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Dynamic analysis and motion measurement of ski turns using inertial and force sensors

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Abstract

This paper proposes the dynamic motion analysis method of ski turns using inertial and force sensors. The motion analysis of ski turns in gliding on an actual field is important to resolve the mechanism of ski turns. However, it is difficult to measure physical exertion due to the severe experimental surrounding such as the outside snow conditions and the weather on the mountain. Therefore, few studies have analyzed ski turns quantitatively. The control force of skier gliding on the actual snow field must be clarified to resolve the mechanism of ski turns. In the previous studies, we developed the 3D posture estimation method of skier gliding at high speed. This method can estimate the Roll-Pitch-Yaw angles in local coordinate by the information of inertial sensors using the Unscented Kalman filter. The control force of skier (joint torque) can be calculated by combining this method and the measurement of reaction force from snow surface. We conducted the experiment of skier gliding on the actual snow field. The inertial sensors were attached to the body segments (upper body, lumber, femur, and lower thigh) of skier and ski boots, and the 6-axis force sensors were installed between boots and skis. The inertial sensors measure angular velocity and acceleration of body segments, and the force sensors measure the reaction force from snow surface. The joint torque (lumber spine, hip, knee and ankle) of skier is calculated by applying the measurement information to the Newton-Euler method. The analysis results using joint torque indicates the control force of skier gliding on the actual snow field. Therefore, the analysis method and results can be used to evaluate the skill of turns and to resolve the mechanism of ski turns.

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Keywords: Ski; motion analysis; posture; joint torque; inertial sensor; force sensor

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1. Introduction

Skiing has progressed with the improvement of technique and the development of new equipment such as carving ski. The motion analysis of skier gliding on an actual snow field is important to resolve the mechanism of ski turns. However, it is difficult to measure physical exertion due to the severe experimental surrounding such as the outside snow conditions and the weather on the mountain. Therefore, few studies have analyzed ski turns quantitatively. There are a few studies on the motion measurement and analysis. The motion measurement of skier using potentiometer and strain gages [1], the motion analysis of skier using 3D magnetic positioning system and 6-axis force sensor [2] and biomechanical analysis of ski racing using inertial measurement units and GPS receiver [3] have been conducted.

The motion measurement method using inertial sensor has proposed as the simply measurement method in sports [4]. This method is effective in the measurement of wide range such as snow sports. The 3D posture calculated by the inertial sensor output includes the drift error. Thus, the sensor fusion methods have been proposed to compensate the drift error using inertial and magnetic field sensors [5, 6]. However, these performances of drift error compensation are inadequacy in the condition generating the large dynamic acceleration since these methods deals the dynamic acceleration as the white noise. In the previous studies, we conducted the motion analysis using the joint angles of skier and gliding velocity [7], and we conducted the development of the sensor fusion method and the application to the motion measurement of skier gliding on the actual snow field [8]. The sensor fusion can estimate the 3D posture by the inertial sensors outputs. This method can avoid the effect of dynamic acceleration. Furthermore, the dynamic motion analysis can be enabled by using the method and the measurement of reaction force from snow surface.

In this study, we proposed the dynamic motion analysis method of skier gliding on the actual snow field using the inertial sensors and force sensors, and we indicate the major features of skier in gliding on the actual snow field using the joint torque.

2. Measurement system

2.1. Motion measurement system

The motion measurement system shows in Fig. 1. This system that consists of three gyro sensors (Analog Devices, ADIS16110) and a 3-axis accelerometer (Hitachi Metals, H30CD) measures 3-axis angular velocity and 3-axis acceleration. The size of this system is 45×65×25mm, and the weight is 60g.

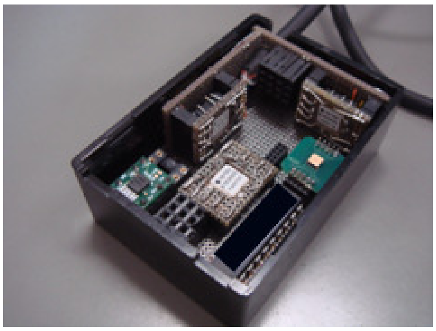

Fig. 1. Motion measurement system

2.2. Measurement system of reaction force from snow surface

The measurement system of reaction force from snow surface is shown in Fig. 2. The 6-axis force sensors (Nitta Corporation, IFS-105M50A220-I63) are installed between boots and skies. This system measures the center of pressure and the reaction force of 3-axis force and 3-axis moment vectors.

Fig. 2. Measurement system of reaction force from snow surface

3. Theory

3.1. 3D posture estimation

The 3D posture is estimated by the sensor fusion [8] using the Unscented Kalman filter. This method estimates the Roll-Pitch-Yaw angles in local coordinate representing the 3D posture. Then, the Roll-Pitch-Yaw angles are translated to the rotational matrix in local coordinate by Eq. (1), where ${}^{i\text{-}1}R_i$ is the rotational matrix in local coordinate, φ is the Roll angle, θ is the Pitch-angle and ψ is the Yaw angle.

$$
{}^{i-1}R_i = R(\psi)\cdot R(\theta)\cdot R(\varphi) = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}\cdot \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix}\cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\varphi & -\sin\varphi \\ 0 & \sin\varphi & \cos\varphi \end{bmatrix} \tag{1}
$$

3.2. Joint torque estimation

In this study, we conducted the dynamic motion analysis of skier gliding on the actual snow field using the joint torque. The joint torque is estimated by applying the Newton-Euler method. Therefore, the skier is defined as the 3D link rigid body model consists of body and lower limb. The lumber spine, hip and ankle joints are 3DOF, and the knee joints are 1DOF in the model. The 3D postures of the body segments are estimated by the sensor fusion, the angular velocities of body segments used the output of gyro sensor attaching to the body segments, the angular accelerations of body segments are calculated by the time differential of the angular velocities, and the acceleration of joint is calculated by accelerometer output, angular velocity, angular acceleration and the position vector from the motion measurement systems to the joints. The inexact differential is used to reduce the increase of noise by differential calculation. The block diagram for calculation of joint torque is shown in Fig. 3. The mass, the moment of inertia and the center of mass position are estimated by using the length of each body segments [9]. The centers of joints are calculated by the center of mass position and the length of each body segments. The Newton-Euler method is calculated as the lumber segment is the base link and the reaction forces from the center of pressures are the terminal link.

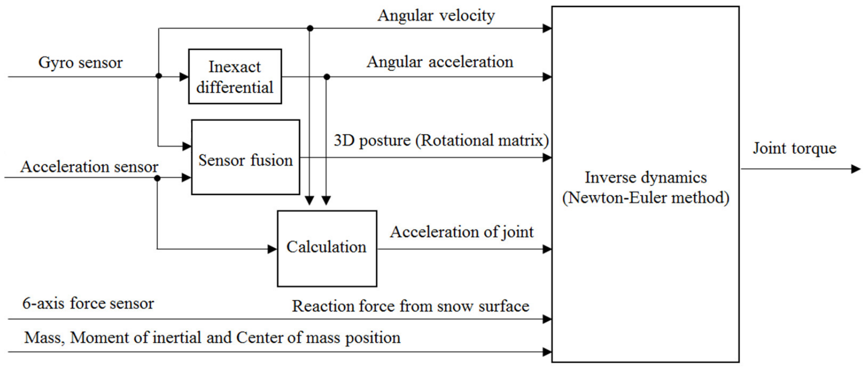

Fig. 3. Block diagram for calculation of joint torque

4. Experiment

4.1. Experimental condition

We conducted the measurement experiment by skier attaching the measurement systems. The motion measurement systems are attached to the body segments (upper body, lumber, femur and lower thigh) and the ski boots, and the measurement systems of reaction from snow surface are installed to between the ski boots and skies. Furthermore, we attached the GPS receiver to the top of skier to measure the switchovers of turns. The skier conducted the carving turns, and we measured the motion of skier and reaction force from snow surface in gliding on the actual snow field. The joint torque (lumber spine, hip, knee and ankle joints) of skier were calculated by applying the proposed method. The sampling frequencies of the measurement systems and the GPS receiver are 100Hz and 5Hz, respectively. The measurement time is 30sec.

4.2. Experimental result

Results for the joint torque of skier are shown in Fig. 4-7. In the result of lumber spine joint torque, the right rotation torque of lower body and right side flexion torque of upper body were generated to incline the body to the center of turn in forepart of left turn, and the left rotation torque of lower body and left side flexion torque of upper body were generated to conduct the rotational motion in forepart of right turn. In the results of hip, knee and ankle joint torque, the adduction torque of right hip joint and the dorsal extension torque of ankle joint were generated to product the reaction force from snow surface in forepart of left turn, and the flexion torque of left hip joint, the extension torque of left knee joint and the dorsal extension torque of ankle joint were generated to product the reaction force from snow surface in forepart of left turn. The left side flexion torque and flexion torque of lumber spine joint, the adduction torque, the flexion torque and internal torque of hip joint, the extension torque of knee joint and the dorsal extension of ankle joint were generated to support the body of skier in the last half of right turn.

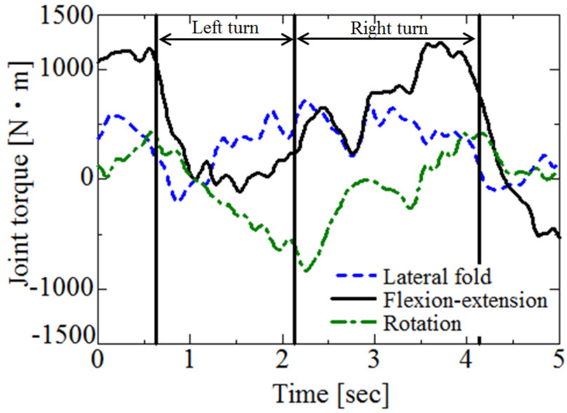

Fig. 4. Lumber spine joint torque

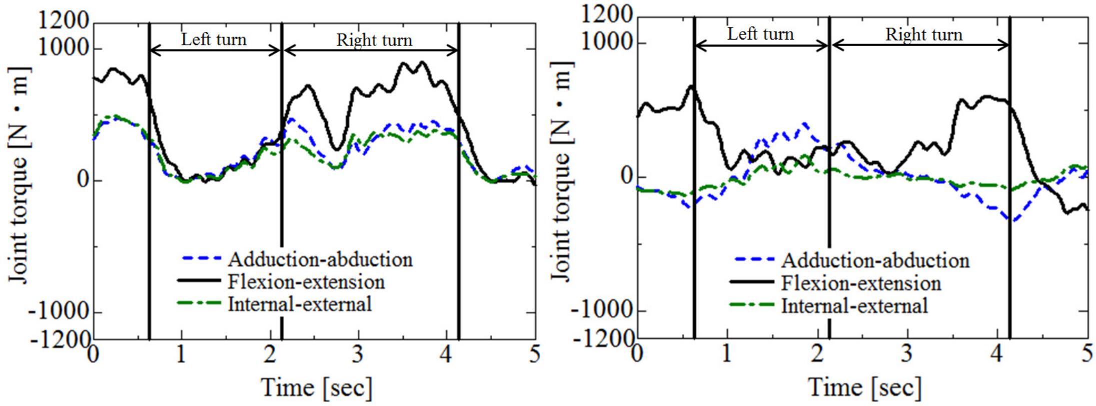

Fig. 5. Hip joint torque; (a) Left hip; (b) Right hip

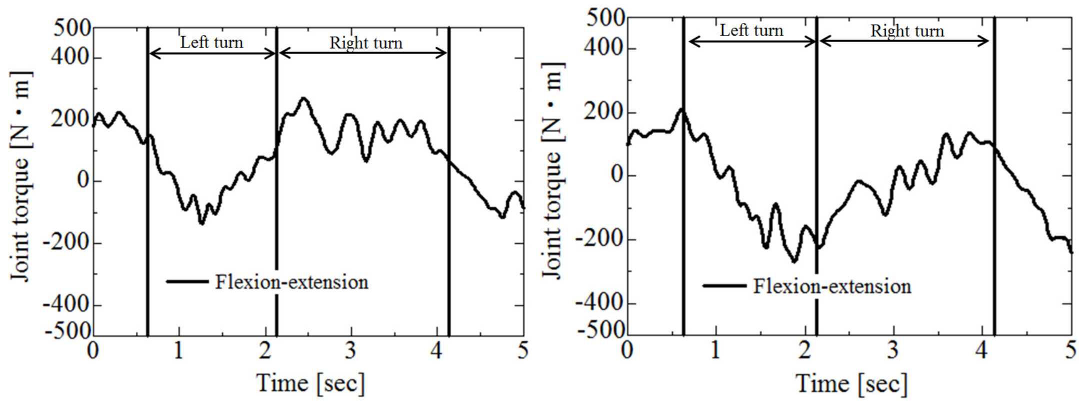

Fig. 6. Knee joint torque; (a) Left knee; (b) Right knee

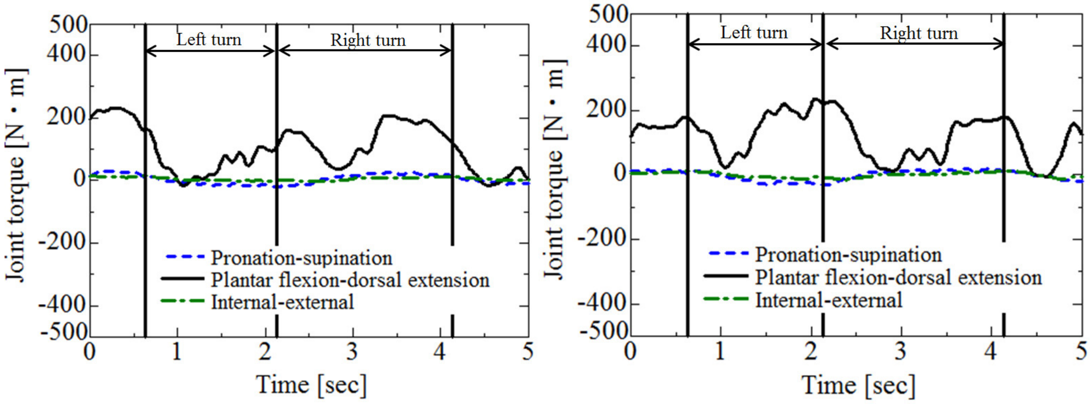

Fig. 7. Ankle joint torque; (a) Left ankle; (b) Right ankle

5. Conclusion

In this study, we proposed the dynamic motion analysis method of ski turns using the inertial and force sensors. The 3D postures were estimated by the sensor fusion, and the angular velocities of body segments, the angular accelerations of body segments and the accelerations of joints are calculated by using the inertial sensor outputs. The reaction force from snow surface is measured by the force sensors installing ski boots and skies. Then, the joint torque was estimated by applying the Newton-Euler method. The result of motion analysis using joint torque indicated the major features of skier gliding on an actual snow field. Therefore, the analysis method and results can be used to evaluate the skill of turns and to resolve the mechanism of ski turns.

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