OUTLINE OF A COHERENT THEORY OF SKIING

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I. Introduction

The word "theory" has to be used with caution in connection with something as practical and, consequently, as complex as skiing. As in many (if not most) cases of practical interest, what theory can do here is a sound analysis of the empirical findings, in an attempt to single out the promising ones, or at least to point out the worst errors.

Skiing has changed enormously in the last 10 years. Besides the internal logics of the strive for perfection and performance (especially in a competition sport) this evolution is largely due to the introduction of sophisticated design, new materials and technology into the fabrication of skiing equipment. The properties of today's, even middle priced skis and boots are mostly determined by the purpose for which they were made and not by a restricted choice of materials, as was the case earlier. For example, ski boots made in the last 2-3 years can be at the same time rigid in one direction and elastic in another.

The evolution of the technique of skiing, in interaction with the improvement of the equipment, seems to happen in a very logical direction : towards a simplification. As compared to his predecessors, today's skiers have to do less to achieve the same result or they can go further with the same effort and risk. The body movements become more and more reduced,sober and esthetic at the same. Essentially, modern skiing tends towards an extreme economy of gestures with the main emphasis on the fine movements of maintaining the equilibrium of the body on the skis ; in this respect some of the movements are analogous to the spontaneous balance keeping in everyday walking.

In what follows we will try to outline a coherent image of the key physical aspects of modern skiing. We will consider the basic mechanical properties of skis and boots, the main effects of the ski-snow interaction forces, the mechanisms for piloting the skis and for maintaining the balance.

As far as references are concerned in the literature of skiing it is not customary, and practically not possible, to give a proper referencing of ideas and achievements as it would be ideally meant in science. In any case to our knowledge, the considerations as presented in this paper are original and they are based on a concept of modern skiing developed by one of the authors (G.J.) and described in his latest book (1).

II. The skis and boots

The exact behaviour of a pair of skis on the snow depends on a large number of mechanical parameters. Some dozen of these (shape, resistance to bending and twisting, frequency and attenuation of vibrational modes, etc.) are actually measured and checked by the manufacturers of top quality skis. However, even these data turn out to be insufficient to characterize how skis "feel" in action. At least for the moment, the mechanical analysis is way behind the practical experience. In any case, the most pertinent features are the followings.

The shape of modern skis, narrower at the center than at both the tip and the tail (as exageratedly shown in Fig. 1)

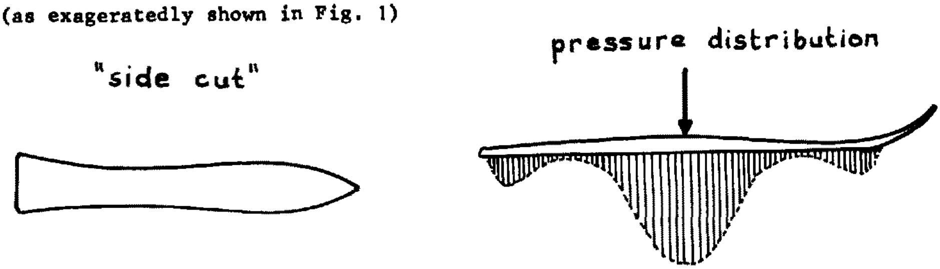

Fig. 1

serves two main purposes :

- the ski put on its edge has a natural tendency to turn following the curved line of the edge, the "side cut".
- the widening towards the tail provokes an extra friction on the snow at this level, which has been found to be vital for the directional stability of the skis at higher speeds.

The typical distribution of pressure under the ski on a flat snow surface is also shown in Fig. 1. It has been found empirically that this is the type of pressure distribution which is best suited for downhill skiing. (For cross country skis the distribution has to be more uniform). The pressure maxima at the extremities and the exact shape (width) and position of the main pressure peak at the ski center are determined by the camber and the stiffness distribution of the ski, respectively. More pressure, for example, towards the tip produces more friction and snow packing resistance at this point, which results in lesser directional stability, i.e. in a sense the ski is easier to turn. Therefore downhill racing skis have relatively soft tips, which not only improve their stability but also make them faster because the deformation of the snow under the ski tips happens more gradually.

The notion of "stiff" and and "soft" here is meant to be with respect to an empirically established "neutral" average. In much of what follows we have to assume that we are dealing with such "neutral", well balanced skis. In particular skis, which have lost their original elasticity due to a long wear and tear, will most often respond quite differently. In general, our analysis leads to the demonstration of tendencies which are clearly perceptible and effective close to an equilibrium situation, but can be obscured by serious deviations. E.g. a bad directional stability of the skis in straight gliding can be due to a habitual forward lean of the skier, and not to the skis. (Furthermore in such a case the compensation of this effect by the use of soft tipped skis might only give very temporary results, since the skier is likely to give freer reign to his, now less dangerous, bad habit). More generally, the modification of the above ski-snow contact pressure distribution by a displacement of the point of application of the body weight, ideally between the centre of the boot sole and a point a few centimeters behind it, is a fine but crucial element in controlling the behaviour of the skis.

The most delicate and not very well understood quality of a pair of skis is its hold on icy snow. The torsional stiffness, vibrational properties and the "side cut" certainly play an essential role. For an average skier the main perceptible difference between a medium and a top priced ski is just in the grip on ice.

The ski boots have to satisfy two main mechanical conditions :

- They should be completely rigid laterally to permit a precise control of the ski edge.
- They should be elastic within certain limits in the forward-backward direction. This latter property has been given much emphasis in the last few years. It is essential for the fine control of the skis and for a smooth maintenance of equilibrium, because it permits delicate displacements of the body centre of gravity with respect to the feet without parasitic torques. Let us consider the example of an off-balance forward lean of the skier. If the boots block any movement of the shins, immediately the torque puts an extra weight on the ski tips producing an increased snow resistance, which in turn tends to add to the forward lean. If, on the other hand, the shin has a certain freedom, the skier will have a chance to reestablish a perfect balance by pushing his feet forward without putting much torque on the boots. However, if he should fail to do so, finally the boots have to step in by gradually blocking the shin at a limit of forward bend and providing the skier with a support for a "passive" recovery of the equilibrium. The same argument applies to a backward lean too but in this case the amplitude of the movement is about 3 times less. This relative freedom of the shin (of about 15° total amplitude) in the forward-backward direction is also necessary for a soft, balanced up-down motion of the skier, e.g. to absorb the shock of bumps.

II. Ski-snow contact forces and the steering of the skis.

From the mechanical point of view, downhill skiing can be divided into three main components : control of the skis, the maintenance of balance and the trajectory of the body centre of gravity.

The particularity of the control of the skis is due to their large moment of inertia, in comparison with the moment of inertia of the bare feet or even that of the whole straightened out body with respect to the vertical axis through the centre of gravity. Thus it is understandable that in most cases the sheer muscular force of the skier(the "active pivoting")proves to be insufficient in itself to change the direction of the long axis of the skis rapidly enough.

In actual fact, the most frequently used mechanism for rotating the skis into a desired direction procedes by the utilization of the friction and snow resistance forces acting on the skis which we call "ski-snow forces". We have already mentioned some of their effects : namely those which assure a good directional stability to the skis when they are flat on the snow and sliding in a straight line. We now come to the point where we show how the ski-snow forces can also make the skis turn ("passive pivoting").

One of these cases has also been mentioned above : the ski carving the snow on an edge tends to turn following the curved line of the edge. The curvature of the ski-snow contact line is even increased by the bending of the edged ski under the weight of the body.This "carved turning effect" plays a major role in performance skiing (high speeds, icy slopes) since it produces little friction and allows the skier to avoid undue slide-slips, but it cannot result in sharp turns. In addition, it often requires an extraordinary muscular "fixation" effort to keep the ski on the edge, and the roughness of the snow surfaces and/or the vibrations of the ski can make continuous carving impossible. Thus the "carved turns" more often than not represent but an objective for the top level skier to be approached by a constant effort in both holding the ski and readjusting its position in order to minimize the sideslip.

The predominantly utilized mechanism of "passing pivoting" of the skis is what we call the "sideslip turning effect". This is effective when the skis are put more or less on the edge, but not sufficiently to produce a carving effect, thus they sideslip rather freely. The friction and snow resistance forces acting on the sideslipping ski (Fig. 2)

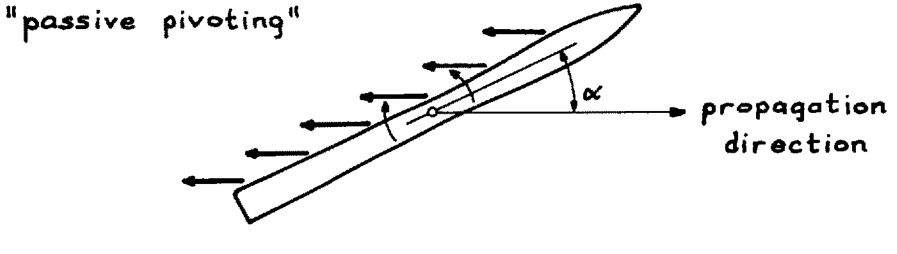

Fig. 2

will in general produce a resultant torque with respect to the ski centre of gravity which can be in either sense, depending on the distribution of these forces along the ski. Thus, putting more weight towards the tip increases the ski-snow forces in front of the ski centre, which results in a net torque turning the ski even further from the propagation direction, i.e. increasing the sideslip angle α. To the contrary, more pressure on the tails tends to turn the skis into the direction of sliding, i.e. to reduce α.

In practice, consciously or not, skiers use to different degrees all of the three pivoting mechanisms we have considered. Up to a good medium level one can steer one's skis with the help of, nearly exclusively, the "sideslip turning effect" and a very little of "active pivoting". In competition skiing the strive for a minimum friction requires a preferential use of "active pivoting" and "carved turning effects".

In addition, there is a dynamical aspect of these turning effects, which plays an essential role in wedeln, i.e. in a fast succession of left and right turns. At the final phase of a turn the skis are subject to a maximum of pressure, vertically and sideways, which makes them bend, since they are more or less on the edge. At the end of e.g. a left turn there is a release of this pressure and the unbending ski rebounds from the snow upwards and to the left. If the tail of the ski was under bigger pressure, i.e. bent more strongly, then the rebound will also turn the ski to the right, similarly to what has been discussed in connection with Fig. 2. At the same time the muscles in the body compressed and stretched to the maximum by the twist of the feet to the left will react like springs at the release producing an upward rebound and a strong turning effect on the skis to the right. Thus at the end of a turn the pressure release creates both an "active" (muscular) and a "passive" rebound pivoting, which both act in the sense of starting an opposite turn if the pressure was predominantly on the ski tails.

III. Maintenance of equilibrium

The particularity of keeping balance on skis as compared with our everyday experience is the low friction in the direction of the ski axis. In the "forward-backward" plane S defined by the direction of the ski and the vertical the condition of equilibrium is that the application line of the resultant force $\vec{F}$, exerted by the snow surface on the skier's feet via the skis and the boots, passes through the body centre of gravity C. (Fig. 3 a). The sum of $\vec{F}$, of the gravity $\vec{G}$ and of the air resistance $\vec{R}$ produces the acceleration of the skier. Due to the small friction the force $\vec{F}$ is close to perpendicular to the ski-snow line in the plane S. The principal method of equilibration is then to displace the feet, i.e. the action line of $\vec{F}$ with respect to the centre of gravity C, which we call a "lean". E.g. by pushing the feet forward, $\vec{F}$ will pass in front of C, and this creates a backward torque. Notice that this "backward lean" does not mean necessarily a backward inclination of the body.

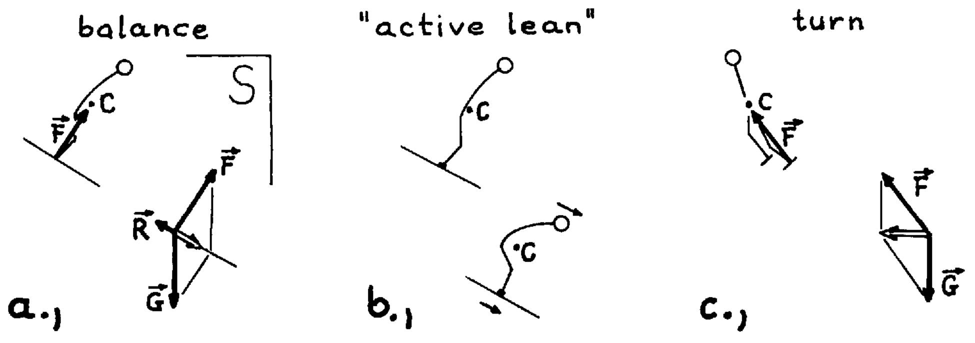

Fig. 3

There are basically two ways of producing a lean. The "active lean" consists of pushing the feet and the upper part of the trunk together with the head and the arms simultaneously in the same direction (Fig. 3 b). The basic feature of this manoeuvre is that it does not involve a change of the angular momentum of the skier : the movement of the feet is compensated by that of the upper body i.e. the skier-ski system behaves as a closed system. This is why it can be executed very rapidly. This is one of the fundamental element of modern skiing.

We call "passive" those leans which involve a change of the body angular momentum. These are obtained either by the torque produced by a pressure against the boots and/or by just letting the body lean under the effect of an off-balance. The maintenance of balance is ideally achieved by a judicious combination of reaction and anticipation. The unconscious reactions of continuous balance readjustment are in fact active leans. Pressure against the uppers of the boot can only serve as an emergency solution.

Anticipation is particularly essential at higher speeds when the skier has to adjust his position by "active" or "passive" leans in view of the obstacles to come. E.g. a slowing down due to a patch of deep snow has to be anticipated by a backward lean, an acceleration due to a steeper slope by a forward lean.

We have seen above that the fine piloting of the skis requires a precise positioning of the weight along the skis which means relative displacements of the body centre of gravity with respect to the feet. Thus the balance keeping "leans" have at the same time an effect on the turning of the skis. E.g. a forward lean during a (sideslipped) turn will tend to pivot the skis more into the turn, while a slight backward lean will tend to straighten out the turn. This is precisely the key tendency in modern skiing: minute adjustments of the centre of gravity serve at the same time the maintenance of equilibrium and the control of the skis. The virtuosity in the use of these fine controls is one of the main qualities of the very good skiers, which makes them slide faster and with less effort even on very easy slopes.

IV. The trajectory and the turns.

To conclude we can now consider the ski turns which allow the skier to choose his trajectory. In a turn, the direction of the velocity of the centre of gravity is modified. This innocent definition is in fact fundamental : a ski turn is not primarily the rotation of the body, and not even that of the skis, since due to the sideslip the direction of the skis and of the skiers' displacement can be quite different.

Let us first notice that the free trajectory of a sliding object on a slope is obviously a parabola turning downward from any initial diagonal direction and approaching the fall-line of the slope. In order to follow this trajectory (on a smooth snow) the skier only has to let his skis be as loose and free as possible, i.e. to keep them flat while in a perfectly balanced stance. On the other hand, the skier has to make an effort to leave the free trajectory, e.g. to make the turn sharper right from the beginning or to turn beyond the fall-line.

In a turn, the skier has to exert a laterally oblique pressure on the snow, the reaction of which produces the centripetal acceleration of the centre of gravity. The lateral equilibrium is maintained by an inward lean of the centre of gravity C with respect to the ski which carries most of the pressure. This lean is achieved more naturally and with less displacement of C if most of the weight is on the foot external to the turn (Fig. 3 c). The internal foot serves as security for the case when the external ski would not hold laterally on the snow.

The main problem the skier has to solve is to steer his skis with respect to the desired trajectory of the centre of gravity, on a trajectory which produces the necessary oblique pressures to provide the centripetal force and corresponds at the same time to a perfect lateral and forward-backward equilibrium. The delicacy of the problem is that, as we have seen, balance and pivoting of the skis are strongly related. Let us consider a very important practical aspect of this. The outside ski, which carries most of the skier's weight and thus meets more snow resistance, moves along a longer trajectory in the turn compared with the rest of the body. If the skier does not make a specific effort of pushing his outside ski forward during the turn, it will drag behind i.e. a forward lean will occur. The situation is aggravated by the fact that in the second half of the turn, where the skier's path deviates most from the free trajectory, there will be maximum pressure on the skis, quite similar to that experienced when going through a depression. This pressure tends to increase any initial (forward) off-balance, and makes the balance correction very difficult. As we have seen above, the forward lean tends to increase the sideslip angle, and the skier ends his turn in a position badly adapted for starting the next turn, especially since he has to recover balance first. On the other hand, a slight extra pressure on the ski tail creates a rebound which literally projects the skis into the next turn.

Finally we are left to consider the beginning of a turn. The passive pivoting of the skis assumes some sideslip with the ski tips toward the inside of the turn.

To initiate this sideslip on a smooth snow surface a minimum of active pivoting is sufficient in the first part of the turn which corresponds to the free trajectory. To do this in a heavy, catchy snow, one has to unweight, i.e. to accomplish the initial pivoting while the skis are more or less in the air during a rebound or even a jump. In this case the conservation of angular momentum requires an angular acceleration of the body in the opposite sense, i.e. opposite to the turn being commenced. In effect the moment of inertia of the straight body is fairly small, but it becomes appreciable in a somewhat bent position with the seat, the shoulders the head and the widely opened arms moved away from the vertical axis. Thus instead of an apparent twist of the body, the angular momentum change rather corresponds to taking the so called "position of angulation", i.e. moving the slightly bent upper body towards outside to the turn. In addition, particularly, in deep snow where there is no possibility of freeing the skis, an extra momentum can be given to the turn starting pivoting by a "hip projection". This means an initial rotation of the slightly bent body in the sense of the turn to come and a pivoting of the skis during the subsequent de-acceleration of the angular angular momentum acquired in the body rotation.

V. Conclusion

The key points of modern skiing can be summarized as follows. Most of the piloting of the skis can be obtained by utilizing the "free-trajectory" tendency of the skis to approach the fall line and by "passive pivoting" based on a fine control of the ski-snow contact forces. This latter is achieved by delicate adjustment of the equilibrium, which is predominantly maintained by "active leans" i.e. closed system displacements of the feet with respect to the body centre of gravity. The moment of inertia of the body does not play an essential role in the turning of the skis, except under extreme conditions,like heavy snow, certain competition turns and - when the skier, out of balance, has no other means left at his disposal.

Reference

(1) G. Joubert, Le Ski: un art.....une technique.
(Arthaud, Grenoble 1978)