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Speed Skiing

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ABSTRACT

Precise computations of the coefficient of friction between ski sole and snow as well as the experimental determination of air resistance allow the calculation of sliding velocities in a speed ski race. By means of the derived model, influences like improvements in ski preparation or the impact of specialized racing suits can be estimated. The article shows at which snow temperatures the highest velocities can be reached and shines light on the question how high the ultimate speed is. Finally, valuable hints for optimizations are given.

1 Introduction

Speed skiing is the kind of winter sports that accounts for highest sliding velocities. The prevailing world record, held by Italien Ivan Origone, is 254,958 km/h, a speed hardly no one has ever reached with his passenger car. By the mere action of gravity the athlete reaches 100 km/h after 4.5 seconds. In comparison, it takes a Formula 1 car about 2.5 seconds to reach this speed. Only friction and air resistance prevent the athlete from getting even faster. Whereas wind resistance can be quantified by wind tunnel tests, friction during the run can hardly be measured. To solve this problem, accurate modeling of the ski-snow contact is necessary to derive a mathematical treatment of the problem. This contribution focuses on the quantification of friction and air resistance and their influences on the speed of a typical run. The paper gives an estimation of the ultimate sliding speed and discusses ways to improve fast skiing.

2 Modelling

2.1 Friction

The calculation of friction is based on the most modern model introduced in 2017 by Böttcher *et al.* [1]. The model utilizes a microscopic approach originating from the pioneering studies of Bowden in 1939 [2]. Friction, in this approach, is mainly determined by the shear resistance and the contact area between ski sole and snow. Shear depends on the amount of water present on the micrometer-sized grains snow is composed of, see Fig. 1. Even without any contact between ski and snow, the grains carry a water films with a thickness of some nanometers (1 nm = 10^{-9} m). This type of water has to be considered liquid-like and physicists call the effect of water generation pre-melting [3–5], meaning that the near-surface crystalline structures of the ice grain gradually becomes disordered, i.e., liquid-like. To achieve lowest coefficients of friction, the water film thickness must be in the nanometer range. However, due

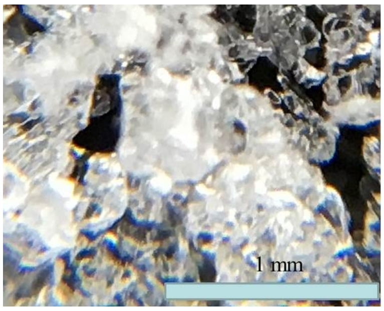

Figure 1: Light microscopy image of snow of a downhill track. Due to repeated day/night cycles that means, periodic warm/cool transitions, the individual snow grains gradually round.

to frictional heat the water film growths. At a certain thickness the friction-reducing effect vanishes, since viscous drag arising from turbulences inside the water film confined between ski sole and snow grain slows down the ski. This last statement is crucial since it emphasizes the impact of the environmental conditions during competition. It is obvious that only appropriate conditions allow top speeds.

Equation 1 was used to calculate the coefficient of friction μ. Besides ice hardness H friction depends on thermal conductivities λ and heat capacities c of ski sole and ice [6–8]. To account for hydrodynamic effects, Eq. 1 has to be furnished with the appropriate value of water viscosity η at the prevailing snow temperature T. The exact derivation of Eq. 1 can be found in [1].

$$\mu = f\left[\frac{1}{\sqrt{a}H}(\eta, \lambda, c, T)\right] \tag{1}$$

$$a = 4\sqrt{\frac{F_i r}{\pi E l}} \tag{2}$$

A crucial contribution to the model is adequate contact mechanics to compute the real area of contact between snow and ski sole. In order to derive Eq. 2, the contact situation was reduced to a single grinding ridge as shown in Fig. 2. Snow is treated as flat plane. Since the ski sole has a certain number of grinding ridges n, the fraction of normal force acting on a single ridge has to be calculated by $F_i = mg/n$. m is the mass of the athlete and g the gravitational constant. Taking into account the elastic moduli of ski sole and ice E, radius r and length l of the ridge, the individual contact width a can be determined and inserted into Eq. 1.

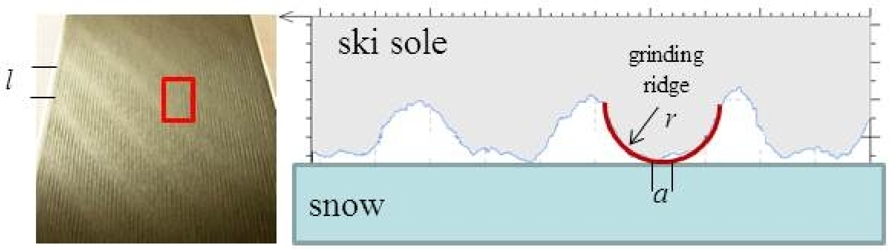

Figure 2: Left: Photography of grinding ridges. Right: Schematic of the grinding structure with single ridges contacting snow. The length l has to be chosen carefully in order to reflect the grinding structure of the ski.

At the current state the model does not consider free water between the ice grains. It is therefore possible that in the snow temperature range between 0°C and -2°C the coefficient of friction shows deviations from observations in real field experiments. In addition, neither snow grain shapes nor grain size distributions are constituents of the model.

2.2 Air Resistance

In contrast to friction, air resistance can be measured with great precision. To this end the athlete is positioned in a wind tunnel on a force-measuring plate to monitor the force in wind direction F_{w}.

$$F_w = c_{\mathrm{w}} A \rho \frac{v_{\mathrm{w}}^2}{2} \tag{3}$$

ρ is the density of air and A is the area of the silhouette of the athlete. Finally, v_w is the speed of wind. By optimal posture a c_w value of 0.12 can be obtained.

Figure 3 shows the silhouettes of Ivan Origone and Klaus Schrottshammer with distinctively different features. Whereas Schrottshammer impresses with an athletic stature, Origone is tall and slender. The area of both silhouettes was calculated using image processing software (ImageJ). The values are given inside Fig. 3 and underline a significant difference. In addition, both athletes have a different spacing between the ski.

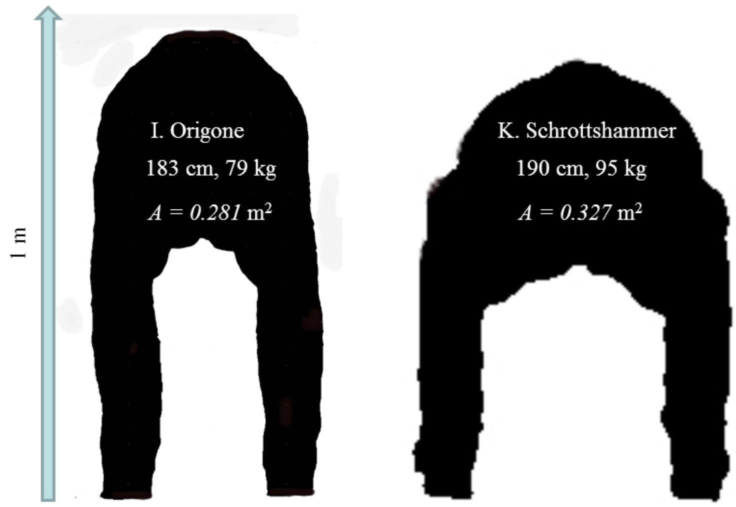

Figure 3: Silhouettes of speed ski racers Ivan Origone and Klaus Schrottshammer showing significant differences in shape and area.

Due to air flow directed towards the athlete a lift-up is experienced. The lift-up of force has a magnitude of about 80 N at 250 km/h which is almost 10% of the acting normal force [9].

2.3 Speed Calculations

Figure 4 shows a snapshot of the athlete during the run. The arrows indicate the acting forces. For the calculation of friction the force normal to the track must be considered, which can be derived from the gravitational force multiplied by the sine of slope angle α. The driving force – the downhill slope force F_d – depends on the mass of the athlete and α. Since air resistance F_w and friction F_f act in opposite direction, downhill motion is impeded. Equations 4 and 5 show how the acting forces are combined to receive the sliding velocity along the run.

$$ma = F_d - F_f - F_w \tag{4}$$

$$m\frac{dv}{dt} = mg\,sin(\alpha) - \mu(v)mg\,cos(\alpha) - c_w A\rho\frac{v^2}{2} \tag{5}$$

Since in Eq. 5 both friction and air resistance depend on speed, an analytical solution of the differential equation is not possible. Therefore, Eq. 5 was solved numerically using finite differences according to the approach of Euler. In order to receive high resolution, minute time steps ($\Delta t = 0.1$ second) where used.

For the calculations the values shown in Tab. 1 were supplied to the equations:

3 Results

3.1 Acting Forces

Friction force as function of speed shows the typical Stribeck behavior [10] which is characterized by high friction at low sliding speed due to lack of lubricating water, followed by a minimum at optimum water film thickness and increasing friction caused by turbulent losses in the growing water film, see Fig. 5. The shape of the curve varies with snow temperature. Figure 5b) demonstrates an almost ideal Stribeck

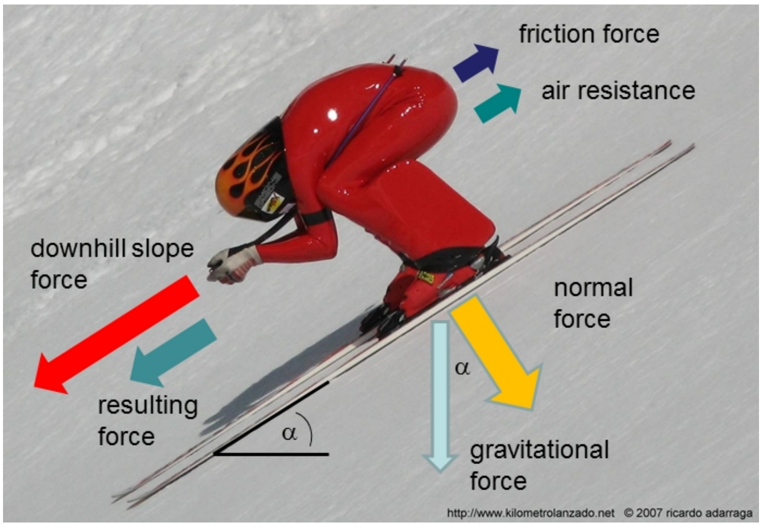

Figure 4: Forces acting on an athlete during a speed ski run. The downward motion is impeded by friction and air resistance.

Table 1: Table 1: Parameters and values used in calculations.

entity	value	unit
athletes mass including ski	120	kg
length of ski	2.4	m
temperature of snow	-2 ... -10	°C
air drag coefficient	0.15	-
slope (α)	40 - 45	°

behavior. Air resistance starts from zero and increases nearly quadratic due to v^2. Depending on snow temperature and speed the contributions of friction and air resistance eventually become equal, marked by the circle. From this point on, air resistance is the major factor. With decreasing snow temperature the break-even points shifts to lower speeds. Figure 5a) and b) show the ideal case, that means constant air drag coefficient and area of silhouette. However during the run both values increase leading to a further shift to lower speeds as indicates in Fig. 5c).

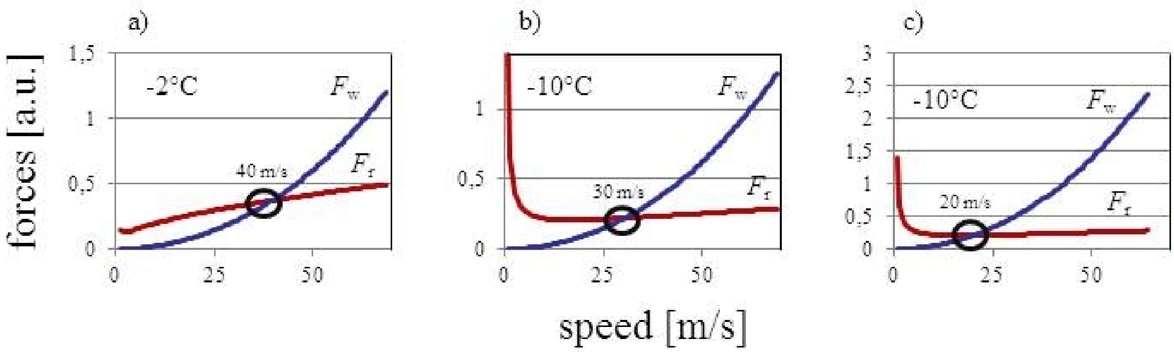

Figure 5: Acting forces due to friction and wind resistance as function of sliding speed. a) and b) show the ideal situation with lowest air drag coefficient, whereas c) illustrates the case of increased air drag coefficient.

3.2 Speed along the Run

Both influences – friction and air resistance – cause that the speed along the track gradually approaches a maximum value as shown in Fig. 6. With respect to snow temperature the top-speed is located at -4°C. The figure shows 3 different speed ranges. Between 11 and 12 m/s, i.e. in the first fraction of the run, only a slight maximum can be found. Snow temperatures between -5°C and -2°C impose a similar effect on speed. The maximum becomes more pronounced as speed increases. Between 32 and 34 m/s snow warmer than -4°C still allows higher speeds than at cold conditions. At highest speeds, however, friction produces so much water that aside the maximum only lower speeds can be obtained.

However, taking into account the conditions at the largest available speed ski track (Les Arcs with 575 m vertical height and 800 m acceleration zone) [11] and the current equipment and safety rules, a speed higher than 260 km/h seems to be very difficult to achieve.

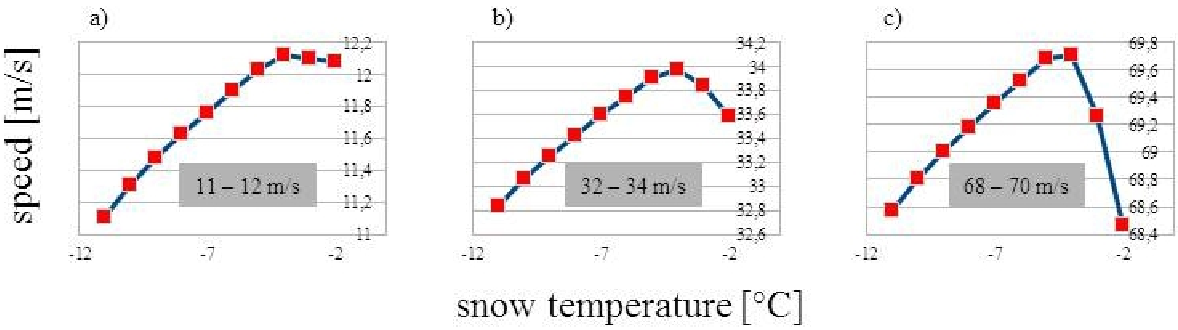

Figure 6: Top speed versus snow temperature in three different speed ranges.

3.3 Optimizations

The most important issue at start is to overcome static friction. By jumping into position the athlete immediately enters the regime of sliding friction. The jump into position should be performed gently in order to prevent the built-up of excessive normal force. Due to lack of friction-reducing water, an optimized grinding structure helps to generate frictional heat. Friction power density can be increased by a hyper-structure on top of the grinding ridges. Suchlike features reduce the area of contact to the tips of the hyper-structure. As a result, friction power density increases and more water is produced.

At the end of the run, however, the water film is sufficiently thick or even too thick and the grinding structure has to take care of this effect. It is therefore recommended that the ski is equipped with a deep grinding structure as used for wet conditions. Another remedy to achieve high velocities at start is proper brushing. As shown in [12] brushing acts on the nanostructure of the ski sole. Repeated contacts with the steel bristles lead to a flocati-like structure of the polyethylene which reduces friction by lowered shear resistance. Brushing therefore can be considered nanotechnology without adequate tools for the ski technician to probe the results of his treatments.

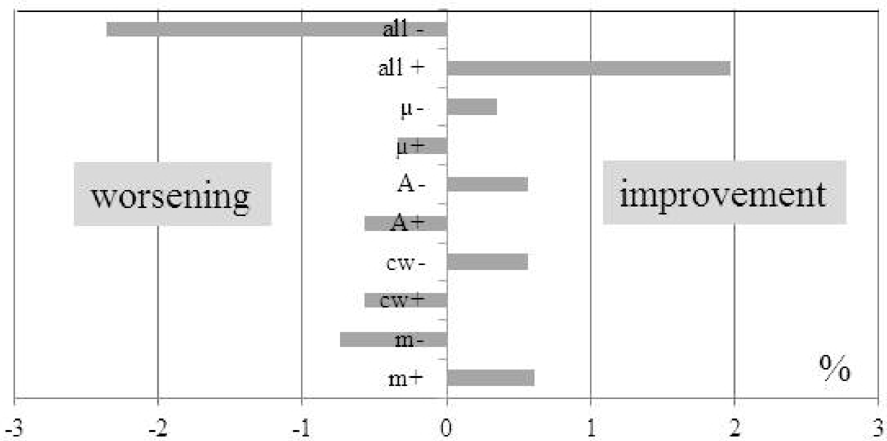

Figure 7: Potentials gained and lost by variation of mass, c_w value, area of silhouette, friction and the combination of factors. The largest factor, not shown in the graph, is, however, the slope angle α. A variation of $\pm$ 10% around a base angle of 40° results in a speed change of 10 km/h.

Aside from ski sole issues, the position of the skis on snow has to be thoroughly analyzed in order to prevent canting. A high-resolution pressure measuring plate can be used for this analysis. Any x or o form of the legs can be detected and corrected. If no correction is possible based on a changed running position, boot fitting might be the appropriate alternative. In the range of acting air resistance wind channel tests are the advisable means for optimization [9]. Especially the perfect fit of the helmet and its transition to the shoulder region is important. In addition, size and shape of the spoilers is an important field of optimization.

Figure 7 presents a calculation of a 10% change (up and down) of athlete mass, air drag coefficient, area of silhouette, friction and combinations of influencing parameters. The calculation was performed for $m_0 = 120$ kg, that means $m_+ = 132$ kg and $m_- = 108$ kg. T_0 was set to -4°C and the air drag coefficient was 0.15. The increase from 120 kg to 132 kg resulted in an increase in top speed of $\approx 0.7\%$. Consequently, a reduction of mass causes a decrease of top speed. Any change of the air drag coefficient yields a large impact on the top speed, similarly pronounced as the change in the area of silhouette. Finally changes in friction caused by ski preparations influence the top speed. It becomes obvious that optimization is a multi-dimensional problem and that modeling and calculation a valuable means to achieve higher sliding speeds. When all improving measures are taken (all+), an increase in speed of about 2% is possible. On the other hand, combined worsenings result in a speed decrease of more than 2%.

4 Summary

Although the friction model is far from complete – e.g. due to missing incorporation of snow grain size effects – valuable conclusions can be drawn. It was shown that at a certain speed the influence of friction and air resistance become equal and that this point is determined mainly by snow temperature and running position of the athlete. Top-speeds can only be achieved in a snow temperature range between -2°C to -5°C. Extensions of the presented model can help to support the decision of race officials when to start the race and when it becomes too dangerous for the athlete to compete. Finally, the model helps to navigate through the wide range of influencing parameters and to find an appropriate plan for race preparations.

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Ricardo Adarraga has been a speed skier since 2003 competing in the FIS World Cup and Pro Races. He owns the Spanish Speed ski record since 2004, currently with a speed of 240,642 km/h. Adarraga owns a masters degree in industrial engineering from Karlsruhe Institute of Technology, Germany and is member of the FIS speed ski committee.

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References

[1] Roman Böttcher, Marc Seidelmann, and Matthias Scherge. Sliding of uhmwpe on ice: Experiment vs. modeling. *Cold Regions Science and Technology*, 141:171 – 180, 2017.

[2] Frank Philip Bowden and T. P. Hughes. The Mechanism of Sliding on Ice and Snow. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 172(949):280–298, aug 1939.

[3] H. Dosch, a. Lied, and J.H. Bilgram. Glancing-angle X-ray scattering studies of the premelting of ice surfaces. *Surface Science*, 327(1-2):145–164, apr 1995.

[4] B. Pittenger, S. Fain, M. Cochran, J. Donev, B. Robertson, A. Szuchmacher, and R. Overney. Premelting at ice-solid interfaces studied via velocity-dependent indentation with force microscope tips. *Physical Review B*, 63(13):134102 1–15, mar 2001.

[5] Tomoko Ikeda-Fukazawa and Katsuyuki Kawamura. Molecular-dynamics studies of surface of ice Ih. *The Journal of Chemical Physics*, 120(3):1395–401, jan 2004.

[6] V.F. Petrenko and R.W. Whitworth. *Physics of Ice*. OUP Oxford, 1999.

[7] Erland M Schulson. The Structure and Mechanical Behavior of Ice. *Journal of the Minerals, Metals and Materials*, 20(February 1999):21–27, 1999.

[8] David M Cole. The microstructure of ice and its influence on mechanical properties. *Engineering Fracture Mechanics*, 68:1797–1822, 2001.

[9] Takeshi Asai, Sungchan Hong, and Koichi Ijuin. Flow visualization of downhill ski racers using computational fluid dynamics. *Procedia Engineering*, 147:44 – 49, 2016. The Engineering of SPORT 11.

[10] Richard Stribeck. Die Wesentlichen Eigenschaften der Gleit- und Rollenlager. *Z. Verein. Deut. Ing.*, 46:1341–1348, 1902.

[11] Raimo von Hertzen, Ulf Holmlund, and Matti A. Ranta. On the velocity maximization in downhill skiing. *Journal of Biomechanics*, 30(5):525 – 529, 1997.

[12] Matthias Scherge. Wachs oder kein Wachs – Das ist hier die Frage. *Gliding*, 1:1–3, 2016.