Development of a Measuring System for Joint Angles of a Skier and Applied Forces during Skiing*

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To investigate the relationship between the joint angles of a skier and the forces acting on the skis from the snow surface in a turn, a new compact measuring system has been developed. It consists of a goniometer on the hip and knee joints, a force sensor placed between a ski and its binding, and a notebook computer as a data recorder. Using this system, measurements are carried out during a long parallel turn. The results obtained from the experiments are summarized for one cycle of a turn. They are very useful for the development of ski equipment and to clarify the dynamic mechanism of turn on skis.

Key Words: Ski, Sensor, Sports, Load, Joint Angle, Turn, Skier, Measurement

1. Introduction

Currently, skiing is being enjoyed by many people as a life-long sport. Considerable research in the development of ski equipment and skiing skills[1],[2] has been carried out because of the increasing popularity of skiing. To develop this research further, the dynamic mechanism of a skiing turn must be clarified. There have been several approaches to clarify this mechanism, such as theoretical research using a computer simulation with some assumptions of simple models[3]-[6] and experimental research using robots[7]-[9]. From these results, many useful views and opinions have been derived. However, the relation between the posture of a skier and the forces resulting from the surface of the snow on the skier during a turn is not well defined. It is very important to establish what kind of motion by a skier causes what kind of turn.

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To clarify the correlation between joint motions and operating forces for a skier who is actually gliding down a slope, two primary measuring devices have been developed. One is a goniometer attached to the skier's leg that is able to detect five joint angles of a skier. Another is a force sensor that is able to detect three forces and three moments. It is inserted between a ski and its bindings. Using these apparatuses, measurements are carried out during a long parallel turn. The results obtained from the experiments are summarized for one cycle of a turn. They are very useful in developing ski equipment. Other studies have measured the loads acting on a skier during a descent[10]-[20], but most of them have not been performed for the same purpose as this study nor have all force components been measured.

Experimental results using a prototype measuring system were already presented at a previous meeting[21], but a few problems were discovered after checking the data in detail. In this paper, the measuring system has been improved based on a consideration of the previous problems, and new experimental data were obtained using this equipment.

2. Measuring System

2.1 Goniometer

To measure the posture of a skier in real time, a goniometer was designed as shown in Fig. 1. The apparatus is attached only to the right leg because of the symmetry of the turn and to simplify the equipment. The definitions of joint angles are shown in Fig. 2. The equipment is fixed at three positions, i.e., on the hip, the knee and ski boot, using belts. Each angle is translated into an electrical signal by a potentiometer at each location. Two potentiometers are always situated on the right side and backside of the hip joint, while the third is on the right side of the knee joint. Using the linkage mechanisms, each axis of the potentiometer rotates according to the motions of the joint. Flexion angle α, valgus angle β of the hip and flexion angle γ of the knee are measured independently by each potentiometer. Sliding mechanisms that rotate around the femur and tibia according to the twist of the thigh and leg have been developed. They are attached as parts of the belt and are fixed to the knee and the ski boot. External rotation angles of the thigh θ and of the leg ϕ are measured by potentiometers through translation of the sliding ring motion into an axis rotation by a rack-and-pinion. Two inclinometers are installed on the right side in the hip belt. They are used to measure the front inclination angle of the hip ζ and the lateral angle ξ. These inclinometers are made by Instruments & Control Inc. with a measuring capability of ±60 degrees. The total weight of the equipment is 2.4 kg.

It is also possible to use an image processing technique[22] for measuring the joint angles, but the technique using the goniometer has some unique advantages, such as being available anywhere, increasing the sampling frequency and synchronizing with force data.

2. 2 Force sensor

To measure the forces applied from the snow surface on a skier during descent, a force sensor that is able to detect three forces and three moments while inserted between a ski and its bindings was produced. It is 452 mm long, 63 mm wide and 22 mm high with a mass of 0.7 kg. The force detection unit has a parallel plate structure[23] using strain gauges as shown in Fig. 3. In a case where a force acts in the direction illustrated in this figure, strain gauges A and C are compressed and gauges B and D are tensed. Using a wheatstone bridge, the force is detected as a voltage change caused by the change in electrical resistance of the strain gauges. The sensor was manufactured from a single block into a structure combined with twelve parallel plate units, and twenty-four strain gauges were fixed on the unit surfaces to fabricate six bridge circuits as shown in Fig. 4. The directions of forces or moments are defined as those translated from the surface of the snow to a ski as shown in Fig. 5.

2. 3 Data recording device

The data recording device consists of a notebook

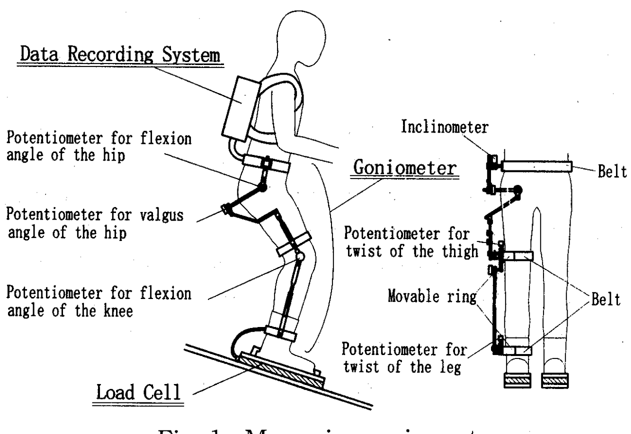

Fig. 1 Measuring equipment

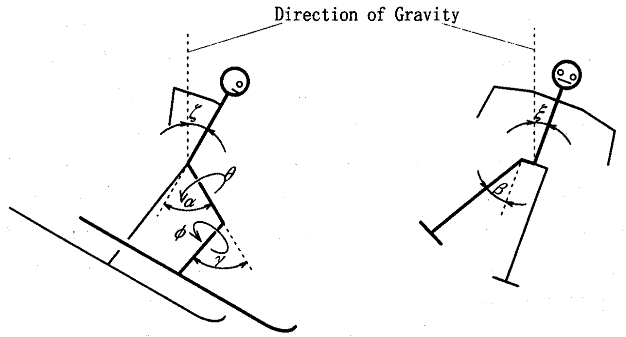

Fig. 2 Definitions of joint angles in a skier

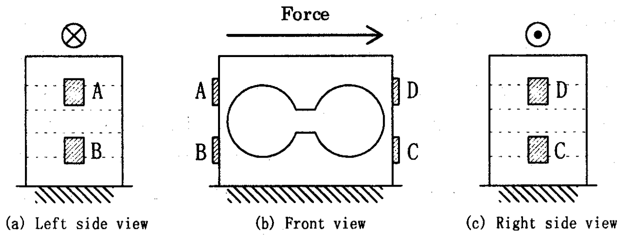

Fig. 3 Force detection unit

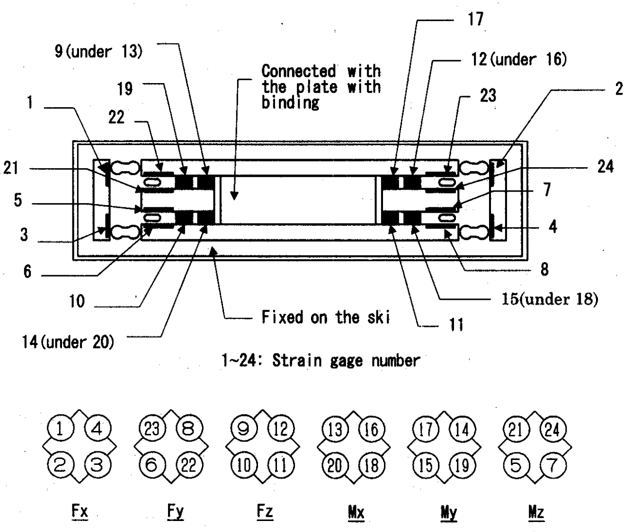

Fig. 4 Structure of the force sensor

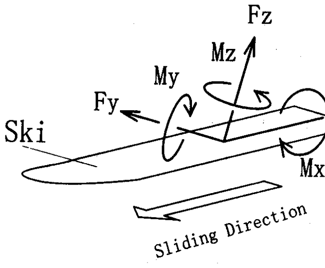

Fig. 5 Definition of forces and moments

computer, a 14 bit A/D converter, a voltage amplifier and a power supply. These units fit compactly into a small bag carried by the skier ; the bag has sufficient thermal insulation and is waterproof. The total weight of the device is 3.5 kg, including batteries. Data are sampled at intervals of 2 ms over a period of 32 s.

3. Performance of the Measuring System

Initially, the performance of the goniometer was investigated. If the fitting position of the goniometer is appropriate, the output voltage corresponds exactly to the joint angles. However, some measuring errors are caused by small differences in the positions of the attached belts. Therefore, data obtained from the goniometer were compared with the angles measured by a protractor. It was found that the precision of α and γ was good. The precision of β was also good, but sometimes tended to decrease slightly because the position of the belt attached on the skier's waist was changed by the skier's motion. The values of θ and ϕ were also accurate under room temperature conditions in the laboratory. Sometimes the sliding mechanisms did not work well under outside conditions in a snowfield at low temperature. Although the mechanism must be improved further, the data can still be investigated qualitatively.

According to catalog specifications, the inclinometer has an accuracy of at least 0.1 degree. The influence of vibrations during descent can be eliminated by smoothing the data using Fast Fourier Transform.

To evaluate the force sensor, several combined loads were applied. Typical examples of the results are shown in Fig. 6. The accuracy of the force sensor is confirmed by this figure. In another case, similar results were obtained.

4. Experimental Procedure

Experiments were carried out at Kanazawa Seymour Ski field, because there was a smooth slope of 18 degrees with a fall line more than 150 m long. A skilled skier (height 172 cm, body weight 78 kg), who is one of the authors and is also an instructor for SAJ,

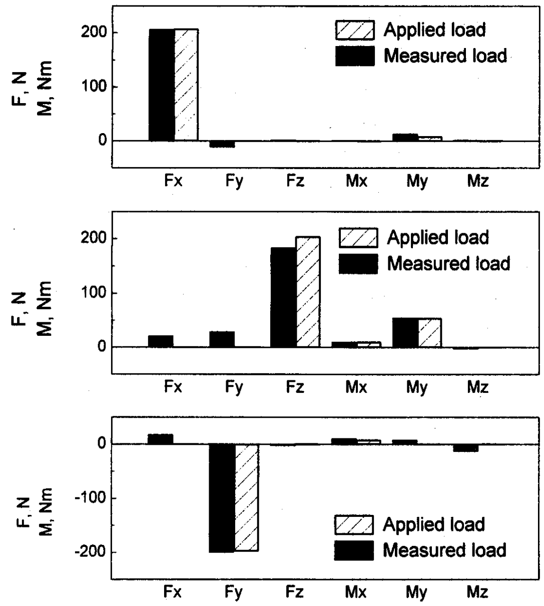

Fig. 6 Accuracy check using combined loads

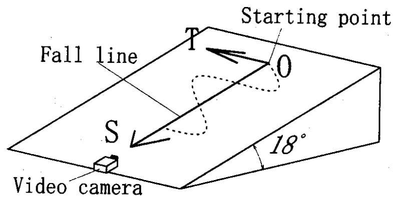

Fig. 7 Coordinates on the snow surface

was chosen as a test skier. The coordinate system was defined as shown in Fig. 7 on the basis of a fall line on the snow face. A video camera was set up at the point 150 m below the start position along the fall line (S axis). The camera settings, such as position, direction and magnification, were always fixed to record accurate coordinate points of the skier during the continuous skiing turns. After the start of an experiment with a signal from a radio and flash light, the skier first skied straight and then began long parallel turns as symmetrically as possible.

5. Experimental Results

5.1 Trace of the ski turn

Turning directions are defined as shown in Fig. 8. A left turn means that the right leg is positioned outside the turning arc. The movement of the skier's position in one turning cycle observed from the video picture is plotted in Fig. 9. The trace of the turn is almost symmetrical and can be approximated as a cyclic curve with an amplitude of 3 m and a wavelength of 30 m. All turn traces may be approximated by the same curve. The average descent velocity is approximately 10 m/s. The investigation using this approximation will be described in an upcoming report[24].

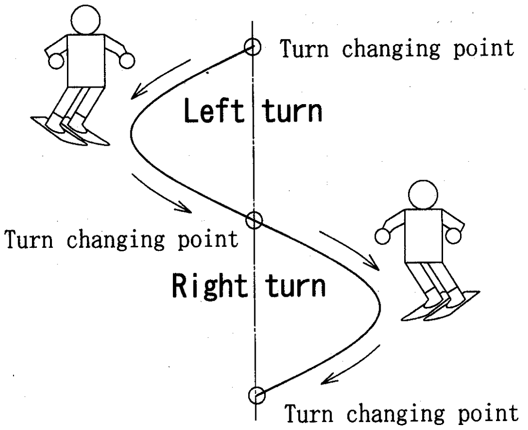

Fig. 8 Left turn and right turn

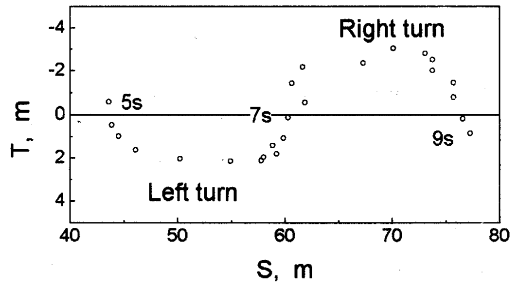

Fig. 9 Turn trace in one cyclie of a long turn

5.2 Joint angles of the skier

Each joint angle change in one cycle of a turn is shown in Fig. 10. The time corresponds to the trace shown in Fig. 9. The dotted lines indicate a changing point in the direction of the turn.

The angles α and γ have minimum values at the changing point in the direction of the turn. This means that a skier stretches the hip and the knee joints at that time to change the turning direction. This is the characteristic stretching technique in a long parallel turn. The angles in the right turn are larger than those in the left one, because the outside leg is extended to apply the load, and the inside leg is bent and lifted up so as not to interfere in the motion. The angle β opens slightly in the left turn and closes a little in the right turn. This suggests that bending the backbone may also play an important role. The tendency of the value to decrease with time is due to a small sift in the position of the belt in the goniometer. This error can be corrected by the inclinometers. The angle θ shows that both thighs are twisted to the inside during the turn. The angle ϕ shows that the outside leg is twisted to the outside during the turn because the knee is situated inside of the arc of the turn. This is an important motion to obtain enough edge angle for turning, and it corresponds to the action described as "A skier pushes his knee inside the arc of the turn." On the other hand, the motion of the inside leg is not as important in making a turn.

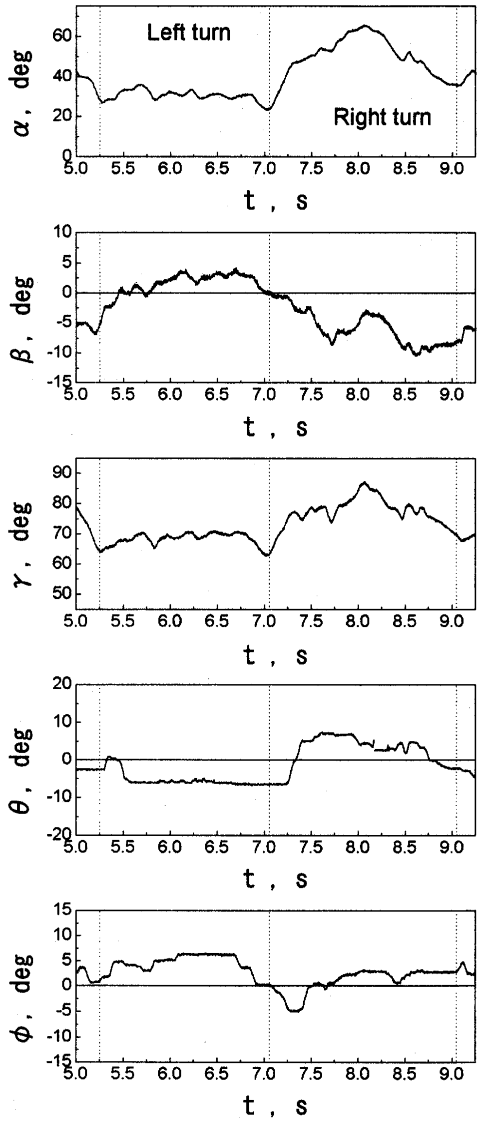

Fig. 10 Joint angles in one cycle of a long turn

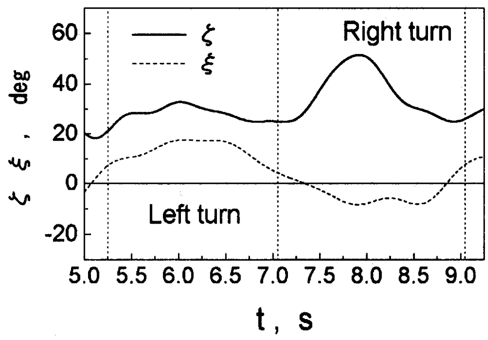

Fig. 11 Inclination angles of a skier

Inclination angles of the skier from the vertical direction are shown in Fig. 11. The data were processed through a FFT low pass 3 Hz filter[17]. The angle ζ shows that the skier always leans forward. Furthermore, the angle ξ indicates that the backbone is bent and the body is tilted inside in synchrony with β.

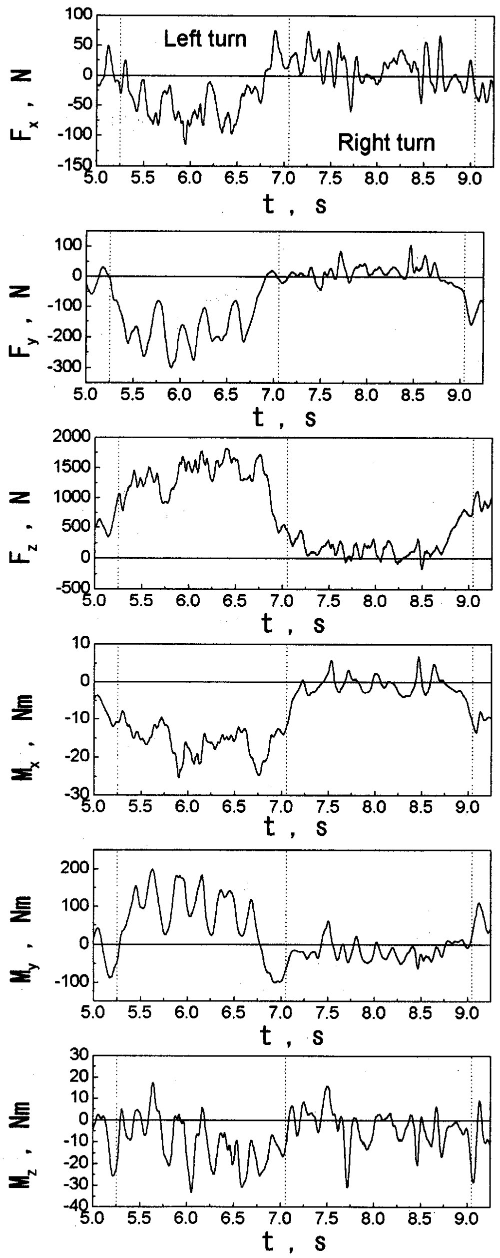

Fig. 12 Forces and moments in one cycle of a long turn

5.3 Forces from the snow surface

Forces operating on the skier from the snow surface are shown in Fig. 12. All forces and moments are almost at zero in the right turn, because the skier does not put weight on the inside leg during the long turn. On the other hand, various forces and moments produced by strong stepping motions are applied in the left turn.

The value of F_z gradually increases and then remains constant in the left turn. The value is larger than the weight of the skier at the top of the turn. A small F_x force is applied in the forward direction along the ski. It might be suggested that the skier pushes the ski backwards as is done in walking. The force F_y acts in the inside direction of the arc of a turn. This force is generated from the reaction of the centrifugal force with the snow plowing resistance. However, F_y does not represent the centripetal force of the turn, because the ski is inclined at the edge angle. The moment M_x is applied in a direction which decreases the angle of the ski edge. The value is small because the ski is narrow. The moment M_y shows that the skier pushes the front of the ski surface down to a great extent compared to the other moments to make it easy to rotate the ski during the turn. The skier does not forcibly rotate the ski because M_z hardly acts during the turn. These results support the importance of putting weight on the outside leg during the turn as instructed in the Japanese skiing curriculum[1].

6. Conclusion

A measuring system for joint angles in a skier and for applying forces during skiing has been developed to clarify the mechanism linking the motion and the dynamics of a turn. A long parallel turn was carried out by a skier with the measuring equipment attached. The results have been summarized for one cyclic turn. It is confirmed that a skier rotates the thigh to the inside of the arc of the turn with small rotation of the hip joint to the outside. The skier leans on the part of the outside ski through the outside leg with a lateral force in the outside direction.

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