Measurement of Muscle Motion for Improving Accuracy of Body-mounted Motion Sensor

Tao Liu, Yoshio Inoue, and Kyoko Shibata

*Department of Intelligent Mechanical Systems Engineering
Kochi University of Technology*

185 Miyanokuchi, Tosayamada-cho, Kochi Japan 782-8502

liu.tao@kochi-tech.ac.jp

Abstract – A new method of measuring joint angle using a combination of 3D accelerometers and reaction force sensors is presented. Muscle motion is a common source of error to all body-mounted sensors. The effect of skin artefact was minimized based on the estimation of muscle motion measured using a new reaction force sensor banded with human body segment. The force sensor was designed using pressure sensitive electric conductive rubber (PSECR). Fourier transform of the total pressure forces induced by body-mounted motion sensor modules was implemented to analyse frequency property of muscle motion of human body surface. We processed data from 3D accelerometers using measurements of muscle motion including the total pressure force and two-directional coordinates of center of pressure (Cop). Experimental study was implemented to verify the new sensor system proposed for estimation of knee joint angles, and measurements of the developed sensor system showed a high correlation to the results from the optical motion analysis system in the walking analysis experiment.

Index Terms – *Muscle motion; Reaction force sensor; Accelerometer; Knee.*

I. INTRODUCTION

In the study of human dynamic analysis based on measurements of orientations of body segments, wearable motion and force sensors are gradually considered for clinical applications. This is due not only to the tremendous increase in research interests devoted to this area but also to the large number of companies that have recently started investing aggressively in the development of wearable products for clinical applications [1]. Some cheaper and more comfortable wearable sensor systems with multi-sensor combinations like force sensitive resistors, inclinometer, goniometers, gyroscopes and accelerometers, were proposed to implement measurements of motions and forces for human dynamics analysis.

A quantitative analysis of human motion was investigated in [2], and by using assembled multi-axis accelerometer sensors, a measurement system was made for estimation of three-dimensional position and orientation of a body segment. In [3], Tong and Grant proposed a measurement device using two gyroscopes, one placed on the thigh and the other on the shank, which can estimate knee rotation angle during walking. Pappas in [4] used a detection system consisting of three force-sensitive resistors, which measure the force loads on a shoe insole, and a gyroscope which measures the rotational velocity of the foot. There are growing interests in developing

commercial products of wearable sensor system, for example the solutions MTx furnished by the Xsens (Xsens, Enschede The Netherlands) [5] which realized a motion sensor based on three angular rate sensors three accelerometers and three magnetic sensors which reconstruct an angular displacement by means of a dedicated algorithm.

The above techniques exhibit different characteristics, but they share the drawback that the inertial sensors of gyroscopes and accelerometers are suffered from the fluctuating offset induced by temperature change or small changes in the structure (mechanical wear). Luinge proposed a Kalman filter that fuses tri-axial accelerometer and a tri-axial gyroscope signals for ambulatory recording of human body segment orientation [6]. However, when accelerometers are used in clinical applications a complex calibration procedure is impractical and can cause misuse.

In our research, we integrated a muscle motion measurement with developed body-mounted motion sensor [7] to estimate joint angles of human lower limb. Noise effects from body muscle motion on motion sensors like accelerometer were decreased to improve accuracy of joint angle measurements. The paper is organized as follows. In Section 2, we describe the design of the muscle motion measurement device and a body-mounted motion sensor system and its algorithm for estimating joint angle of human lower limb. The experimental study on measurement of muscle motion for improving accuracy of body-mounted motion sensor system is described in Section 3. In Section 4, the results of the experimental study using the developed sensor system are described.

II. METHODS AND MATERIALS

A. Reaction Force Sensor for Measuring Muscle Motion

We proposed a new method to analyze muscle motion from measurements of pressure distribution between body-mounted sensor and human body. A human body reaction force sensor constructed by four pressure sensing points can measure surface muscle motion of human movement. As shown in Fig. 1, an elastic trap was used to fix the reaction force sensor on human body, in which four contact points of the sensor can measure pressure force distribution induced by muscle motion.

Pressure sensing cells of the reaction force sensor were designed using pressure sensitive electric conductive rubber

(PSECR) which has been used for measuring pressure force distribution. PSECR has been developed for the sheet-switch of the electronic circuits, and has a unique property in that it conducts electric current only when compressed, and acts as an insulator when the pressure is released. The material properties of PSECR are given in table I.

Fig. 1 Muscle motion measurement

Fig. 2 Reaction force sensor for measuring muscle motion

Color	gray-black
Tensile strength	1.86 MPa
Elongation at break	220 %
100% modulus	0.86 MPa
Tear resistance	7 kN/m
Hardness in Durometer	50

Four pectinate circuits were made to construct a sensing matrix in the reaction force sensor. The interface of the sensor is made to transform input 4-positional pressure forces into measurement of reaction force distribution on its base plate (Fig. 2). The total pressure force (F) and the coordinates of the center of pressure (COP) including x_{cop} and y_{cop} were calculated using measurements of the four pressure sensing cells as follows:

$$F = F_1 + F_2 + F_3 + F_4 \quad (1)$$

$$M_x = (F_1 + F_2 - F_3 - F_4)L/2 \quad (2)$$

$$M_y = (F_1 + F_4 - F_2 - F_3)L/2 \quad (3)$$

$$x_{cop} = M_y / F \quad (4)$$

$$y_{cop} = M_x / F \quad (5)$$

where F_i is measured pressure force of each support point, and M_x and M_y are two-directional moments on the sensor plate. As shown in Fig. 3, a prototype of the reaction force sensor was developed, and we mounted motion sensor module designed using 3D accelerometers on it to measure joint angle of human lower limb.

Fig. 3 Prototype of reaction force sensor

B. Motion sensor module

As shown in Fig.4, a sensor module was designed by integrating two 3D accelerometers (MM-2860, made by Freescale Semiconductor). The sensor can work under low energy consumption (800 μ A at 5V), which includes conditional module and power regulator, so it is appropriate for ambulatory measurements.

The two 3D accelerometers were attached on based board plate of the sensor module to measure two-directional accelerations along tangent direction of x-axis and sagittal direction of y-axis when mounted on human body segments. In this motion analysis system the data from accelerometers were fused to estimate angular displacement of the attached leg segments. As shown in Fig. 5, the motion sensor system includes two sensor modules composed of two 3D accelerometers and a reaction force sensor. Two sensor modules were mounted on thigh and shank respectively, and a data sampling system were attached on the waist.

Fig. 4 Prototype of motion sensor module

Fig. 5. Wearable motion sensor system. A strap system was designed for the binding between the sensor modules and human body. The sensor module is attached to the strap. During walking, the strap is tied around the limb to secure the position of each sensor module.

As shown in Fig. 6, because each sensor module including two 3D accelerometers only perform measurements of acceleration in segment-fixed reference frame during human moving, two local coordinates were defined for the sensor modules fixed on the thigh and shank. Considering the two-dimensional (2D) model of a segment motion, the vector $[R_a, R_b]$ indicates the distance between sensor module and knee joint, while 2D local coordinate systems ($\Sigma x^t y^t$ and $\Sigma x^s y^s$) represent the orientations of the sensor modules with respect to body segments. We aligned y-direction along the connection line of the two near body joints, and let x-direction be anterior-posterior direction.

For the simplified model, human body segments were considered as rigid bodies. We analyzed the motion of the sensor module fixed on a body segment by dividing the

motion into the linear motion of the segment's rotation point, and the angular motion of the sensor module about the point. Therefore, to estimate joint angle, the first step was to calculate two-directional accelerations of the knee joint on every local coordinate system using measurements of the sensor modules fixed on the body segments, and the calculation equations are given as follows:

$$[a_x^K, a_y^K]^s = [a_x^{A1}, a_y^{A1}]^s - [(R_a + D)\dot{\omega}_s, (R_a + D)\omega_s^2] \quad (6)$$

$$[a_x^K, a_y^K]^s = [a_x^{A2}, a_y^{A2}]^s - [(R_a)\dot{\omega}_s, (R_a)\omega_s^2] \quad (7)$$

$$[a_x^K, a_y^K]^t = [a_x^{B1}, a_y^{B1}]^t - [(R_b)\dot{\omega}_t, (R_b)\omega_t^2] \quad (8)$$

$$[a_x^K, a_y^K]^t = [a_x^{B2}, a_y^{B2}]^t - [(R_b + D)\dot{\omega}_t, (R_b + D)\omega_t^2] \quad (9)$$

where $[a_x^{A1}, a_y^{A1}]^s$, $[a_x^{A2}, a_y^{A2}]^s$, $[a_x^{B1}, a_y^{B1}]^t$ and $[a_x^{B2}, a_y^{B2}]^t$ are outputs of 3D accelerometers obtained from the two sensor modules fixed on body segments including shank and thigh respectively; $[a_x^K, a_y^K]^t$ and $[a_x^K, a_y^K]^s$ are knee joint accelerometers which were calculated from measurements on the two local coordinates of the attached segments; ω_s and ω_t were defined as angular velocities of shank and thigh relative to the knee joint.

The next step was to calculate joint angle for two segments using two sensor modules fixed on each segment. Since one point should physically have a unique acceleration, the two estimated accelerations on local coordinates at rotation joint should give equal accelerations.

$$[a_x^K, a_y^K]^t = R(\theta)[a_x^K, a_y^K]^s \quad (10)$$

where $R(\theta)$ is axis rotation matrix of the calculated joint accelerations in relation to the two connected local coordinates by angle θ .

Fig. 6 Local coordinates of the sensor modules.

C. Data Sampling and Signal Processing

As shown in Fig. 7, an integrated hardware system was developed and incorporated into the sensor system for data sampling and signal processing. The pressure forces applied on the flexible interface of the reaction force sensor were converted to the resistance changes of sensing points using PSECR. Then the resistance changes were converted to the voltage signals by the conditioning modules, and were amplified by amplifier modules. The conditioned voltage signals from the reaction force sensor and 3D accelerometers were fed into PC after A/D conversion using a micro-computer H8 3964. Since eight points for pressure sensing in the two reaction force sensor were used to measure muscle motions, while eight accelerations outputs were used to estimate joint angle, so there were totally 16 channels of the voltage signals. A pair of wireless module (ZIG-100B) for data communication between micro-computer and a personal computer was used to connect RS232 ports instead of the common serial communication cable.

Data processing program designed using MATLAB specially was adopted to calculate the joint angle by fusing the measurements of muscle motions and accelerations. Fourier transform of the total pressure forces induced by body-mounted motion sensor modules was implemented to analyze frequency property of human body surface muscle motion. We designed a band pass filter to reduce the effect from muscle motion on the measurements of 3D accelerometers. Fig. 8 gives the architecture of accelerometer data processing method using measurements of muscle motion including the total pressure force and two-directional coordinates of Cop.

Fig. 7 Hardware system of data sampling

Fig. 8 Data processing for 3D accelerometer mounted on human body.

III. EXPERIMENTAL STUDY

Experimental study was implemented to verify the new sensor system proposed for decreasing effects of muscle motion on the estimation of joint angles using body-mounted sensors. A healthy subject, who had given informed consent, participated in this experiment. The volunteer performed flat walking trials when wearing the developed sensors at self-selected speed.

The coordinates of Cop for each sensor module can be calculated from the measurements of pressure force distribution. As show in Fig. 9, two-directional accelerations of Cop were calculated from double differential of two components of Cop displacements. Fig. 10 shows measured body reaction force and their fourier transform results for shank and thigh during walk. Fig. 11 gives the results of estimation of knee angle using processed data of measured by 3D accelerometers.

Fig. 9 Cop accelerations obtained from two sensor modules.

Fig. 10 Pressure force response and fourier transform.

Fig. 11 Knee joint angles during walking.

As show in Fig. 12, to validate the sensor system performance, comparison of the quantitative results of the sensor system and the measurements obtained with a commercial optical motion analysis system Hi-DCam (NAC image technology. Japan) was performed. The motion analysis system (Hi-DCam) tracked and measured the 3-D trajectories of retro-reflective markers placed on the subject's body. The cameras with sampling frequency of 100 Hz were used to track the marker positions with accuracy of 1 mm. The compare results of the two motion analysis system are shown in Fig. 13.

Fig. 12 Test condition for verification experiment

Fig. 13 Verification results of the developed motion analysis system.

IV. DISCUSSIONS AND CONCLUSIONS

The measurement results from the developed sensor system showed a high correlation to the results obtained from the optical motion analysis system in the multi-step walking validation experiment. In the walking experimental study, the proposed method based on body-mounted reaction force sensor and 3D accelerometers gave an accurate estimation of knee joint angles. Though the paper has focused on the use of body-mounted sensors for measuring knee joint angle, the method can be applied to measure other joint angles like ankle (by attaching sensors on shank and foot). Although multi-axial measurement is more powerful, in many cases a simple uniaxial measurement can be effective as well, giving a lot of information for pathologies related to knee.

To resolve the problem that muscle motion artefact, a common source of error to all body-mounted devices, we proposed a new method to measure response of human body surface muscle motion. The thigh sensor is more susceptible

to skin and soft tissue artifact where the majority of the femur is concealed by a substantial amount of soft tissue. Experimental tests indicate that the effect of skin artefact was minimized by using the reaction force sensor contacting with human body.

Technically, the system is wearable, and it can also be used for long-term monitoring without hindrance to the natural gait. In comparison with the traditional camera-based systems, this system can be an alternative solution for capturing kinematic information over a non-limited distance and outside a laboratory environment. Moreover, in the study of robotics, the wearable sensor system can be applied for real-time control of humanoid robot which may walk in the same phase as human walking.

REFERENCES

- [1] Bonato, P., "Wearable sensors/systems and their impact on biomedical engineering," *IEEE Eng. Med. Biol. Mag.*, 2003, 22, pp. 18-20.
- [2] Giansanti, D., Macellari, V., Maccioni, G., Cappozzo, A., "Is it feasible to reconstruct body segment 3-D position and orientation using accelerometric data?" *IEEE Trans. Biomed. Eng.*, 2003, 50, pp. 476-483.
- [3] Tong, K. and Granat, H. M., "A practical gait analysis system using gyroscopes," *Med. Eng. Phys.*, 1999, 21, 87-94.
- [4] Pappas, I. P.I., Popovic, M.R., Keller, T., Dietz, V., and Morari, M., "A reliable gait phase detection system," *IEEE Trans. Rehab. Eng.*, 2001, 9, pp. 113-125.
- [5] Xsens, 2003. <http://www.xsens.com>
- [6] Luinge, H.J., Veltink, P.H., "Inclination measurement of human movement using a 3-D accelerometer with autocalibration," *IEEE Trans. Rehab. Eng.*, 2004 12, pp. 112-121.
- [7] Liu, T., Inoue, Y., Shibata, K., Morioka, H., "Development of Wearable Sensor Combinations for Human Lower Extremity Motion Analysis," *Proceedings of IEEE International Conference on Robotics and Automation*, 2006, pp.1655-1660.