On the Technique of Speed Skating

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The mechanics of speed skating, as many other endurance sports, can be described by an energy flow equation. With such an equation the influence of suit, local pressure, altitude, shielding, and body position on speed is predicted. Next to these model predictions, the peculiar properties of the skating technique are discussed and their practical implications for skating the straight parts and the curves are indicated.

Though humans have moved on ice on pieces of wood or polished bones for more than 3,000 years, one can speak about the technique of speed skating only since the introduction of iron blades which came into usage in Northern Europe about 600 years ago. Prior to the introduction of artificial ice rinks, the development of this sport was limited to countries with large amounts of still water and not too much snow. This was the case in England (Goodman & Goodman, 1882), Scandinavia, Holland, Northern Germany, Poland, and Russia (Buttinga Wichers, 1888; Goodfellow, 1981; Schøyen, 1920). In those countries, speed skating is one of the oldest recreational sports practiced by a broad public. Though speed skating is possible in many more countries today, the literature on the technique of this sport originates mainly from countries with this long skating history.

The first studies were performed in Germany and in Russia (Djatschkow, 1977; Haase, 1954a, 1954b; Krause, 1972; Kuhlow, 1973, 1975, 1980; Nicol, 1974). These studies were mainly descriptive in nature. Kuhlow (1974, 1975, 1980) and Nicol (1974) measured speed fluctuations during a race and showed that better skaters maintain their speed on a more constant level than skaters of a lower performance level. Djatschkow (1977) and Doctorevic (1975) subdivided the strokes in phases. In particular Djatschkow’s study can be regarded as one of the first important publications on the biomechanics of speed skating. Many of his observations and recommendations were affirmed by later studies.
An Energy Flow Model

When studying the mechanics and energetics of an endurance activity such as speed skating, it seems logical to use an approach that provides a causal relation between the liberation of metabolic power (\(\dot{E}\)) and the ultimate destinations of external mechanical power. If the whole skater is taken as a free body diagram, this external power \(P_o\) is defined as the sum of the rate of work done against external forces and the increases of the energy state of the skater. The external forces are the air and ice frictional forces, gravity, and the push-off force on the ice perpendicular to the gliding direction of the skate. Since the small fluctuations in skating velocity and in potential energy within the course of a stroke have little effect on the mean external power (Delnoij, de Groot, de Boer, & van Ingen Schenau, 1987), this energy flow can be summarized in the following equations:

\[
\dot{E} = e_m \cdot P_o \quad \text{and} \quad P_o = P_f + m \cdot v \cdot a \tag{1}
\]

where \(e_m\) is the mechanical efficiency, \(P_f\) is the power lost to air and ice friction, \(m\) the mass of the skater, \(v\) the speed, and \(a\) the acceleration (\(v\) and \(a\) as stroke averages).

Given a skater with a certain skating technique and physical condition resulting in a more or less constant \(P_o\) at a certain skating distance, equation 1 is a valuable tool to predict influences of skating position (Figure 1), altitude, body composition, and suit on final times. Such predictions are possible if the influences on power lost to air and ice friction are known.

Figure 1 — The angles that define the position of the speed skater. The knee angle \(\theta_0\) (\(= \theta_2 + \theta_3\)) is mainly determined by the position \(\theta_2\) of the upper leg.
Ice Friction and Air Friction

Power lost to ice friction is the product of the ice frictional force and the speed of the skater. In the past, the ice frictional force was measured with the help of a sledge (Ingen Schenau, de Boer, & de Groot, in press; Kobayashi, 1973). This force appeared to be proportional to the normal force N (approximately equal to body weight) according to

\[ F_{\text{ice}} = \mu N \]

with \( \mu \) the ice friction coefficient which was reported to vary between \( \mu = 0.003 \) and \( \mu = 0.007 \) at properly treated ice rinks. Recently developed skates that measure the ice friction force during actual skating, however, showed about 50% higher values during actual skating (Ingen Schenau, de Boer, & de Groot, in press). The difference can easily be explained by the fact that the blades under the sledges were at right angles to the ice, while during actual skating the blades are under less optimal angles, in particular during skating the curves.

In most aerodynamical analyses of endurance sports, the air frictional force is approximated by the product of pressure drag \( \frac{1}{2} \rho v^2 A_p \) and a dimensionless drag coefficient \( C_D \):

\[ F_{\text{air}} = \frac{1}{2} \rho v^2 A_p C_D = k_1 v^2 \]  

where \( \rho \) equals the density of the air and \( A_p \) the frontal or cross-sectional area. It is mostly assumed that the product \( \frac{1}{2} \rho A_p C_D \) is constant \( (k_1) \) and thus independent of \( v \). Wind tunnel experiments, however, showed that this is not the case (Ingen Schenau, 1982). Skaters have such a speed and dimension that the Reynolds number becomes critical \( (10^4 < R_e < 10^6) \). This dependence of \( C_D \) on \( v \) had to be taken into account in the model expressed by equation 2. The influence of other factors such as trunk position \( (\theta_t) \), knee angle \( (\theta_k) \), suit, shielding, and body dimensions were also measured with the help of wind tunnel experiments (Ingen Schenau, 1982). All these factors as well as the (exponential) dependence of air density on altitude were incorporated in equation 2. With this model a number of predictions could be made.

Model Predictions

In the procedure used in the model predictions, an imaginary top-level skater of 1.80-m body length and 70-kg body mass was taken as reference. Taking mean values of skating position and speed of elite skaters, the power \( P_o \) and the frictional losses \( P_f \) can be calculated for given environmental conditions.

To calculate the influence of one particular factor \( c \) on the mean speed \( v \), all other factors are assumed to be constant. Basically this procedure means that the partial derivative \( \frac{\partial v}{\partial c} \) is solved with the help of equation 2. These dependencies were determined for a number of different factors (Ingen Schenau, 1982; Ingen Schenau, de Boer, & de Groot, in press), the results of which are summarized in Table 1. The relative influences are based on performances in 3,000-m races. Apart from the influence of the suit, all values are slightly higher for the longer distances (5,000 m and 10,000 m) and slightly lower for the shorter distances (500 m, 1,000 m, and 1,500 m).
Table 1
The Influence of Different Factors on Lap Times

<table>
<thead>
<tr>
<th>Factor</th>
<th>Predicted relative influence on lap times</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trunk position</td>
<td>3.9% per 10°</td>
<td></td>
</tr>
<tr>
<td>Knee angle</td>
<td>3.3% per 10°</td>
<td></td>
</tr>
<tr>
<td>Local pressure</td>
<td>Max: 3.0%</td>
<td>Differences between extremes</td>
</tr>
<tr>
<td>Skinsuit vs. woolen suit</td>
<td>Max: 2.4%</td>
<td>At highest speeds</td>
</tr>
<tr>
<td>Altitude</td>
<td>0.3% per 100 m</td>
<td>At a distance of 1m</td>
</tr>
<tr>
<td>Shielding</td>
<td>Max: 9%</td>
<td></td>
</tr>
<tr>
<td>Fat</td>
<td>0.5% per kg</td>
<td></td>
</tr>
</tbody>
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Note. The relative values also hold for the calculation of the influence on final times.

The advantage of the skin suit is closely connected to the dependence of $C_D$ on $v$ and disappears at speeds of approximately 7–10 m/s. At lower speeds the old fashioned rough woolen suit is faster than the modern smooth skin suit. A horizontal trunk is the most optimal position. However, many skaters have problems maintaining that position for a long time interval. Table 1 shows that a horizontal trunk position is one of the most important technical factors that should be trained. More difficult to train is the knee angle, since this angle is directly connected to the force level of the hip and knee extensor muscles (Ingen Schenau & Bakker, 1980). A small knee angle is an important prerequisite for speed skaters, not only because of its influence on air friction but also because of its potential influence on power production (Ingen Schenau, de Groot, & Hollander, 1983).

Local air pressure may vary considerably. This factor is often ignored but can cause significant differences in final times since the air density is strongly dependent on air pressure. It is not the local ice-maker’s fault that the performances under seemingly optimal weather conditions (high pressure) are often disappointing. On the other hand, the surprisingly good times that sometimes can be observed while rain or snow is coming down are often simply due to low pressure conditions. The presented influence of altitude on speed (Table 1) was one of the predictions that easily could be tested on the basis of actual times made at different altitudes.

A famous ice rink is the Medeo-rink (1,700 m) near Alma Ata in the Soviet Union. For five Russian speed skaters who skated several times at the Medeo-rink and at sea level at 500-m, 1,500-m, and 5,000-m distances, the mean advantage of Medeo over the rinks at sea level was calculated to be 4.9%. On the basis of the model prediction (Table 1) it should be 5.1%. The small difference might be caused by the fact that the times at sea level were realized during the most important races (the European and World Championship). In any case there is good agreement between the predicted and the actual differences. Using the rule
of thumb presented in Table 1, one is able to demythologize the fabulous world records realized at the ice rinks in Medeo or Davos (Switzerland).

The effects of shielding are only present when skating in a group is allowed. Apart from the marathon races that are only popular in Holland, this condition only arises in training. Coaches, however, should take these enormous effects into account when judging the lap times of tempo training sessions. The last point made in Table 1 concerns the influence of excess weight on speed. For speed skaters, fat can be regarded as excess weight. The influence looks small but an example will illustrate its importance. Let us compare two female skaters of about 70 kg body weight, one having 25% body fat and the other 15% (both values are realistic). The 10% difference in percentage of fat results in a difference in time of 3.5%, which translates to approximately 4.30 sec in the 1,500-m race of 17 s at the 5,000 m.

Other model predictions that were performed concern the influence of wind, body weight and length, and the ice friction coefficient on speed. The most important of these points concerns the ice condition. As a result of hoarfrost and ice temperature, the ice friction coefficient can vary more than 50% during one championship. So speed skating at outdoor rinks with changing weather conditions often is like a lottery. Remarkably, most skaters have little problems with these stochastic effects. The reason might be that traditionally speed skating is not only a competition with other participants but also an individual fight against the elements.

**Stroke Mechanics**

The technique of speed skating differs considerably from other types of locomotion. Even when compared to cycling, running, and cross-country skiing, in which the lower extremities are also used for propulsion, essential differences can be observed. The most striking difference concerns the direction of the push-off.

Speed skating is possible because of the peculiar qualities of ice. On the one hand, ice is weak enough to allow a wetted small blade to be pushed into the ice. On the other hand, the friction coefficient between skate and ice in the gliding direction is extremely low (comparable to the rolling coefficient of a race bicycle). This allows an effective but unnatural way of propulsion, usually called the “gliding technique.” The basic element of the gliding technique concerns the push-off against the ice while gliding forward. This is only possible in a direction that lies in a plane at right angles to the gliding direction of the skate. This x–z plane is visualized in Figure 2.

The reason skaters are forced to push off while gliding forward is that their speed is larger than the maximal (horizontal) speed differences that can be achieved between the hip joint and the skate. This maximal difference in speed is estimated to be of the magnitude of 7 m/s (Djatschkow, 1977). Thus apart from the start, it is essentially impossible to push off against a fixed location in the ice. Though the push-off perpendicular to the gliding direction of the skate does cause the skater to display a sinuous trajectory with an amplitude of 0.25 m up to more than 0.50 m, the gliding technique allows skaters to achieve speeds (over 50 km/h) which are far in excess of the maximal speeds that can be achieved in running.

Closely connected to the gliding technique, a second peculiar aspect can
be mentioned: the constrained plantar flexion. The gliding technique is only possible with a skate kept in a horizontal position during the push-off. Plantar flexion would cause an enormous increase of ice friction since the point of the skate would be pulled into the ice. To prevent this opposing effect, skaters are taught to push off on the back part of their skate.

Mechanically stated, the line of action of the push-off force has to be located through or just in front of the ankle joint. In that position the plantar flexors are allowed to relax to a certain extent (they are mainly used to maintain equilibrium in cooperation with m. tibialis anterior). High-speed film analyses showed that the absence of plantar flexion causes a premature termination of the push-off. It was shown that skaters lift their skate from the ice at a mean knee angle of 147° (mean of 10 elite male and 10 elite female skaters). The remaining part of the knee extension takes place in the air.

It was shown that this phenomenon is directly due to constraints connected to the transfer of rotational velocities into a translational velocity (Ingen Schenau, de Groot, & de Boer, 1985; Ingen Schenau, Bobbert, & Rozendal, 1987b). The consequences of this constrained push-off will be discussed at the end of this paper. For now it is sufficient to realize that the push-off in speed skating has to be performed over a knee extension angle of only about 30°. Since the static gliding phase takes more than 80% of the total stroke time, it will be clear that the push-off in speed skating has to be performed with an extremely explosive knee extension. It was calculated that at a moderate mean power output of 300–400 watts, the peak value in the instantaneous power during the push-off reaches values over 2,000 watts, which is 3 to 4 times higher than during cycling at a comparable
mean power output. It is obvious that such a short but intensive push-off will require the recruitment of motor units of the hip and knee extensor muscles that are rarely (if at all) recruited during other activities such as cycling, running, and rowing. This might explain why speed skaters are usually good cyclists, although the opposite is not necessarily true. Moreover, this may explain why skaters do not show the typical characteristics of long-distance runners and cyclists with respect to maximal oxygen consumption and fiber type distribution.

Since most of the work per stroke must be delivered by the hip and knee extensors, one can easily understand why a small $\theta_o$, and more particularly a small position $\theta_2$, of the upper leg is an important technical aspect of speed skating (Ingen Schenau et al., 1983). However, within a homogeneous group of elite speed skaters these angles do not correlate with performance (de Boer, 1986; Ingen Schenau et al., 1985).

A factor that correlates significantly with performance within such groups with only small differences in performance concerns the direction of the push-off force in the x-z plane (Figure 2). The more horizontal this force is directed during push-off, the more effective the result of the push-off. In fact, only the horizontal component $F_x$ of $F$ contributes to an increase of velocity. This increase of velocity is visualized in Figure 3. Assume the skater has a velocity $v_1$ prior

![Figure 3](image)

Figure 3 — Since skaters can only push off in a direction perpendicular to the gliding direction of the skate (solid line), the center of gravity follows a sinuous trajectory (broken line). The result of the push-off is a velocity increment $v_2$ which increases the total velocity of the skater from $v_1$ to $v_3$. Due to the sideward push-off, the result of the push-off is not only an increase of kinetic energy but also a change of direction $\alpha$ of the center of gravity.
to the push-off. The effect of the push-off is a velocity increment \( v_2 \) of the skater's center of gravity relative to the push-off skate. This velocity vector \( v_2 \) lies approximately at right angles to the direction \( v_1 \). Expressed in work per stroke \( A \), the effect of the push-off is an increase of kinetic energy \( A = \frac{1}{2}mv_2^2 \). This increase of kinetic energy depends on the horizontal component \( F_x \) of the push-off force \( F \), and consequently on the magnitude of \( F \) and on \( \phi \), the angle between the direction of \( F \) and the horizontal (Figure 2). Surprisingly, de Koning et al. (1987) showed that the magnitude of \( F \) is not a good predictor for skating performance. As shown for females (Ingen Schenau et al., 1985) as well as for males (de Boer, 1986), the direction of the push-off seems to be one of the most important characteristics of speed skating.

### The Mechanics of Skating the Curves

One result of the peculiar gliding technique in speed skating is the sinuous trajectory that skaters are forced to make during skating the straight parts of the 400-m skating rink. Approximately 44% of that 400 m consists of the two curves. Recently it was shown that the sideward push-off is also responsible for an important constraint for the technique of skating the curves (de Boer et al., 1987; de Boer, Ettema, van Gorkum, de Groot, & Ingen Schenau, in press; Ingen Schenau, de Boer, & de Groot, in press).

In most activities in which a backward push-off is possible, as is the case in running and cycling, the centripetal force necessary to describe a curve is delivered by a frictional force between foot or tire and the floor. Since this force is at right angles to the direction of the propulsive force and to the velocity of the athlete, no work is done by this centripetal force.

Basically a skater can also create such a centripetal force by making a curved stroke. In that case, however, he/she would not be able to make any push-offs during the curve since speed skaters can only push off in a direction perpendicular to the gliding direction. The need to push off and to deliver external power is realized in practice by making straight strokes in the curves and by using the change of direction \( \alpha \) (Figure 3), which is the result of a push-off, in order to follow the curvature of the lane. The need to create a centripetal force is thus fulfilled by the same force that also is responsible for propulsion. From a geometrical point of view, one might say that the only difference between skating the curves and the straight parts is that during the curves skaters push themselves to the left only, while when skating the straight parts they push off alternately to the left and to the right.

This peculiar phenomenon leads to a model that predicts stroke frequency and external power on the basis of geometrical variables only (de Boer, Ettema, et al., in press; Ingen Schenau et al., 1987): Assume that \( v_1 \) is the skater's mean speed, \( v_2 \) the result of the push-off (Figure 3), \( R \) the radius of the curve, \( f \) the stroke frequency, and \( T \) (\( = \frac{1}{f} \)) the stroke time in the curves. At first approximation, the change of direction \( \alpha \) of the center of gravity as a result of the push-off equals,

\[
\alpha = \frac{v_2}{v_1}
\]
During the curve the total change in direction is equal to \( \pi \). So the skater is allowed to make \( n = \pi / (v_2 / v_1) \) strokes during the curve. The length of the curve equals \( R = n \cdot T \cdot v_1 \). Elimination of \( n \) yields

\[
v_2 \cdot f = \frac{v_1^2}{R}
\]

which is approximately equal to the mean centripetal acceleration \( (v_2 / T) \) necessary to follow the curve. With \( P_c = A \cdot f \) and \( A = 1/2 \ m \ v_2^3 \), equation 3 can be extended to

\[
P_C = 1/2 \ m \ v_2^3 \cdot \frac{v_2}{R}
\]

It has been shown (Ingen Schenau et al., 1985) that skaters control their external power by stroke frequency while the amount of work per stroke is more or less constant. With this in mind, the practical implications of equations 3 and 4 are explained as follows. If a skater of a certain performance level (i.e., he or she has a certain more or less fixed \( A \) and thus \( v_2 \)) wants to follow the radius \( R \) of the curve with a speed \( v_1 \), he/she is forced to use a stroke frequency according to equation 3, and consequently to deliver an amount of external power according to equation 4. This means that the skill of skating the curves is strongly dependent on the skater’s capacity to deliver a large amount of work per stroke. A second prerequisite for skating a good curve is the skater’s speed prior to the curve.

The constraints for skating the curves explain why performance in speed skating correlates with the amount of work per stroke and not with stroke frequency (de Boer, Ettema, et al., in press; Ingen Schenau et al., 1985). Stroke frequency in the curves is not an independent variable. If skaters use a stroke frequency higher or lower than what is predicted by equation 3, they do not follow the radius of the curve but they will display a smaller or larger curvature.

The external power predicted by equation 4 can be calculated for actual skating events and be compared with the power predicted on the basis of air and ice frictional losses (equation 2). Both calculations were performed by de Boer, Ettema, et al. (in press) for 16 participants of the 5,000 m during the 1985 European Championships for women. The power \( P_o \) calculated on the basis of air and ice friction and rate of change of kinetic energy was determined using high-speed film analysis (for skating position), anthropometric measures, and change of speed during the curve, whereas the power predicted from equation 4 was calculated from the radius of the curve, the mean speed in the curve, and the mean amount of work per stroke \( P_o / f \) calculated from equation 2 and the mean stroke frequency during the entire lap. The mean power \( P_o \) expressed per kilogram of body weight appeared to be \( 4.85 \pm 0.86 \) watt/kg, while the mean power predicted from the geometry of the curves equaled \( P_c = 4.71 \pm 0.99 \) watt/kg. Such a high agreement between both model predictions was also reported for roller skating (de Boer, Ettema, et al., in press).

The fair agreement between both model predictions allows one to formulate a number of explanations and recommendations that might be useful in coaching and training:
The most important prerequisite in skating the curves is a large amount of work per stroke. Specific training of the work per stroke can be performed by forcing the skaters to make less, but nonetheless straight, strokes than they are used to at a given skating speed.

If a skater wants to accelerate in the curve, he/she should never try to do so by increasing the stroke frequency. An increase of stroke frequency can only be achieved by a decrease in the amount of work per stroke and a decrease in power. This strategy should only be applied when the forced amount of external power is too high (which is often the case in the second curve of the 500-m race). An extra acceleration in the curve can be achieved only by either an increase of the velocity prior to the curve or a temporary increase in the amount of work per stroke (smaller preextension knee angle and/or more horizontally directed push-off).

Poor skaters and those with less speed (which often occurs at the end of a race) can be forced to deliver much less power in the curve than they physically might still be able to deliver. In particular, the last outer curve is notorious in this respect. In the short term, one can only try to avoid this problem by increasing the skating speed prior to the curve. In the long term, one should try to solve this problem basically by training for a more powerful and more effective push-off.

These and other practical applications, concerning for example the influence of body length, sudden wind, and radius manipulations, are elaborated in more detail elsewhere (de Boer et al., 1987; de Boer, Ettema, et al., in press; Ingen Schenau, de Boer, & de Groot, in press).

The Constrained Push-Off

The last subject discussed in this short review of scientific studies on speed skating technique concerns some peculiarities of the leg extension in speed skating. It has already been noted that skaters do not fully extend their knees during the push-off. Part of the knee extension appears to take place after the push-off skate is lifted from the ice. A closer look at the nature of the transformation of rotations in joints into the translation of the body center of gravity makes this phenomenon easy to explain.

The push-off in speed skating can be regarded as a ballistic movement. That is, the purpose of the push-off is an acceleration of the center of gravity with respect to the blade of the skate. The higher this velocity difference at the end of the push-off, the larger the amount of work per stroke. This translational velocity of the center of gravity must be achieved by contracting the muscles that can only bring about rotational velocities in the joints. When compared to running and jumping, the push-off in speed skating is constrained by the need to hold the trunk as well as the skate in a more or less horizontal position. This means that the velocity difference between the center of gravity and the skate is mainly determined by the velocity difference \( V_{HA} \) between the hip (H) and the ankle (A). This velocity difference, however, reaches a peak value far before the knee is extended. Imagine, for example, that the knee is extended with a constant angular velocity \( \omega \). With simple trigonometry applied to the triangle HKA...
(Figure 1), one can prove that the velocity difference $V_{HA}$ is proportional to $\omega \sin \theta_o$ for large angles $\theta_o$. This means that $V_{HA}$ goes to zero at $\theta_o = 180^\circ$ independent of $\omega$ (the hip then can no longer be removed from the ankle). This decrease in the possibility to transfer a rotational velocity into a translational velocity is called a geometrical constraint.

A second constraint is more anatomical in nature. In reality the angular velocity will not be constant but will start at $\omega = 0$ at the onset of knee extension and be increased up to a certain maximal value. Prior to full extension, $\omega$ has to be decelerated to zero to prevent damage of the knee by overextension. This is called an anatomical constraint. The result of both constraints is a peak value $V_{HA}$, which lies at a mean knee angle of approximately $\theta_o = 147^\circ$. For 10 elite female speed skaters, the mean knee angle $\theta_o$, the angular velocity $d\theta_o/dt$, and the velocity difference $V_{HA}$ are shown in Figure 4. As soon as the peak value of $V_{HA}$ is reached, the heavy trunk and contralateral leg will pull the lighter push-off skate from the ice and the push-off is ended.

In running and jumping, of course, the same phenomenon occurs in the extension of the knee. At the instant that $V_{HA}$ peaks, however, the loss of contact with the floor is prevented by an explosive plantar flexion (Bobbert, Huijing, & Ingen Schenau, 1986a, 1986b; Ingen Schenau, Bobbert, & Rozendal, in

Figure 4 — Knee angle $\theta_o$ (solid line), — angular velocity $d\theta_o/dt$ and velocity difference $V_{HA}$ between hip and ankle during push-off as a function of time. Curves are means of measurements from 10 elite female skaters. Bars indicate standard deviations.
press). In that case it was shown that the bi-articular m. gastrocnemius plays a unique role, which can be fully understood from the geometrical as well as the anatomical constraints that are coupled to the transformation of rotations in the joints into translation of the body (Ingen Schenau, Bobbert, & Rozendal, in press). It was shown by de Boer, Cabri, et al. (in press) that the demands concerning a horizontal trunk position and the absence of plantar flexion lead to a completely different intermuscular coordination than what was reported for jumping (Bobbert & Ingen Schenau, 1987; Gregoire, Veeger, Huijing, & Ingen Schenau, 1984). Recently experiments were started with a skate that allows plantar flexion without the disadvantage of an increased ice friction. Possibly this will be the start of a new technique.

References


