Ice friction in speed skating: can klapskates reduce ice frictional loss?

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ABSTRACT

HOUDIJK, H., A. J. WIJKER, J. J. DE KONING, M. F. BOBBERT, and G. DE GROOT. Ice friction in speed skating: can klapskates reduce ice frictional loss? *Med. Sci. Sports Exerc.*, Vol. 33, No. 3, 2001, pp. 499–504. **Purpose:** Reducing ice friction was one of the motives for developing the klapskate. However, the magnitude of power dissipation that occurs with conventional skates when a skater plantar flexes his ankle and the tip of the blade is pressed into the ice has not been quantified previously. In this study, we examine how ice friction varies during a single stroke with conventional skates and estimate the reduction in ice friction that might be obtained with klapskates. **Methods:** Five elite speed skaters performed a series of trials at constant velocity and a series of maximal accelerations. Energy dissipated to ice friction during a stroke with conventional skates was analyzed using an instrumented skate and high-speed 3D kinematic analysis. The energy that would be dissipated when klapskates were used was estimated from the collected data with conventional skates. **Results:** The estimated difference in power loss between conventional and klapskates was less dramatic than has been suggested frequently. Pressing the tip of the blade into the ice comprises only 0.84 W of the total power dissipated by ice friction (54 W) during constant velocity speed skating. During an all-out acceleration, this power loss reached 4.55 W. **Conclusion:** We conclude that only a minor part of the benefit of klapskates can be attributed to a reduction in ice friction. It is shown that this relatively small increase in ice friction is related to the large length of the skate blade. **Key Words:** WINTER SPORTS, EQUIPMENT, TECHNIQUE, BIOMECHANICS, LOCOMOTION

Despite the high speeds that can be reached using conventional, Norwegian, skates (5,11), they impose a serious constraint on the push-off movement. With conventional skates, speed skaters are instructed to suppress ankle plantar flexion so as to prevent the tip of the blade from digging into the ice at the end of the push-off phase. Pressing the tip of the blade into the ice increases ice friction and hence decelerates the skater (1,2,5,6,9). The ability to suppress plantar flexion is regarded as one of the key factors of a good skating technique. It distinguishes trained skaters from novices. However, despite training, an absolute suppression of ankle plantar flexion proves to be impossible (1,3,9).

In recent years, the klapskate has been developed, which allows skaters to plantar flex their ankle without the drawback of digging the tip of the blade into the ice (6). Klapskates are equipped with a hinge between the shoe and the blade that allows the ankle to plantar flex and the foot to rotate, while the full blade remains gliding over the ice. The klapskate was designed to improve skating performance by allowing skaters to fully use their plantar flexor muscles at the end of the push-off and hence increase power output. Simultaneously, the klapskate was believed to reduce the power lost to ice friction that results from pressing the tip of the blade into the ice. The introduction of the klapskate in competitive speed skating resulted in dramatic improvements in skating performance. An improvement in personal best times of 3–5% has been observed for competitive speed skaters (6,8). This equates to a net difference in external power of 7–12%. That is, the faster speeds facilitated by klapskates reflect some combination of a reduction in the power lost to ice friction and/or an increase in the ability of skaters to generate power.

To determine how much of the performance differences between klapskates and conventional skates can be explained from a reduction in ice friction, frictional forces should be measured for both types of skates during speed skating. However, at present, no instruments are available that allow us to measure ice friction for klapskates directly. Moreover, constructing an instrumented klapskate capable of recording ice frictional forces will be highly complicated. We must therefore rely on data collected with conventional skates, to estimate the amount of power dissipated to ice friction that could possibly be saved using klapskates.

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Although it has frequently been suggested that plantar flexion and the concomitant digging of the blade into the ice with conventional skates increases the power dissipated by ice friction considerably (1,2,5,6), no specific quantitative data have been reported. Frictional forces during speed skating with conventional skates have been studied by De Koning et al. (10) using an instrumented conventional skate. They found that the average power dissipated to ice friction on well prepared ice and at competition speed is between 25 and 50 W. Although their study was designed to investigate average ice friction during multiple strokes, they showed that the coefficient of ice friction varies throughout a stroke and rises to a distinct peak at the end of the push-off. This peak was attributed to a plantar flexing movement of the skaters' ankle.

For two reasons, however, these data do not allow us to estimate the power that is dissipated to ice friction when the tip of the blade is pressed into the ice. First, the frictional force reported by De Koning et al. (10) corresponded to the force acting in parallel with the blade of the skate. However, when the skater plantar flexes his ankle, lifting the back of the blade off the ice, this force component is not longer equivalent to the frictional force between the skate and the ice. Thus, the frictional force during the final phase of the push-off was probably overestimated in their study. Second, because power is defined as the vector product of force and the velocity of its point of application, data for the velocity of the blade are required to calculate the power dissipated to ice friction. Although mean skating velocity was reported by De Koning et al. (10), data on the instantaneous velocity of the blade during each stroke were not available and hence power loss within a stroke cannot be derived.

The purpose of the present study was to examine ice friction within a stroke with conventional skates and thus estimate the reduction in ice friction that might be obtained using klapskates. Using an instrumented conventional skate combined with motion analysis, we measured the power loss to ice friction that occurs when the ankle plantar flexes and the tip of the blade is pressed into the ice at the end of the push-off. Based on these data, it was estimated how much klapskates could possibly reduce the ice frictional power loss in speed skating.

METHODS

Subjects and protocol. Five male speed skaters (mass 77.3 ± 4.6 Kg) of the Dutch elite level participated in the experiment. The skaters were informed on the purpose and protocol of the study and gave informed consent according to the policy statement of the ACSM. Experiments were done at a 400-m indoor skating oval during regular training hours. Subjects skated four laps (1600 m) at a set velocity (9 $m \cdot s^{-1}$) to investigate ice frictional loss during steady state endurance speed skating. Subsequently, they performed four accelerations on one of the straights to establish a worst case estimate of the frictional loss. Force and kinematic data were collected for the push-off on the straight.

Forces. An instrumented conventional skate was used to measure the forces that act on the blade. This skate was equipped with three elements containing temperature compensated strain gauges. Two elements were orientated such that they measured the push-off force perpendicular to the blade and one such that it measured the force that is exerted parallel to the blade. Force data were amplified and low pass filtered (cut-off frequency 100 Hz) before being sampled at 1 kHz. Data were stored in a datalogger that the skater carried on his back (mass 1.7 kg). Technical details of this skate were described earlier by Jobse et al. (7) and De Koning et al. (10).

Kinematics. During the gliding phase, the frictional force between skate and ice coincides with the force measured by the force transducer orientated in parallel to the blade. However, during the phase in which the ankle plantar flexes and the skate rotates, the frictional force should be derived from both the parallel and perpendicular force transducers of the skate. Hence, information on the orientation of the skate with respect to the ice is required to determine the orientation of the force vectors on the ice and to calculate the true frictional force. Three-dimensional kinematic data of the skate were collected using a tetherless 3D motion registration system (Optotrak 3020, Northern Digital Inc., Waterloo, Ontario, Canada), operating at a frame rate of 200 Hz. Six position sensors were placed in line, to cover an area with the length of 12 m at the end of one of the straights. The locations of the sensors were calibrated with respect to a global reference frame, which was defined on the ice. Five markers were attached to the left skate. A virtual rigid body was constructed using the positions of these markers, to define the local reference frame of the skate in which the forces are measured. From this defined rigid body and the recorded 3D coordinates of the markers on the skate during the stroke, the force vector measured by the skate was transformed to the global reference frame using the transformation equations described by Veldpaus et al. (13). A pulse, generated by the Optotrak controller, was transmitted to the datalogger of the skate to synchronize force and kinematic data.

Ice friction and power dissipation. The velocity of the blade and hence the point of application of the frictional force in the global reference frame was obtained using a 5-point differentiating filter (12). The frictional force was found by decomposing the transformed 3D force vector between ice and skate into a force component in opposite direction to the velocity of the blade (i.e., frictional force) and a component perpendicular to it (i.e., normal force). Power lost to ice friction was calculated as the product of frictional force and the velocity of its the point of application.

The power lost to ice friction with klapskates was estimated from the data for conventional skates. First, the coefficient of friction, i.e., the quotient of the frictional force and normal force (10) between the blade of the conventional skate and the ice was calculated throughout the entire push-off phase of each trial. We assumed that the friction coefficient with klapskates is equal to that of conventional skates as long as the full blade is in contact with the ice. Rotation of the foot in speed skating typically occurs during the final 50 ms of the push-off (3). With conventional skates, the friction coefficient then rise when the tip of the blade is pressed into the ice. In contrast, with klapskates, the friction coefficient is assumed to remain approximately constant during this final phase. The friction coefficient for klapskates was therefore estimated by fitting a second order polynomial through the calculated friction coefficient versus time curve for conventional skates, over the time frame of 250 to 50 ms before the end of the push-off. Assuming further that normal force and velocity of the blade remain equal with both types of skates, the hypothetical frictional force with klapskates was then calculated by multiplying the estimated ice friction coefficient by the measured normal force. Subsequently, the estimated power loss could be calculated for skating with klapskates. The area in between the power curves for conventional and klapskates, finally, represents the amount of energy per stroke and, multiplied by stroke frequency, the mean power that would be saved by using klapskates.

RESULTS

The subjects skated the constant velocity trials at an average velocity of 8.55 (± 0.22) $m \cdot s^{-1}$ and a stroke frequency of 0.92 (± 0.07) $strokes \cdot s^{-1}$. The mean coefficient of ice friction during the strokes on the straight was 0.0084 (± 0.0041) on average for all skaters. This is high compared with ice prepared for competition but appropriate for recreational ice conditions (10). Given the average mass of the subjects (77.3 kg), the mean power lost to ice friction during the constant velocity tests amounted to 54 W. During the acceleration trials, the skaters accelerated from a low velocity, coming out of the curve, to an average velocity of 9.13 (± 0.94) $m \cdot s^{-1}$ at the end of the straight. The average stroke frequency on the straight was 1.37 (± 0.15) $strokes \cdot s^{-1}$. The mean coefficient of ice friction on the straight was 0.0124 (± 0.0043).

The average normal force, frictional force, and coefficient of ice friction during a stroke at constant velocity and while accelerating are displayed in Figure 1. It can be seen that the frictional force changed in proportion to normal force until the final 50 ms of the push-off. At that instant (indicated by the vertical dotted line), the ankle plantar flexed, lifting the back of the blade of the ice. After this instant, the frictional force rose to a small peak whereas the normal force continued to drop. Consequently, the coefficient of ice friction, being the ratio of frictional force to normal force, was found to peak markedly during the final phase of the push-off. This was clearly the result of ankle plantar flexion, which presses the front end of the blade into the ice.

Although the blade continued to glide over the ice throughout the entire stroke, the velocity of the blade decreased almost continuously (Fig. 2). Only during the period from 100 to 50 ms before the end of the push-off, an acceleration of the blade occurred in both the constant velocity and acceleration condition. Fifty ms before the end of the push-off, the blade again decelerated rapidly. During the constant velocity trials, the velocity of the blade slowed from 8.7 $m \cdot s^{-1}$ at the beginning of the push-off to 7.7 $m \cdot s^{-1}$ before the blade left the ice. In the acceleration trials, the velocity of the blade slowed from 9.3 to 7.9 $m \cdot s^{-1}$ during the explosive push-off phase.

The estimated differences between the coefficients of friction with conventional and klapskates are shown in Figure 3 (upper panels). It is obvious that by extrapolating the coefficient found during the gliding phase with conventional skates, the peak that resulted from pressing the tip of the

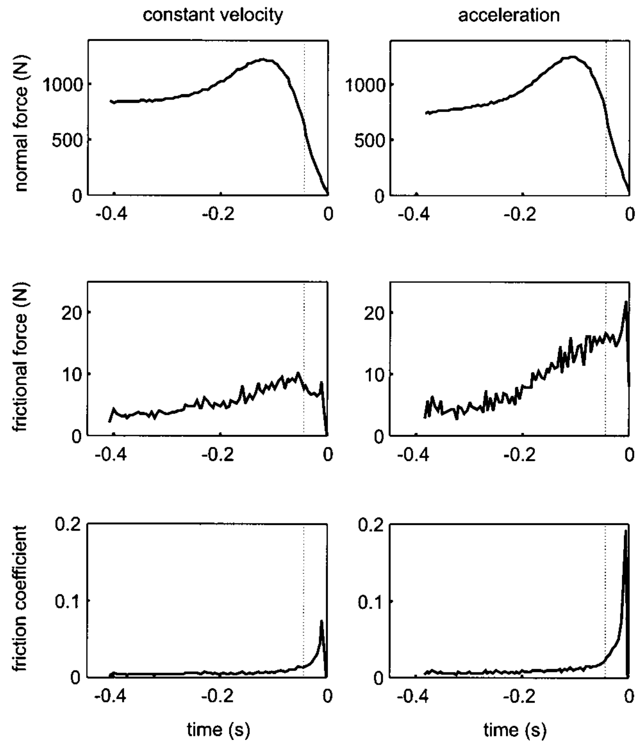

FIGURE 1—Average normal force, frictional force, and ice friction coefficient during a stroke with conventional skates during constant velocity trials (left) and during acceleration trials (right). The *vertical dotted line* indicates the instant the tip of the blade is pressed into the ice.

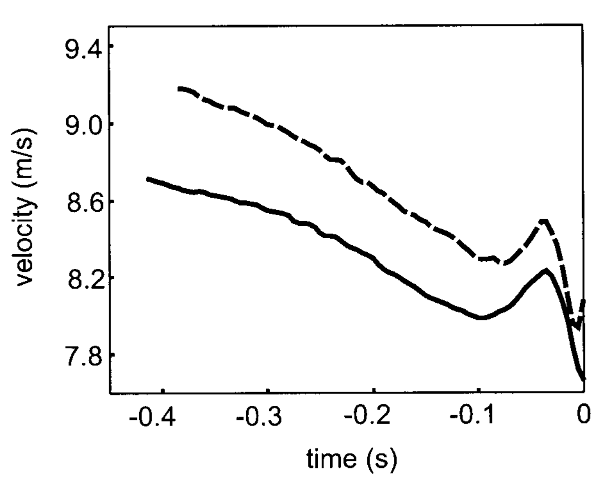

FIGURE 2—Average velocity of the blade during a stroke for constant velocity trials (*solid*) and for acceleration trials (*dashed*).

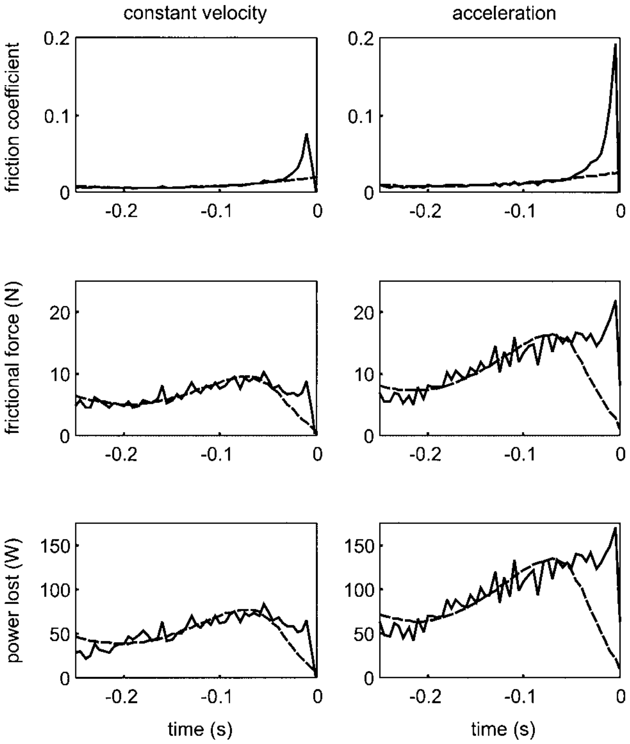

FIGURE 3—Measured ice friction for conventional skates (*solid*) and predicted ice friction for klapskates (*dashed*) during a stroke at constant velocity (left) and during acceleration (right). The friction coefficient (upper panels) on klapskates is fitted from data for conventional skates. Frictional force (middle panels) and power lost to ice friction (lower panels) for klapskates are calculated using the predicted friction coefficient.

blade into the ice disappeared. With the estimated coefficient of friction, the frictional force (Figure 3, middle panels) and subsequently the power dissipated by ice friction (Figure 3, lower panels) that would occur with klapskates were estimated. As can be seen, the frictional force with klapskates diminished continuously during the final 50 ms of the push-off. Consequently, power dissipated by ice friction also lacked a peak during this final phase of the push-off.

During constant velocity skating, the energy lost to ice friction during the final 50 ms amounted to 2.35 (± 1.65) J for conventional skates and was estimated to amount to 1.44 (± 0.94) J for klapskates. Hence, a reduction in energy dissipated by ice friction of 0.91 (± 1.00) J per stroke was estimated for skating at a constant velocity. In the acceleration trials, ice friction dissipated 5.99 (± 4.95) J during the final 50 ms for conventional skates. For klapskates an energy loss of 2.67 (± 2.23) J was predicted. This resulted in an estimated reduction of 3.32 (± 2.95) J per stroke. At the observed stroke frequencies the estimated difference in power dissipated to ice friction, between conventional and klapskates, amounted to 0.84 during the constant velocity trials and 4.55 W during the acceleration trials.

DISCUSSION

With the invention of the klapskate, skaters have acquired the ability to execute an explosive plantar flexion without a concomitant increase of ice friction. Hence, they can benefit from the increase in mechanical power generated by the ankle plantar flexors as well as from a reduction in the power that would be dissipated to ice friction as a consequence of plantar flexion. In the present study, the power dissipated to ice friction during the final phase of the push-off with conventional skates was measured and the potential reduction of ice friction provided by klapskates was estimated.

Pressing the tip of the blade into the ice was shown to comprise less than 1 W of the power flowing to ice friction during skating at a constant pace. This power loss can reach a maximum of 4.5 W when a forceful acceleration is performed. We predict that the power dissipated in the constant velocity trials is representative of the power lost during endurance events of elite speed skating competition. The highest values found during acceleration, probably only occur during the start of the race when a skater changes from a running style, pushing off against a fixed spot on the ice, to a gliding style, pushing off against a forward gliding skate (11).

Using a power balance as described by van Ingen Schenau (4), it can be calculated that for a skater skating at a competition velocity of 12 $m \cdot s^{-1}$, a decrease in ice friction of 1–5 W results in an increase in skating velocity of 0.01–0.08 $m \cdot s^{-1}$. This potential increase in velocity of 0.1–0.7% can only account for a small fraction of the increase in skating velocity that has been shown to occur when skaters switch from conventional to klapskates (6,8). Consequently, because power dissipation is affected only marginally, the enhanced speed skating performances that are observed when klapskates are used must be explained by an increase in the power output generated by the skaters. A recent study indeed showed that the differences in push-off mechanics allow klapskate users to increase their mechanical power output by as much as 12% compared with conventional skates (3). This increase in power output is sufficient to account for all of the increase in skating velocity observed for klapskates.

Our estimate of the power loss to ice friction with klapskates hinges on several assumptions. We assumed that the ice friction coefficient during the final 50 ms of the push-off with klapskates could be found by extrapolating the coefficient that is found during the gliding phase. In addition, we assumed that the normal force and the velocity of the blade were equal for conventional and klapskates. This method provided the simplest model for the ice friction with klapskates, which are of course not frictionless during the final phase of the push-off. It might be argued whether these assumptions are valid. However, these assumptions prove not to be critical to the major conclusion of this study. The difference between conventional and klapskates can at most be equal to the total power dissipated during the final 50 ms with conventional skates. The results show that even the total power loss in this phase is insubstantial. When skating at constant velocity, less then 2 W is lost to ice friction during these final 50 ms of the push-off. So, refining the assumptions could only slightly influence the estimated difference in power dissipated to ice friction between klapskates and conventional skates.

Power that is dissipated to ice friction when the tip of the blade is pressed into the ice is not as great as has been suggested frequently (1,2,5,6,9). The maximal power loss that can be ascribed to it, as observed during the all out accelerations, is of the same order of magnitude as the variations that can normally occur due the changing ice conditions throughout a competition day (10). Moreover, the extra power lost to ice friction appears to be less than the power that can be generated during the same final 50 ms of the push-off (3,9). This indicates that failing to suppress plantar flexion is not counterproductive as was believed. The deep-rooted belief, that plantar flexing the ankle while using conventional skates would tremendously increase ice friction, may originate from the fact that the coefficient of ice friction will rise when the tip of the blade is pressed into the ice. The coefficient of friction between blade and ice does indeed show a distinct peak at this instant. However, a powerful plantar flexion only occurs after the normal force has already declined considerably. Therefore, frictional force does not increase as much as the coefficient of ice friction does.

It can be shown by an analysis of the mechanics that govern the rotation of the skate during the push-off in speed skating that a large power loss is inherently prevented by the long blade of the conventional skate. Rotation of the skate, pressing the tip of the blade into the ice, occurs when the net ankle moment, mainly generated by the plantar flexor muscles, exceeds the moment of the external forces that act on the foot (Fig. 4). During the initial push-off phase, these two moments are in balance and the skate remains gliding on the ice. As the hip and knee reach the end of their extensions, the magnitude of the external reaction forces on the foot decreases. Yet, the balance of both moments is maintained because the point of application of the ground reaction force shifts forward along the blade, which increases the moment arm of the external forces. This is the case until the center of pressure of the ground reaction force reaches the front tip of the blade. Thereafter, the plantar flexor moment will exceed the external moment and the skate starts to rotate. Because the conventional skate is designed with a relatively long blade, the external forces decrease considerably before rotation of the skate is initiated. Consequently, the long blade of the skate essentially limits a large increase of the frictional force. In fact, these mechanics probably underlie the centuries old design of the long blade of the Norwegian skate, which has never been justified explicitly.

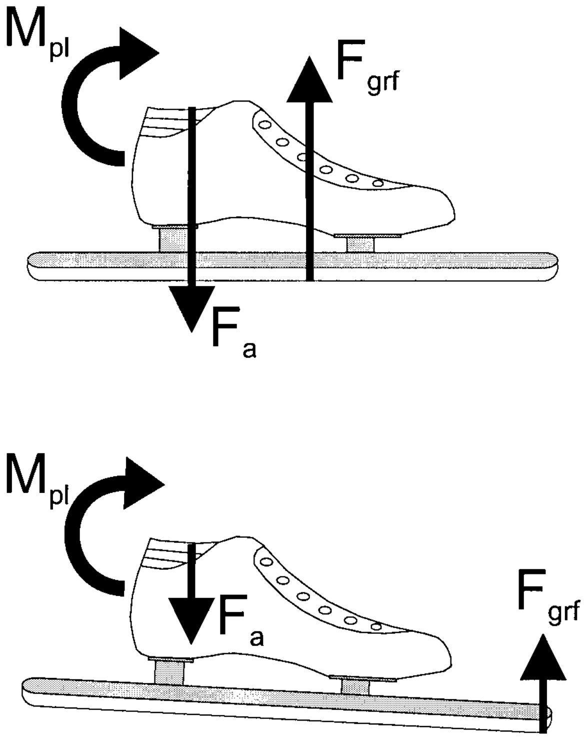

FIGURE 4—Top, During the gliding phase and initial push-off phase the net joint moment of the ankle (M_{pL}) is in balance with the external moment, caused by the couple of net joint force at the ankle (F_a) and ground reaction force (F_{grf}). Bottom, Due to the relatively long blade, the external force needs to drop considerably before the plantar flexor moment exceeds the external moment and the skate starts to rotate.

In summary, it has been shown that pressing the tip of the blade into the ice at the end of the push-off with conventional skates does not result in an excessive increase in power dissipated by ice friction. Consequently, a reduction in ice friction cannot account for the improved performance that has been observed when skaters changed from using conventional skates to klapskates. The major benefits of the klapskate should therefore be attributed to improved push of mechanics and a subsequent increase in mechanical power output.

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