Gross Efficiency in Cyclic Sports
Noordhof, D.A.

2013

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Changes in Speed Skating Velocity in Relation to Push-Off Effectiveness

Dionne A. Noordhof, Carl Foster, Marco J.M. Hoozemans, and Jos J. de Koning

Speed skating posture, or technique, is characterized by the push-off angle or effectiveness (e), determined as the angle between the push-off leg and the ice; the preextension knee angle (θ0); and the trunk angle (θ1). Together with muscle-power output and environmental conditions, skating posture, or technique, determines velocity (v). **Purpose:** To gain insight into technical variables that are important to skate efficiently and perform well, e, θ0, θ1, and skating v were determined every lap during a 5000-m World Cup. Second, the authors evaluated if changes (Δ) in e, θ0, and θ1 are associated with Δv. **Methods:** One camera filmed the skaters from a frontal view, from which e was determined. Another camera filmed the skaters from a sagittal view, from which θ0 and θ1 were determined. Radio-frequency identification tags around the ankles of the skaters measured v. **Results:** During the race, e progressively increased and v progressively decreased, while θ0 and θ1 showed a less consistent pattern of change. Generalized estimating equations showed that Δe is significantly associated with Δv over the midsection of the race (β = –0.10, P < .001) and that Δθ0 and Δθ1 are not significantly associated with Δv. **Conclusions:** The decrease in skating v over the race is not due to increases in power losses to air friction, as knee and trunk angle were not significantly associated with changes in velocity. The decrease in velocity can be partly ascribed to the decrease in effectiveness, which reflects a decrease in power production associated with fatigue.

**Keywords:** gross efficiency, fatigue, kinematics, performance

Speed skating performance depends on the mechanical power output (PO) that can be delivered by the skater and the amount of power that is necessary to overcome frictional forces (PF; eg, ice and air friction). The balance between PO and PF determines the change in momentary skating velocity (v). Because of the cyclic nature of speed skating, PO is defined by the external work per stroke (A) that can be produced by the athlete times stroke frequency (f).1 Analyses of different speed skating events by van Ingen Schenau et al2 and de Boer et al3 have shown that differences in PO within a skater, between different speed skating distances, are achieved by changing f, while differences between skaters are mainly due to differences in A. In addition, van Ingen Schenau et al4 showed that A decreases during a race and that the decrease is smaller in elite than in trained speed skaters. Producing a high A and maintaining this during the race is thus important to deliver a high PO and to perform well.

Power production in speed skaters has been associated with kinematic characteristics of the skating technique. A small preextension knee angle (θ0, Figure 1[A]) and an effective directed push-off, reflected by a small e (effectiveness), the angle between the push-off leg and the horizontal (Figure 1[B]), have been identified as important for delivering a high A.2,3 De Koning et al5 studied the differences in push-off force between 3 male skaters of different performance levels. They showed that push-off force and performance were not related but that A and performance were, which suggests that the skaters with high values for A are likely pushing off more effectively instead of harder.

Another sport in which technique is important for performance is cross-country skiing.6 Sandbakk et al7 investigated the relationship between physical and kinematic variables and gross efficiency (GE) in cross-country skiers and found that world-class cross-country skiers had a higher GE during submaximal skating (G3 technique) than did national-level skiers. GE can be defined as the ratio between mechanical PO and metabolic power input.8 Since aerobic and anaerobic capacity did not seem to differ between skiers of different levels,7 it appears that it is important to have a high GE to be able to deliver a high mechanical PO and become a world-class skier. The world-class and national-level cross-country skiers also differed in cycle length and cycle rate (eg, conceptually similar to A and f in the analysis of speed skating1,2), with the world-class skiers having a longer cycle length and lower cycle rate.7 By defining the relationship between kinematic (eg, technical) variables and performance outcomes it might be possible to get more insight into

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Noordhof, Hoozemans, and de Koning are with MOVE Research Institute Amsterdam, the Faculty of Human Movement Sciences, VU University Amsterdam, Amsterdam, The Netherlands. Foster is with the Dept of Exercise and Sport Science, University of Wisconsin-La Crosse, La Crosse, WI.

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variables that are important to ski or skate efficiently and perform well.

Speed skating, in the specific skating posture, has some major effects on muscle physiology. The large intramuscular forces resulting from the crouched position appear to compromise blood flow, resulting in muscle $O_2$ desaturation and increased blood lactate accumulation. Accordingly, the specific skating posture may result in local muscle fatigue, which might affect skating technique. Logically, this may compromise skating GE and exacerbate the loss of muscle-power production, which most likely reduces $A$ and contributes to reductions in $v$. As $e$ is probably the most related to efficiency, studying $e$ will give us insight into changes in GE during the race.

A decrease in skating GE during the course of skating events will result in a lower delivered PO, even when one assumes that the actual muscle PO stays the same, with a resulting decrease in $v$. Alternatively, it is also possible that the amount of power lost to air friction increases during the race due to an increase in $\theta_0$ and trunk angle ($\theta_1$; Figure 1[A]), also resulting in decreases in $v$. Changes in kinematic (eg, technical) variables may thus influence power production (PO) and/or power dissipation (PF). Thus far, a constant GE has been assumed during high-intensity speed skating events, and changes in $\theta_0$ and $\theta_1$, during races have only been reported for the 1500-m in an experimental setting. To get more insight into the cause of variations in $v$ during speed skating races, the magnitude of changes in kinematic variables within a race needs to be determined. Previous studies on speed skating and cross-country skiing determined differences in technique and performance between athletes or within athletes between different racing distances. The current study will, however, focus on changes in technique and $v$ within individual athletes during a race. A 5000-m speed skating event was chosen, as there are many complete laps (12) during which kinematic variables and $v$ can be analyzed, and we expected that these variables would change substantially over the course of this event.

The first purpose of this study was to determine $e$, $\theta_0$, $\theta_1$, and $v$ during the course of a 5000-m World Cup event. The second purpose was to evaluate whether changes in $e$ and changes in $\theta_0$ and $\theta_1$ are associated with changes in $v$. In this way, more insight will be gained into how changes in kinematic (ie, technical) variables affect changes in $v$.

**Methods**

**Subjects**

Two-dimensional video recordings of 34 male elite speed skaters were made during an ISU (International Skating Union) 5000-m World Cup race held on November 15, 2008, in Thialf, Heerenveen (the Netherlands). The study was sanctioned by the ISU.

**Data Acquisition**

**Frontal Cameras.** Two JVC GR-DX317E mini digital-video cameras (JVC USA, Wayne, NY) were placed at the end of the straight part of the 400-m ice rink, one filming the inner lane and the other filming the outer lane (Figure 2). These 2 video cameras filmed the skaters from a frontal view, which made it possible to determine $e$. To increase the time resolution of both cameras, images were split by deinterlacing, which resulted in a frame rate of 50 Hz. Every lap $e$ was determined from 1 stroke in the analyzing section (Figure 2), independent of the right or left leg. The 2 frames just before the moment the hinge of the klapskate of the push-off leg opened were used to determine the average $e$ of each lap, because this moment can be determined the most objectively. Two-dimensional pixel coordinates of the middle of the push-off leg and the tip of the skate blade were determined. The angle between the push-off leg and the ice represented $e$. A correction for a slightly skewed camera position was made to the calculated $e$ using the vertical coordinates of 2 markers that were placed at both sides of the individual lanes in the analyzing section.
Sagittal Cameras. Another set of cameras was placed on the infield of the 400-m ice rink perpendicular to the skating direction, filming from a sagittal view (Figure 2), from which \( \theta_0 \) and \( \theta_1 \) could be determined. One of the 2 panning Canon XM2 digital-video cameras (Canon USA, Lake Success, NY) filmed the skater who started in the inner lane every lap, and the other camera filmed the skater who started in the outer lane every lap. Skaters were filmed during almost the entire straight part of the lap, where they do not switch between inner and outer lane. However, only the stroke where the camera was most perpendicular to the gliding direction of the skater, independent of the right or left leg, was used for kinematic analysis. After deinterlacing, 2-dimensional pixel coordinates of the middle of the neck, hip joint, knee, and ankle were determined for 2 frames during the midsection of the gliding phase, as \( \theta_0 \) and \( \theta_1 \), determined at this instant are part of the equation for air friction in speed skating.\(^{13} \) During the gliding phase the trunk moves over the skate from the lateral to the medial side; the midsection of the gliding phase was therefore defined as the moment at which the trunk is exactly above the skate. Immediately after this moment the push-off starts. The \( y \)-coordinates (left–right direction) were corrected for not being filmed completely perpendicular to the gliding direction, due to the fixed camera location (Figure 3). The average \( \theta_0 \) and \( \theta_1 \) of each lap were determined by averaging both angles over these 2 successive frames.

Skating Velocity

Each skater was equipped with radio-frequency identification tags around the ankles, which were used to measure \( v \) on each section of the ice rink (Figure 2). The average \( v \) was determined over sections 5 and 6, which corresponds to the analyzing section, where \( e, \theta_0, \) and \( \theta_1 \) were determined.

Figure 2 — Overview of Thialf, the 400-m ice rink in Heerenveen (The Netherlands). The dots represent the 4 cameras. Kinematic characteristics and skating velocity were determined in the analyzing section using the radio-frequency identification tags around the ankles.

Figure 3 — Representation of the correction for filming not completely perpendicular to the gliding direction. Distance \( d_1 \) was determined based on number of frames from completely perpendicular skating velocity, and distance \( d_2 \) was known. The corrected \( y \)-coordinates were calculated using \( y' = (1/\cos \alpha)y \).
Data Analysis and Statistics

The start of a speed skating race is significantly different from the remaining part of the race, so the first 200 m of the race were excluded. To get a general idea of the changes in skating technique over the race, $e$, $\theta_0$, $\theta_1$, and $v$ were averaged over 3 successive 400-m laps, which resulted in 4 averaged values representing laps 1 to 3, 4 to 6, 7 to 9, and 10 to 12. The differences in kinematic variables and $v$ between different race sections were tested using repeated-measures ANOVA (PASW statistics 18.0, IBM Corp). If the assumption of sphericity was met, post hoc comparisons were tested using contrasts, and when the assumption of sphericity was violated, the degrees of freedom were adapted using the Greenhouse Geisser correction, and post hoc comparisons were tested using the Bonferroni method. Changes ($\Delta$) were determined between these averaged values. The change between race sections was described as $\Delta$lap, the change between laps 1 to 3 and laps 4 to 6 is described as $\Delta$lap = 1, the change between laps 4 to 6 and 7 to 9 as $\Delta$lap = 2, and the change between laps 7 to 9 and 10 to 12 as $\Delta$lap = 3. The relationship between $\Delta e$ and $\Delta v$ and between $\Delta \theta_0$ and $\Delta \theta_1$ and $\Delta v$, with part of the race as covariate, was established using generalized estimating equations (GEE), a regression-analysis technique that accounts for the dependency of the repeated measurements. There was no perfect multicollinearity between $\Delta \theta_0$ and $\Delta \theta_1$, which allowed the use of both $\Delta \theta_0$ and $\Delta \theta_1$ in the regression equation. An independent working correlation matrix was chosen. Interaction terms were included when significant. Residuals were checked for normality, and a significance level of $P < .05$ was used.

Results

Over the course of a 5000-m race, $e$ increased significantly ($F_{2,2,21,1} = 16.6, P < .001; Figure 4[A]$). The difference in $e$ was significant between all race sections, except between laps 1 to 3 and 4 to 6 and between laps 7 to 9 and 10 to 12. A significant increase was also seen in $\theta_0$ ($F_{3,99} = 8.3, P < .001; Figure 4[B]$); the difference in $\theta_0$ between laps 1 to 3 and all other race sections was significant. A significant decrease was seen in $\theta_1$ ($F_{2,2,74,0} = 10.2, P < .001; Figure 4[C]$); $\theta_1$ was significantly lower over laps 10 to 12 than in all other race sections. Skating $v$ showed a significant decrease from the beginning to the end of the race ($F_{1,6,51.2} = 28.6, P < .001$); all differences were significant (Figure 4[D]).

The results of the GEE analyses between $\Delta e$ and $\Delta v$ are summarized in Table 1. To understand the meaning of the significant interaction effect between $\Delta$lap = 2 and $\Delta e$, the GEE analysis was repeated with $\Delta$lap = 2 (Table 1B) and $\Delta$lap = 3 (Table 1C) also as references. The GEE results indicate that $\Delta e$ is associated with $\Delta v$.

Figure 4 — Kinematic characteristics of the speed skating technique and skating velocity over the course of an official 5000-m event, mean ± SD. (A) Effectiveness ($e$). (B) Preextension knee angle ($\theta_0$). (C) Trunk angle ($\theta_1$). (D) Skating velocity ($v$). 1Significantly different from laps 1–3. 2Significantly different from laps 4–6. 3Significantly different from laps 7–9. 4Significantly different from laps 10–12.
Table 1  GEE Results of the Relationship Between Changes in Effectiveness and Changes in Velocity

<table>
<thead>
<tr>
<th>Reference</th>
<th>Parameter</th>
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</tr>
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<td>Δlap = 1</td>
<td>Intercept</td>
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<td></td>
<td>Δe</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Δlap = 1</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>[Δlap = 3] × Δe</td>
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<td></td>
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<tr>
<td>[Δlap = 2] × Δe</td>
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<td>.034</td>
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</tr>
<tr>
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<td>—</td>
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</tr>
<tr>
<td>Δlap = 2</td>
<td>Intercept</td>
<td>−0.12</td>
<td>&lt;.001</td>
</tr>
<tr>
<td></td>
<td>Δe</td>
<td>−0.10</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Δlap = 1</td>
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<td></td>
<td></td>
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<tr>
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<td>.87</td>
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<td>[Δlap = 3] × Δe</td>
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<td>—</td>
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</tbody>
</table>

Abbreviations: GEE indicates generalized estimating equations; β, the regression coefficient; Δlap, the change in part of the race; Δe, the change in effectiveness.

However, only when Δlap equals 2 (the difference between laps 4–6 and laps 7–9), with Δlap = 1 as reference value, is the association significant, which means that the association between Δe and Δv is different for Δlap = 2 than for Δlap = 1. Based on the regression coefficients, it can be concluded that over the course of a 5000-m race a change of 1° in e results in a decrease in v of 0.036 m/s when Δlap equals 1 (change in e and v between laps 1–3 and 4–6), a change of 1° in e between laps 4 to 6 and 7 to 9 results in a decrease in v of 0.10 m/s, and a change of 1° in e over the final part of the race (between laps 7–9 and 10–12) results in a final drop in v of 0.056 m/s.

Table 2 displays the results of the regression analysis between Δθ0 and Δθ1 and Δv, with Δlap as covariate. No significant interaction effect between race section (Δlap) and Δθ0 or between race section and Δθ1 was found. Therefore, Δlap was only included as a covariate. The regression coefficients and the corresponding P values point out that Δθ0 and Δθ1 are not associated with Δv in this group of elite speed skaters.

Table 2  GEE Results of the Relationship Between Changes in Knee Angle and Trunk Angle and Changes in Velocity

<table>
<thead>
<tr>
<th>Parameter</th>
<th>β</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
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<td>&lt;.001</td>
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<td>Δθ1</td>
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<td>Δlap = 2</td>
<td>−0.090</td>
<td>.063</td>
</tr>
<tr>
<td>Δlap = 1</td>
<td>0</td>
<td>—</td>
</tr>
</tbody>
</table>

Abbreviations: GEE indicates generalized estimating equations; β, the regression coefficient; Δθ0, the change in knee angle; Δθ1, the change in trunk angle; Δlap, the change in part of the race.

Discussion

The main finding of this study was that during a 5000-m race e increases progressively (eg, a more vertically directed push-off) and that v decreases progressively in elite speed skaters, while θ0 and θ1 show a less clear pattern. A significant association between Δe and Δv over the midsection of the race (difference between laps 5–7 and 8–10) was found. No significant association between Δθ0, Δθ1 and Δv was found.

The influence of a change in e over the course of a 5000-m race on v can be evaluated with the use of the regression coefficients displayed in Table 1. The average speed of the speed skaters over the first 3 complete laps was 12.91 m/s (see Figure 4[D]). If a hypothetical skater were able to maintain this speed throughout the race, he would finish in a time of 6:27.30. When e of this hypothetical skater stays constant, 54.76° (Figure 4[A]) during the first 3 complete laps, but then increases by 0.59°, the average Δe between laps 1–3 and 4–6, v will decrease by 0.021 m/s (−0.036 × 0.59 = −0.021) to 12.89 m/s. A further increase in e of 0.75° for the following 3 laps results in a further decrease in v of 0.075 m/s to 12.81 m/s (−0.10 × 0.75 = −0.075). During the final part of the 5000-m race, e increases by another 0.61°, which results in a final drop in v of 0.034 (−0.056 × 0.61 = −0.034) to 12.78 m/s. A 5000-m race with the described changes in e and v will result in a final time of 6:29.11. Thus, an almost 2-second difference in final time might be found between a race with a constant e and a race with a progressively increasing e (more vertically directed push-off), which corresponds to a difference of 0.47% in final time (100.47% of 6:27.30). When both estimated finish times are compared with the official World Cup results of the races in Heerenveen, 6:27.30 would have been the eighth place and 6:29.11 would have resulted in the twelfth place.

Comparing the finish times, standardized to the time of the winner (100%), of the skaters during the World Cup race in Heerenveen with the standardized finish times during the World Cup race skated in Berlin a week before resulted in a standardized typical error of 0.31%. Our
hypothetical skater is thus 0.47% ± 0.31% slower due to the change in $e$ over the course of a 5000-m race. It can therefore be concluded that maintaining a small $e$ is important for good speed skating performance. Skaters skate 240 m on the straight part of the track and 160 m on curved sections. However, the kinematic variables obtained in this study are only representative of the straight part of the track. It could be that different results would have been obtained for both curves, but we do not expect this. The only study that determined changes in technical variables of long-distance skaters during the curves was that of Juda et al. They compared several technical variables between the first and second halves of the race and found that the thigh angle was greater during the second half. Unfortunately, Juda et al. did not investigate the change in $e$ during skating the curves.

As it seems reasonable that $e$ and speed skating GE are related, $\Delta e$ gives us more insight into the change in speed skating GE during a race and its influence on $\Delta v$. The data of the current study suggest that speed skating GE decreases during a 5000-m race and that those changes are associated with changes in skating $v$ during the midsection of the race. These results are in agreement with the finding of a significant decrease in GE during a 4-minute bout of maximal cycling exercise. A possible explanation for the decrease in GE could be an increase in motor-unit recruitment. Burnley et al. showed that an increased primary VO$_2$ amplitude during a second bout of high-intensity cycling exercise was accompanied by a 19% higher averaged integrated electromyogram, from which they concluded that the increased VO$_2$ was related to an increase in motor-unit recruitment. Leirdal and Ettema showed that a measure of pedaling technique was correlated with GE; however, there are no studies that evaluated pedaling technique and GE during fatiguing cycling exercise. It is therefore hypothesized that the decrease in GE found in the study of Uitslag et al. is most likely due to changes in active muscle mass—the physiological component of GE. Technique is very important in speed skating, so skating GE essentially consists of a technical and a physiological component. The increase in $e$ found in the current study reflects a decrease in the technical component of GE. In the sport of speed skating the timing of the push-off is subtle, and fatigue potentially influences this timing and consequently $e$—the technical component of skating GE. Changes in $e$ are associated with $\Delta v$ over the midsection of the race and will explain part of the decrease in $v$. The unexplained part may be due to a drop in the physiological component of GE, caused by, for example, the recruitment of more muscle fibers or the recruitment of less efficient fibers. The absence of a significant association between $\Delta e$ and $\Delta v$ over the first and final parts of the race could be due to the slightly smaller change in $e$ ($\Delta \text{lap} = 1$, $\Delta e = 0.59^\circ \pm 1.3^\circ$; $\Delta \text{lap} = 2$, $\Delta e = 0.75^\circ \pm 1.5^\circ$; $\Delta \text{lap} = 3$, $\Delta e = 0.61^\circ \pm 1.5^\circ$) and $v$ ($\Delta \text{lap} = 1$, $\Delta v = -0.12 \pm 0.2 \text{ m/s}$; $\Delta \text{lap} = 2$, $\Delta v = -0.2 \pm 0.2 \text{ m/s}$; $\Delta \text{lap} = 3$, $\Delta v = -0.17 \pm 0.3 \text{ m/s}$) over the first and final parts of the 5000 m.

The unexpected finding of no significant association between $\Delta \theta_0$ and $\Delta \theta_1$ and $\Delta v$ is most likely caused by a significant change in $\theta_0$ only over the first part of the race and a significant decrease in $\theta_1$ only over the final part of the race, while skating $v$ changes continuously over the course of the 5000 m. The $\theta_0$ and $\theta_1$ data suggest that frontal area is relatively stable over the race, which results in little change in air-frictional losses and thus in PF. The GEE results suggest that in the range of $\theta_0$ and $\theta_1$ values found in this group of elite male speed skaters, changes in these angles do not immediately result in changes in $v$. van Ingen Schenau et al. found a significant correlation between the mean knee angle at the beginning of the gliding phase and $v$, but there was no significant correlation between the preextension knee angle $\theta_0$ and $v$, which supports the results of the current study. de Koning et al. reported the changes in $\theta_0$ and $\theta_1$ over a 1500-m event and determined the relationship between changes in both angles, represented as a combined air-friction coefficient, and changes in $v$. They found that ~42% of the variation in $v$ could be attributed to changes in skating posture. In both studies, a 2-dimensional movement-registration method was used. Differences between the results of the current study and the study of de Koning et al. might be due to the different skating events that were studied (5000- vs 1500-m). In addition, the correlation coefficient calculated by de Koning et al. does not account for the dependency of the repeated measurements, and the changes in $\theta_0$ and $\theta_1$ were represented as a combined air-friction coefficient.

The results of the current study only hold for elite male speed skaters during 5000-m races. Follow-up research is required to determine whether similar results will be found for other speed skating events, for women, and for skaters of a lower performance level.

**Practical Applications**

The most important message is that coaches and athletes should pay attention during training and competition to achieving and maintaining a small $e$ while performing fatiguing exercise. This study clearly showed that analyzing a 3-dimensional movement with the use of a 2-dimensional movement-registration method produces valuable results for coaches and athletes in elite speed skating. Coaches and trainers could therefore use methods as presented in this article to analyze kinematic variables of their athletes.

Thus far, the energy-flow model for speed skating used to simulate performances assumes a constant GE, $\theta_0$, and $\theta_1$ during races. Based on the results described herein, the current version of the energy-flow model can be adapted to simulate speed skating races more precisely.

**Conclusion**

It seems that speed skaters are able to maintain relatively stable knee and trunk angles during a 5000-m race, which results in fairly stable power losses to air friction.
A decrease in skating velocity therefore does not seem to be attributable to increases in the power necessary to overcome frictional forces but seems to be mainly caused by changes in mechanical power output. As changes in effectiveness and changes in velocity are significantly associated over the midsection of the race, this suggests that decreases in mechanical power output are at least partly due to less effective push-offs.

Acknowledgments

The authors thank Ankie Vink, MSc, and Sander van Ginkel, MSc, for their help with the data analysis.

References