The course of our ski research
3. Diagram of sliding ski drawn on a sheet of paper

スキー研究の軌跡
3．紙面上に描くスキー滑降図

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Summary.
We explain the meaning of drawing, on a sheet of paper, a locus of skis sliding on a snow plane and describe the method of drawing.

キーワード：スキー，スキー滑降，スキー回転機構，スキーロボット，スキー科学
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1. Introduction *Principle of ski movement*

We started our research on skis in July 1983. At that time, sports associated with skis included snow skiing, water-skiing, sand skiing and skiing on plastic slopes. Our focus of interest was whether or not a physical principle common to these various kinds of skis existed. The center of our attention was, of course, snow skis. Assuming that there is a principle common to the above kinds of skis, if we investigate the skis which are the easiest to study, then we should be to obtain the principle for snow skis.

We fabricated a small ski and investigated the ski movement on water flow in a nearby stream. The flow of water in the stream was not uniform and the ski showed movements too complex to analyze. Therefore, we considered various on-water experiments by producing a gutter to enable uniform water flow. We also performed ski-sliding experiments on fabric stretched over an inclined desk. It would have been impossible to clarify the principle of ski sliding from only these experiments; sliding of the above-mentioned kinds of skis seemed to be based on a principle different from that observed for skis sliding on a desk.

We have identified the difference only recently. Namely, snow is deformed by the weight of a ski, and whether the deformed plane is horizontal or not determines the movement of the ski. This should be the principle of ski movement. We present this principle in the Bulletin of Daido Institute of Technology [1].

We terminated our on-desk ski-sliding experiments in the early stage, and attempted to find a material on which the locus of a sliding ski remains. We considered that sugar or salt might be a good material for replacing snow since they are white; however, they were not appropriate due perhaps to instability under humid or high temperature conditions. We also adopted sand in the experiments because sand skiing actually exists. Details are explained in Bulletin of Daido Institute of Technology [2]. Eighteen years have passed since the start of our research. Sometimes we still perform sand-ski experiments, since it is convenient because we need not go to snowy mountains, and we can perform experiments at any time.

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2. Science

2.1 History of science

Currently, studies in natural science refer to those established by and after Galileo and Newton. Let us consider ski science by looking back at its history around their time.

The sun rises from the east in the morning and sets in the west at night. The time of sunrise and sunset is announced every day on TV, and nobody thinks it unusual. It is based on the geocentric theory that the earth is located at the center of the universe, and the universe is rotating around the earth. However, while the geocentric theory may be correct for fixed stars such as the sun, the motions of planets could not be explained properly with this theory. Is the sky truly moving ? Tycho Brahe (b. 1546) made an observation instrument for stars, performed accurate measurements, and clarified the time and the position of moving stars using the observed data. His pupil Johannes Kepler (b. 1571) discovered the mathematical laws using the relationship between the position of the stars and the time. These laws are called Kepler's first, second and third laws, and are described in physics textbooks used in universities. Based on these three laws, Isaac Newton (b. 1642) introduced the existence of the force (universal gravitation) between masses. This gravitation is the centripetal force required for the rotation of the earth around the sun. Thus, the starting point of natural science was the measurement of position and time.

2.2 Current status of the ski research

Such developmental process of studies will be useful in our research on skiing. Studies on the "turning mechanism of skis" performed to date are classified into four categories. In any one of them, the relationship between the positions of skis and the time are described only ambiguously, or not explicitly described.

(1) Forces acting on skis[3,4] and forces acting on a skier's body[5-7] were investigated using advanced technology. However, in those studies, the relationship between the time when these forces are acting and the position of the skis/skier at that time were not clearly described. In concrete terms, it is necessary to experimentally show when and where forces measured using advanced technology are acting during skiing.

(2) Based on the assumption of the motion of the skis/skier, the motion was numerically investigated using a computer.[8-11] A general investigative method is to compare the assumed motion of the skis/skier and the actual motion of the skis/skier on a snow plane; however, no such studies have yet been reported.

(3) Ski robots are becoming popular. A human body has many bones and joints, which move cooperatively during skiing. A robot with only some of the movable joints (among the many joints of the human body) was constructed and used for studies of the "motion of a ski robot."[12-16] The reason why specific joints were selected may have been the ease of fabrication, and not that the motion of the ski robot resembles that of actual skiers. There have been no studies which logically and quantitatively examine points of similarity and identical points between the motion of a ski robot and that of a skier.

(4) There is a study in which experiments measuring the load applied to skis were carried out,[17] but the position and the time of the skis are not clear. There is also an experiment on the cutting resistance of ice by a ski,[18] but again, the position and the time of the ski were not investigated. Besides these two studies, both the position and the time of skis have been measured for a straight descent or a descent close to a straight descent, but in only a limited number of studies.[19-21]

To assume skiing motions is the same as to imagine skiing motions. The investigation of skiing motions by means of experiments is to observe true skiing motions. Large measurement errors of skiing motions correspond to obscure observations, and small measurement errors to clear observations. Even the obscure observation of ski descents may be better than imagined ski descents.

2.3 Motion and resistance of skis/skier

The motion of the skis/skier is determined by the gravity and resistance acting on the skis/skier. When a skier is flying through the air, the resistance is determined by the friction of the air and buoyancy, which is not so large as to stop the motion of the skier. In contrast, the resistance when skis are sliding on a snow plane is generated from the friction between the skis and the snow plane, which can be large enough to stop the motion of the skis. Skiing descent on a snow plane is mostly determined by this friction. The friction includes the motion cutting a snow plane using skis, i.e., side slipping. In analyses of ski motions, the friction between a ski plate and snow experimentally measured in a laboratory[22] is not very useful.

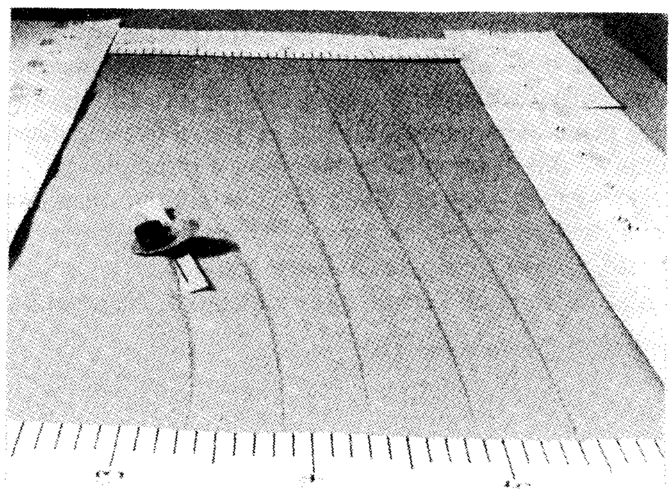

Fig. 1. Model ski sliding on a sand plane. Taken on December 10, 1983.

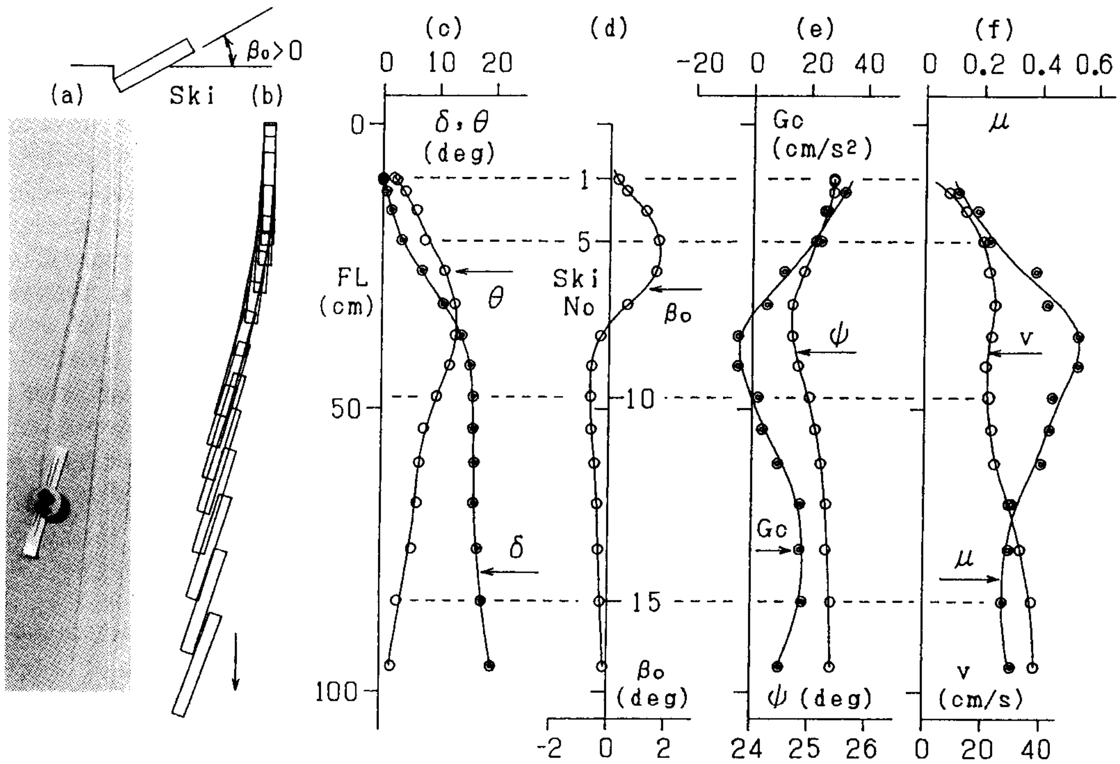

Fig. 2. (a) Model ski, (b) locus of the sliding ski, (c) ski angle δ and tangential angle θ, (d) edging angle β_0 relative to the horizontal plane, (e) acceleration *Gc* of the ski in the sliding direction and inclination angle ψ of the ski slope in the sliding direction, (f) velocity *v* and coefficient of kinetic friction μ of the ski in the sliding direction.

To investigate the friction between skis and a snow plane, it is essential to obtain data on the ski position on a snow plane at certain times. This is the basis of the investigation of the motions of the skis/skier on a snow plane, namely, the starting point of ski science.

3. Sliding-ski experiment

3.1 Model ski (sand ski)

In 1983, we qualitatively investigated turning descents of a model ski in a laboratory. At that time, it was difficult to quantitatively investigate the loci of a ski descent. The sand ski plane used in the experiments was made of a box of 180×80×5 (cm^3) into which well-dried sand was introduced. To maintain an exactly flat plane without bumps and dips, the box was placed on a ping-pong table. We took continuous photographs of a sliding-ski on the sand plane, and investigated the loci of the ski based on the analysis of the photographs. In this experiment, a ruler with cm units was placed on the sand plane, as shown in Fig. 1, and a camera was positioned diagonally above the plane. In the photographs, the shape of the rectangular ski slope was deformed and the contraction scale of the up, down, left and right rulers differed. Therefore, we corrected these differences by tilting the photographic paper at the time of enlargement of the photographs, so that the contraction scales of the four rulers became identical. From the analysis of the photographs, we found that during the time period when the ski was sliding on the sand plane for approximately 1.5 m, we could measure the ski motion with an accuracy of 1 mm. Using this analytical method, we were able to measure ski motions in terms of the following factors: velocity *v*, acceleration *Gc*, sliding direction θ, and the direction δ of the ski length.[2] For details on the measurement of the angle (edging angle β) between the surface of the ski slope and the sliding plane of the ski, refer to the Bulletin of Daido Institute of Technology.[2] We obtained the angle (edging angle β_0) between the horizontal plane and the sliding plane of the ski from the equation[23] using the slope angle α, β and θ. We also found that the sliding direction of a ski is determined by the sign of β_0.[2] Our success in obtaining the physical constant of ski motion, β_0, proves that our work can be called ski science.

Figure 2(a) shows an example of a model ski sliding on a sand plane. This sand-ski photograph was initially analyzed in December 1983. Figure 2 shows the reanalysis of the photograph in 2000. The term μ represents the coefficient of friction; refer to the paper[24] on β, θ, δ and ψ.

(a) (b)

Fig. 3. (a) Straight descent, skier: Nakaya, at Hoonoki-daira Ski Resort, taken on January 27, 1992.
(b) Turning descent, at Kumanoyu Ski Resort, taken on January 8, 1984.

3.2 Snow ski

In the winter of 1984, we investigated the values of β_0 on a snow plane. In the straight descent of skis, all edging angles satisfied $\beta_0=0°$. We measured loci of ski descents carved by many skiers which remained on the snow plane. As a result, we confirmed that $\beta_0=0°$ for straight descents (Fig. 3(a)), and $\beta_0 \neq 0°$ for turning descents (Fig. 3(b)). However, to explain this in a paper, it was necessary to describe the track of a ski on a sheet of paper, using the ski's positions and the values of the edging angle. In the case of straight descents, showing the track is possible using length measurement data and a photograph. However, in the case of turning descents, it is not so easy; we tried to develop a method of drawing a track of turning descent using photographs. We explain the method in the following section.

4. Locus of the ski drawn on a sheet of paper

4.1 Snow plane and photograph

As shown in Fig. 4, when a camera is positioned at q perpendicularly above the snow plane and a photograph is taken, a pattern whose size is proportional to the pattern on the snow plane is expressed. However, such an experiment was too costly for us. Therefore, we took photographs by placing a camera diagonally above the snow plane ehjq, as shown in Fig. 5. When a photograph is taken from position p, the size of the photograph is proportional to the plane kbjq; we call the plane kbjq the photo plane. The magnification factor of the photograph can be determined from the film size and the focal distance. We take an example in which a ski is placed in the direction of ac at the center of the snow plane ehjq, and the ski appears on gc in the photo plane, in order to explain the method of reproducing the ski on the snow plane using a photograph.

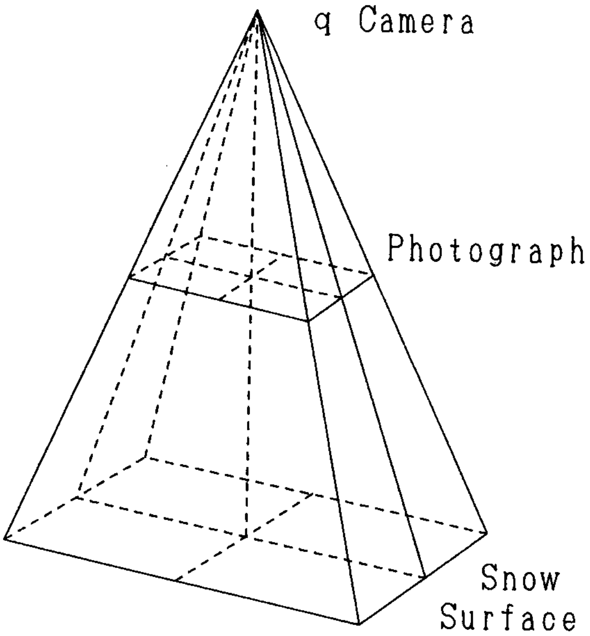

Fig. 4. Photograph is taken using camera q perpendicular to the snow plane.

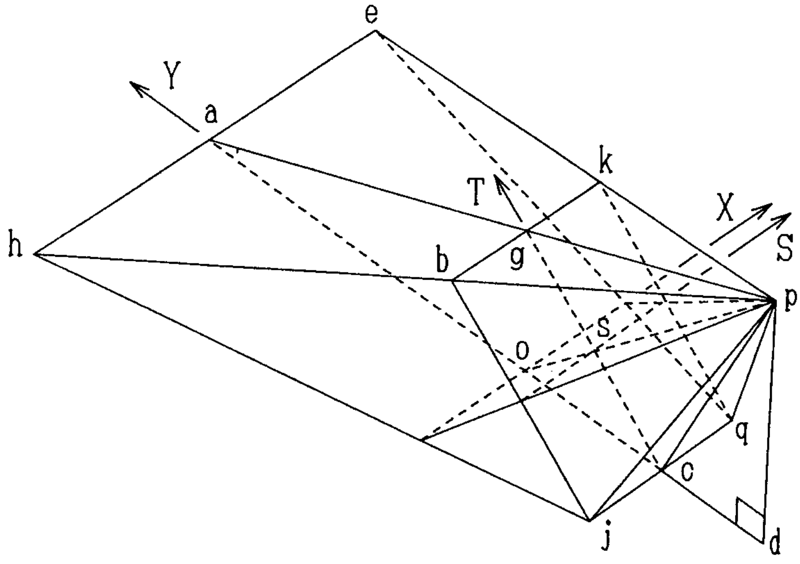

Fig. 5. Photograph is taken using camera p diagonally above the snow plane.