Kinematic Analysis of the Technique for Elite Male Long-Distance Speed Skaters in Curving

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The purpose of this study was to investigate technical factors for maintaining skating velocity by kinematic analysis of the skating motion for elite long-distance skaters during the curve phase in official championship races. Sixteen world-class elite male skaters who participated in the 5,000-m race were videotaped with two synchronized high-speed video cameras (250 Hz) in a curve lane by using a panning DLT technique. Three-dimensional coordinates of the body and blades during the first and second halves of the races were collected to calculate kinematic parameters. In the group that maintained greater skating velocity, the thigh angle during the gliding phase of the left stroke during the second half was greater than that during the first half, and the center of mass was located more forward during the second half. Thus, it was suggested that long-distance speed skaters should change the support leg position during the gliding phase of the left stroke of the curve phase under fatigued conditions so that they could extend the support leg with a forward rotation of the thigh and less shank backward rotation.

Key Words: panning DLT technique, fatigue, maintaining skating velocity

High skating velocity is a primary factor in speed skating performance. It has been confirmed that skating velocity is affected by the external power output of a skater, air resistance, and ice resistance (Van Ingen Schenau, 1982; Van Ingen Schenau et al., 1987; De Koning et al., 1992). Van Ingen Schenau and colleagues (1983) demonstrated that the external power output of elite skaters is significantly greater than that of ordinary skaters, and they suggested that it is important to increase external power output to improve performance. Since external power output is defined as the product of work per stroke and stroke frequency (Van Ingen Schenau & Bakker, 1980), higher skating velocity is obtained by effective push-off motion to increase the amount of work per stroke and stroke frequency.

Because differences exist between the skating motions during the straight phase and those during the curve phase, push-off motion has been investigated for each phase. During the straight phase, De Boer et al. (1986) found that the elite skater’s push-off angle, defined as the sideward tilt angle of the body at the onset of the push-off, was greater than that of the ordinary skater. Yuki and colleagues (1996) discovered that a quick tilting of the blade toward the medial direction after the onset of the stroke was an important technical factor in obtaining higher skating velocity. In their study of the curve phase, De Boer et al. (1987) reported that shorter time for the stroke and greater extension range of the knee joint were technical characteristics of elite
skaters. Yuda and coworkers (2003) demonstrated that the tilt angles of the body and shank at the onset of the stroke for elite skaters were greater than those for junior skaters. Because these important technical factors were determined with the use of kinematic analyses, kinematically analyzing the skating technique of elite skaters provides useful information for investigating skating techniques and improving performance.

Maintaining high skating velocity throughout a race is another important factor for excellent performance in long-distance speed skating. Thus, several biomechanical studies have focused on maintaining skating velocity. Van Ingen Schenau et al. (1983) confirmed that during the 3,000-m race, the rates of the declines in stroke frequency and work per stroke for elite skaters were much smaller than for ordinary skaters. Because skating velocity depends on stroke frequency and work per stroke (Van Ingen Schenau & Bakker, 1980), the elite skaters in their study were able to maintain skating velocity by maintaining stroke frequency and work per stroke throughout the race. Yuda and colleagues (2002) reported that elite skaters were able to obtain higher skating velocity in the first half of the 5,000-m race and throughout the race. Yuda et al. (2004) indicated that minimizing the decrease in the impulse of the horizontal blade reaction force was an important factor in maintaining skating velocity in long-distance speed skating. However, they did not offer technical suggestions on skating motion. Although the importance of maintaining skating velocity has been pointed out, studies of long-distance speed skating have not investigated the relationship between the maintenance of the skating velocity and skating techniques. Because an effective push-off motion to maintain skating velocity under fatigued conditions is still not defined, technical factors for maintaining skating velocity should be investigated to obtain useful findings for improving performance in long-distance speed skating.

Yuda et al. (2002) reported that elite skaters who maintained higher skating velocity longer kept high cycle frequency during the curve phase throughout the 5,000-m race. Because the skater always exerted the push-off force to the right direction and tilted the body to the inside of the skating rink to resist the centrifugal force during the curve phase (De Boer et al., 1987), it was pointed out that technical difficulty in the curve phase was greater than that in the straight phase. De Koning et al. (1991) found that the average power output of the skater was 4.38 ± 0.48 W/kg on the left leg and 3.00 ± 0.63 W/kg on the right leg in the curve phase, whereas it was 3.94 ± 0.72 W/kg in the straight phase. They indicated that the load on the left leg during the curve phase was greater than during the straight phase. These findings implied that the push-off motion during the curve phase would greatly affect the maintenance of skating velocity in long-distance speed skating. Thus, the skating motion for elite skaters during the curve phase should be investigated thoroughly to obtain information on maintaining skating velocity in long-distance speed skating.

The purpose of this study was to identify technical factors for maintaining skating velocity by kinematic analysis of the skating motion for elite long-distance skaters during the curve phase. Further, a comparison of the kinematic differences between endurance skaters and nonendurance skaters in official championship races would facilitate a better understanding of the technical factors involved in the maintenance of the skating velocity.

**Methods**

The data were collected during the World Speed Skating Championships Single Distance 2000, held in Nagano. The skaters investigated were 16 elite skaters who participated in the men’s 5,000-m race. Two synchronized high-speed video cameras (HSV-500C3; NAC Image Technology Inc.) were used to record the skaters’ motions at the middle portion of the inner second curve lane. The camera placed at the midpoint of the outside of the curve was used as a panning camera to follow the skaters. The fixed camera was placed at the end of the back straight. The cameras were operating at 250 Hz, and exposure time was 1/500 s. The skating motion at 850 m or 1,250 m was analyzed during the first half of the race, and that at 4,050 m or 4,450 m during the second half.

The segment end points of the skater’s body, skate blades, and reference markers were manually digitized in every frame (Frame-Dias; DKH Inc.) from video images according to a 14-segment model comprising hands, forearms, upper arms, foot-skates, shanks, thighs, head, and trunk. When the analyzing points in this study were not visible, these were digitized by the estimation of one skilled
digitizer. Three-dimensional coordinates of 25 points were obtained using a panning DLT technique (Takamatsu et al., 1997), and smoothed by a fourth-order Butterworth low-pass digital filter cutting off at 2.5 to 8.1 Hz, determined by a residual method (Winter, 1990). Standard errors in the constructed coordinates of the control points were 0.015 m (x-axis), 0.012 m (y-axis), and 0.012 m (z-axis).

For analysis and description of data, one skating cycle was divided into right and left strokes (Figure 1). The stroke was further divided into gliding and push-off phases, on the basis of the onset of the push-off, which was defined as the instant at which the angular velocity of the knee joint of the support leg exceeded 50 deg/s (Yuda et al., 2003). The skater’s center of mass (CM) was estimated by body segmental parameters, after Ae and colleagues (1992). The averaged horizontal velocity of the CM during one cycle (CM velocity) was obtained by differentiating the displacement. Cycle frequency was calculated as a reciprocal of the time for one cycle. The skating motion was analyzed with respect to a moving reference frame fixed on the skater’s CM. The y′-axis of this coordinate frame coincided with the instantaneous horizontal velocity vector of the skater’s CM. The z′-axis was the vertical direction, and the x′-axis was perpendicular to the y′- and z′-axes. The joint and segment angles are defined in Figure 2. The joint and segment angles of the lower limbs were calculated as the angles projected on the plane y′z′ of the moving reference frame. The time for these kinematic variables was normalized by the time of each stroke.

The percentage decline in skating speed was calculated by using the following equation:

$$\text{PD} \,(\%) = [1 - (\text{SP}^{2nd}/\text{SP}^{1st})] \times 100$$

where PD is a percentage decline in the skating speed, SP$^{1st}$ shows the averaged speed in the section from 200 m to 2,600 m, and SP$^{2nd}$ shows the averaged speed in the section from 2,600 m to 5,000 m.
Because no markers were used in this study, the reliability and accuracy of the digitization procedures were examined. One skater was randomly selected; during the first half of the race, his skating motion was digitized three times by the skilled digitizer. During the left stroke, the thigh and shank angles of the left support leg were calculated. The root mean squares in the differences between the three tests (1st vs. 2nd, 2nd vs. 3rd and 1st vs. 3rd) for the thigh and shank angles at each frame were 0.69° and 0.52°, respectively. The digitization procedure in this study was appropriate for the comparison of the results because the digitizing differences were small.

Based on the average of the PD (2.87%), the skaters were divided into maintaining (n = 7) and declining (n = 9) groups. When the PD of the skater was smaller than the average (2.87%), he was classified in the maintaining group, and when the PD was larger than the average, the skater was classified in the declining group. In fact, the skating velocity of the maintaining group decreased during the second half of the races. The maintaining group in this study demonstrated that these skaters were able to maintain the skating velocity when compared with their counterparts in the declining group. Therefore, we defined this group as the maintaining group. The differences between the race record of the maintaining group and that of the declining group were tested for significance using an unpaired t test. Center of mass (CM) velocity, cycle frequency, and stroke time were tested by two (maintaining group vs. declining group) × two (first half vs. second half) factors ANOVA with repeated measures. When significance was found in ANOVA, a post hoc analysis was performed by LSD test to detect the differences in the variables. The correlation coefficient between two variables was calculated and tested for significance. The level of significance was set at 5%.

**Results**

The race time of the 5,000-m race for the maintaining group (6 min 34 s 90 ± 5 s 96) was better than that of the declining group (6 min 38 s 37 ± 6 s 46). The PD for the maintaining group was significantly smaller than that for the declining group (maintaining group, 1.16 ± 0.98%; declining group, 4.20 ± 0.81%; p < 0.001). Although no significant differences in the averaged skating speed per lap, which was calculated by official results during the section from 200 m to 3,400 m were observed between the maintaining and declining groups, these of the declining group during the section from 3,400 m to 5,000 m were significant smaller than those of the maintaining group (p < 0.05–0.01).

Figure 3 depicts the CM velocity and cycle frequency for the maintaining and declining groups during the first and second halves of the races. The CM velocities for the maintaining and declining groups in the second half (12.70 ± 0.34 m/s and 12.31 ± 0.32 m/s) were significantly lower than those in the first half (12.94 ± 0.34 m/s, p < 0.05; 13.11 ± 0.20 m/s, p < 0.001), but a significant difference in the cycle frequency between the first and second halves was evident for only the declining group (first half, 0.89 ± 0.05 Hz; second half, 0.86 ± 0.04 Hz; p < 0.05). No significant differences in the CM velocity and the cycle frequency were evident between the maintaining and declining groups during the first half. In contrast, during the second half, those for the maintaining group (12.70 ± 0.34 m/s and 0.91 ± 0.07 Hz) were significantly greater than those for the declining group (12.31 ± 0.32 m/s, p < 0.01; 0.86 ± 0.04 Hz, p < 0.001).

Figure 4 compares the stroke time of the maintaining group and that of the declining group in the first and second halves of the races. The total time for the left and right strokes of the declining group in the second half (Left, 0.61 ± 0.04 s; Right, 0.55 ± 0.05 s) was significantly greater than for those of the maintaining group (Left, 0.59 ± 0.03 s; Right, 0.52 ± 0.06 s; p < 0.05). For the declining group, the left stroke time for the gliding phase in the second half (0.38 ± 0.06 s) was significantly greater than in the first half (0.32 ± 0.05 s, p < 0.05). For the maintaining group, although the right stroke time for the gliding phase in the second half (0.29 ± 0.07 s) was significantly smaller than in the first half (0.35 ± 0.03 s, p < 0.05), that of the push-off phase in the second half (0.22 ± 0.06 s) was significantly greater than that of the first half (0.17 ± 0.02 s, p < 0.05).

Table 1 indicates the correlation coefficients between the velocities of the CM and the temporal parameters in the first and second halves of the races. Although no significant relationship existed between the CM velocity and the cycle frequency in the first half, a significant positive relationship was evident in the second half (r = 0.565, p < 0.05). No significant relationship was observed between the
Figure 3 — CM velocity and cycle frequency for the maintaining and declining groups during the first and second halves of the races.

Figure 4 — Comparison of the stroke time between the maintaining and declining groups in the first and second halves of the races.
Table 1  Correlation Coefficients Between the Velocities of the Center of Mass (CM) and Temporal Parameters in the First and Second Halves of the Races

<table>
<thead>
<tr>
<th>CM velocity</th>
<th>First half</th>
<th>Second half</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle frequency</td>
<td>0.068</td>
<td>0.565*</td>
</tr>
<tr>
<td>Left stroke time</td>
<td>-0.153</td>
<td>-0.173</td>
</tr>
<tr>
<td>Total</td>
<td>-0.431</td>
<td>-0.544*</td>
</tr>
<tr>
<td>Gliding phase</td>
<td>0.351</td>
<td>0.629**</td>
</tr>
<tr>
<td>Push-off phase</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right stroke time</td>
<td>0.06</td>
<td>-0.665**</td>
</tr>
<tr>
<td>Total</td>
<td>0.106</td>
<td>-0.687**</td>
</tr>
<tr>
<td>Gliding phase</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Push-off phase</td>
<td>-0.053</td>
<td>0.197</td>
</tr>
</tbody>
</table>

*p < 0.05, **p < 0.01.

CM velocity and the stroke times in the first half. However, in the second half, significant negative relationships were observed between CM velocity and the total time for the right stroke (r = -0.665, p < 0.01), and the times for the gliding phases in the left and right strokes (Left, r = -0.544, p < 0.05; Right, r = -0.687, p < 0.01). Furthermore, a significant positive relationship was observed between the CM velocity and the left stroke times for the push-off phase in the second half (r = 0.629, p < 0.01).

Figure 5 depicts averaged patterns of the segment angles of the support leg for the maintaining and declining groups during the first and second halves of the races. In the maintaining group, the torso angle in the left stroke during the push-off phase of the second half was smaller than that of the first half. For both groups, the thigh angle over both strokes in the second half was greater than in the first half. For the maintaining group, no remarkable change in the shank angle over both strokes was observed between the first and second halves; however, for the declining group, this angle was greater during the second half than during the first half. It was noteworthy that the changes in these angles during the left stroke were greater than during the right stroke.

Figure 6 plots averaged trajectories of the CM for both groups during both halves of the races, depicted relative to the ankle of the support leg on the horizontal plane. The circles are drawn at every 20% time of stroke. For the maintaining group, in the left stroke, the CM during the gliding phase in the second half moved more forward than in the first half (y’ direction at 60% stroke; first half, 0.19 ± 0.02 m; second half, 0.22 ± 0.19 m). In contrast, for the declining group, in the second half it was located more backward than in the first half (y’ direction at 60% stroke; first half, 0.22 ± 0.02 m; second half, 0.20 ± 0.03 m). In the right stroke, for the maintaining group the CM during the gliding phase of the second half was located slightly more leftward relative to the skating direction than that of the first half (x’ direction at 60% stroke; first half, −0.39 ± 0.03 m; second half, −0.40 ± 0.04 m); in contrast, for the declining group, that of the second half was located more rightward (x’ direction at 60% stroke; first half, −0.42 ± 0.03 m; second half, −0.40 ± 0.03 m).

Discussion

It is important for skaters of higher velocity to exert great external power (Van Ingen Schenau et al., 1983). Increased external power output may result from increased cycle frequency because external power output is defined as the product of the amount of work per stroke and stroke frequency (Van Ingen Schenau & Bakker, 1980). This study found a significant positive relationship between CM velocity and cycle frequency in the second half (r = 0.565, p < 0.05; Table 1). The maintaining group was able to maintain high cycle frequency during the second half, whereas the cycle frequency of the declining group was significantly smaller during the second half than during the first half (Figure 3). Thus, the maintaining group could maintain external power output by minimizing the decrease in cycle frequency during the second half, and maintain skating velocity. These results supported the suggestion of Yuda et al. (2002) that maintaining high cycle frequency in the curve phase throughout the race is an important factor in maintaining skating velocity in long-distance speed skating.

It is necessary to consider the temporal variables that relate to cycle frequency (i.e., the time for the right and left strokes). In the second half, although there was a significant negative relationship between the total time for the right stroke and the CM velocity (r = -0.665, p < 0.01), no significant relationship was observed in the left stroke (r = -0.173, Table 1). The total time for the right stroke in the second half was significantly smaller for the maintaining
Figure 5 — Averaged patterns of the segment angles of the support leg for the maintaining and declining groups during the first and second halves of the races.
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Figure 6 — Averaged trajectories of the CM for the maintaining and declining groups in the first and second halves of the races, depicted as relative to the ankle of the support leg on the horizontal plane. The circles are drawn at every 20% time of stroke.

group than for the declining group (Figure 4). These results indicate that shortening the time for the right stroke may allow skaters to maintain high cycle frequency and thus high skating velocity. Moreover, although a significant negative relationship was evident between the time for the gliding phase during the right stroke and the CM velocity in the second half ($r = -0.687$, $p < 0.01$), no significant relationship was observed with the push-off phase ($r = 0.197$, Table 1). The time for the gliding phase during the right stroke in the second half was significantly smaller for the maintaining group than for the declining group (maintaining group, $0.29 \pm 0.07$ s; declining group, $0.38 \pm 0.04$ s; $p < 0.01$; Figure 4). These results indicate that a shorter time for the right stroke in the second half may be achieved by shortening the gliding phase. The gliding and push-off phases were divided by the onset of the push-off; thus, for higher cycle frequency in the second half, it may be essential to decrease the time from the instant of blade contact with the ice to the onset of the push-off.

Although no significant relationship was observed between the total time for the stroke and
CM velocity during the left stroke in the second half, significant negative and positive relationships with CM velocity were observed in the time for the gliding phase \( r = -0.544, p < 0.05 \) and push-off phase \( r = 0.629, p < 0.01 \) (Table 1). Therefore, for higher skating velocity in the second half, it may be essential to shorten the gliding phase and lengthen the push-off phase, rather than shortening the total time for the left stroke. In the second half, the maintaining group decreased the time for the gliding phase during the left stroke and increased that for the push-off phase (Figure 4). However, the declining group increased the time for the gliding phase and decreased that for the push-off phase. These results indicated that the maintaining group could quickly extend the left support leg even under fatigued conditions. Thus, it was suggested that long-distance speed skaters should maintain higher cycle frequency by shortening the time of the gliding phase in the right stroke during the curve phase in the second half, while increasing the time of the push-off phase in the left stroke.

For the maintaining group, the onset of the push-off during the left stroke in the second half was earlier than that of the first half (First half, 61.7 ± 6.3%; Second half, 54.6 ± 7.6%), but that in the second half was delayed (First half, 55.7 ± 9.7%; Second half, 64.2 ± 8.0%). This result implied that the change in skating motion increased the push-off phase. Yuki et al. (1996) found that the horizontal blade reaction force for an elite skater during the straight phase developed quickly, although the peak was small. Yuda et al. (2004) indicated that minimizing the decrease in impulse during the curve phase by a quick development of the horizontal blade reaction force was important for maintaining skating velocity in long-distance speed skating. Since the horizontal blade reaction force depends on the push-off force, defined as the compressive force vertically acting on the blade (Yuki et al., 1996; Yuda et al., 2004), skaters must quickly develop push-off force to obtain greater skating velocity. Moreover, the onset of the push-off can be perceived as the onset of greater increase of the push-off force because the skaters could not remarkably increase push-off force until the onset of the push-off (De Koning & Van Ingen Schenau, 2000). Thus, the quick onset of the push-off in the maintaining group increased push-off time and push-off impulse on the ice, resulting in maintenance of skating velocity.

During the gliding phase of the left stroke in the second half, the shank angle for the maintaining group was almost unchanged, whereas the declining group increased the shank angle and rotated the shank more backward, compared to the first half (Figure 5). The CM for the maintaining group during the gliding phase in the second half located more forward than in the first half, but these changes seemed to be unclear for the declining group (Figure 6). These results indicated that the kinematic changes of the support leg during the left stroke with fatigue were different in the two groups. To clarify the difference in the change in support leg motion between the two groups, Figure 7 illustrates a model of a skater during the gliding phase of the left stroke. The CM for the maintaining group in the second half was located more forward than in the first half, as a result of the greater rotation of the thigh. Both the thigh and shank angles in the declining group increased, and the backward rotation of the shank may have cancelled out the effect of the thigh rotation during the gliding phase; therefore, no difference in the horizontal location of the CM would exist between the first and second halves. The push-off motion in speed skating drives the CM forward by the extension of the support leg. Thus, in the maintaining group, the position of the CM as it shifted forward may have helped skaters extend the joints of the left support leg and drive the body forward effectively.

De Koning et al. (1991) contended that the great load on the left leg during the curve phase caused fatigue sooner. Yuda and colleagues (2005) indicated that the knee extension power of the support leg decreased with fatigue, because the left knee of the support leg greatly contributed the push-off motion in the left stroke during the curve phase. These findings suggest that the endurance of the left knee extensors is an important factor in long-distance speed skating. However, for excellent performance, skaters need to acquire not only endurance of power output, but also a technique for maintaining effective push-off even under decreased power output. In this study, the change in the support leg motion of the maintaining group during the second half may indicate an effective technique for maintaining skating velocity under fatigued conditions. Thus, it implies that an important technical factor in long-distance speed skating is the support leg motion during the gliding phase in the left stroke of the curve phase,
such as a forward rotation of the thigh with less shank backward rotation.

A clear relationship between skating velocity and cycle frequency during the first half was not observed in this study. The skating velocity is affected by the external power output, defined as the product of work per stroke and stroke frequency. Because skaters try to maintain the skating velocity in the long distance speed skating, they will save their energy and skating velocity during the first half. Thus, they would skate on controlling the push-off force during the first half for the prevention of great muscle fatigue: The effort for exerting the power output is not the maximal. In addition, the change in the push-off force affects the work per stroke. On the other hand, the push-off force decreases in the second half owing to muscle fatigue. Thus, the skaters have to increase the stroke frequency for maintaining the external power output during the second half: The effort for exerting the power output is the maximal. These would cause the result that significant correlations between the skating velocity and the cycle frequency were observed only during the second half. The changes in the push-off force would strongly affect the skating velocity during the first half. This problem, however, cannot be referred to here because the push-off force during skating was not measured in this study. This remains to be examined in the future.

This study has some limitations. Because the subjects in this study were world-class elite male long-distance speed skaters, the conclusions of this study might not be appropriate to novice skaters and sprinters. Because the data were collected during official races, we were not able to affix the markers on the body surface of the skaters. Thus, the skilled digitizer identified the segment end points of the skater’s body by using the configuration of the individual segments and the design of the racing suit that fitted his body well.

In conclusion, a significant positive relationship was found between CM velocity and the cycle

Figure 7 — A model of change in the support leg motion between the maintaining and declining groups during the gliding phase of the left stroke.
frequency during the second half. Significant negative relationships were observed between CM velocity and the total time and the time for the gliding phase for the right stroke. These results indicated that skaters should maintain higher cycle frequency during the curve phase under fatigued conditions by shortening the time for the gliding phase in the right stroke. In contrast, no significant relationship was observed between the total time for the left stroke and CM velocity during the second half. However, changes in the skating motion of the maintaining group, which decreased the gliding phase and increased the push-off phase during the left stroke during the second half, differed from those of the declining group. These changes appeared to help the maintaining group locate the CM more forward at the onset of the stroke. These findings suggested that long-distance speed skaters should change the support leg position during the gliding phase in the left stroke of the curve phase under fatigued conditions so that they could extend the support leg with a forward rotation of the thigh and less shank backward rotation.

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References