Noordhof DA, Foster C, Hoozemans MJM, de Koning JJ. 
The association between changes in speed skating technique and changes in skating velocity. 
Abstract

A meaningful association between changes ($\Delta$) in push-off angle or effectiveness ($e$) and changes in skating velocity ($v$) has been found during 5,000 m races, although no significant association was found between changes in knee ($\theta_0$) and trunk angle ($\theta_1$) and $\Delta v$. It might be that speed skating event, sex, and performance level influence these associations. Therefore the purpose of this study was to evaluate the effect of skating event, sex, and performance level on the association between $\Delta e$ and $\Delta v$ and between $\Delta \theta_0$ and $\Delta \theta_1$ and $\Delta v$. Video recordings were made from a frontal ($e$) and sagittal view ($\theta_0$ and $\theta_1$) during 1,500 m and 5,000 m World Cup races of male and female skaters. Radio frequency identification tags provided data of $v$. Skating event influenced the association between $\Delta e$ and $\Delta v$, which resulted in a significant association between $\Delta e$ and $\Delta v$ for the 5,000 m ($\beta = -0.069$, 95% confidence interval [-0.11, -0.030]), but not for the 1,500 m ($\beta = -0.011$, [-0.032, 0.010]). The association between $\Delta \theta_0$ and $\Delta \theta_1$ and $\Delta v$ was not significantly influenced by skating event. Sex and performance level did not substantially affect the association between $\Delta e$ and $\Delta v$ and between $\Delta \theta_0$ and $\Delta \theta_1$ and $\Delta v$. In conclusion, skating event significantly influenced the association between $\Delta e$ and $\Delta v$, a 1° increase in $e$ results in a 0.011 m/s decrease in $v$ during the 1,500 m and in a 0.069 m/s decrease in $v$ during the 5,000 m. So, it seems especially important to maintain a small $e$ during the 5,000 m.
Introduction

Speed skating velocity ($v$) is dependent on the balance between the mechanical power output (PO) delivered by the skater and the amount of power necessary to overcome frictional forces. The characteristic speed skating technique can be described by different kinematic characteristics; the pre-extension knee angle ($\theta_0$; Figure 7.1A), trunk angle ($\theta_1$; Figure 7.1A), and the effectiveness of the push-off (i.e. direction of the push-off force), reflected by a small $e$, the angle between the push-off leg and the horizontal (Figure 7.1B).

Previous research has clearly shown that these kinematic characteristics are important to speed skating performance.\textsuperscript{1–3} Changes ($\Delta$) in $\theta_0$ and $\theta_1$ will mainly affect the power losses to air friction.\textsuperscript{4} Changes in $e$, which is thought to be a surrogate of gross efficiency\textsuperscript{3,5} (GE, the ratio between PO and metabolic power input\textsuperscript{6,7}), will influence power production. Changes in $e$, $\theta_0$, and $\theta_1$ and their relationship with $\Delta v$ therefore provide us insight into the cause of the change in $v$ during the race.

In a previous study, speed skating performances during 5,000 m races were analyzed (see Chapter 7A).\textsuperscript{8} An increase in $e$ (i.e. a less effective push-off), corresponding to a decrease in skating GE, was seen during these races. The increase in $e$ was associated with the decrease in $v$ over the mid section of the race. No significant association was found between $\Delta \theta_0$ and $\Delta \theta_1$ and $\Delta v$, which resulted in the conclusion that the decrease in $v$ during the race was not due to changes in power losses, but could be partly ascribed to the increase in $e$, reflecting a decrement in GE, with a resultant decrease in power production.\textsuperscript{8}

It would be interesting to know if the association between changes in speed skating technique and $\Delta v$ differs between different skating events, between males and females, and between skaters of different performance levels.

The association between changes in speed skating technique and $\Delta v$ could differ between different speed skating events, as the observed pacing strategy is different between 1,500 m and 5,000 m speed skating events. During short- (500 m and 1,000 m) and middle-distance (1,500 m) speed skating events a relatively all-out strategy is adopted\textsuperscript{9,10} and during long-distance (5,000 and 10,000 m) events a more or less evenly paced race strategy is used.\textsuperscript{10,11} It might be possible that the all-out strategy with an all-out use of anaerobic energy\textsuperscript{10} and smaller $\theta_0$ and $\theta_1$\textsuperscript{12} results in earlier fatigue and consequently a more pronounced increase in $e$ and $\theta_0$ during the race.

There is a large difference in performance outcomes between male and female skaters.\textsuperscript{13} van Ingen Schenau and de Groot\textsuperscript{13} investigated the nature of the differences in performance outcomes between elite male and female skaters, concluding that differences were primarily caused by differences in skating posture and percentage body fat. No differences in the amount of body weight corrected work per stroke were found between
Gross efficiency in cyclic sports

males and females. The difference in skating posture was mainly caused by larger $\theta_0$ values in females. It was estimated that half of the difference in speed between males and females during the 3,000 m would disappear if female skaters were able to skate with a similar $\theta_0$ as males. van Ingen Schenau and de Groot did not determine $e$, so sex related differences in $e$ need to be investigated. In addition, it is unknown if sex influences the association between $\Delta e$ and $\Delta v$ and between $\Delta \theta_0$ and $\Delta \theta_1$ and $\Delta v$.

Besides the known sex differences in performance outcomes, there are also differences between elite and trained speed skaters. Elite speed skaters showed a longer gliding phase, due to a similar stroke time and a shorter push-off phase, which resulted in a 25% smaller push-off angle at the start of the knee extension. The smaller push-off angle resulted in a more effective push-off and more explosive knee extension. de Boer and Nilson even showed that within a group of Olympic speed skaters there is a relation between technique variables (long gliding phase, long stride, small $e$) and work per stroke. Unfortunately, both studies did not evaluate the effect of performance level on the association between $\Delta e$ and $\Delta v$ and between $\Delta \theta_0$ and $\Delta \theta_1$ and $\Delta v$.

In summary, the first purpose of this study was to investigate the effect of speed skating event, sex, and performance level on $e$, $\theta_0$, $\theta_1$, and $v$ during a race. The second purpose was to evaluate if skating event, sex, and performance level influence the association between $\Delta e$ and $\Delta v$ and between $\Delta \theta_0$ and $\Delta \theta_1$ and $\Delta v$, in order to get more insight into the underlying cause of the change in $v$ during the race. It was hypothesized that there would be differences in $e$, $\theta_0$, $\theta_1$, and $v$ between different skating events, males and females and skaters of different performance level. It was expected that 1,500 m speed skaters will push-off more effectively, would show a smaller $\theta_0$ and $\theta_1$ and a resultant higher $v$, compared to 5,000 m skaters. In addition, it was expected that, due to the more all-out pacing strategy during the 1,500 m, with probably earlier signs of peripheral fatigue, that the association between $\Delta e$ and $\Delta v$ and between $\Delta \theta_0$ and $\Delta \theta_1$ and $\Delta v$ would be strongest for the 1,500 m. Sex differences in percentage body fat would result in a smaller $\theta_0$ for male skaters and most likely also in a smaller $e$. We hypothesized that the association between $\Delta e$ and $\Delta v$ and between $\Delta \theta_0$ and $\Delta \theta_1$ and $\Delta v$ would be similar for male and female skaters. Finally, we hypothesized that even a slight performance difference would be due to differences in kinematic variables.

Methods

Subjects
2-D video recordings were made during World Cup races held in Thialf, Heerenveen (The Netherlands). Video recordings were made of 93 males and 73 females during a 1,500 m
race and of 34 male and 23 female speed skaters during a 5,000 m race. The data of the 34 males during the 5,000 m race were also analyzed in the study of Noordhof et al.8 (see Chapter 7A). The study was sanctioned by the International Skating Union. As the event was public, individual informed consent was not secured.

Data acquisition

Frontal cameras
Two JVC GR-DX317E mini digital video cameras (JVC USA, Wayne, NY, USA) were placed at the end of the straight part of the 400 m rink. These two cameras filmed the skaters from a frontal view, with a frame rate of 50 Hz (after deinterlacing). Every lap e was determined as the average e of two frames from one stroke (independent of right or left leg) in the analyzing section, as described in Noordhof et al.8 (see Chapter 7A).

Sagittal cameras
Two panning Canon XM2 digital video cameras (Canon USA, Lake Success, NY, USA) placed on the infield of the 400 m rink, perpendicular to the skating direction, filmed the skaters from a sagittal view, with a frame rate of 50 Hz (after deinterlacing), from which $\theta_0$ and $\theta_1$ were determined (see Chapter 7A).8 The skater that started in the inner lane was filmed by one camera and the skater that started in the outer lane was filmed by the other camera. During the entire straight part (were the skaters do not switch between inner and outer lane) the skaters were filmed, however only the stroke were the camera position was most perpendicular to the gliding direction was chosen for data analysis. Knee and trunk angle were calculated as the average of $\theta_0$ and $\theta_1$ for two frames during the midsection of the gliding phase. Because of the fixed position of the panning cameras, the y-coordinates were corrected for not being filmed completely perpendicular to the gliding direction (see Figure 7.3).8

Skating velocity
Each skater was equipped with radio frequency identification tags around the ankles, in order to measure v. The average v was determined over the same part of the track as where e, $\theta_0$, and $\theta_1$ were determined (see Figure 7.2).8

Data analysis and statistics
Only one skating event of each skater was included in the data analysis, because not all skaters skated both distances. So, if a skater skated both the 1,500 and 5,000 m the data of the 1,500 m were excluded from analysis. This resulted in data of 46 males and 36 females
competing in the 1,500 m and of 32 males and 23 females competing in the 5,000 m. The intraclass correlation coefficient (ICC) was calculated based on kinematic variables determined every lap, which resulted in an ICC agreement of 0.97, 0.97, and 0.95, for $e$, $\theta_0$, and $\theta_1$, respectively. The intra-observer reliability can be rated as excellent.\textsuperscript{15} In case of the 1,500 m the first 300 m were excluded from data analyses and in the 5,000 m the first 200 m, because $v$ is non-uniform during the start and skating technique is significantly different during the start of the race.\textsuperscript{2,13} Kinematic variables ($e$, $\theta_0$, and $\theta_1$) and $v$ were averaged over four successive laps for the 5,000 m (laps 1-4, 5-8, and 9-12, respectively). To study the effect of skating event, sex, and performance level (10 fastest or 10 slowest male and female skaters in the 1,500 and 5,000 m, based on finish times) on $e$, $\theta_0$, $\theta_1$, and $v$, mixed design ANOVAs (PASW 18.0, SPSS Inc., Chicago, IL, USA) were performed. If the assumption of sphericity was met, post-hoc comparisons were tested using contrasts. With violations of the assumption of sphericity the degrees of freedom were adjusted using the Greenhouse Geisser (if $\hat{\epsilon} < 0.75$) or Huynh-Feldt (if $\hat{\epsilon} \geq 0.75$) correction and pairwise comparisons were tested using the Bonferroni method.

Changes in kinematic variables and $v$ were described as changes between race sections. For both distances there were three race sections (1,500 m laps 1, 2, and 3; 5,000 m laps 1-4, 5-8, and 9-12, respectively), differences between race sections were described as $\Delta$lap. The regression technique generalized estimating equations (GEE) was used to assess the relationship between $\Delta e$ and $\Delta v$ and between $\Delta \theta_0$ and $\Delta v$. An independent working correlation matrix was chosen for the GEE analysis and residuals were checked for normality. Differences were accepted to be significant if $p < 0.05$.

**Results**

**Skating event**

A significant increase in $e$ ($p < 0.001$) over the race was seen for both skating events (Figure 7.5A), without a significant difference in $e$ between events ($p = 0.59$). However, a significant interaction between race section and skating event was present ($p < 0.05$), with a steeper increase in $e$ over the race for the 1,500 m. Over the course of both skating events a significant increase in $\theta_0$ was seen ($p < 0.001$; Figure 7.5B). The difference in $\theta_0$ between the 1,500 and 5,000 m was significant ($p < 0.001$), with higher $\theta_0$ values during the 5,000 m. No significant interaction between race section and skating event was found ($p = 0.51$). Over the course of both skating events no significant increase in $\theta_1$ was seen ($p = 0.87$), the difference in $\theta_1$ between both events was also not significant ($p = 0.60$). However, a significant interaction between race section and skating event was found ($p < 0.001$), with a slight increase in $\theta_1$ from race section 2 to 3 for the 1,500 m and a slight
The association between changes in speed skating technique and changes in skating velocity

decrease in $\theta_1$ from race section 2 to 3 for the 5,000 m (Figure 7.5C). During both skating events $v$ decreased significantly ($p < 0.001$), the decrease in $v$ is much larger during the 1,500 m, compared to the 5,000 m ($p < 0.001$; Figure 2D). In addition, skating $v$ is significantly higher during the 1,500 m ($p < 0.001$).

Evaluating the effect of skating event on the association between $\Delta e$ and $\Delta v$ resulted in no significant interaction between $\Delta \text{lap}$ and $\Delta e$ (Table 7.3). The interaction between skating event and $\Delta e$ was significant (Table 7.3), therefore the GEE analyses was performed with both the 1,500 m (Table 7.3) and 5,000 m (not displayed) as reference. In case of the 1,500 m $\Delta e$ and $\Delta v$ were not significantly associated ($\beta = -0.011, [-0.032, 0.010]$). However, for the 5,000 m $\Delta e$ and $\Delta v$ were significantly associated ($\beta = -0.069, [-0.11, -0.030]$). Studying the effect of skating event on the association between $\Delta \theta_0$ and $\Delta \theta_1$, and $\Delta v$ resulted in no significant interaction between $\Delta \text{lap}$ and $\Delta \theta_0$, $\Delta \text{lap}$ and $\Delta \theta_1$, skating event and $\Delta \theta_0$, and skating event and $\Delta \theta_1$ (Table 7.4).

Figure 7.5 Kinematic characteristics of the speed skating technique and skating velocity (mean values ± standard deviations) over the course of an official 1,500 m (filled circles) and 5,000 m (open circles) event. A: Effectiveness ($e$) B: Pre-extension knee angle ($\theta_0$) C: Trunk angle ($\theta_1$) D: Skating velocity ($v$). $^{1,2,3}$Significantly different from race section 1, 2, and 3, respectively. *Significantly different between the 1,500 m and 5,000 m. **Significant interaction effect.
Table 7.3 Generalized estimating equations results (regression coefficient $\beta$ and 95% confidence interval) of the relationship between changes in effectiveness and changes in skating velocity.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Skating event</th>
<th>Sex</th>
<th>Performance level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A = 1500 m</td>
<td>A = male skaters</td>
<td>A = fastest 10</td>
</tr>
<tr>
<td></td>
<td>B = 5000 m</td>
<td>B = female skaters</td>
<td>B = slowest 10</td>
</tr>
<tr>
<td>Intercept</td>
<td>-0.70* [-0.76, -0.64]</td>
<td>-0.50* [-0.59, -0.41]</td>
<td>-0.45* [-0.58, -0.32]</td>
</tr>
<tr>
<td>$\Delta e$</td>
<td>-0.011 [-0.032, 0.010]</td>
<td>-0.040* [-0.069, -0.011]</td>
<td>-0.038 [-0.078, 0.003]</td>
</tr>
<tr>
<td>$\Delta$lap = 2</td>
<td>0.053 [-0.027, 0.13]</td>
<td>0.054 [-0.041, 0.15]</td>
<td>0.12 [-0.010, 0.26]</td>
</tr>
<tr>
<td>$\Delta$lap = 1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\Delta$lap = 2 \cdot $\Delta e$</td>
<td>-0.009 [-0.041, 0.023]</td>
<td>-0.011 [-0.051, 0.028]</td>
<td>-0.021 [-0.084, 0.042]</td>
</tr>
<tr>
<td>$\Delta$lap = 1 \cdot $\Delta e$</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$B$</td>
<td>0.51* [0.42, 0.59]</td>
<td>0.017 [-0.11, 0.14]</td>
<td>0.001 [-0.16, 0.16]</td>
</tr>
<tr>
<td>$A$</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$B \cdot \Delta e$</td>
<td>-0.058* [-0.099, -0.016]</td>
<td>0.014 [-0.023, 0.052]</td>
<td>0.008 [-0.043, 0.060]</td>
</tr>
<tr>
<td>$A \cdot \Delta e$</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

$\Delta e$, the change in effectiveness; $\Delta$lap, the change in race section. *Significantly different from zero ($p < 0.05$).
The association between changes in speed skating technique and changes in skating velocity

**Table 7.4** Generalized estimating equations results (regression coefficient \( \beta \) and 95% confidence interval) of the relationship between changes in knee angle and trunk angle and changes in skating velocity.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Skating event</th>
<th>Sex</th>
<th>Performance level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( A = 1500 ) m</td>
<td>( A = \text{male} ) skaters</td>
<td>( A = \text{fastest} ) 10</td>
</tr>
<tr>
<td></td>
<td>( B = 5000 ) m</td>
<td>( B = \text{female} ) skaters</td>
<td>( B = \text{slowest} ) 10</td>
</tr>
<tr>
<td>Intercept</td>
<td>-0.70* [-0.76, -0.65]</td>
<td>-0.54* [-0.62, -0.46]</td>
<td>-0.51* [-0.63, -0.39]</td>
</tr>
<tr>
<td>( \Delta \theta_0 )</td>
<td>0.003 [-0.007, 0.013]</td>
<td>0.005 [-0.008, 0.018]</td>
<td>0.011 [-0.022, 0.044]</td>
</tr>
<tr>
<td>( \Delta \theta_1 )</td>
<td>-0.009 [-0.024, 0.006]</td>
<td>-0.007 [-0.029, 0.014]</td>
<td>-0.038 [-0.088, 0.012]</td>
</tr>
<tr>
<td>( \Delta \text{lap} = 2 )</td>
<td>0.023 [-0.037, 0.082]</td>
<td>0.024 [-0.038, 0.086]</td>
<td>0.082 [-0.024, 0.19]</td>
</tr>
<tr>
<td>( \Delta \text{lap} = 1 )</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( \Delta \text{lap} = 2 \cdot \Delta \theta_0 )</td>
<td>-0.011 [-0.028, 0.006]</td>
<td>-0.013 [-0.035, 0.010]</td>
<td>-0.031 [-0.068, 0.006]</td>
</tr>
<tr>
<td>( \Delta \text{lap} = 1 \cdot \Delta \theta_0 )</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( \Delta \text{lap} = 2 \cdot \Delta \theta_1 )</td>
<td>0.007 [-0.015, 0.028]</td>
<td>-0.014 [-0.042, 0.014]</td>
<td>0.014 [-0.044, 0.073]</td>
</tr>
<tr>
<td>( \Delta \text{lap} = 1 \cdot \Delta \theta_1 )</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( B )</td>
<td>0.44* [0.36, 0.52]</td>
<td>0.028 [-0.075, 0.13]</td>
<td>0.040 [-0.10, 0.18]</td>
</tr>
<tr>
<td>( A )</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( B \cdot \Delta \theta_0 )</td>
<td>-0.012 [-0.029, 0.005]</td>
<td>-0.010 [-0.028, 0.007]</td>
<td>-0.011 [-0.043, 0.020]</td>
</tr>
<tr>
<td>( A \cdot \Delta \theta_0 )</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( B \cdot \Delta \theta_1 )</td>
<td>0.017 [-0.005, 0.039]</td>
<td>0.019 [-0.003, 0.042]</td>
<td>0.044* [0.003, 0.084]</td>
</tr>
<tr>
<td>( A \cdot \Delta \theta_1 )</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

\( \Delta \theta_0 \), the change in knee angle; \( \Delta \theta_1 \), the change in trunk angle; \( \Delta \text{lap} \), the change in race section

*Significantly different from zero (\( p < 0.05 \)).

**Sex**

Evaluating the effect of sex on \( e \), resulted in a significant increase in \( e \) over the race (\( p < 0.001 \)), with a significant lower \( e \) in male skaters compared to female skaters (\( p < 0.01 \); Figure 7.6A). There was a significant interaction between race section and sex (\( p < 0.01 \)), a steeper increase in \( e \) between race section 2 and 3 was seen for the females compared to the males. A significant increase over the race was also seen in \( \theta_0 \) (\( p < 0.001 \)), without a significant difference between males and females (\( p = 0.76 \)), and without a significant interaction between race section and sex (\( p = 0.99 \); Figure 7.6B). Race section and sex did not significantly influence \( \theta_1 \) (\( p = 0.98 \); \( p = 0.084 \)) and there was no significant interaction between race section and sex (\( p = 0.97 \); Figure 7.6C). Skating \( v \) decreased significantly during the race (\( p < 0.001 \)), male skaters showed a significantly higher \( v \) than female skaters.
skaters ($p < 0.001$), but there was no difference between males and females in the decrease in $v$ over the race ($p = 0.93$; Figure 7.6D).

No significant interaction between $\Delta \text{lap}$ and $\Delta e$ and sex and $\Delta e$ was found (Table 7.3). When gender was included in the regression equation, no significant interaction was found between $\Delta \text{lap}$ and $\Delta \theta_0$, $\Delta \text{lap}$ and $\Delta \theta_1$, sex and $\Delta \theta_0$, and sex and $\Delta \theta_1$ (Table 7.4).

![Figure 7.6](image)

**Figure 7.6** Kinematic characteristics of the speed skating technique and skating velocity (mean values ± standard deviations) in male (filled circles) and female (open circles) speed skaters. A: Effectiveness ($e$) B: Pre-extension knee angle ($\theta_0$) C: Trunk angle ($\theta_1$) D: Skating velocity ($v$). 1,2,3Significantly different from race section 1, 2, and 3, respectively. *Significantly different between males and females. **Significant interaction effect.

**Performance level**

A significant increase in $e$ ($p < 0.001$) over the race was seen for the 10 fastest and 10 slowest speed skaters (Figure 7.7A). The slowest skaters showed significantly larger values of $e$ during the race than the fastest skaters ($p < 0.01$). No significant interaction was found between race section and performance level ($p = 0.077$). Over the course of the race $\theta_0$ increased significantly ($p < 0.01$), without a significant difference in $\theta_0$ between the 10 fastest and 10 slowest skaters ($p = 0.96$; Figure 7.7B). No significant interaction between race section and performance level was present ($p = 0.62$). No significant main effects (race section $p = 0.44$; performance level $p = 0.64$) and interaction effect ($p = 0.46$) was found on $\theta_1$ (Figure 7.7C). Skating $v$ decreased significantly over the course of the race ($p < 0.001$), with the 10 slowest skaters showing lower values of $v$ compared to the fastest skaters ($p < 0.001$; Figure 7.7D). No significant interaction effect between race section and performance level was found ($p = 0.84$).
The effect of performance level on the association between $\Delta e$ and $\Delta v$ was studied and resulted in no significant interaction between $\Delta\text{lap}$ and $\Delta e$ and performance level and $\Delta e$ (Table 7.3). The inclusion of performance level resulted in a significant interaction between performance level and $\Delta\theta_1$, but not between performance level and $\Delta\theta_0$, $\Delta\text{lap}$ and $\Delta\theta_0$, and $\Delta\text{lap}$ and $\Delta\theta_1$ (Table 7.4). Because of the significant interaction between performance level and $\Delta\theta_1$ the GEE analyses was performed with both the 10 fastest (Table 7.4) and 10 slowest (not displayed) speed skaters as reference. The association between $\Delta\theta_1$ and $\Delta v$ was for both the 10 fastest and 10 slowest skaters not significant.

**Figure 7.7** Kinematic characteristics of the speed skating technique and skating velocity (mean values ± standard deviations) in the 10 fastest (*filled circles*) and 10 slowest (*open circles*) speed skaters. **A**: Effectiveness ($e$) **B**: Pre-extension knee angle ($\theta_0$) **C**: Trunk angle ($\theta_1$) **D**: Skating velocity ($v$). $^{1,2,3}$Significantly different from race section 1, 2, and 3, respectively. *Significantly different between the 10 fastest and 10 slowest skaters. **Significant interaction effect.

**Discussion**

**Skating event**

The main findings regarding skating event are a more rapid increase in $e$ during the 1,500 m, a higher $\theta_0$ during the 5,000 m, and a more rapid decrease in $v$ during the 1,500 m. In addition, $\Delta e$ and $\Delta v$ were significantly related during the 5,000 m, but not during the 1,500 m. Finally, skating event did not affect the relationship between $\Delta\theta_0$ and $\Delta\theta_1$ and $\Delta v$.

The larger increase in $e$ during the 1,500 m means that the effectiveness of the push-off of elite speed skaters, and therefore the ability to produce power, deteriorates
more during the 1,500 m, compared to the 5,000 m. This is probably due to the more all-out pacing strategy adopted during short- and middle-distance speed skating events, which likely results in earlier signs of peripheral fatigue.\textsuperscript{9,10} An all-out usage of anaerobic energy with associated disturbances in intramuscular homeostasis will result in earlier signs of peripheral fatigue (higher blood lactate concentration, rating of perceived exertion, and higher EMG activity)\textsuperscript{16} and probably therefore in a less effective push-off.

The crouched skating position, with the small $\theta_0$ during the gliding phase of the skating stroke, results in muscle O\textsubscript{2} desaturation.\textsuperscript{17} The higher $\theta_0$ during the 5,000 m compared to the 1,500 m results thus in lower levels of muscle O\textsubscript{2} desaturation and resulting lower levels of muscle and blood lactate accumulation during the race.\textsuperscript{17} In contrast a higher $\theta_0$ during the race results in larger power losses to air friction.\textsuperscript{14} Skaters need to find a balance between the physiological disadvantage of a smaller $\theta_0$ during the 5,000 m,\textsuperscript{17} with higher levels of muscle O\textsubscript{2} desaturation and the biomechanical advantage of a smaller $\theta_0$, with less air friction.\textsuperscript{14} It seems that the ideal $\theta_0$ during the 5,000 m is significantly bigger than during the 1,500 m. Although $\theta_0$ is higher during the 5,000 m, compared to the 1,500 m, skaters will be fatigued during the final laps of the race. It can be hypothesized that the variation between strokes gets bigger, when skaters get fatigued. The variation between strokes can be determined for the 5,000 m event, by calculating the coefficient of variation (CV) over the first 4 laps and the final 4 laps. The CV of the kinematic variables was significantly larger during the final 4 laps of the race ($e$, $p < 0.01$; $\theta_0$, $p < 0.05$; $\theta_1$, $p < 0.01$), without a significant difference in CV between the first and final laps for $v$ ($p = 0.21$). Even larger CVs can be expected for the 1,500 m, due to the all-out pacing strategy adopted during the 1,500 m. Unfortunately the CV of the different kinematic variables cannot be determined for the 1,500 m, because of insufficient data points.

In a previous study it was shown that $\Delta e$ and $\Delta v$ were significantly associated over the midsection of a 5,000 m race (see Chapter 7A).\textsuperscript{8} However, as speed skaters specialize as sprinters, all-rounders or long-distance skaters, it is interesting to study the effect of skating event on the association between $\Delta e$ and $\Delta v$ and between $\Delta \theta_0$ and $\Delta \theta_1$ and $\Delta v$. We found that the association between $\Delta e$ and $\Delta v$ differed between the 1,500 m and 5,000 m (Table 7.3), with a much stronger association for the 5,000 m. An increase in $e$ of 1° results in a decrease in $v$ of 0.069 m/s during the 5,000 m and a decrease in $v$ of 0.011 m/s in the 1,500 m. Thus, a less effective push-off has a larger effect on $v$ during the 5,000 m, compared to the 1,500 m. The reason for the non-significant association between $\Delta e$ and $\Delta v$ for the 1,500 m could be the slightly bigger variation in pacing strategy. All-round skaters adopt a more evenly paced race strategy and the sprinters adopt an all-out strategy.
for the 1,500 m, accordingly, the variation in $e$ is slightly bigger over the three race sections of the 1,500 m, compared to the 5,000 m. To our knowledge there are no published studies that have investigated the association between changes in kinematic variables and $\Delta v$. The previous studies\textsuperscript{1,18} were all based on correlation coefficients between kinematic characteristics and performance outcomes, therefore making comparisons difficult with the present study and that of Noordhof et al.\textsuperscript{8} (Chapter 7A). The statistical approach used in the current and previous investigation\textsuperscript{8} allows researchers to account for the dependency of the repeated measurements in studies in which the effect of kinematic variables on performance outcomes is assessed numerous times.

**Sex**

Male skaters showed a significantly lower $e$ and a significantly less steep increase in $e$ over the course of both skating events (Figure 7.6A). Thus, it seems that male skaters push-off more effectively and are better able to maintain a small $e$ during fatiguing exercise. Sex did not significantly affect the changes in $\theta_0$, $\theta_1$, and $v$. There was a significant difference in $v$ between males and females, with the males showing a significantly higher $v$ over the course of a race. The association between $\Delta e$ and $\Delta v$ and between $\Delta \theta_0$ and $\Delta \theta_1$ and $\Delta v$ was not significantly influenced by sex.

The findings of the present study are in disagreement with the findings of van Ingen Schenau and de Groot,\textsuperscript{13} who found a difference in skating posture between males and females, which was mainly caused by a difference in $\theta_0$. In the present study, no significant difference in $\theta_0$ was found between males and females. de Boer and Nilson\textsuperscript{10} also studied the gliding and push-off technique of male and female skaters. Females showed a larger mean $\theta_0$ during the 1,500 m and 5,000 m compared to males.\textsuperscript{12} The difference between the former studies\textsuperscript{12,13} and the present study may be due to the progression of speed skating performances over the past 20-30 years.\textsuperscript{19}

van Ingen Schenau and de Groot\textsuperscript{13} found no significant difference in $\theta_1$ between males and females, which is supported by the data of the present study. Based on the results of the present study, we can conclude that the sex related performance difference is not due to a difference in $\theta_0$ and $\theta_1$, but seems to be mainly caused by differences in $e$. de Boer and Nilsen\textsuperscript{12} correlated the average kinematic variables per distance with the average work per stroke and found significant correlations between the push-off angle at the start of the knee extension and/or the push-off angle at the end of the stride and work per stroke for the male skaters (1,500 m and 5,000 m). However, no significant correlations were found between the push-off angle and work per stroke for the female skaters. These results are not supported by the findings of the present study, as the association between $\Delta e$ and
Δν was not affected by sex. Thus, although male speed skaters showed a more effective push-off, the association between Δe and Δν did not differ between males and females.

**Performance level**

The 10 fastest skaters pushed-off more effectively compared to the 10 slowest skaters. Of course, the fastest skaters were also significantly faster. No significant differences between the 10 fastest and 10 slowest skaters were found in θ₀ and θ₁. The association between Δe and Δν was not significantly influenced by performance level. However, performance level did affect the association between Δθ₁ and Δν, but for both the 10 fastest and 10 slowest skaters the association between Δθ₁ and Δν was not significant.

Previous research already showed that elite skaters push-off more effectively than trained skaters and that even within a group of Olympic speed skaters differences in performance (work per stroke) can be related to differences in e. The current study also showed that within a group of elite speed skaters, the fastest skaters can be distinguished from the slowest skaters competing in World Cup events based on e. No significant differences in θ₀ and θ₁ were found between skaters of different performance levels, which supports the results of de Boer et al. and de Boer and Nilsen. In conclusion, performance differences between males and females and between the fastest and slowest skaters cannot be explained by differences in θ₀ and θ₁, but can be partly attributed to differences in e.

Future studies regarding this topic are still required, especially because the data of Noordhof et al. (Chapter 7A) and the present study is only representative of the straight parts of the track. Although, we hypothesize that similar results will be found for the curved sections of the lap, it needs to be confirmed by systematic observations.

**Practical applications**

The presented 2-D movement registration method can be used by coaches to analyze kinematic characteristics of their athletes and to give objective technical advice. The present study showed that athletes should practice in obtaining and maintaining a small e, especially during long-distance races, as changes in e result in substantially larger decreases in v during the 5,000 m, compared to the 1,500 m. Sex and performance level do not influence this practical outcome. Thus, changes in e during a race will result in similar changes in v for males and females and the fastest and slowest skaters. However, the least performing skaters push-off less effectively during the entire race, so improving e seems to be particularly important for this group.
Conclusion

Skating event significantly influenced the association between $\Delta e$ and $\Delta v$, a significant association between $\Delta e$ and $\Delta v$ was found for the 5,000 m, but not for the 1,500 m. Thus, for both males and females and the fastest and slowest skaters, the decrease in skating velocity during the 5,000 m can be mainly attributed to the decrement in power production and not to changes in air friction. However, the exact cause of the decrease in velocity during the 1,500 m remains unknown.
References


