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# Triaxial joint moment estimation using a wearable three-dimensional gait analysis system

T. Liu [a,*], Y. Inoue [a], K. Shibata [a], K. Shiojima [b], M.M. Han [c]

[a] School of Systems Engineering, Kochi University of Technology, 185 Miyanokuchi, Tosayamada-Cho, Kami-City, Kochi 782-8502, Japan
[b] TEC GIHAN Co., Ltd., 1-22, Nishinohata, Okubo-Cho, Uji-City, Kyoto 611-0033, Japan
[c] INSENCO R&D LAB. Inc., 7-2-1305, Hikarigaoka, Nerima-Ku, Tokyo 179-0072, Japan

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ABSTRACT

We developed a wireless sensor system composed of a mobile force plate system, three-dimensional (3D) motion sensor units and a wireless data logger. Triaxial joint moments of the ankle, knee and hip joints were calculated using measurements of the sensor system. The accuracy of the joint moment estimation is validated against results obtained from the reference measurement system composed of a camera based motion analysis system and force plates. Triaxial joint moments measured by the sensor system showed normalized root mean square error (NRMSE) and correlation coefficient ($R$) of less than 22% and more than 0.80 in comparison with the stationary system.



## 1. Introduction

In order to implement lower limb kinetic analysis, a complete human kinematic analysis using inertial motion sensors is not enough, and a mobile force plate system to measure ground reaction force (GRF) during gait is necessary for inverse dynamics analysis [1]. By mounting multi-axial force sensors beneath a special shoe, some instrumented shoes have been developed for ambulatory measurements of triaxial GRF in a variety of non-laboratory environments rather than merely in a gait laboratory. To analyze dynamic gait and joint loads, three-dimensional (3D) inertial sensor modules have been integrated into wearable force plates. Schepers 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 joint moments and powers of the ankle [2]. In our past research, a thin and light force plate based on triaxial force sensors and inertial sensors was also proposed to analyze continuous gaits by measuring triaxial GRF and foot orientations [3,4]. We are presently concentrating on the development of some wearable sensors to measure human GRF and segment orientations during gait [5], and using an inverse dynamic method to implement joint dynamics analysis of the lower limb. Compared to other studies [2,6], the novelty of our study is the estimation of the hip and knee moments, in addition to the ankle joint moment estimation. In this paper, a trixial joint moment estimation based on a wireless sensor system is proposed. The sensor system, named mobile 3D force plate (M3D), was developed by integrating a mobile force plate, 3D motion analysis units and a wireless data logger.

## 2. Method

### 2.1. Motion sensor unit

As shown in Fig. 1, motion sensor units (weight: 20 g, size: 35 mm × 50 mm × 15 mm) were designed to

* Corresponding author. Tel.: +81 887 57 2177; fax: +81 887 57 2170.
*E-mail addresses:* liu.tao@kochi-tech.ac.jp (T. Liu), k.shiojima@tecgi-han.co.jp (K. Shiojima), mmh@insenco-j.com (M.M. Han).

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measure 3D orientations of lower limbs using a triaxial accelerometer (LIS331DLH: STM), gyroscopes (LPR530AL and LY530ALH: STM) and a triaxial magnetic sensor (HMC5843: Honeywell) and micro-computer system. The sensor units communicate via serial communication (RS-485) with a personal computer. Nine channel sensor signals (triaxial accelerations, triaxial angular rates, and triaxial magnetic intensities) are provided after a 16-bit A/D conversion. A Kalman-based fusion algorithm was applied to process signals of the triaxial accelerometer and triaxial magnetic sensor by incorporating the excellent dynamics of the gyroscope and the stable static performance of the accelerometer and magnetic sensor [3,7]. When the sensor units are mounted on human body segments, 3D orientations of the body segments can be calculated using the filtered signals.

### 2.2. Mobile force plate

As shown in Fig. 1, two mobile force plates (weight: 110 g, size: 82 mm × 88 mm × 9 mm) were mounted under each shoe to measure triaxial forces and triaxial moments. A detailed description of the method to extract the triaxial GRF and the reaction point of the GRF can be found in our previous publications [3,4]. In this research, the range of force measurement of the developed force plate in the instrumented shoes for the vertical direction and two horizontal directions is 1000 N and 500 N, respectively. The maximum torque measured by the force plate is 30 Nm for all directions.

In order to implement ambulatory GRF measurements when the force plates move with the feet, a 3D motion sensor unit introduced in section 2.1 was added inside the force plate to measure 3D orientations of the mobile force plate. The data from the motion sensors can be combined with the force sensors' data for a dynamic GRF measurement.

As for the coordinate systems of the two force plate systems mounted under the instrumented shoes (see Fig. 2), the *Y*-axis of the motion sensors and force sensors are aligned with the anterior–posterior direction of the feet, and the *Z*-axial direction represents the direction perpendicular to the sole plane. For all the sensor coordinates, the *Z*-axis positive direction is upward, the *Y*-axis positive direction is anterior, and the *X*-axis positive direction is right. When a motion sensor unit was mounted to a leg segment using an elastic band, we aligned the sensor's *Z*-axis along the line connecting the segment's proximal and distal joints and let the *Y*-axis be the anterior–posterior direction. The *X*-axis was chosen such that the resulting global coordinate system would be right-handed.

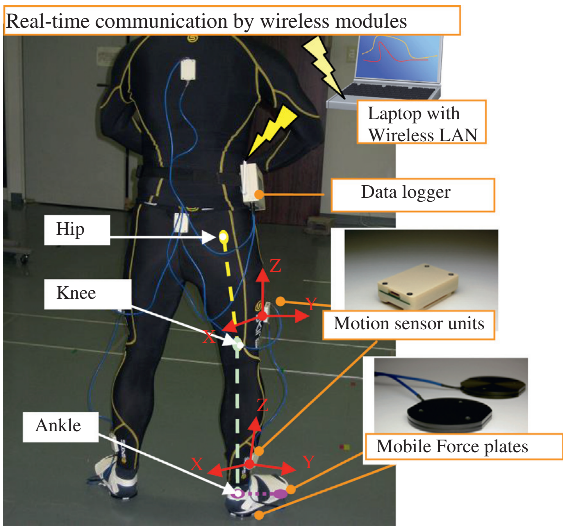


**Fig. 1.** Wireless sensor system (M3D) for gait analysis.

### 2.3. Wireless sensor system: M3D

We constructed a wireless sensor system by combining the motion sensor units and a pair of instrumented shoes with a portable data logger which works as a buffer and transfers sensor data to a personal computer (PC) by a wireless local area network (LAN, IEEE802.11b/g). All the sensors' data can be sampled to the data logger (weight including batteries: 520 g) on the waist, and transferred to the PC through wireless LAN modules with a maximum sampling frequency of 1000 Hz. The wireless sensor system can be powered using four rechargeable batteries AA1.2 V Ni–MH in the data logger. The system is capable of a continuous measurement for about one hour. The interface software for the PC was developed to display real-time signals from the motion and force sensors. All the sensors' raw data can be saved in a comma-separated values (CSV) file for subsequent off-line kinematic and kinetic analysis.

A sensor-segment calibration must be implemented to align the sensor units' sensing axes to the segments' moving coordinates after placing the sensor units [8]. We asked the subject wearing the sensor system to walk along a marked path (a 3 m straight line). The measured lower limb's joint coordinates were imported into a regression algorithm (least squares method) to calculate the offset angle values of the sensor units' sensing axes.

### 2.4. Lower limbs' kinematic and kinetic analysis

Lower limbs' kinematic and kinetic analysis were implemented based on measurements of 3D segment orientations and GRF using the developed sensor system. Firstly, 3D joint coordinates were calculated by combining 3D orientation measurements of the motion sensor units,

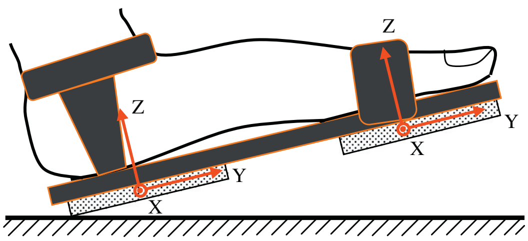


**Fig. 2.** The coordinate systems of the two force plate systems.