A Mobile Force Plate System and Its Application to Quantitative Evaluation of Normal and Pathological Gait

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Abstract— In clinical applications, the quantitative analysis of gait variability using kinematic and kinetic characterizations can be helpful to medical doctors in monitoring patient recovery status. A high-speed camera system and a stationary force plate can only accurately measure complete ground reaction force (GRF) and body orientations during a few steps, but data on successive gait measurements including three-dimensional (3D) force and motion in different environments is really desired by clinical researchers and doctors. We have developed a mobile force plate and 3D motion analysis system (M3D) by integrating small triaxial force sensors and 3D inertial sensors for estimating multi-axial GRF and orientations of feet during successive gait movements. In order to verify the measurements of the developed system, we used a stationary force plate as a reference measurement system to simultaneously measure the triaxial GRF and center of pressure (CoP) when a subject was required to wear the M3D. Static and dynamic test experiments were implemented to validate the triaxial force measurement of the M3D. Experimental results verify that the developed system can be used to measure the triaxial force with acceptable precision (error: less than 6.4% of maximum measurement force). An application trial was carried out to analyze normal gait and paralysis gait using the M3D. Quantitative differences between gaits were analyzed, based on the results of the vertical component of GRF and medial-lateral directional angular flexions of the feet.

I. INTRODUCTION

Rehabilitation training for stroke survivors is important for restoring their life skills including walking, standing up, and so on. It should be helpful if the patient's dynamic balance ability and walking stability could be quantitatively evaluated, so as to implement and motivate effective training [1]-[2]. In order to analyze human gait at the level of human motor control, the muscular activity of the lower limbs which has been estimated from measurements of joint moments and segment orientations may be useful information for biomedical applications [3]-[4]. The method is based on combining high-speed cameras for three-dimensional orientation measurement with stationary force plates for ground reaction force (GRF) measurement and has been widely used for the estimation of lower limb joint movements in laboratory environments [5]-[6]. However,

these commonly used devices for human dynamics analysis require lots of space, special operators, expensive instruments and complex calibration settings; moreover, the range of measurement is limited to capturing a few strides in a gait laboratory. The main shortcomings restrict the application of these stationary devices to experimental research and it is difficult to find applications of gait evaluation in the daily environment or clinic. As an alternative to these conventional techniques, an inexpensive and easy to use mobile measurement system which can accurately estimate triaxial GRF and three-dimensional (3D) body orientations is really desired by researchers of human dynamics analysis in non-laboratory conditions.

By mounting multi-axial force sensors beneath a special shoe, some researchers have developed instrumented shoes for ambulatory measurements of triaxial GRF in a variety of non-laboratory environments, for example Chateau et al. applied an instrumented shoe fixed under a horse's hoof to GRF measurement on a track [7]. However, the sensor system based on a commercial multi-axial force sensor which has a height of 15.7mm not including the mounting frames [8], must increase the height and weight of the shoe, and probably affects natural gait. Therefore, the first problem to be solved in our research is to make a lightweight and thin mobile force plate which can implement ambulatory triaxial GRF measurements on a variety of subjects, and has less influence on their normal gait.

Recently, some inexpensive in-chip inertial sensors including gyroscopes and accelerometers have been gradually coming into practical application in human motion analysis. To expand the scope of application of a mobile force plate system, a small 3D inertial sensor module can be integrated into the force plate. Liedtke et al. proposed a combination sensor system including six degrees of freedom force and moment sensors and miniature inertial sensors (provided by Xsens Motion Technologies) to estimate the joint moments and powers of the ankle [9]. If 3D orientations of the foot are obtained and integrated with measured triaxial GRF during gait, an inverse dynamic method can be used to implement joint dynamics analysis of the lower limb [10].

We are presently concentrating on the development of some wearable sensors to measure human GRF and segment orientations during gait. A multi-axial force sensor has been developed to measure triaxial GRF and the coordinates of the center of pressure, when fixed under a specially designed shoe [11]. However, its hard interface and the weight load on the foot affected normal walking according to our

experimental tests. A thin and light force plate based on 3D tactile sensors and using lower-cost materials was proposed in our past research [12], and a sensor matrix will be constructed to directly perform triaxial GRF measurements. Moreover, in order to quantify human movements, we have developed some wearable sensor modules using gyroscopes and accelerometers for ambulatory measurements of human segment orientations [13]. In this paper, a mobile force plate and 3D motion analysis system (M3D) is introduced. 3D inertial sensor modules which were designed using lower cost inertial sensors including a triaxial accelerometer and gyroscope were integrated into a newly developed force plate. Verification experiments were conducted to compare the estimation results of M3D with measurements performed on a stationary force plate. Finally, an application experiment is introduced to quantify and evaluate human gait. We measured the 3D GRF and orientations of feet using M3D to evaluate paralysis gait

II. METHODS AND MATERIALS

A. Mechanical Design of Mobile Force Plate

Small triaxial force sensors (USL06-H5-500N) provided by Tec Gihan Co. Japan can only detect the three-directional force induced on a small circular plate (Φ 6 mm), see Table I, so it is difficult to apply directly to the measurement of the GRF distributed under a foot. As shown in Fig. 1 (a), a mobile force plate (weight: 156g, size: $80\times80\times15\text{mm}^3$) was constructed using three small triaxial force sensors, in which two aluminum plates were used as top and bottom plates to accurately fix the three sensors. Each small sensor, when calibrated using data provided by the manufacturer, can measure triaxial forces relative to their slave coordinate systems ($\sum s_i$) defined on the center of each sensor, where subscript i represents the number of the small sensor in every force plate (i = 1, 2, and 3). The GRF and center of pressure (CoP) measured using the force plate so developed could be expressed in the force plate coordinate system ($\sum_f$) which is located at the interface between the force plate and the ground, with the origin of the force plate coordinate system taken as the center of the force plate (see Fig. 1 (b)). The y-axis of the force plate coordinate system was chosen to represent the anterior-posterior direction of human movement on the bottom plate, and the z-axis was made vertical, while the x-axis was chosen such that the resulting force plate coordinate system would be right-handed. We aligned the y-axis of each sensor's slave coordinate to the origin of the force plate coordinate system, while the three origins of the slave coordinates were evenly distributed on the same circle (radius: r = 30 mm), and were fixed 120° apart from each other. Fx_i, Fy_i and Fz_i were defined as the triaxial forces measured using the three triaxial sensors. The triaxial GRF and coordinates of the CoP could be calculated from the following equations:

$$Fx = (Fx_1 + Fx_3)\cdot\cos(60°) - Fx_2 - (Fy_3 - Fy_1)\cdot\cos(30°) \quad (1)$$

$$Fy = (Fy_1 + Fy_3)\cdot\cos(60°) - Fy_2 - (Fx_1 - Fx_3)\cdot\cos(30°) \quad (2)$$

$$Fz = Fz_1 + Fz_2 + Fz_3 \quad (3)$$

$$Mx = Fz_2\cdot r - (Fz_1 + Fz_3)\cdot\sin(30°)\cdot r \quad (4)$$

$$My = (Fz_1 - Fz_3)\cdot\cos(30°)\cdot r \quad (5)$$

$$Mz = (Fx_1 + Fx_2 + Fx_3)\cdot r \quad (6)$$

$$x_{COP} = My / Fz \quad (7)$$

$$y_{COP} = Mx / Fz \quad (8)$$

$$z_{COP} = 0 \quad (9)$$

where Fx, Fy and Fz are defined as the triaxial GRF (F_{GRF}) measured using the force plate in the force plate coordinate system, and Mx, My and Mz indicate triaxial moments estimated from measurements of the three sensors, while x_{COP}, y_{COP} and z_{COP} are the coordinates of the CoP,

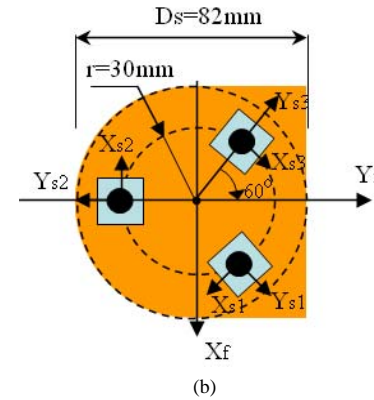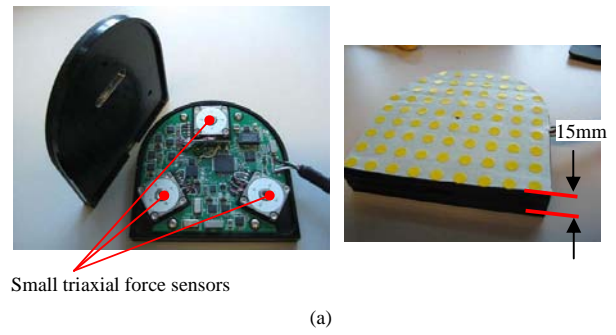Small triaxial force sensors

(a)

(b)

Fig. 1 (a) Prototype of a mobile force plate, (b) Coordinate systems of the force plate.

TABLE I MAIN SPECIFICATIONS OF THE SMALL TRIAXIAL FORCE SENSOR USED FOR THE MOBILE FORCE PLATE.

Type		USL06-H5-500N
Rated Capacity (N)	X- and Y- axis	250
	Z-axis	500
Rated Capacity (με)	X- and Y- axis	900
	Z-axis	1700
Nonlinearity (After calibration of cross effect)		Within 1.0%
Hysteresis (After calibration of cross effect)		Within 1.0%
Size (mm)		$20\times20\times5$
Weight (g)		15

In order to examine the inside force distribution of the mobile force plate, ANSYS FEA software was used to perform a static analysis and to simulate the effects of multi-axial forces which may be distributed over the three contact points of the small sensors on the top aluminum plate.

Fig. 2 shows the finite element mesh and a representative result of the deformation of the top plate which is attached to the small sensors using three M3 screws. When we load the top plate with a z-axial force $Fz = 733.57$ N (vertical pressure: 0.125 MPa) and y-axial force $Fy = 263.5$ N (spread over 527 nodes), and x-axial force $Fx = 263.5$ N (spread over 527 nodes), the induced three-directional forces on the small sensor can be calculated by the finite element method and the results are given in Table II. The maximum force (274.6 N) on the z-axis of the three sensors, and the maximum x- and y-axis forces of 136.61 N never exceed the measurement capacity of the small sensor.
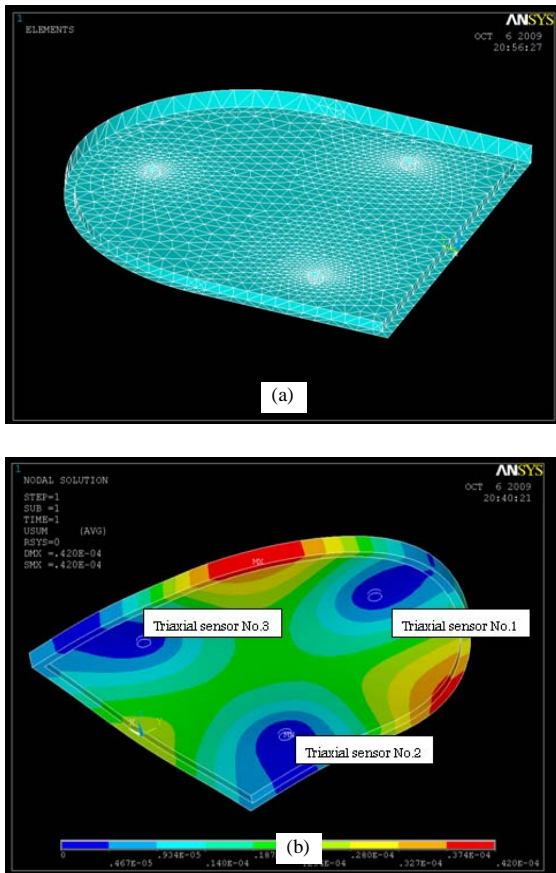

(a)

(b)

Fig. 2 (a) Finite element mesh, (b) Results of deformation plot.

TABLE II THREE-DIRECTIONAL FORCES ON THE SMALL SENSOR WHEN WE LOAD THE FORCE PLATE BY FZ= 733.57N, FY=263.5N AND FX=263.5N.

No.	Triaxial Forces (N)		
	X	Y	Z
1	89.48	136.61	274.6
2	59.19	69.03	219.7
3	114.83	58.16	239.27

B. Estimation of 3D Orientation

As shown in Fig. 3, we constructed a 3D motion sensor module composed of a triaxial accelerometer (MMA7260Q, supplied by Sunhayato Co.) and three uniaxial gyroscopes (ENC-03R, supplied by Murata Co.) on the PCB board inside the mobile force plate. The module can measure triaxial accelerations and angular velocities which can be used to estimate a 3D orientation transformation matrix, so we can implement ambulatory GRF and CoP measurements using the combined system of mobile force plate and 3D motion analysis system (M3D).

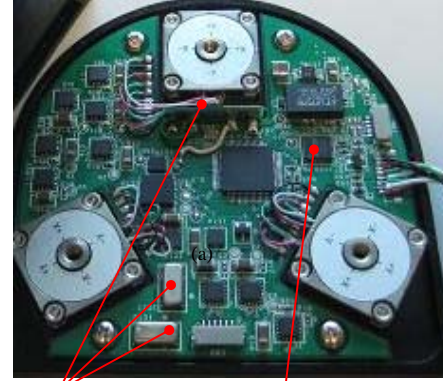Three uniaxial gyroscopes   Triaxial accelerometer

Fig. 3 3D motion sensor module constructed using three uniaxial gyroscopes and a triaxial accelerometer.

We defined two local coordinate systems fixed to the two M3Ds under the heel and the forefoot as $\sum_{f\_heel}$ and $\sum_{f\_toe}$ respectively (see Fig. 4). The relative position of the two force plates was aligned using a simple alignment mechanism composed of three linear guides and a ruler to let the origins of $\sum_{f\_toe}$ be on the y-axis of $\sum_{f\_heel}$, and to let the y-axes of the two force plate coordinate systems be collinear, before we mounted them to a shoe. For calculation purposes, such as estimating joint moments and reaction forces of the ankle during loading response and terminal stance phases [14], all vectors including the joint displacement vector, GRF vector and gravity vector have to be expressed in the same coordinate system, that is the global coordinate system ($\sum_{g}$). Moreover, the origin and orientation of this global coordinate system are renewed for each foot placement to coincide with the heel force plate coordinate system ($\sum_{f\_heel}$), when the heel is flat on the ground.

The integration of the measured angular velocity vector ($\omega = [\omega x, \omega y, \omega z]$) in each force plate coordinate system was defined as $C = [Cx, Cy, Cz]$, which could be used to calculate the 3D orientation transformation matrix (R) between the global coordinate system and a force plate coordinate system by solving the following equations proposed by Bortz [15]:
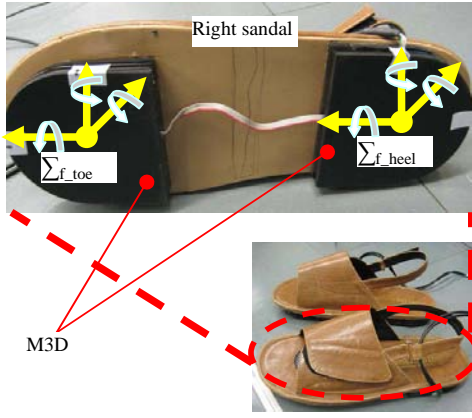
Fig. 4 M3D and the coordinate systems.

$$C_i^{i+1} = [\omega x(i) + \omega x(i+1), \omega y(i) + \omega y(i+1), \omega z(i) + \omega z(i+1)] \cdot (\Delta t / 2) \quad (10)$$

$$\left| C_i^{i+1} \right| = \sqrt{(Cx_i^{i+1})^2 + (Cy_i^{i+1})^2 + (Cz_i^{i+1})^2} \quad (11)$$

$$R_i^{i+1} = \frac{C_i^{i+1} \cdot C_i^{i+1T}}{\left| C_i^{i+1} \right|^2} (1 - \cos(\left| C_i^{i+1} \right|)) + \begin{bmatrix} \cos(\left| C_i^{i+1} \right|) & 0 & 0 \\ 0 & \cos(\left| C_i^{i+1} \right|) & 0 \\ 0 & 0 & \cos(\left| C_i^{i+1} \right|) \end{bmatrix}$$

$$+ \frac{\sin(\left| C_i^{i+1} \right|)}{\left| C_i^{i+1} \right|} \begin{bmatrix} 0 & -Cz_i^{i+1} & Cy_i^{i+1} \\ Cz_i^{i+1} & 0 & -Cx_i^{i+1} \\ -Cy_i^{i+1} & Cx_i^{i+1} & 0 \end{bmatrix} \quad (12)$$

$$R = R_0 \cdot R_0^1 \cdot R_1^2 \cdot R_i^{i+1} \cdots \quad (13)$$

where $[\omega x(i), \omega y(i), \omega z(i)]$ is a sample vector of the triaxial angular velocities of the force plate during a sampling interval Δt, C_i^{i+1} is an angular displacement vector in the sampling interval, and R_0 is an initial transformation matrix initialized as a unit matrix ($|R_0|=1$). If the force plate is flat on a level ground, we can update R according to $R = R_0$.

C. Transformation of Triaxial GRF Measured by Mobile Force Plates

The triaxial GRF measured by the two M3Ds can be transformed to global coordinates and then combined to calculate the total GRF (F_{FRG}^g) and the global coordinate vectors of CoP ($[x, y, z]_{CoP}^{g\_heel}$ and $[x, y, z]_{CoP}^{g\_toe}$) using the following equations:

$$F_{FRG}^g = R_g^{f\_heel} \cdot F_{FRG}^{heel} + R_g^{f\_toe} \cdot F_{FRG}^{toe} \quad (14)$$

$$[x, y, z]_{CoP}^{g\_heel} = R_g^{f\_heel} \cdot [x, y, z]_{CoP}^{heel} \quad (15)$$

$$[x, y, z]_{CoP}^{g\_toe} = R_g^{f\_toe} \cdot [x, y, z]_{CoP}^{toe} \quad (16)$$

where F_{FRG}^{heel} and F_{FRG}^{toe} are the triaxial GRF measured by the two M3Ds under the heel and forefoot with their respective coordinate systems; $[x, y, z]_{CoP}^{heel}$ and $[x, y, z]_{CoP}^{toe}$ are coordinate vectors of CoP measured using

the two M3Ds; $R_g^{f\_heel}$ and $R_g^{f\_toe}$ are the orientation transformation matrices of the two M3Ds for transforming the triaxial GRF measured by the two M3Ds in their attached coordinate systems into the measurement results relative to the global coordinate system.

III. EXPERIMENTAL STUDY

Verification experiments were conducted to compare the estimation results of M3D with the measurements of a stationary force plate. Finally, an application experiment is implemented to quantify and evaluate human gait, in which we measured the 3D GRF and orientations of the feet using M3D to analyze paralysis gait.

A. Verification Experiment

A stationary TF-4060-A force plate (Tec Gihan Co. Japan) was used as a reference measurement system to verify the measurement results of the M3D system being developed. As shown in Fig. 5, a young volunteer wearing M3D was asked to walk on the stationary force plate and the signals from the two measurement systems were simultaneously sampled at a rate of 100 samples/s, after a trig signal was sent from the data logger of the M3D.

First, a static test experiment was conducted to validate the triaxial force measurement of the M3D without movement. Only one foot wearing the M3D is put on the stationary force plate and the subject arbitrarily moved his center of pressure. As shown in Fig. 6, the triaxial measurement results obtained with the stationary force plate (FP) and M3D almost completely overlap and the maximum errors in the triaxial force measurements were less than 5% of the corresponding maximum forces. Second, in order to verify the M3D ambulatory measurement, a dynamic test was performed on a walking measurement, in which the subject was asked to step on the force plate at a normal speed of about one step/s (see Fig. 7). The verification experiment results indicate that the sensor can measure the triaxial force with high precision (error: less than 6.4% of the maximum measurement force) under static and dynamic working conditions.
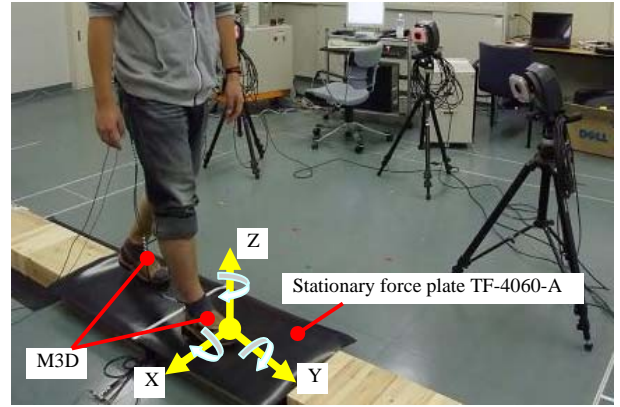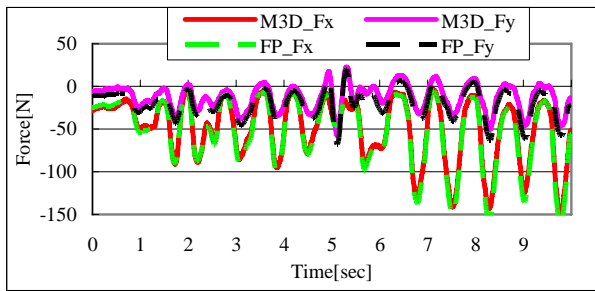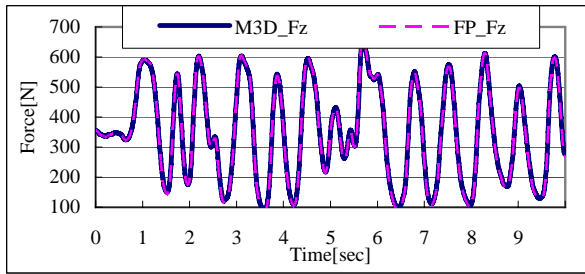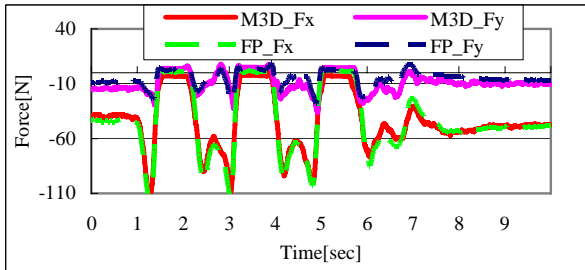

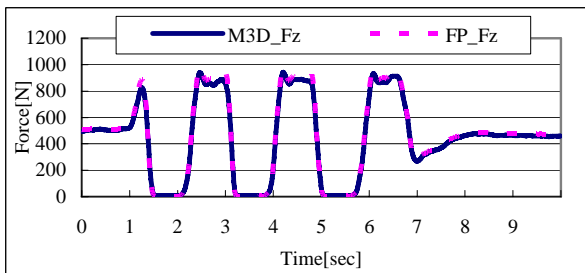Fig. 5 Verification experiments to validate the measurements of the M3D.

(a) X and Y - axial forces when standing on the stationary force plate

(b) Z-axial force when standing on the stationary force plate
Fig.6   Experiment results of the static test.

(a) X and Y - axial forces when stepping on the stationary force plate

(b) Z-axial force when stepping on the stationary force plate
Fig.7   Experiment results of the dynamic test.

B. Measurement of Paralysis Gait Using M3D

As an application of the research, experiments were performed to quantitatively compare and analyze normal walking and paralysis walking using the M3D. The main features of paralysis gait can be summarized as follows: the toe on the paralyzed side rotates to the outside with a larger angle than in normal gait; the knee is stretched to the outside during the swing phase. A healthy subject was trained to imitate the walking feature of paralysis, and we separately measured the imitated paralysis gait of the left leg and right leg. The walking distance of the experimental tests is about 6 m.

Figs. 8 and 9 give the vertical components of GRF on the two feet (Solid blue line: GRF on the left foot; Solid pink line: GRF on the right foot) measured with the M3D system in normal gait and on the right foot imitating paralysis gait, respectively. We note that there are no large differences in the shape of the vertical force (z-axial force) curves induced on the right and left foot during normal walking, and that the GRF on the two feet have good balance and symmetry during continuous strides. When we compare the curves in Fig. 9 with the normal gait data, we can clearly note that the two peaks of the z-axial force on the left foot which is not on the paralyzed side are depressed. Moreover, it has been understood that the stance phase period of the healthy leg (the left leg) was about 1.6 times longer than the paralyzed side (the right leg) during a stride.

The rotation angles of the toe and heel of the feet around the medial-lateral direction (x-axis, see Fig. 5) are shown in Fig. 10, in which the dotted lines indicate the movements of the right foot and the rotation angles of the left foot are plotted with solid lines. The positive angle values represent the plantar flexion of the foot segments, and the negative values indicate dorsal flexion. The flexion angles of the paralysis foot (the right foot) are reduced significantly and the heel-strike angles and toe-off angles were less than 20 degrees. Moreover, it is noted that the toe joint of the paralysis foot was almost never rotated during the gait, because the heel and toe had the same flexion angles during the entire walking measurements. We also obtained similar results in the measurements of left leg paralysis using the M3D.
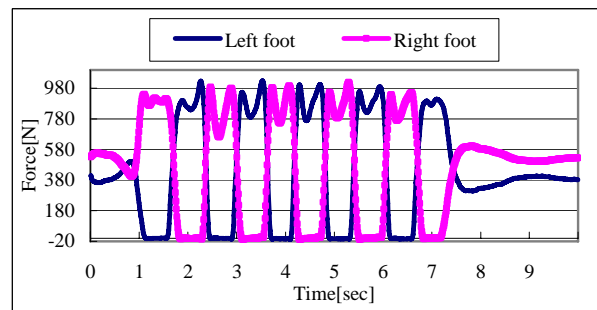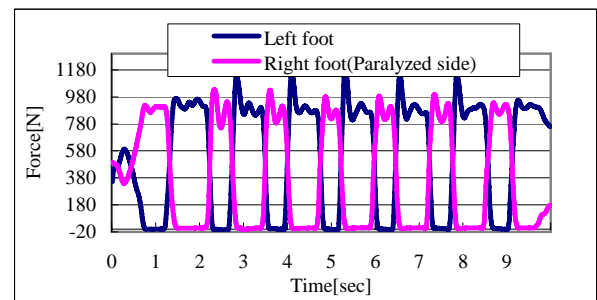

Fig.8   Z-axis force during normal walking

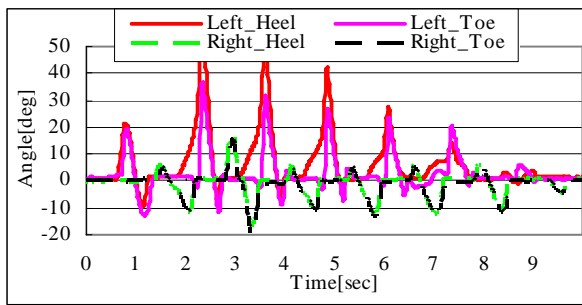Fig.9   Z-axis force during paralysis gait

Fig.10   X-axial angles of the feet during paralysis gait

IV. DISCUSSIONS AND CONCLUSIONS

A mobile force plate and 3D motion analysis system (M3D) was developed using lower cost inertial sensor chips and small triaxial force sensors. In order to apply the system to human gait evaluation, verification experiments were implemented to compare the results estimated by M3D with measurements made with a stationary force plate. In the static tests, the force measurements by the M3D system along three axes were highly correlated in both amplitude and dynamic response to the reference measurements using the stationary force plate (see Fig. 6) and this verifies that the M3D system could measure the triaxial GRF in its fixed local coordinate system with acceptable precision (less than 5% of the corresponding maximum force). However, as shown in Fig. 7, there were larger errors in the triaxial GRF measurements. The most likely source of amplitude error in the triaxial GRF measurement was in the orientation estimate of M3D movements using a triaxial accelerometer which could only implement x- and y-axial angular displacement re-calibration. In the future, we will integrate a triaxial magnetic sensor [16] for estimating the heading angle (z-axial angular displacement) during gait, because the z-axial (vertical) cumulative error induced by the drift effect of the gyroscope sensor could be re-calibrated using measurements from the magnetic sensor. Since only straight level walking was tested with M3D, it is necessary to examine more movements to verify ambulatory measurements obtained with M3D in future gait experiments. Moreover, the sensitivity of results to initial sensor drift and initial orientation fix will be addressed so that the system can be applied to many other applications.

In our research application using the new system, the quantitative differences between paralysis gait and normal gait were analyzed based to the results of z-axial GRF (Fig. 9) and x-axial angular flexions (Fig. 10). In clinical applications, the quantitative analysis of gait variability using kinematic and kinetic characterizations can be helpful to medical doctors in monitoring patient recovery status. Moreover, these quantitative results may help to strengthen their confidence in rehabilitation. Walking speed, stride length, center of mass (CoM) and CoP have been considered as influencing factors in evaluations of human gait [17]. In this paper, only the z-axial GRF (vertical force) and x-axial orientation were analyzed to evaluate different gaits.

However, according to one study on slip type falls [18], the friction force was used to draw up important safety criteria for detecting safe gait, so the transverse components of GRF may provide important information when quantifying gait variability. The M3D system can be used to obtain multi-dimensional motion and force data on successive gait in non-laboratory environments, so we will develop a new method based on measurements from the mobile system for quantifying gait variability. Moreover, a statistical analysis of the multi-dimensional GRF and orientation data extracted from successive gait measurements will be used to evaluate normal and pathological gait.

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