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Calculation of Joint Reaction Force and Joint Moments Using by Wearable Walking Analysis System

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Abstract— **In gait analysis, which is one useful method for efficient physical rehabilitation, the ground reaction force, the center of pressure, and the body orientation data are measured during walking. In the past, these data were measured by a 3D motion analysis system consisting of high-speed cameras and force plates, which must be installed in the floor. However, a conventional 3D motion analysis system can measure the ground reaction force and the center of pressure just on force plates during a few steps. In addition, the subjects' stride lengths are limited because they have to walk on the center of the force plate. These problems can be resolved by converting conventional devices into wearable devices. We used a measuring device consisting of portable force plates and motion sensors.**

We developed a walking analysis system that calculates the ground reaction force, the center of pressure, and the body orientations and measured a walking subject to estimate this system. We simultaneously used a conventional 3D motion analysis system to compare with our development system and showed its validity for measurements of ground reaction force and the center of pressure. Moreover we calculated joint reactions and joint moment of each joint.

I. Introduction

The importance of rehabilitation in the treatment for walking disorders due to such illnesses as strokes continues to increase [1]-[2]. When a physical therapist instructs a patient during rehabilitation, information about the joint moment in the lower limbs is very useful [3]-[4]. Conventionally, the joint moments of lower limbs are calculated by reverse dynamics applied to data obtained from a force plate and a 3D motion analysis system (high-speed cameras). However, because these analysis devices must be installed in experimental facilities, their use conditions and measurable amount of steps are limited. If multiple force plates are installed, a large space and great expense are necessary, and the possibility is very low. In addition, the locations of the force plates do not match the steps of all people. A method to resolve those problems can be converting force plates and the 3D motion analysis system into wearable devices. In motion analysis, a wearable motion sensor is used that consists of acceleration, gyro, and geomagnetism sensors, but the wearable force plate is not put to practical use. An analogous device, which is inserted in footwear and measures pressure distribution, is commercially available and is suitable for the qualitative evaluation of pressure distribution. But maintaining the precision of a force plate is difficult, because the time variation of the output and quantitative precision is insufficient. In addition, this force plate only measures force vertically.

Based on the above situation, we developed a wearable walking analysis system called the "M3D system" [5] (mobile force plate and 3D motion analysis system) that consists of a small, portable force plate and a motion sensor consisting of acceleration, gyro, and geomagnetism sensors. The M3D system is more economical and has fewer constraints. In walking experiments, ground reaction force, pressure distribution, and limb postures are calculated by the outputs of mobile force plates and motion sensors.

In this research, we focused on the ground reaction force and the center of pressure. We measured different kinds of walking experiments to evaluate our M3D system and simultaneously used a conventional 3D motion analysis system for comparison. Moreover we calculated joint reactions and joint moment of each joint. As a result, the validity of our M3D system for analysis of walking was demonstrated.

II. M3D System

A. Constitution of M3D System

First, we explain the constitution of the M3D system (Fig.1).

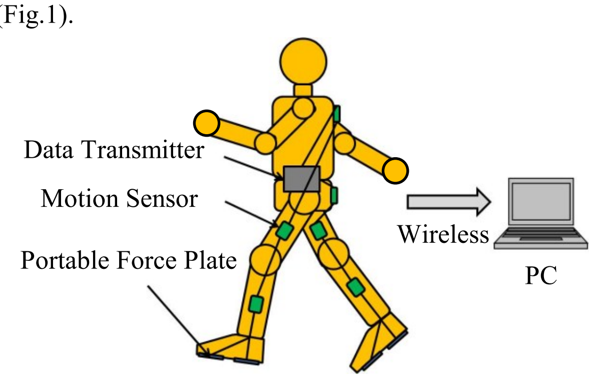

Fig. 1 Constitution of M3D System

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The M3D system consists of six motion sensors (called "M3D-MS"), four mobile force plates ("M3D-FP"), and a data transmitter ("M3D-DT"). The specifications and dimensions of these are shown in Table 1 and Table 2.

TABLE I SPECIFICATION OF SENSORS

Sensor	Rated Value	Nonlinearity	Responsive
Force	XY: ±250 (N), Z: ±500 (N)	±1 (%FS)	±2 (kHz)
Acceleration	±19.6 (m/s^2)	±0.5 (%FS)	±2 (kHz)
Gyro	±1200 (deg/s)	±1 (%FS)	±140 (Hz)
Geomagnetism	±70000 (nT)	±0.1 (%FS)	±10 (kHz)

TABLE II DIMENSION OF M3D COMPONENTS

Component	Width (mm)	Depth (mm)	Height (mm)	Weight (g)
M3D-MS	35	50	10.5	16.5
M3D-FP	88	82	6	135
M3D-DT	145	100	40	565

Fig. 2, 3, and 4 show the M3D-MS, M3D-FP, and M3D-DT sensors. Since they are small and lightweight, the subjects only receive a light strain.

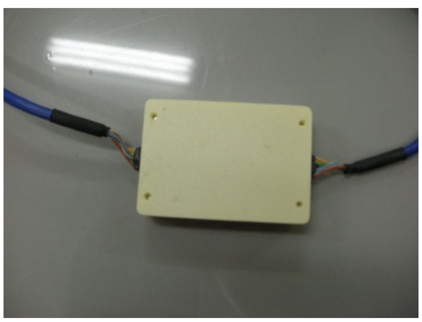

Fig. 2 Motion Sensor (M3D-MS)

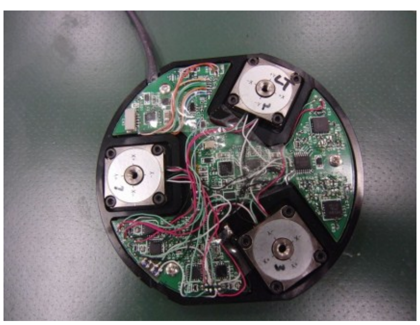

Fig. 3 Portable Force Plate (M3D-MS)

Fig. 4 Data Transmitter (M3D-DT)

M3D-MS consists of a built-in three-axis acceleration sensor (LIS331DLH: STM), a three-axis gyro sensor (two-axis gyro sensor: LPR530AL and one-axis gyro sensor: LY530ALH: STM), and a three-axis geomagnetism sensor (HMC5843: Honeywell). In motion measurement, six M3D-MSs are fixed (Fig. 1) and measure the kinematics of the lower limbs and the trunk. M3D-FP has two force plates. A force plate includes three force sensors. This force sensor is a thin three-axis force sensor (USL06-H5-500N-C: TEC Gihan). M3D-FP can measure the foot kinematics because it also has an acceleration sensor, a gyro sensor, and a geomagnetism sensor like M3D-MS.

The data measured by M3D-MS and M3D-FP are transferred to PC via M3D-DT and recorded on PC. We calculated the ground reaction force and center of pressure during experiments using the recorded data.

B. *Definition of Coordinate System*

Hereafter, "S", when written as a subscript to the upper left, means the sensor coordinate system, and "G" means the global coordinate system. Both coordinate systems are right-handed coordinate systems. The positive direction of the rotation of each axis is clockwise.

We define a sensor coordinate system comprised of ${}^{S}X$, ${}^{S}Y$, and ${}^{S}Z$ in a M3D-FP (Fig. 5.) Two M3D-FPs are used in a one-sided foot. We identify the origin of the total force coordinate system in a one-sided foot with the origin of the sensor coordinate system in the heel-side M3D-FP (Fig. 6).

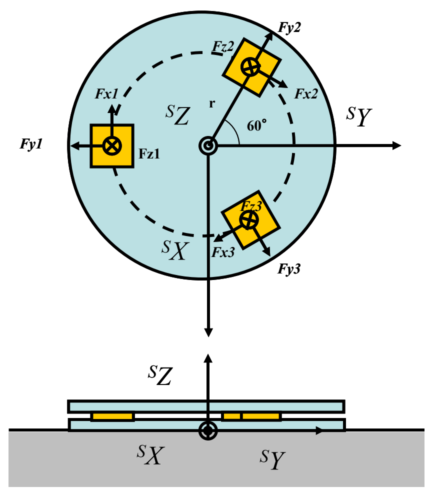

Fig. 5 Sensor Coordinate System of a M3D-FP

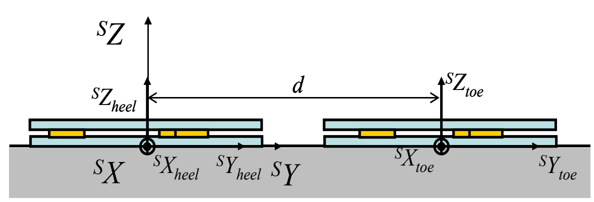

Fig. 6 Definition of Total Force coordinate system

In a one-sided foot, we express the following: ground reaction force (${}^{S}\mathbf{F}$), moment (${}^{S}\mathbf{M}$), and center of pressure (${}^{S}\mathbf{Cop}$) [6]-[7]:

$$ {}^{S}\mathbf{F} = \begin{bmatrix} {}^{S}FX_{toe} + {}^{S}FX_{heel} \\ {}^{S}FY_{toe} + {}^{S}FX_{heel} \\ {}^{S}FZ_{toe} + {}^{S}FX_{heel} \end{bmatrix} . \quad (1) $$

$$ {}^{S}\mathbf{M} = \begin{bmatrix} {}^{S}MX_{toe} + {}^{S}MX_{heel} + {}^{S}FZ_{toe}\,d \\ {}^{S}MY_{toe} + {}^{S}MY_{heel} \\ {}^{S}MZ_{toe} + {}^{S}MZ_{heel} + {}^{S}FX_{toe}\,d \end{bmatrix} \quad (2) $$

$$ {}^{S}\mathbf{Cop} = \begin{bmatrix} -{}^{S}MY / {}^{S}FZ \\ {}^{S}MX / {}^{S}FZ \\ 0 \end{bmatrix} \quad (3) $$

Here, d: [m] is the distance between the centers of two M3D-FPs.

III. Verification Experiment

A. Experimental Setup

To evaluate our M3D system, we conducted two kinds of walking experiments. At the same time, we used a MAC3D system (Motion Analysis Corp.) and compared it with our development system that consisted of ten infrared cameras (Eagle Digital Camera: Motion Analysis) and two force plates (BP400600: AMTI) installed in our experimental facility. Fig. 7 shows the composition of the measurement instruments in our experiments. We synchronized the M3D system and the 3D motion analysis system. The sampling rate was 500 Hz in both systems.

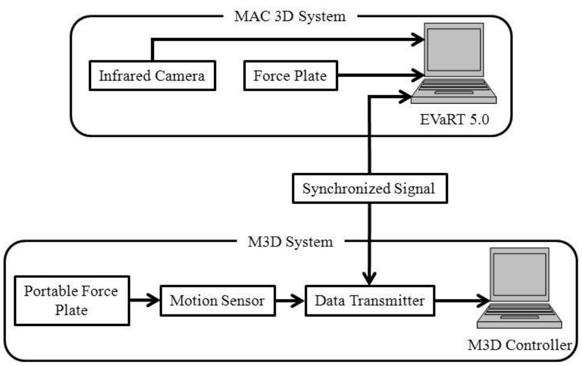

Fig. 7 Experimental Setup

B. Experiment Procedure

One healthy 23-year-old male subject who weighed 62kg and was 170 cm tall participated in walking straight experiment as shown below.

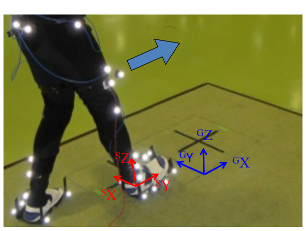

Fig. 8 Conditions

IV. Experiment Result

A. Ground Reaction Force

For comparison, since the result of the ground reaction force is expressed by a global coordinate system, the M3D-FP output is obtained by a coordinate transformation in its vertical axis circumference. The outputs are expressed as follows:

$$ \begin{pmatrix} {}^{G}FX \\ {}^{G}FY \\ {}^{G}FZ \end{pmatrix} = \mathbf{E}_{Z\,toe} \begin{pmatrix} {}^{S}FX_{toe} \\ {}^{S}FY_{toe} \\ {}^{S}FZ_{toe} \end{pmatrix} + \mathbf{E}_{Z\,heel} \begin{pmatrix} {}^{S}FX_{heel} \\ {}^{S}FY_{heel} \\ {}^{S}FZ_{heel} \end{pmatrix} . \quad (4) $$

Here, rotation matrix $\mathbf{E_Z}$ is calculated by the coordinates of the infrared markers that are attached to M3D-FP. $\mathbf{E_Z}$ is expressed as follows:

$$ \mathbf{E_Z} = \begin{bmatrix} \cos {}^{G}\theta_Z & -\sin {}^{G}\theta_Z & 0 \\ \sin {}^{G}\theta_Z & \cos {}^{G}\theta_Z & 0 \\ 0 & 0 & 1 \end{bmatrix} . \quad (5) $$

The ground reaction force is shown in Fig. 9. Here, we show the right foot. The errors between M3D-FP and the mounted force plate are less than 1.3% in all axis directions.

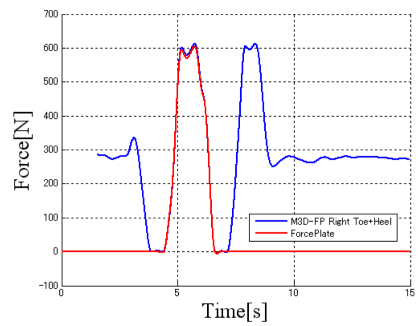

Fig. 9 Ground Reaction Force: Right Foot

B. Center of Pressure

Likewise, the ground reaction force is shown in Fig. 9. The errors between the two are less than 4.6%

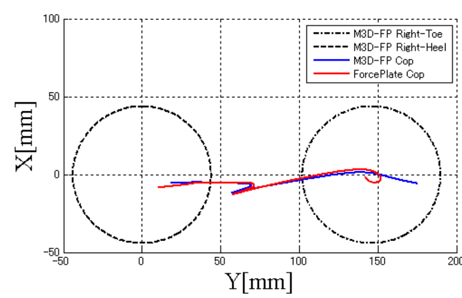

Fig. 10 Center of Pressure: Right Foot

V. Joint Reaction and Joint Moment

We calculated joint reaction forces and joint moment of ankle, knee and hip joint using by the M3D system data of the COP, lower limb posture and ground reaction force.

A. Joint Reaction

The joint reaction of ankle is as shown Fig. 11. Here this figure shows as ankle of left leg. This result is obtained by solving Eq. (6), (7). Here, m_{LF} is mass of foot, ${}^{G}\ddot{X}_{LF}$ is acceleration of foot and g is acceleration of gravity.

$$JRX_{L\_Ankle} = {}^{G}FX - m_{LF}\,{}^{G}\ddot{X}_{LF} \quad (6)$$

$$JRZ_{L\_Ankle} = {}^{G}FZ - m_{LF}\,{}^{G}\ddot{X}_{LF} - m_{LF}\cdot g \quad (7)$$

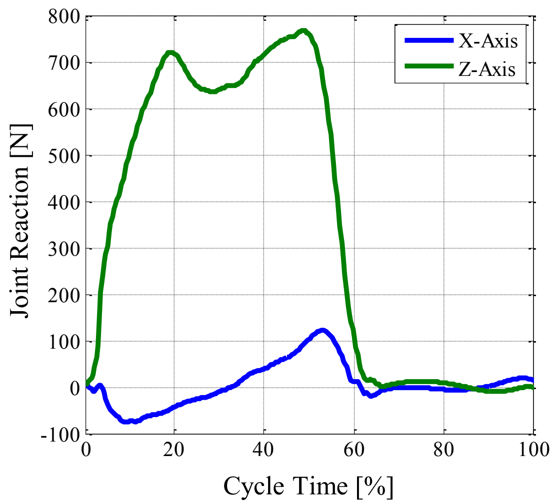

Fig. 11 Joint Reaction of Left Ankle

It can be seen that this result is qualitatively similar to typical pattern of joint reaction of walking.

B. Joint Moment

Likewise, we calculated each of joint moment. Here, we show about left ankle. The joint moment of ankle is calculated by following equation. Here, I_f is inertia moment of foot, $\ddot{\theta}_f$ is angular acceleration of foot and L_{AC} is length between ankle and position of COP.

$$JM_{LA} = I_f\cdot\ddot{\theta}_f + {}^{G}FX\cdot L_{AC\,Z} + {}^{G}FZ\cdot L_{AC\,X} - m_{LF}\cdot g \quad (8)$$

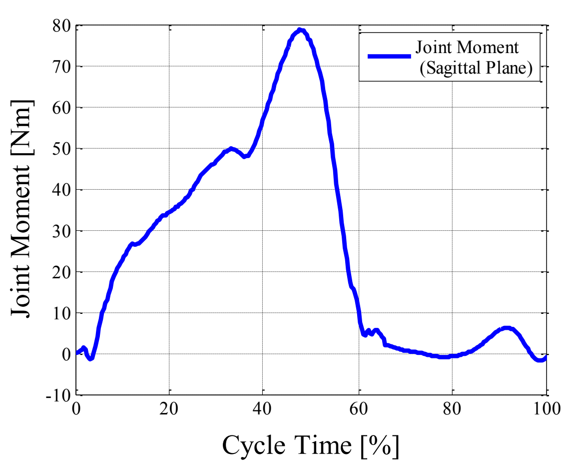

Fig. 12 Joint Moment of Left Ankle

As with the joint reaction, above result is similar to typical pattern of joint moment of walking.

These results indicate that joint reaction and joint moment are calculated by using the M3D system.

VI. Conclusion

In this research, we developed an M3D system, which is a walking analysis system that consists of mobile force plates and motion sensors. We conducted two experiments to compare our M3D system with a conventional 3D motion analysis system for evaluation. Moreover we calculated joint reactions and joint moment of each joint. Based on this research, we obtained the following conclusions:

1) Our walking analysis system: M3D system can measure the ground reaction force and the center of pressure in a sufficiently small error compared to the conventional system.
2) Using by M3D system, the joint reactions and joint moments are obtained by calculated. These results are qualitatively similar to typical patterns.

Conclusions were obtained by such as those, in the future we will perform walking analysis in earnest.

Acknowledgment

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References

[1] M. C. Cramp, R. J. Greenwood, M. Gill, A. Lehmann, J.C. Rothwell, O. M. Scott, "Effectiveness of a community-based low intensity exercise programme for ambulatory stroke survivors," *Disability and Rehabilitation*, 32(3), pp. 239-247, 2010.

[2] A. Srivastava, A. B. Taly, A. Gupta, S. Kumar, and T. Murali, "Post-stroke balance training: Role of force platform with visual feedback technique," *J. Neurol. Sci.*, 287(1-2), pp. 89-93, 2009.

[3] J. Z. Wu, S. S. Chiou, and C.S. Pan, "Analysis of musculoskeletal loadings in lower limbs during stilts walking in occupational activity," *Ann. Biomed. Eng.*, 37(6), pp. 1177-1189, 2009.

[4] Y. C. Lin, J. P. Walter, S. A. Banks, M. G. Pandy, and B. J. Fregly, "Simultaneous prediction of muscle and contact forces in the knee during gait," *J. Biomech.*, Article in Press, 2009.

[5] T. Liu, Y. Inoue, K. Shibata, Y. Hirota, and K. Shiojima," A Mobile Force Plate System and Its Application to Quantitative Evaluation of Normal and Pathological Gait," *2010 IEEE/ASME Int. Conf. Advanced Intelligent Mechatronics (AIM)*, pp. 272-277, 2010

[6] Peter H. Veltink, Christian Liedtke, Ed Droog, Herman van der Kooij, "Ambulatory Measurement of Ground Reaction Forces," *IEEE Trans. Neural Syst. Rehabi. Eng.*, Vol. 13, No. 3, pp. 423-427, 2005.

[7] Peter H. Veltink, H. Martin Schepers, and H. F. J. M. Koopman, "Ambulatory Assessment of Ankle and Foot Dynamics," *IEEE Trans. Biomed. Eng.*, Vol. 54, No. 5, pp. 895-902, 2007.