Push-off mechanics in speed skating with conventional skates and klapskates

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ABSTRACT

HOUDIJK, H., J. J. DE KONING, G. DE GROOT, M. F. BOBBERT, and G. J. VAN INGEN SCHENAU. Push-off mechanics in speed skating with conventional skates and klapskates. *Med. Sci. Sports Exerc.,* Vol. 32, No. 3, pp. 635–641, 2000. **Purpose:** Personal and world records in speed skating improved tremendously after the introduction of the klapskate, which allows the foot to plantar flex at the end of the push-off while the full blade continues to glide on the ice. The purpose of this study was to gain insight into the differences in skating technique with conventional versus klapskates and to unveil the source of power enhancement using klapskates. **Methods:** Ten elite speed skaters skated four 400-m laps at maximal effort with both conventional and klapskates. On the straight high-speed film, push-off force and EMG data were collected. An inverse dynamics analysis was performed in the moving reference plane through hip, knee, and ankle. **Results:** Skating velocity increased 5% as a result of an increase in mean power output of 25 W when klapskates were used instead of conventional skates. The increase in mean power output was achieved through an 11-J increase in work per stroke and an increase in stroke frequency from 1.30 to 1.36 strokes·s^{-1}. The difference in work per stroke occurs during the final 50 ms of the push-off. This is the result of the ineffective way in which push-off forces are generated with conventional skates when the foot rotates about the long front end of the blade. No differences in muscle coordination were observed from EMG. **Conclusion:** A hinge under the ball of the foot enhances the effectiveness of plantar flexion during the final 50 ms of the push off with klapskates and increases work per stroke and mean power output. **Key Words:** LOCOMOTION, TECHNIQUE, BIOMECHANICS, COORDINATION, WINTER SPORTS, EQUIPMENT

A new era in speed skating has started after the recent introduction of the klapskate in the international arena. This new type of skate is equipped with a hinge between shoe and blade under the ball of the foot. This hinge allows plantar flexion of the foot at the end of the push-off while the full blade remains in contact with the ice (8). The introduction of the klapskate was accompanied by a remarkable improvement of personal records and all world records were shattered during the season of 1997–98. Skaters who switched to klapskates were able to increase their skating speed by as much as 4%. This is equivalent to an increase in mean power output of about 10%.

The idea that speed skating performance might be improved using a skate that allows plantar flexion of the foot while the blade continues to glide over the ice was described in literature as early as 1987 (6). It was based on biomechanical research into the specific characteristics of the gliding push-off technique in speed skating and the push-off mechanics of vertical jumping.

Despite the high velocity that can be achieved in speed skating with the gilding push-off technique (6), this push off is a very constrained movement. Speed skaters must keep their trunk horizontal to limit the influence of air friction, which is considerable at high velocity (4). At the same time the speed skater, skating with conventional skates, has to suppress plantar flexion of the foot in order to perform a gliding push-off and to prevent the tip of the blade from scratching through the ice (7). Thus, with conventional skates, only rotation of upper and lower legs can contribute to the acceleration of the skater's body center of mass (BCM). Furthermore, it has been noticed that the absence of a powerful plantar flexion not only limits the contribution of the ankle plantar flexors but is also accompanied by an incomplete knee extension at the end of the push off (7). This is attributed to the way that rotational velocity of the leg segments is transferred into translational velocity of the BCM. As can be derived mathematically this transfer is constrained by the geometry of the system, causing the velocity at which the hip moves away from the ankle to decrease before the knee is fully extended (5). For speed skaters, this decrease in push off velocity occurs at a knee angle of about 150° (7). After this time, the inertial force of the relatively heavy trunk and contralateral leg will pull the push-off leg from the ice. The remaining range of knee extension is performed while the leg is in the air and, hence, cannot contribute to push-off energy.

It should be noticed that only a small percentage of skaters on conventional skates succeed in suppressing plantar flexion entirely (13). However, this plantar flexion, pressing the front tip of the blade in the ice, was considered

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to be undesirable and even counterproductive. Therefore, in most kinematic studies of speed skating, the end of the (effective) push-off is defined as the instant that the rear end of the blade leaves the ice despite of additional contact between ice and front tip of the blade.

In less constrained movements, such as jumping and sprint running, the geometrical constraint is dealt with by executing an explosive plantar flexion at the instant the extension velocity of the hip relative to the ankle decreases. In this way, the extension velocity of the leg (the velocity at which the hip moves away from the surface) can be increased further and contact between the push-off leg and surface can be maintained. Thus, the ability to plantar flex the foot not only enables the ankle but also the knee extensor muscles to do additional work. It was hypothesized that by enabling the speed skater to plantar flex his foot while the full blade remained on the ice, a similar increase in work per stroke could be obtained. A skate was developed in which a hinge between shoe and blade enables the skater to plantar flex his foot while the blade remains gliding on the ice (8).

A remarkable progress in the performances of speed skaters switching to klapskates has been observed. Although the benefits of the klapskate are undisputed, limited data on the push-off mechanics using klapskates are available. In a kinematic analysis performed previously (3), the expected increase of push-off duration and range of knee and ankle joint extension was confirmed. However, a kinematic analysis does not elucidate the amount or source of power enhancement. Moreover, in that study, two different groups of skaters were studied, introducing possible confounding factors. In the present study, we have investigated the push-off mechanics within one group of skaters, skating with both conventional and klapskates. The purpose of this study was to gain insight into the differences in skating technique with conventional and klapskates, and to unveil the source of power enhancement using klapskates. The use of high-speed film, an instrumented skate recording push-off force, and EMG recordings enabled us to gain important insight into the benefits of the klapskate.

METHODS

Ten Dutch national speed-skating team members participated in this experiment during their October training stage at the outdoor skating rink of Inzell. This group consisted of three seniors and seven juniors, two of whom were female. All subjects were familiar with klapskates. Most of them had switched to klapskates at the end of the previous season, but some of them had klapskate experience of up to 3 years. Each subject participated voluntarily and provided informed consent.

The experiment consisted of eight trials in which a 400-m lap had to be skated. Each skater skated four subsequent trials with conventional skates and four subsequent trials with klapskates. The skaters were asked to skate at maximal effort, taking into account that this same effort should be maintained during each trial. The order in which they used the different types of skates was alternated. About 15 min of practice was given to adjust to each skate, and between two consecutive test trials, sufficient rest was given to avoid fatigue. During the 400-m lap, one straight and subsequent curve were used to accelerate. On the next straight and curve a constant speed had to be maintained. Kinematic, force, and EMG data were recorded on the second straight.

Kinematics. The speed skaters were filmed using two 16-mm high-speed film cameras (Photosonics 1PL, Burbank, CA) operating at a frame rate of 100 Hz. One panning camera was placed inside the rink, following the skaters in the sagittal view as they proceeded along the straight. The other camera was stationary. It was placed outside the rink at the end of the straight filming the frontal view. Markers were placed on the skater's suit and skate to mark the locations of the neck, hip, knee, ankle, and axis of the klapskate or a comparable location between shoe and blade when the conventional skate was used. A series of markers was placed along the inside of the straight indicating the y-axis of a global reference frame. The position of both cameras with respect to this global reference frame was measured using a theodolite.

For each trial the stroke of the left leg most perpendicular to the sagittal camera was analyzed. For this stroke the position of the body and reference markers of each frame were digitized manually (NAC motion analyzer, Simi Valley, CA). Three-dimensional (3D) coordinates of the body markers were calculated using the method described by de Koning (12) and Yeadon (18). The calculated 3D position data were low-pass filtered (Butterworth 4th order bidirectional filter, cut-off frequency 15 HZ). Velocity of the body markers was obtained using a 5-point differentiating filter (16).

Force measurement. Push-off force on conventional skates was measured using an instrumented skate described elsewhere (10). To measure push-off force on klapskates, an instrumented klapskate was developed (Fig. 1). This skate, based on the instrumented conventional skate, contained two elements equipped with strain gauges, one located underneath the heel and the other at the location of the hinge. The vertical force that the skater exerted perpendicular to the blade could be measured and the center of pressure of this force could be calculated. A potentiometer, fixed to the hinge of the klapskate, registered the angular displacement of the shoe with respect to the blade. The skater was allowed to use his own shoe on both types of skates. The location of the hinge of the instrumented klapskate was identical to that of the klapskates regularly used by the skater. The signals from the skates were recorded and stored in a portable computer (mass 1.7 kg, sample rate 1 kHz) that the skaters carried on their back.

The instrumented skates only measured the component of the push-off force coinciding with the z-axis of the local reference frame of the instrumented skate (Fig. 1). The forward-backward component along the y-axis as well as the sideward component along the x-axis was ignored. In experiments on conventional skates de Koning et al. (14) demonstrated that the forces in forward-backward direction had a maximum of 10 N. This is less then 1% of the force in z-direction at the same instant. We therefore felt that this component could safely be neglected. The force along the x-axis has never been measured. We assume that the push-off

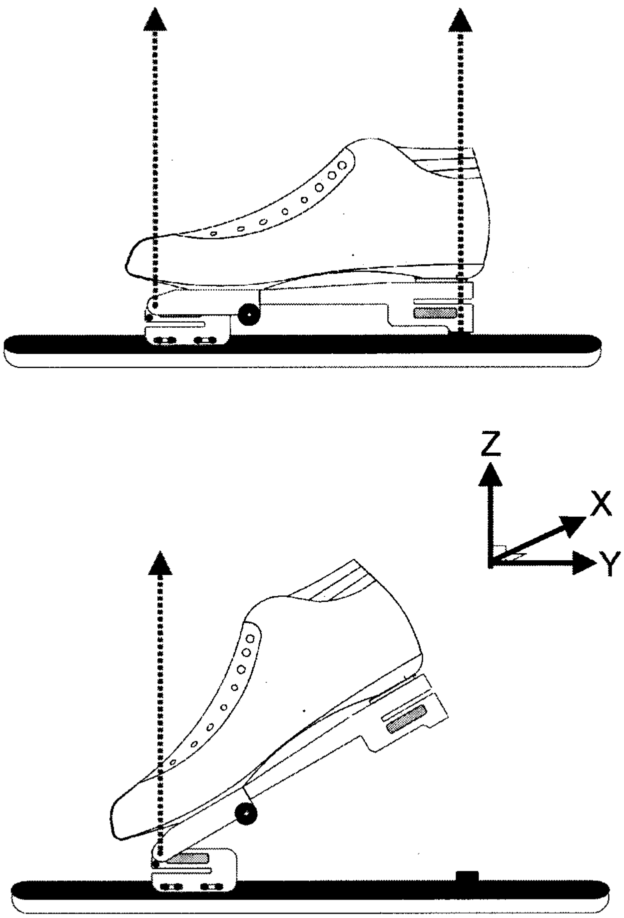

Figure 1—Instrumented klapskate. Two elements equipped with strain gauges (gray shade areas) are located underneath the heel and at the location of the hinge. The *dotted arrows* indicate the lines of action of the force measured in both elements. The local reference frame of the skate is shown.

force vector is directed to the BCM of the skater continuously, the line of action running closely along the hip. Because no excessive inversion or eversion of the foot occurs during the push-off in speed skating, the push-off force vector coincides almost completely with the z-axis of the instrumented skate. Hence, the sideward component will be negligible.

The portable computer carried on the skaters' back generated a synchronization signal. This signal was visible on force, film and EMG tracings, so that force, kinematic, and EMG time histories could be synchronized.

Electromyography. Electromyographic data was recorded from the m. gluteus maximus, m. semitendinosus, m. biceps femoris (caput longum), m. rectus femoris, m. vastus lateralis and medialis, lateral and medial head of the m. gastrocnemius, m. soleus, and m. tibialis anterior of the left leg. Pairs of surface electrodes (medi-trace, pellet electrodes) were attached to the skin after standard skin preparation (1). The EMG signals were preamplified and telemetrically transmitted (Biomes 80, Glonner Electronics GmbH, Planech-Steinkirchen, Germany) to the side of the rink where the signals were processed through an analog amplifier and band pass filter (5-200 Hz) before being sampled (sample rate 1 kHz). Off-line the EMG signals were full-wave rectified and low-pass filtered (15 Hz) to obtain smoothed rectified EMG signals (SREMG). Before the start of the experiments, EMG activation during isometric maximal voluntary contractions (MVC) was obtained for each muscle in a neutral position. SREMG is expressed as a fraction of mean activation during MVC.

Data analysis. Push-off mechanics were analyzed in a moving reference plane running through ankle, knee, and hip joint (Fig. 2). The y-axis of this reference plane coincides with the intersecting line between this plane and the ice. The z-axis is orientated perpendicular to the y-axis and runs through the hip joint. Forward velocity of the hip joint is approximately constant in the global reference frame, which minimizes the influence of inertial forces in the analysis.

The projection of the body markers and the orientation of the force vector in the moving reference plane were calculated. From the position of the body markers in the reference plane segment angles and joint angles were calculated. Positions of the segmental mass centers were calculated using antropometric data of Clauser et al. (2). Linear and angular velocity and acceleration were obtained using a 5-point differentiating filter (16). An inverse dynamics analysis was used to calculate net joint torques. Joint power output was calculated as the product of net joint torque and joint angular velocity (15). Work done across the individual joints was obtained by integrating joint power over time and mean power output (Pj) was obtained multiplying total work per stroke by stroke frequency. For all subjects, at least three trials on each skate were successfully analyzed. For each type of skate, the data were averaged per subject and per skate, after synchronization at the instant push-off force dropped to zero. This instant will be referred to as t_0 throughout this paper.

As an alternative to using an inverse dynamics analysis, mean power output can also be obtained using a power balance model. With this power balance model, the mean power output (Pf) can be calculated based on models of power losses against air and ice friction (4). The input of the models consists of knee and trunk angle in the gliding phase, length, and mass of the skater and ice and weather conditions. So, this model is entirely independent from the

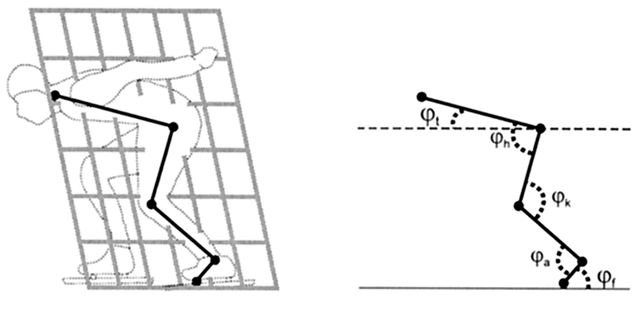

Figure 2—Left: Positions of markers and the moving reference plane, through hip, knee and ankle, in which the data is analyzed. Right: Definition of angles; trunk angle (φ_t), hip angle (φ_h), knee angle (φ_k), ankle angle (φ_a), and foot angle (φ_f).

TABLE 1. Mean values, standard deviations, and *P*-values of differences in push-off mechanics in skating with conventional skates and klapskates.

	Conventional	Klap	*P*
Velocity (m·s^{-1})	11.23 (0.23)	11.86 (0.43)	<0.01
Stroke frequency (strokes·s^{-1})	1.30 (0.05)	1.36 (0.03)	0.03
Angles at t_0 (°)			
Foot	57.7 (12.0)	62.9 (8.4)	0.13
Ankle	122.2 (3.7)	123.6 (6.7)	0.57
Knee	170.8 (4.9)	166.0 (5.7)	<0.01
Hip	122.6 (4.9)	121.8 (4.8)	0.31
Peak angular velocity (°·s^{-1})			
Foot	419.9 (201.3)	588.6 (162.3)	0.06
Ankle	655.6 (127.9)	688.0 (133.4)	0.52
Knee	628.7 (79.6)	530.2 (93.2)	<0.01
Hip	425.0 (56.9)	370.8 (53.8)	<0.01
Work (J)			
Total	162.8 (28.2)	173.1 (37.3)	0.05
Ankle	27.3 (7.7)	30.9 (14.2)	0.26
Knee	58.3 (14.6)	84.0 (19.5)	<0.01
Hip	76.2 (17.8)	58.2 (20.2)	0.04

parameters used in the inverse dynamics model. Although this method does not provide insight in the way that power output is generated, it was used here to test the reliability of the inverse dynamics analysis.

Statistics. Differences between skating with conventional skates and klapskates were tested for significance using a Student *t*-test for paired comparisons. The level of significance was set at 5%.

RESULTS

During the experiments each skater skated faster with klapskates than with conventional skates. Average velocity of the skaters during the analyzed strokes was 11.86 m·s^{-1} with klapskates versus 11.23 m·s^{-1} with conventional skates (Table 1). Extrapolated to a 400-m lap time, this is equal to 33.7 s and 35.6 s, respectively. Stroke frequency was significantly higher when skaters used klapskates compared with conventional skates, 1.36 vs. 1.30 strokes·s^{-1}.

Remarkably similar kinematic patterns were found for skating with both conventional and klapskates (Fig. 3, Table 1). The timing of joint extension and the duration of the push off phase appear to be identical with both skates. In the gliding phase, defined as the time interval 600 to 400 ms before t_0, the skaters maintained a 2.5° smaller average knee angle and a 1.4° smaller hip angle with klapskates compared to conventional skates. The trunk angle in the gliding phase did not differ between the two conditions.

During the push-off phase, starting approximately 200 ms before t_0, skaters surprisingly extended their knee more completely with conventional skates than with klapskates. At the instant the push-off force dropped to zero, a knee angle of 170.8° was reached with conventional skates versus 166.0° with klapskates. The ankle was plantar flexed to the same extent during ice-contact with both skates. Obviously, with klapskates the full blade remained on the ice while the foot was plantar flexed, whereas with conventional skates plantar flexion was performed with the foot vaulting over the front tip of the blade.

Peak angular velocities of knee and hip joint were significantly higher using conventional skates (Fig. 3; Table 1). Knee extension velocity reached a maximum of 628°·s^{-1} with conventional skates and 530°·s^{-1} when klapskates were used. Peak hip extension velocity reached 425°·s^{-1} with conventional skates and 370°·s^{-1} with klapskates. Peak ankle plantar flexion velocity did not differ significantly between the two conditions.

The product of net joint torque (Fig. 4, left panels) and joint angular velocity results in the mechanical joint power (Fig. 4, right panels). Total power output, which equals the sum of the individual joint powers, was fairly constant during the gliding phase and first part of the push-off phase regardless of the skates that were used. Starting 100 to 50 ms before t_0 a drop in total power output was seen for the push-off with conventional skates compared with klapskates. This drop in total power output is mainly caused by a decrease in joint power across the knee joint, which actually was negative, thus absorbing power in the final 50 ms of the push-off. Peak power across the ankle was only slightly higher with klapskates. Hip joint power showed a second peak in the final 50 ms of the push-off with conventional skates, but the extra hip joint power could not compensate for the power absorbed across the knee. Total work per stroke averaged 173 J with klapskates versus 162 J with conventional skates, an increase of 11 J (Table 1). An increase of +3.6 J was found across the ankle joint. The largest part of the increase, +25.7 J, occurred across the knee, whereas work done across the hip was lower with klapskates, −18 J.

Mean power output was 234 W when klapskates were used and 209 W when conventional skates were used, an increase of

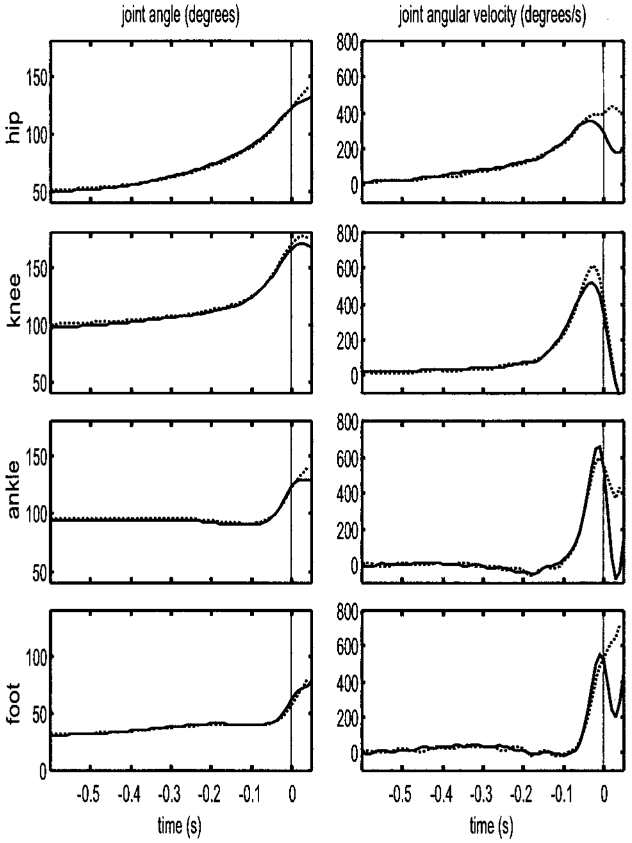

Figure 3—Joint angles and joint angular velocity during the push-off with conventional (*dotted*) and klapskates (*solid*). The end of the push off is marked by the vertical line at 0 s.

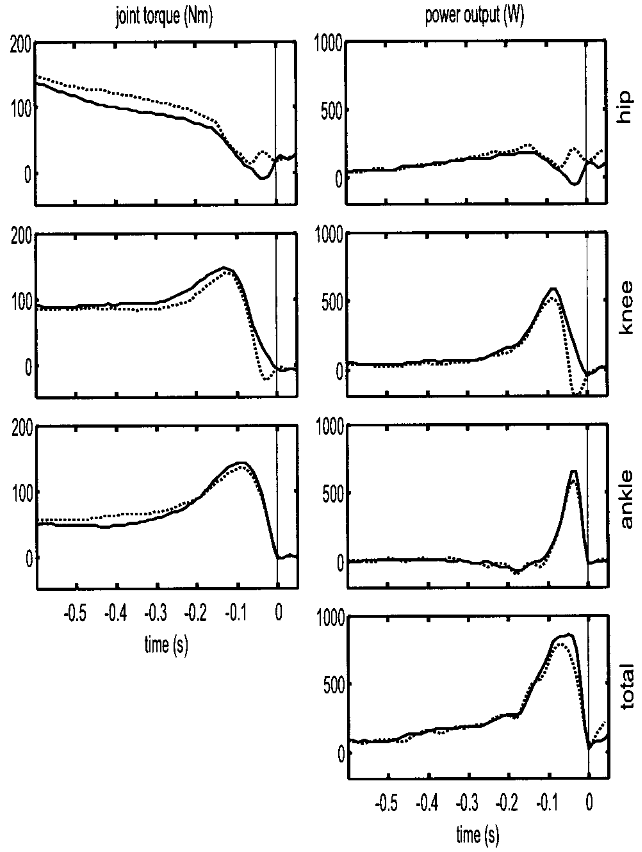

Figure 4—Left panels: Net joint torques during the push off with conventional (*dotted*) and klapskates (*solid*). Right panels: Power output across each joint and total power output during the push-off with conventional (*dotted*) and klapskates (*solid*). The end of the push off is marked by the vertical line at 0 s.

12%. Compared with the inverse dynamics model (Pj), the frictional model (Pf) resulted in somewhat higher mean power output values (Table 2). Pf amounted to 261 W when the skater used klapskates versus 236 W when the skater skated with conventional skates. Although a systematic difference of 27 W existed between the two models, the increase in power output using klapskates was the same for Pj and Pf.

No visible changes in muscle activation were found for skating with conventional and klapskates. Neither timing nor amplitude of muscle activation was altered using either skate. EMG activity of 10 muscles expressed as a fraction of MVC is displayed in Figure 5.

DISCUSSION

The data of this experiment confirm the improvement of speed skating performance using klapskates as is seen in speed-skating competition. The results, however, shed a new light on the way the increase in mean power output is developed. In this section, the increase in mean power output and the mechanism leading to it will be discussed.

Speed skating velocity increased more than 5% when skaters used klapskates instead of conventional skates. This was realized through an increase in mean power output of 25 W. The increase in velocity and mean power output corresponds to the increase seen in international speed skating competition after the introduction of the klapskate (9). However, in contrast to what might be expected, the increase in mean power output could not be explained solely by an increased amount of work per stroke. Of the 25-W increase in mean power output, only 15 W could be attributed to an increase in work per stroke. The other 10 W originated from the higher stroke frequency displayed in skating with klapskates. This increase in stroke frequency should, however, not be primarily regarded as an effect of the klapskate. It is more likely to result as a side effect of the experimental set-up and increased velocity. The time it takes to cover the straight decreases a little with increasing speed, but the number of strokes can only change by a discrete number. Therefore, when the skater does not yet decide to change the number of strokes on the straight, stroke frequency has to change. Despite this forced change in stroke frequency, the skater still should be able to generate the required power output to sustain this higher frequency. Recent experiments have shown that the increased performance with klapskates is accompanied by an increase in mechanical efficiency (11). This increase in mechanical efficiency could explain the ability to increase stroke frequency next to the 11-J increase in work per stroke.

The klapskate was designed to increase work per stroke in speed skating (8). The ability to execute a powerful plantar flexion with klapskates at the end of the push-off should elongate push off duration and enhance the range of knee extension. Work per stroke was expected to increase due to an enhanced contribution of ankle plantar flexors as well as knee extensors (8). However, the kinematics of skating with klap- and conventional skates appear to be remarkably similar in this experiment. As can be seen in Table 1 and Figure 3, angular displacement of the foot segment was only slightly larger with klapskates than with conventional skates and so was foot angular velocity. Consequently, push-off duration was similar with either skate, and knee extension at the end of the push-off was even slightly higher with conventional skates compared with klapskates.

The observed plantar flexion using conventional skates in this study should, however, not be regarded as an abnormal skating technique. De Koning et al. (13), also using an instrumented skate, previously reported that most speed skaters do not succeed in suppressing plantar flexion entirely with conventional skates. Although no foot plantar flexion angles were reported in their paper, it was shown that knee extension reached 164° at the instant the rear end of the blade left the ice but continued to an angle of 171° before the front end of the blade left the ice and push-off force dropped to zero. Push-off duration was reported to be approximately 200 ms. These values are similar to those found in the present study. In addition, it should be realized that in the different kinematic

TABLE 2. Mean power output during skating with conventional skates and klapskates calculated through an inverse dynamics model (Pj) and a frictional model (Pf).

	Conventional	Klap
Pj (W)	209	234
Pf (W)	236	261

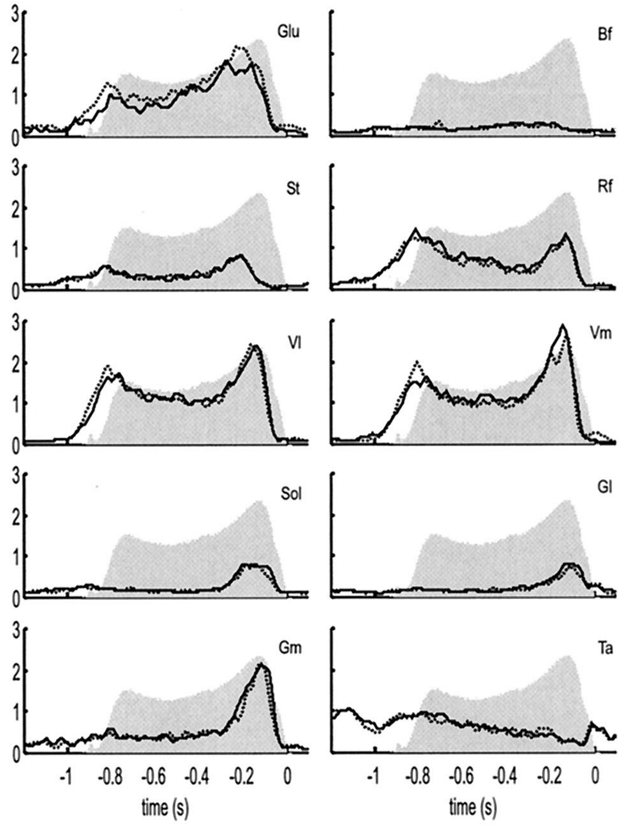

Figure 5—Averaged EMG recordings of 10 leg muscles expressed as a fraction of MVC. m. gluteus maximus (glu), m. semitendinosus (st), m. biceps femoris (bf), m. rectus femoris (rf), m. vastus lateralis (vl) and medialis (vm), m. gastrocnemius lateralis (gl) and medialis (gm), m. soleus (sol), and m. tibialis anterior (ta). The *shaded background* represents the average ground reaction force and is displayed as a reference.

studies of speed skating with conventional skates (3,6) in which an early termination of the push-off and knee extension angles of 146° to 164° are reported, the end of the push-off was defined as the instant the rear end of the blade left the ice, despite the fact that the front tip of the blade frequently remained in contact with the ice for another 20–50 ms. This final phase, in which the foot plantar flexed and the front tip of the blade is pressed into the ice, was not regarded to contribute effectively to push off energy. Moreover, it was even regarded to be counterproductive because balance of the skater could be disturbed and kinetic energy could be dissipated through ice friction. Quantitative data supporting this assumption were, however, never presented.

Because the angular displacements and duration of the push-off are nearly the same using both types of skates, our attention should be directed to the difference in effectiveness of the push-off during its final phase when the foot plantar flexes. It is obvious from the data on power output that the main difference in push-off energy between klap- and conventional skates occurred in these final 50 ms. Stick diagrams of the skater with klap- and conventional skates help to explain the difference. In Figure 6, stick diagrams and push-off force vectors of a skater with conventional and klapskates are depicted during the final 100 ms of the push-off. It can be seen that until 50 ms before the end of the push-off, only minor differences exist; 50 ms before t_0, the center of pressure of the push-off force reaches the ball of the foot where, in the case of klapskates, the hinge between shoe and blade is located. With klapskates, the skater then starts to plantar flex his foot, and the center of pressure remains located at the hinge during the remainder of the push-off. With conventional skates, the center of pressure will pass the ball of the foot during the final 50 ms of the push-off and continues to move forward until it reaches the front end of the blade, which then becomes the center of rotation of the blade. It is important to realize now that during a push-off in speed skating the push-off force needs to be directed perpendicular to the surface. Otherwise, the skate will be accelerated forward or backward because no resistance of frictional forces of the ice is met and the foot will slip away. During the final 50 ms with klapskates, the push-off force can be directed perpendicular to the blade by generating a knee extension and ankle plantar flexion torque. With conventional skates, however, a knee extension torque during the final phase of the push off would result in a forward directed push-off force and would make the foot slip forward. The additional forward displacement of the center of pressure along the blade calls for a flexing knee torque to direct the push-off force perpendicular to the surface. Although the hip and ankle joint are able to do positive work in this phase, the knee is prevented from doing work and is even forced to absorb energy. Although the leg of the skater continues to extend and ice contact is maintained during this phase, the push-off force falls much faster when conventional skates are used compared with klapskates.

This mechanism could explain most of the 11-J difference in mechanical work done during the push-off with klapskates compared with conventional skates. So, it is not merely the suppression of plantar flexion with conventional skates that results in a reduction of mechanical work. The requirement of directing the push-off force perpendicular to the surface in combination with the long length of the blade makes it essentially impossible to generate power effectively in the final phase of the push-off with conventional skates. The irrepressible but ineffective plantar flexion with conventional skates might, next to the difference in work per stroke, also be responsible for the difference in mechanical efficiency found between conventional and klapskaters (11).

It is striking that no differences in EMG patterns between the two skates were found, despite the differences in skating mechanics. This suggests that the differences in skating mechanics are not a result of differences in muscle coordination. Possibly external mechanical factors, such as the length of the conventional blade, interact with muscle activation to produce these specific differences in push-off mechanics (5). It has also been established that muscle properties (force-length-velocity relationship) influence the result of a specific muscle activation (17). In this way, the outcome of the push-off is partly organized on a level below the central nervous system. Because the differences in push-off mechanics found in this study mainly arise in a fraction of 50 ms during which an irrepressible, almost passive plantar flexion is executed, this seems a reasonable explanation.

The mean power output calculated using an inverse dynamics model and a power balance, based on frictional models,

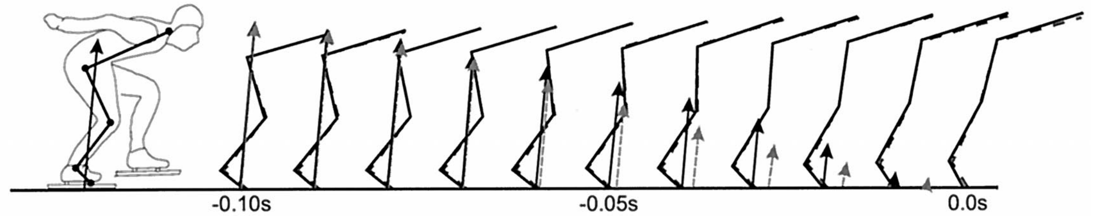

Figure 6—Stick diagrams and ground reaction force vectors of a skater with conventional (*dotted*) and klapskates (*solid*) during the last 100 ms of the push-off. Note that the ground reaction force vector of the conventional skater shifts in front of the knee joint during the final 50 ms of the push-off.

showed similar values and trends. An increase in mean power output of 25 W using klapskates was found using both models (Table 2). However, the values of Pf using the frictional model were 27 W higher then the Pj values found using the inverse dynamics model. The difference in the absolute values of mean power output might be attributed to inaccurate estimates of wind velocity, air pressure, or ice friction coefficient. Furthermore, it should be recalled that we only analyzed skating mechanics in the plane through the ankle, knee, and hip. Outside this plane, some additional work could be done through an exorotation or abduction of the hip (13). However, the identical increase in mean power using klapskates, calculated through both models that use entirely different input parameters, strengthens our confidence in the performed analysis.

An increase in ice friction as a result of the irrepressible plantar flexion using conventional skates was one of the reasons for the development of the klapskate. However, in this study, the increased skating velocity with klapskates could be explained entirely from an increase in mechanical power output generated by the skater. This implies that a change in power lost to ice friction between conventional and klapskates is small. In addition, it could be deduced that the fundamental ineffectiveness of the plantar flexion with conventional skates could be a more important reason why conventional skaters should suppress plantar flexion. This raises serious questions about the purported reduction of ice friction using klapskates instead of conventional skates. The magnitude of power lost against ice friction during the plantar flexion with conventional skates will shortly be addressed experimentally.

In summary, we have shown that skaters are able to generate a higher velocity and mean power output with klapskates compared with conventional skates. The increased power output partly results from an increase in work per stroke and partly from an increased stroke frequency. The necessity to vault over the long front end of the blade of conventional skates results in an ineffective push off. This constraint accounts for the difference in work per stroke despite similar kinematic patterns shown with both skates.

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