoes. Finally the state is posture 3 and is maintained. The movement between each posture is measured for 3 seconds for a total of 15 seconds.

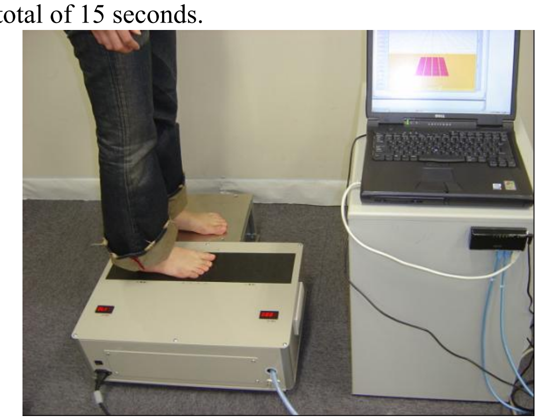

Fig. 7 Experiment Scenery

V. EXPERIMENT RESULTS AND CONSIDERATIONS

The measurement values in postures 1, 2, and 3 are indicated in Figs. 8, 9, and 10, respectively. Action Force [N] in the sensor elements such as No 1X, Y, Z, No 2X, Y, and Z ….. is shown in order from the left interior of the figures right front side. Moreover, the coordinates [mm] of the force center point in postures 1, 2, and 3 were (-6.2, -13.6), (-9.1, -8.8), and (-2.3, -8.3), respectively.

It was founded that not only the force in the Z direction but also in the X and Y directions grow as posture 1, 2 and 3 advanced from this figures. And the movement of a force center point was confirmed. Fig.11 is a close-up Fig.10. When the Y direction of No.3, 9, 15 and 21was paid attention, it was founded that the foot balanced like gripping the ground. This was understood because action force of the foot bottom is measured as distribution information on force in three directions. Therefore, It was shown that the measuring system can measure it that have been never measured the action force of the foot bottom as distribution information on force in three directions.

Moreover, Fig. 12 is a 3D screen of posture 3 that show the vectors of force. The green line is the force center point of the sensor, and the blue line is the force of each sensor element. We can make develop mental software can be easily understood in the sight from the figure.

VI. Conclusion

Our conclusion is as follows:

1) A three axis force sensor used for a measuring system, which can measure the standing pose of the foot, that was made for trial purposes in this research can measure vertical and shear forces by doing mutual interference correction.
2) It was shown that the measuring system can measure the action force of the foot bottom as distribution information on force in three directions.
3) Our proposed measuring system could get the action force that worked at the foot bottom as visualization by using Open GL by using a three-dimensional graph that we can understood easily by sight as a vector.

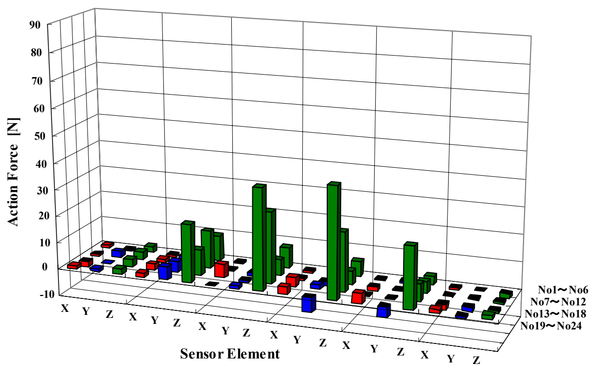

Fig. 8 Experiment Result of Posture 1

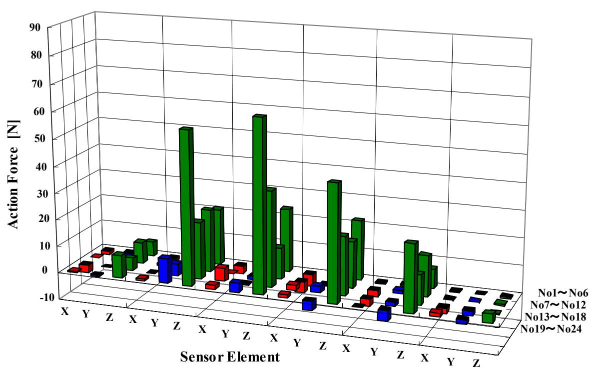

Fig. 9 Experiment Result of Posture 2

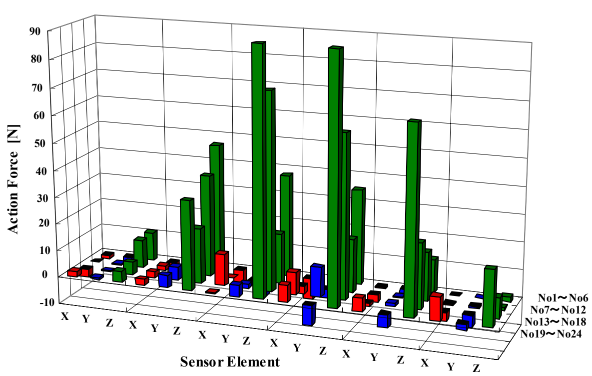

Fig. 10 Experiment Result of Posture 3

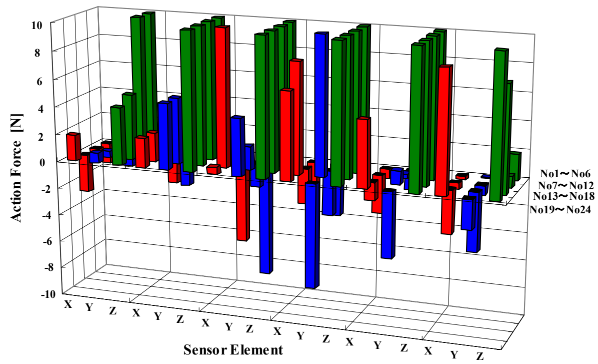

Fig. 11 Experiment Result of Posture 3 (Expansion)

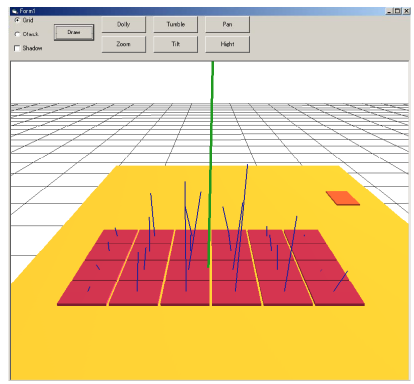

Fig. 12 3D Screen of Vector

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