3.8 s and β

Using the gate-type ski and varying the edging angle in the ranges of $5^\circ \leqq \beta \leqq 35^\circ$ and the sand depth in the range of $0.05\text{cm} \leqq s \leqq 1.4\text{cm}$, the same ski descent experiments as those in the case of Fig.12 were performed. Figure 13 shows the results for the three types of skis. All three types of skis made an uphill turn when $0.5\text{cm} < s$, and the values of R_0 were similar. When $s < 0.2\text{cm}$, the values of R_0 for the three types of skis were different. In particular, the barrel-type ski made not an uphill turn, but zig-zag turns. In addition, the width of the ski track was small. Thus, differences in the descents of the three types of skis were observed when the sand depth was small.

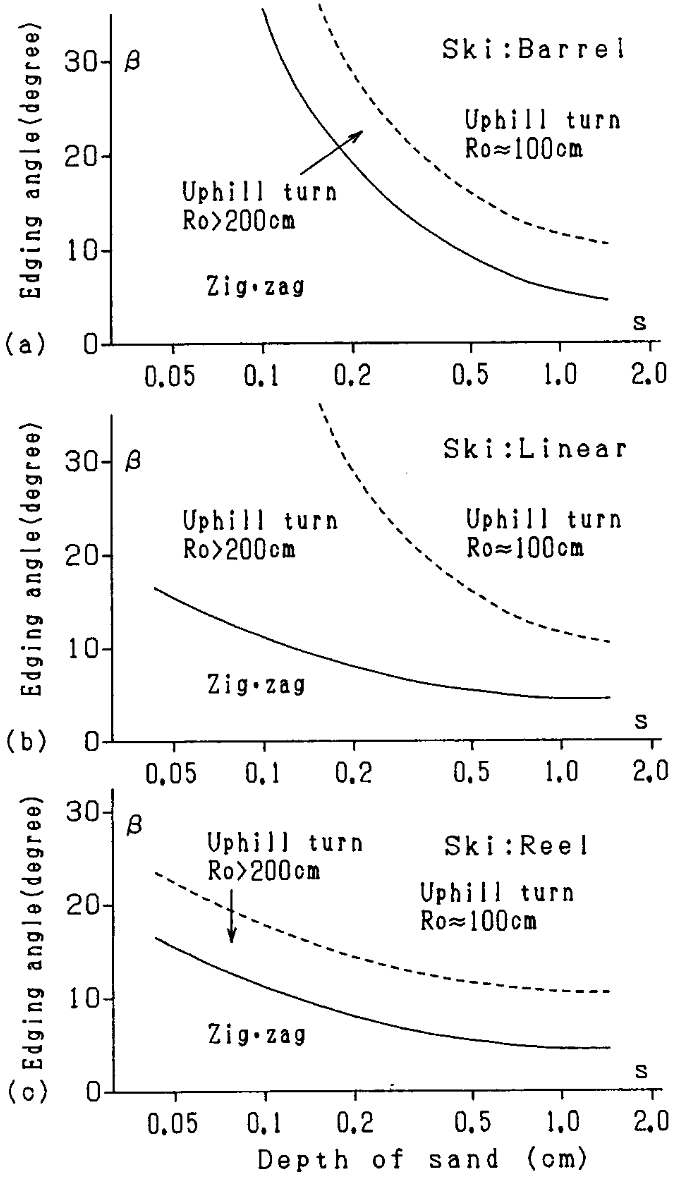


Fig.13. β and s for the gate-type ski.

4. Discussion

4.1 Effects of side–cut

In the previous experiment,[2] we investigated the turning behavior of three types of skis with the center of gravity x_0 set at the same value. We found that the direction of turn was the same for all three types of skis, but the radius of curvature R_0 was largest for the barrel-type ski, followed by the linear-type and the reel-type. That is, the reel-type ski turned the most easily. In this experiment, the average ski width w for each of the three types of skis was similar, but the ski width at the center of the ski was largest for the barrel-type, followed by the linear-type and the reel-type. This confirms that the ski turns easily when the ski width is small, as described in section 3.2. In the current study, the ski width w at the center of the ski was set at the same value and the relationship between the state of descent and the radius of curvature R_0 was investigated (Table I).

The results are as follows for $0.5\text{cm} < s$. For the three types of skis both without gate-holder (Figs.7,8 and 9) and with the gate-holder (Fig.11,12 and 13), the descent conditions and the radius of curvature were similar. Namely, the descent behavior of each of the three types of skis differs slightly depending on the type of side-cut. However, no effects of the type of side-cut on the direction of turn or the radius of curvature were observed. When $s < 0.2\text{cm}$, the three types of skis without the gate-holder (Fig.9) made zig-zag turns; no circular arc of turn was observed. For the three types of skis with the gate-holder (Figs.12 and 13), the descent conditions were different for each type of side-cut; a circular arc of turn in the direction of edging angle β was obtained for reel-type and linear-type skis. However, no circular arc of turn was obtained for the barrel-type ski since it made a zig-zag turn.

When $s < 0.2\text{cm}$, since the amount of sand was small, the skis appeared to be descending on the cotton cloth glued onto the bottom of the box. Therefore, it was difficult to find the ski track. This sand surface is considered to correspond to a hard snow surface such as an icy slope. Thus, when the depth of the surface of descent was $s < 0.2\text{cm}$, the effects of the side-cut were apparent.

Table I Descent conditions and radius of curvature R_0.

		$s < 0.2\text{cm}$	$0.5\text{cm} < s$
Ski without gate-holder	Barrel-type Linear-type Reel-type	Zig-zag	Similar in descent and radius
Ski with gate-holder	Barrel-type Linear-type Reel-type	Zig-zag Similar in descent, but different in radius	Similar in descent and radius
Effect of side-cut		Effective	No effect

4.2 Turning mechanism of skis

4.2.1 Factors of turning descent

When the sand is deep and the track of a descending ski remains clearly on the sand surface, *all skis perform turning descents in the same direction with similar radii of curvature regardless of the types of side-cut.* The fact that the track of the descending ski remains clearly on the sand surface means that the distance b–c shown in Fig.3(b) is large. That is, the contact area between the ski and the sand surface, namely, the area of the sand surface deformed due to edging, is large. When the contact area is large, the ski turns easily regardless of the type of side-cut. Accordingly, we consider that the turning mechanism of a ski can be explained using the linear-type ski.

Two factors[2)] are suggested to influence the mechanism of turning descent: flexion of the front part (forebody) of a ski and edging. Flexion of the forebody of a ski means that the part between the center and the front tip of the ski is almost planar when the ski is still, but begins to curve upward when the ski begins to descend. This means that the area of contact between the sand and the forebody of the ski is the same as that at the rear part (afterbody) of the ski, before the ski begins to descend; however, once the ski begins to descend, the area of contact at the forebody of the ski becomes small whereas that at the afterbody of the ski becomes large.[2)]

Using two factors, we will explain the mechanism by which a ski begins an uphill turn from a state of straight downhill run, by the following three methods.

4.2.2 Mechanism-1

As shown in Fig.14, the top views of the movement of the ski were classified and drawn in (a), (b), (c) and (d). The diagonal lines indicate the area where the ski and the sand surface are in contact with each other.

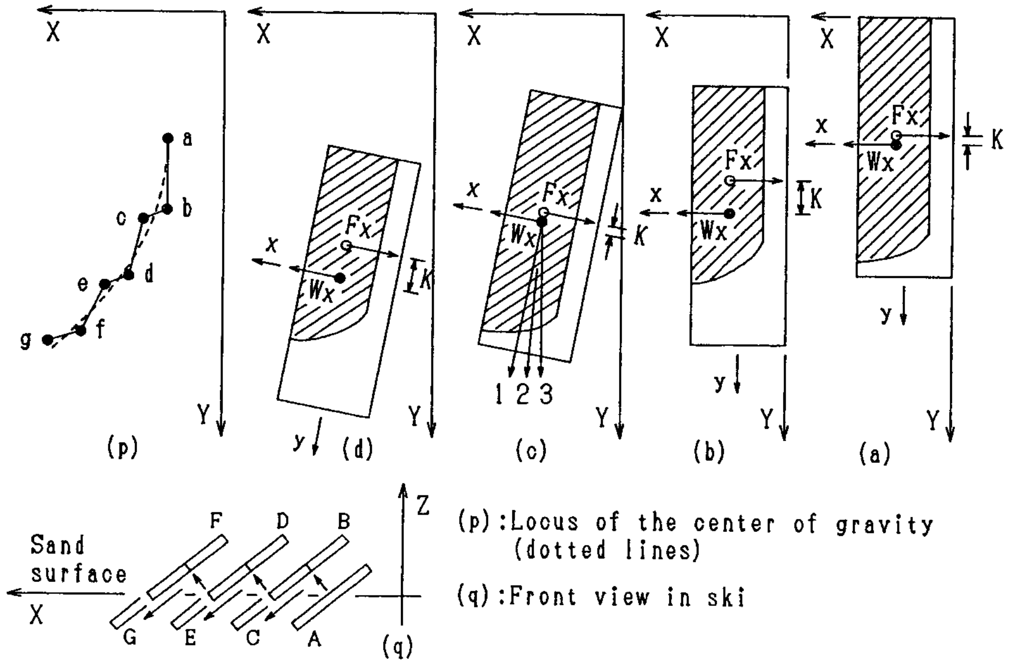
* between the sand and the afterbody

(a) The total weight of the ski is written as Mg and we assume that no acceleration other than gravity acts on the ski. A ski with the edging angle β_0 is positioned in the direction of Y. The component of gravity acting in the $+x$ direction is set as W_x, and the frictional resistance acting in the $-x$ direction is set as F_x. Before the start of descent, the contact area between the sand and the forebody of the ski is almost the same as that* ~~in the afterbody~~. Accordingly, the point of action of frictional force is close to the center of gravity, and the distance K between W_x and F_x may be as small as K=0. Therefore, the ski does not undergo rotational motion and descends in the Y direction. Thus, from Fig.15, the component of gravity becomes

$W_x=Mg_x=Mg\cdot\cos\alpha\cdot\sin\beta_0$, $Mg_y=Mg\cdot\sin\alpha$ and $Mg_z=Mg\cdot\cos\alpha\cdot\cos\beta_0$.

(b) On the forebody of the descending ski, a force with upward direction, which is perpendicular to the ski surface, is applied to the ski from the sand surface. Accordingly, the forebody of the ski was lifted off the slope and becomes flexed, resulting in a decrease in the contact area at the forebody and backward shift of the point of action of frictional resistance F_x. The distance K between W_x and F_x increases, leading to rotational motion ($K\neq0$). This rotational motion is the motion in contact with the ski surface. Namely, the forebody of the ski which was lifted off the sand begins to intrude into the sand (x direction) again. The afterbody of the ski merely follows the forebody, because no upward force acts on the ski there.

(c) Due to the rotational motion in contact with the ski surface, the contact area at the forebody of the ski increases again. The point of action of frictional resistance F_x moves near the center of gravity, and the distance K between W_x and F_x decreases, stopping the rotational motion ($K\approx0$).



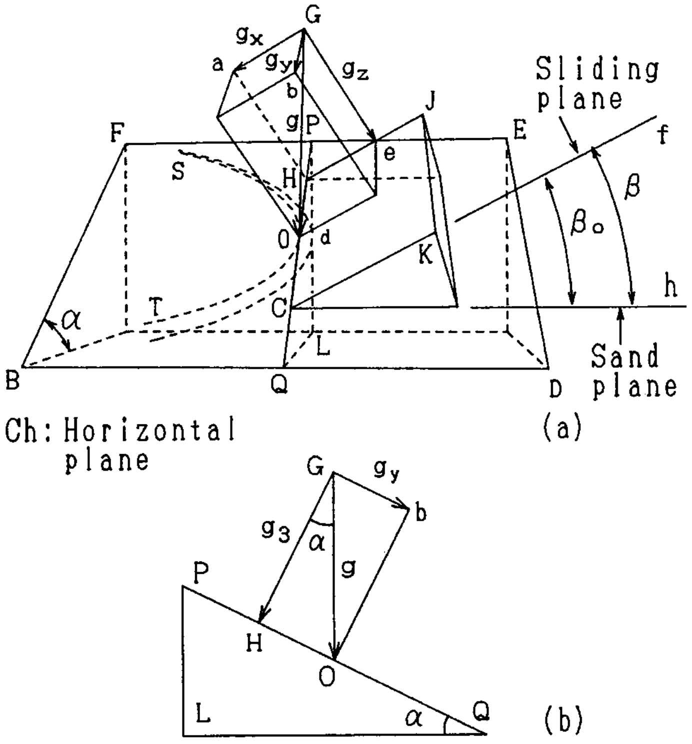
(p):Locus of the center of gravity (dotted lines)
(q):Front view in ski

Fig.14. Diagram explaining the turning mechanism of the ski.

When the ski is in this state, it is easy for it to descend toward direction 1. However, since the gravity component Mg_y in direction 3 of the ski is also large, the ski will descend in direction 2, which is between directions 1 and 3, when the sand surface, which was deformed due to edging of the ski, is soft. This means that side-skidding occurs under condition (c). At this time, if the edging angle is large, the ski edge digs deeply into the sand and side-skidding resistance increases remarkably. Accordingly, the ski descends in direction 1 (in which the resistance is small), making a carving turn.

(d) The forebody of the ski gradually lifts off the sand while continuing to side-skidding, the value of K increases, and rotational motion begins again.

(p) The positions of the center of gravity of skis (a), (b), (c) and (d) are represented as a, b, c and d, respectively, and redrawn here. If the time period between (a), (b), (c) and (d) is decreased infinitely, then a smooth curved line (dotted line) is obtained. This indicates an uphill turn with the edged ski.



$g=980\,\mathrm{cm/s^2}$, $g_3=g\cdot\cos\alpha$, $g_y=g\cdot\sin\alpha$
$g_x=g_3\cdot\sin\beta_0$, $g_z=g_3\cdot\cos\beta_0$

Fig. 15. (a) Gravity component of the edged ski. SOT is a track of a descending skier on skis. When the skier is at the point O, $\beta=\beta_0$, and the bottom surface of the ski is on the CKJH plane with the ski pointing in the direction of PQ. G is the position of the center of gravity of the skier. β is the inclination angle of the snow plane, and PQ is the fall line (FL). (b) Cross section of PQL; GH is perpendicular to the sliding plane BDEF.

When the ski is undergoing rotational motion, the value of W_x can be obtained as follows. Assuming that the angle formed between the direction of descent of the ski and the FL is θ, the inclination angle of the ski slope with respect to the ski descending in the direction of θ, changes from α to ϕ. The value of ϕ is called the apparent inclination angle.1)

$$\phi=\tan^{-1}(h/\sqrt{b^2+c^2}),\ h=\sin\alpha,\ b=\tan\theta,\ c=\cos\alpha.$$

The component of gravity which acts in the x direction changes to

$$W_x=Mg_x=Mg\cdot\cos\phi\cdot\sin\beta_0.$$

4.2.3 Mechanism-2

Figure 14(q) represents the motion of the forebody of the ski observed from the cross section of its forebody. In this diagram, the motion in the Y-axis direction is neglected. The status of the ski (a)→(b) corresponds to the lifting of the ski; therefore the motion is expressed by A→B. (b)→(c) corresponds to the ski intruding into the sand during a turn (rotation), *is therefore expressed by B→C. If the time periods between (a),(b),(c) and (d) are decreased to almost 0, then the forebody of the ski moves toward the X-axis.

*and the motion

4.2.4 Mechanism-3

Figure 14 shows that the sum of the upward force, which is perpendicular to the ski, and the force in the edging direction W_x, generates a force parallel to the sand surface (a force in the X-axis direction). In all three cases, the afterbody of the ski follows the forebody of the ski.

4.3 Mechanism of uphill turn

Due to flexion and edging of a ski, the force in the X direction is made and the force in the Y direction is also made by the inclination of a slope. A sum of the forces in the X and Y direction produces a revolutional motion. When the force in the X direction is different in the forebody and the afterbody of a ski, the difference introduces a rotational motion. An uphill turn is made from the revolutional and rotational motion.

4.4 β for the gate-type ski

In section 3.6, when $5^\circ\leqq\beta\leqq20^\circ$, the ski turned easily with increasing β, and the value of R_0 decreased. However, when $20^\circ\leqq\beta\leqq35^\circ$, it turned with greater difficulty with increasing β, and the value of R_0 increased. This can be explained as follows. The force (in the X-axis direction) resulting from the two forces described in section 4.2.4 is necessary for the ski to turn.

(1) The component of gravity acting in the x direction of edging, W_x. W_x is expressed as $Mg\cdot\cos\alpha\cdot\sin\beta_0$. When the ski is in the FL direction, $\beta=\beta_0$ holds and W_x increases with increasing β.

(2) Upward force which acts perpendicular to the ski.

When β is small, the distance between b and c in Fig.3 is large and the contact area between the ski and the sand is also large. Thus, the force parallel to the sand surface (the force in the X direction described in section 4.2.4)) increases with increasing β, and the ski turns with ease. As β increases, the contact area between the ski and the sand decreases. As a result, the upward force from the sand surface weakens. Accordingly, as the upward force decreases, the force in the X direction also decrease, and the ski turns with difficulty.

4.5 Edging angle β

The direction of ski turns is determined by the sign of the value of β_0.[3] To evaluate the effects of edging, it is necessary to investigate the states of descent while varying the value of β_0. However, it is difficult to maintain a constant value of β_0. Therefore, in this study, we performed experiments using the gate-type ski in order to maintain β at a constant value. As a result, we found that when β is too large, the ski turn becomes difficult. When the direction of descent is close to the direction of FL, $\beta_0 \approx \beta$ holds and the effects of β may be similar to those of β_0. When the direction of descent is not close to the direction of the FL and β is very large, β_0 also becomes large and ski turns edged with β_0 are estimated to become difficult.

4.6 Carpet ski

Shimizu [9] and Ohara [10] performed descent experiments using a ski robot performing edging on a carpet. Shimizu used three types of skis (linear-, reel- and barrel-types) which were similar to ours. The directions of descent of the ski robot varied depending on the ski types. If we assume that the carpet corresponds to shallow sand (s<0.2cm), then the results obtained for the ski robot descending on the carpet are similar to those of skis descending on the sand surface, shown in Figs.12 and 13. The ski robot in Shimizu's experiments is considered to correspond to the gate-type ski in our experiments. Skiing descent on a carpet is unrelated to the deformation of the sliding plane (refer to §4.7). Therefore, this descent on the carpet will be based on a mechanism different from that of snow-ski descent.

4.7 Deformation of the sand (snow) surface

For the track of the ski making turns, $\beta \neq 0°$ holds due to edging of the ski on the sand (snow) surface.[3,4] The track, for which $\beta_0 \neq 0°$, is formed by deformation of the sand (snow) surface due to the weight of the ski (including objects mounted on the ski), as shown in Figs. 5 and 6. The turning mechanism described in section 4.2 is explained in terms of the deformation of the sand surface accompanying the movement of the ski. One of the causes of the ski turns may be the deformation of the sand (snow) surface due to the movement of the ski. On materials which can be deformed by the weight of skis, descent with turns, such as those of skis on snow, may be possible.

5. Conclusions

Many of the snow surfaces on which we ski are deformed by ski edgings, and ski tracks remain on the surface if even the ski-skidding does not exist. In ski descents on such snow surfaces, the effects of a side-cut on the ski turns are considered to be minimal.

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