KJSB

Korean Journal of Sport Biomechanics 2018; 28(2): 93-100
http://dx.doi.org/10.5103/KJSB.2018.28.2.93
http://e-kjsb.org eISSN 2093-9752

ORIGINAL

Kinematic Analysis of the Technique for 500-m Speed Skaters in Curving

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Received : 05 February 2018
Revised : 27 March 2018
Accepted : 27 March 2018

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Objective: The purpose of this study is to analyze the kinematic characteristics of the national speed skaters in the curve phase of 500-m race.

Method: Seven national skaters participated in the study. Race images were acquired using a high - speed camera, and the three-dimensional motion was analyzed.

Results: For skaters, whose average velocity in the curve phase is high, the velocity of entry into the straight phase was also fast. The fast skaters showed a larger maximum angle of extension of the knee joints than the relatively slow skaters, and the trunk ROM was smaller. Fast skaters tended to match the timing of the movement of the lower limb with the pelvis, while slow skaters tended to rotate the left pelvis backward. The velocity of the curve phase did not show a clear relationship with stroke time, average trunk angle, and lap time.

Conclusion: It is important to skate close to the inner line, keep the trunk ROM below 10 degrees, extend the knee angle to over 160 degrees, and match the movement of the pelvis and lower limb to accelerate in the curve phase. The average velocity of the curves was fast for many athletes, but the competition rankings were low. Therefore, it is possible to improve the performance by optimizing the start technique, the running characteristics of the straight phase, and the physical factors.

Keywords: Speed skating, Curve phase, Knee extension, Trunk angle, Pelvis rotation

INTRODUCTION

Among speed skating events, 500 m is the shortest distance, often compared to the 100-m sprint in athletics; athletes have to complete the straight and curve phases of the course at full-speed to achieve the fastest time possible (Lee, Na & Back, 2001). The first published research of the movements in speed skating was a study by Robert Mackenzie in 1898 that emphasized the importance of the crouched skating position. Since then, the development of clap skates in 1997 led to marked improvements in skating technique and race times.

Mechanical analysis of skating technique has shown that skating speed is affected by the skater's power, air resistance, and friction with the surface of the ice (van Ingen Schenau, 1982; van Ingen Schenau, de Boer & de Groot, 1987; de Koning, de Groot & van Ingen Schenau, 1992). According to the results of previous studies, to achieve the fastest skating speed, the knee angle should be maintained in the range of 90~110° during gliding to minimize air resistance and ice friction (van Ingen Schenau, 1983; Yuda, Yuki, Aoyanagi, Fujii & Ae, 2007), the upper body should be kept horizontal, and trunk and ankle rotation should be minimized so that push-off is largely achieved by knee extension (van Ingen Schenau, 1982).

In particular, van Ingen Schenau, de Groot and Hollander (1983) showed that the power generated by elite athletes was much higher than that of amateur athletes, demonstrating that increasing power was the most important factor in improving skating technique. The skater's power can be increased by an effective push-off, resulting in full rotation of the hip, knee extension, and ankle plantarflexion (Park, 2005). Given that different techniques are required in the straight and curve phases of speed skating, there is a need for research on the distinct push-off techniques for each phase.

Among studies on the straight phase, de Boer, Schermerhorn, Gademan, de Groot, and van Ingen Schenau (1986) found that the push-off angle, defined as the transverse orientation of the body's center of mass at the start of push-off was larger in elite athletes than in amateur athletes; meanwhile Yuki, Ae and Fujii (1996) discovered that rapidly tilting the blade medially after the start of the stroke was an important technique that enabled a faster skating speed. Among studies on the curve phase, de Boer, Ettema, Van Gorkum, de Groot and van Ingen Schenau (1987b) found that a short stroke time and large knee extension range were characteristics of elite athletes, while Yuda, Yuki, and Ae (2003) reported

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that the angle of rotation of the body and lower leg in the transverse direction at the start of the stroke were larger in elite athletes than in amateur athletes.

Recently, Korea's national speed skating team has been a major force in global competition, such as the Olympics and the World Cup, which has led to much analysis of the kinematic techniques of the Korean skaters. Because Korean skaters show weaker start technique compared to other countries, most of the analysis has focused on start technique (Yoon, Na, Choi & Kim, 2000; Back, Kwak & Chung, 2004; Lee & Back, 2005; Jun, 2010; Song, 2016; Song, Lee & Moon, 2017), while there have also been studies analyzing the technique during the curve phase in short track speed skating (Jun, 2001; Back, Jun & Lee, 2006; Kim, Jun, Yoo & Park, 2013). However, because short track speed skating is about rankings rather than times, different race strategies lead to considerable differences in technique compared to speed skating, and therefore, the technique needs to be analyzed separately for the two disciplines.

In short distance speed skating, the strengths of the Korean athletes are their physical condition and their excellent technique in the curve phase (Jun, 2010), and curve phase technique training is very important for world-class skaters (Jeon, Choi, Lee & Jegal, 2016). In 500-m races, especially, skaters need to accelerate to maximum speed during the 2 curve phases and maintain this speed during the straight phases (Jeon et al., 2016); therefore, the key to producing fast times is to fight the centrifugal force in the curve phase to produce the maximum acceleration and enter the straight phase at high speed.

In this study, we sought to analyze the kinematic characteristics of elite speed skaters during the second half of the curved 2nd interval and entry into the straight phase. In addition, we aimed to use the results to provide basic information that can help curve phase training for speed skaters.

METHOD

1. Participants

The subjects of our study were 7 elite Korean speed skaters; their physical characteristics are shown in Table 1.

Table 1. Characteristics of subjects

Subject	Gender	Age (y)	Height (cm)	Weight (kg)	Course
M1	Men	24	179.06	54.45	In
M2	Men	22	178.18	75.03	In
M3	Men	21	178.33	77.17	Out
M4	Men	28	177.12	72.08	Out
W1	Woman	18	166.34	53.64	In
W2	Woman	22	158.80	54.28	In
W3	Woman	28	168.25	55.40	Out
Mean (SD)	–	23.29 (3.68)	172.30 (7.90)	63.15 (10.97)	–

2. Procedure

Video data were collected during races at the speed skating national team trials. We set-up 4 high-speed video cameras (NEX-FS700, SONY, Tokyo, Japan), as shown in Figure 1, for three-dimensional (3D) motion analysis of the curve phase technique of athletes participating in 500-m speed skating. For synchronization, the cameras were connected with BNC cables, and a sense trigger was used to control recording. Videos were recorded during 500-m races from the last 4 steps of the 2nd interval (curve phase) until the first contact of the left foot with the ice surface after leaving the curve phase (straight phase entry). The recording frame rate was 120 frames/sec, and the shutter speed was 1/500 s. After the completion of the races, 8 × 1 × 2 m control point frames (Visol, Seoul, Korea) were recorded to form spatial coordinates.

3. Data processing

The video data was processed using KWON3D 3.1 (Visol, Seoul, Korea; version 3.1); the control point frames were used to calculate real spatial coordinates, which were in turn used to obtain 3D coordinates for the

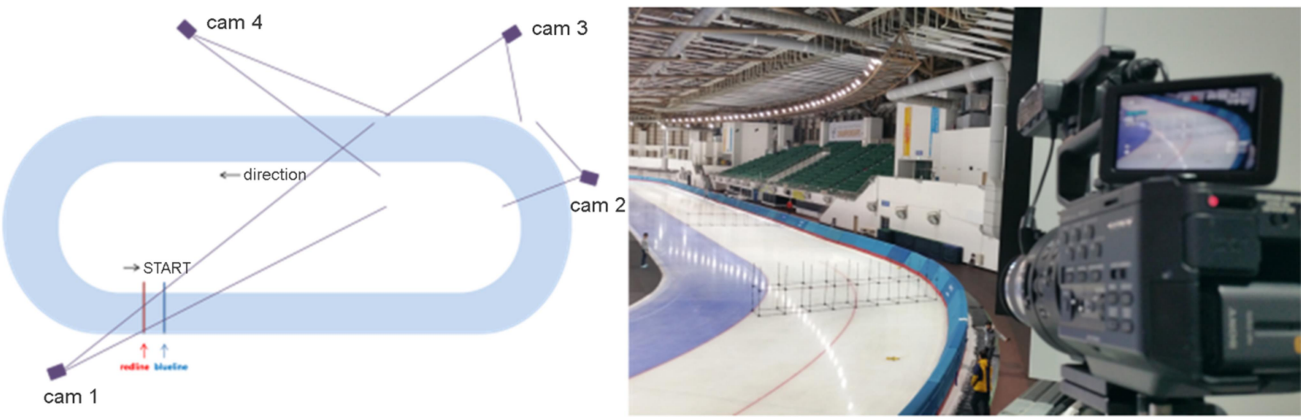

Figure 1. Layout of cameras

body. The left-right direction was defined as the X-axis, the anteroposterior direction (the direction of movement) was defined as the Y-axis, and the superoinferior direction was defined as the Z-axis. The body model was defined as a rigid body system consisting of 16 segments connected by 20 articulation points (head, chin, right/left shoulder, right/left elbow, right/left wrist, right/left hand, right/left hip, right/left knee, right/left ankle, right/left heel, right/left toe). The 2D coordinates obtained from each camera were combined using cubic spline interpolation, and the 3D coordinates were calculated using the direct linear transformation (DLT) method developed by Abdel-Aziz and Karara (1971). To remove error due to noise from various sources, including digitization, we smoothed the data using a second-order low-pass Butterworth filter, with a cutoff frequency of 10 Hz.

1) Events

In this study, we analyzed the 4 steps before the start of the straight phase, and designated the following events:

- Left contact 1 (LC1): First contact of the left blade (start of step 1)
- Right off (RO): Lifting of the right blade
- Right contact 1 (RC1): First contact of the right blade (start of step 2)
- Left off 1 (LO1): First lifting of the left blade
- Left contact 2 (LC2): Second contact of the left blade (start of step 3)
- Right off 1 (RO1): First lifting of the right blade
- Right contact 2 (RC2): Second contact of the right blade (start of step 4)
- Left off 2 (LO2): Second lifting of the left blade
- Left contact 3 (LC3): Third contact of the left blade
- Right off 2 (RO2): Second lifting of the right blade

2) Variables

The variables analyzed in this study were as follows:

- Position of the center of mass, average speed in the curve phase, speed of entry into the straight phase, 100-m and 500-m times
- Stroke time: left - time from lifting the right blade to lifting the left blade, right - time from lifting the left blade to lifting the right blade (Yuda et al., 2007)
- Maximum knee extension angle: the maximum relative angle of extension of the knee joint in the sagittal plane
- Trunk angle: absolute angle of the trunk relative to the Y-axis in the sagittal plane
- Change in trunk angle: the difference between the maximum and minimum trunk angles
- Shoulder/pelvis tilt angles: Absolute angle of the two shoulders/pelvis relative to the X-axis in the horizontal plane (Figure 2A)
- Distance to straight phase: The distance between the heel at first left contact at the start of the straight phase and the last cone of the curve phase (Figure 2B)

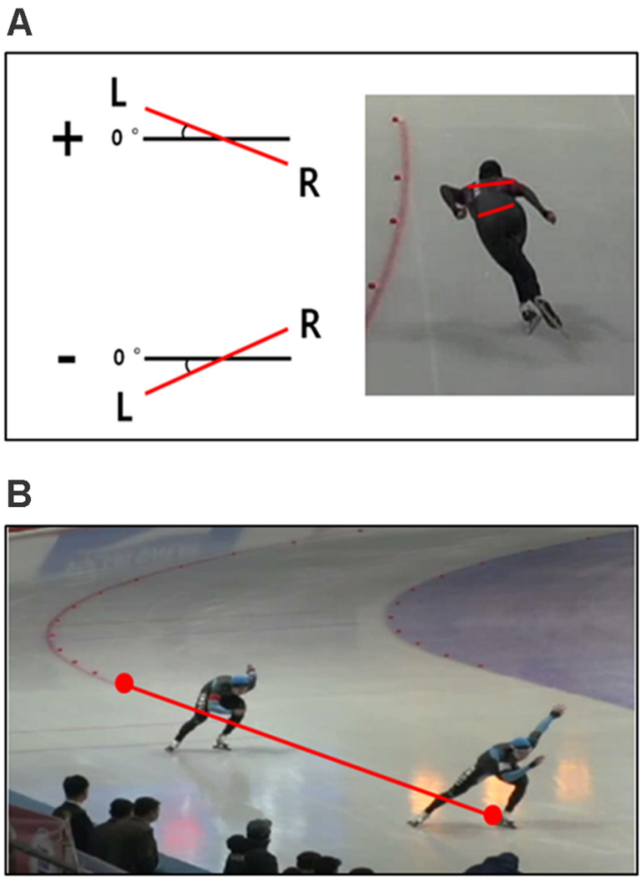

Figure 2. A: tilt angle, B: distance

RESULTS

1. In-course

Figure 3 shows the change in center of mass positions of athletes on the in-course during the last 4 steps of the curve phase before

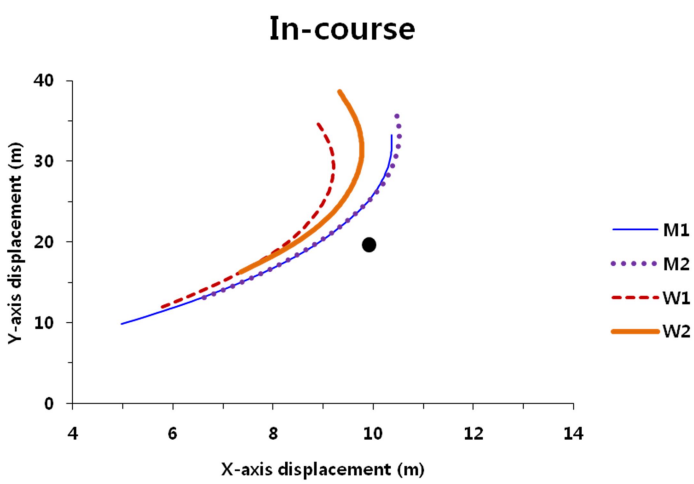

Figure 3. Center of mass positions of skaters starting from in-course (Black circle: The position of the cone at the end of the curve phase)

Table 2. Kinematic variables

Subject	Average velocity in curve phase (m/s)	Stroke time (s)		Maximum knee angle (deg.)		Average trunk angle (deg.)	ROM of trunk (deg.)	Distance to straight phase (m)	Velocity of entry into the straight phase (m/s)	100 m lap (s)	500 m lap (s)	Competition ranking
		Left	Right	Left	Right							
M1	15.66	0.32	0.43	120.03	137.42	17.07	16.40	11.34	16.02	9.83	35.49	2
M2	15.70	0.32	0.39	159.64	165.82	23.65	4.87	14.93	16.03	9.73	35.61	4
W1	14.15	0.34	0.42	164.25	166.53	15.65	5.95	12.05	14.23	11.10	39.94	2
W2	14.01	0.37	0.42	160.02	161.57	20.88	7.07	17.16	14.27	11.08	40.09	4

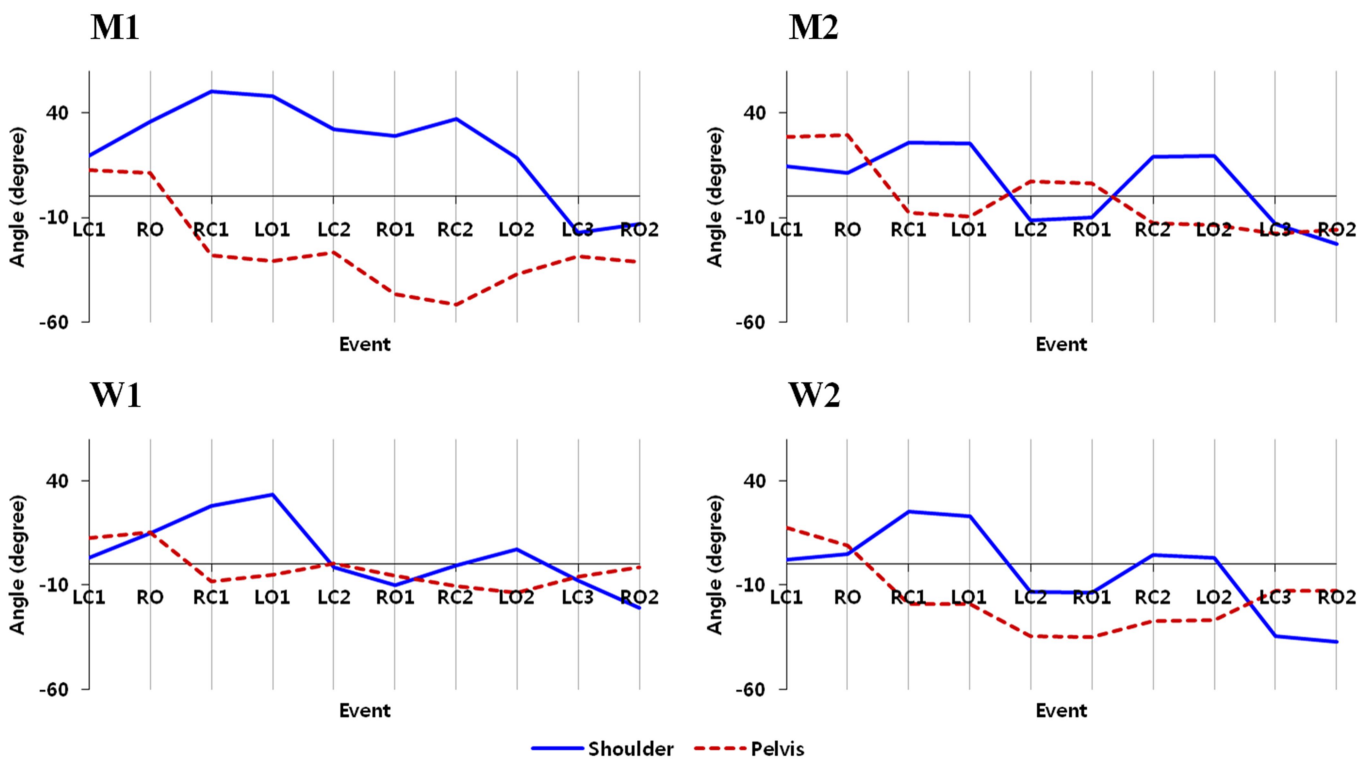

Figure 4. Shoulder and pelvis rotation angles in the horizontal plane of skaters starting from in-course

the straight phase. Table 2 shows the kinematic variables for athletes on the in-course during the curve phase and entry into the straight phase.

M1 left the curve phase ahead of the out-course skater and entered the out-course of the straight phase comfortably. As a result, this athlete was able to enter the straight phase earlier than the other skaters, and although the mean trunk angle was small, the change in angle was somewhat large.

M2 also exited the curve phase ahead of the out-course skater and naturally transitioned to the out-course. Compared to M1, M2's mean curve phase speed was 0.04 m/s faster and straight phase entry speed was 0.01 m/s faster. Right stroke time was 0.04 s shorter than M1. Maximum knee extension was 39° and 28° greater than M1 on the left and right sides, respectively. Mean trunk angle was slightly large, but the athlete maintained a mostly constant angle.

W1 exited the curve phase ahead of the out-course skater like the male skaters above but did not immediately transition to the out-course and continued to take the most inside line possible. The mean curve phase speed was 0.14 m/s faster than W2, and the left stroke time was 0.03 s shorter. Maximum knee extension angle was 4° and 5° greater than W2 on the left and right sides, respectively, and the skater maintained a constant low trunk angle. The time of entry into the straight phase was also fast.

Unlike the male skaters, W2 left the curve phase at a similar time to the out-course skater, making a natural course transition impossible. As a result, the point of transition from a curved course to a straight course was relatively late. The time of straight phase entry was 0.04 s earlier than W1.

Figure 4 shows the angle of shoulder and pelvis rotation in the anteroposterior direction, relative to the X-axis, in athletes on the in-course.

M1's left shoulder was facing anteriorly during the curve phase. Pelvic rotation angle also showed very little change in the positive direction in the LO1-LC2 interval, where the left foot is pulled forward. Subsequently, at RO1, the angle increased in the negative direction. This shows the characteristic of skating with the left pelvis twisted posteriorly.

M2 showed appropriate rotation, with the shoulder rotating simultaneously, in the opposite direction, with the pelvis. Compared to M1, M2 showed greater anterior rotation of the left pelvis in the LO1-LC2 interval, pulling the left foot forward to contact the ice.

W1 showed little pelvis rotation in the curve phase, with the pelvis turned anteriorly, but showed the appropriate rotations to pull forwards and push back the joints of the lower limbs.

W2 showed a similar pattern of shoulder rotation to M2, but pelvis rotation showed a tendency for the left pelvis to be turned towards the inside of the line during the LO1-LC2 interval.

2. Out-course

Figure 5 shows the change in center of mass positions of athletes on the out-course during the last 4 steps of the curve phase before the straight phase. Table 3 shows the kinematic variables for athletes on the out-course during the curve phase and entry into the straight phase.

As shown in Figure 5, M3 traveled close to the inside line during the curve phase, but the mean curve phase speed, speed of straight phase entry, and time of straight phase entry were slower than M4, and the maximum knee extension angle was smaller. The mean trunk angle remained constant.

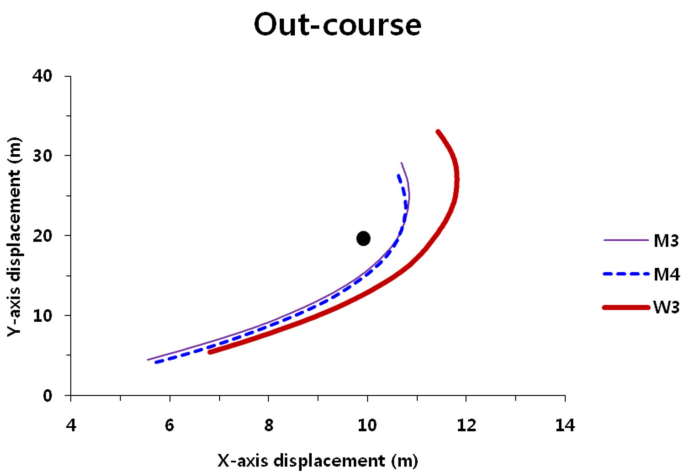

Figure 5. Center of mass positions of skaters starting from out-course (Black circle: The position of the cone at the end of the curve phase)

M4 entered the straight phase after traveling at the fastest speed of all athletes during the curve phase, and also showed an early time of transition from the curve phase to the straight phase. Compared to M3, M4's maximum knee extension angle was 31° and 11° greater on the left and right sides, respectively. The mean trunk angle and change in trunk angle were both somewhat large.

Because W3 exited the curve phase at the same time as the in-course skater, she was unable to transition to the in-course rapidly. As a result, the time of transition to straight phase was relatively late, but the curve phase speed was the fastest, and because the centrifugal force decreased by comfortably exiting the curve phase towards the outside, W3 was able to enter the straight phase with the fastest speed of all the female athletes. W3 also showed the higher angle of knee extension of all the female skaters, and unlike the other skaters, the left knee angle was larger than the right knee angle. Although the mean trunk angle was small, it showed a somewhat large vertical change. Stroke time was a little longer than the other skaters.

Figure 6 shows the angle of the shoulder and pelvis rotation in the anteroposterior direction, relative to the X-axis, in athletes on the out-course.

M3 had his left shoulder facing anteriorly during the curve phase. The pelvis rotation angle increased in the negative direction during the LO1-LC2 interval, when the left foot is pulled anteriorly, showing that this athlete skated with his left pelvis rotated posteriorly.

M4 showed appropriate rotation of the shoulders simultaneously, in the opposite direction, with the pelvis. The pelvis was turned anteriorly, and the left pelvis was pulled sufficiently anteriorly during the LO1-LC2 interval to bring the left foot to contact the ice.

Like M3, W3 showed an increase in pelvis rotation angle in the negative direction during the LO1-LC2 interval, in which the left foot is pulled anteriorly. This shows that W3 had her left pelvis rotated posteriorly during skating.

DISCUSSION

In the present study, we conducted a kinematic analysis of elite speed skaters during the curve phase and entry into the straight phase of 500-m races. By analyzing the technique of each skater, we found several characteristics in athletes who showed fast speeds through

Table 3. Distance, velocity and angle variables of skaters starting from in-course

Subject	Average velocity in curve phase (m/s)	Stroke time (s)		Maximum knee angle (deg.)		Average trunk angle (deg.)	ROM of trunk (deg.)	Distance to straight phase (m)	Velocity of entry into the straight phase (m/s)	100 m lap (s)	500 m lap (s)	Competition ranking
		Left	Right	Left	Right							
M3	15.82	0.33	0.42	134.08	160.89	20.01	4.71	7.58	15.97	9.62	35.39	1
M4	15.86	0.38	0.37	165.01	171.28	24.21	9.72	6.89	16.07	9.76	35.50	3
W3	14.73	0.43	0.48	172.78	165.34	15.92	17.04	11.38	14.96	10.65	38.57	1

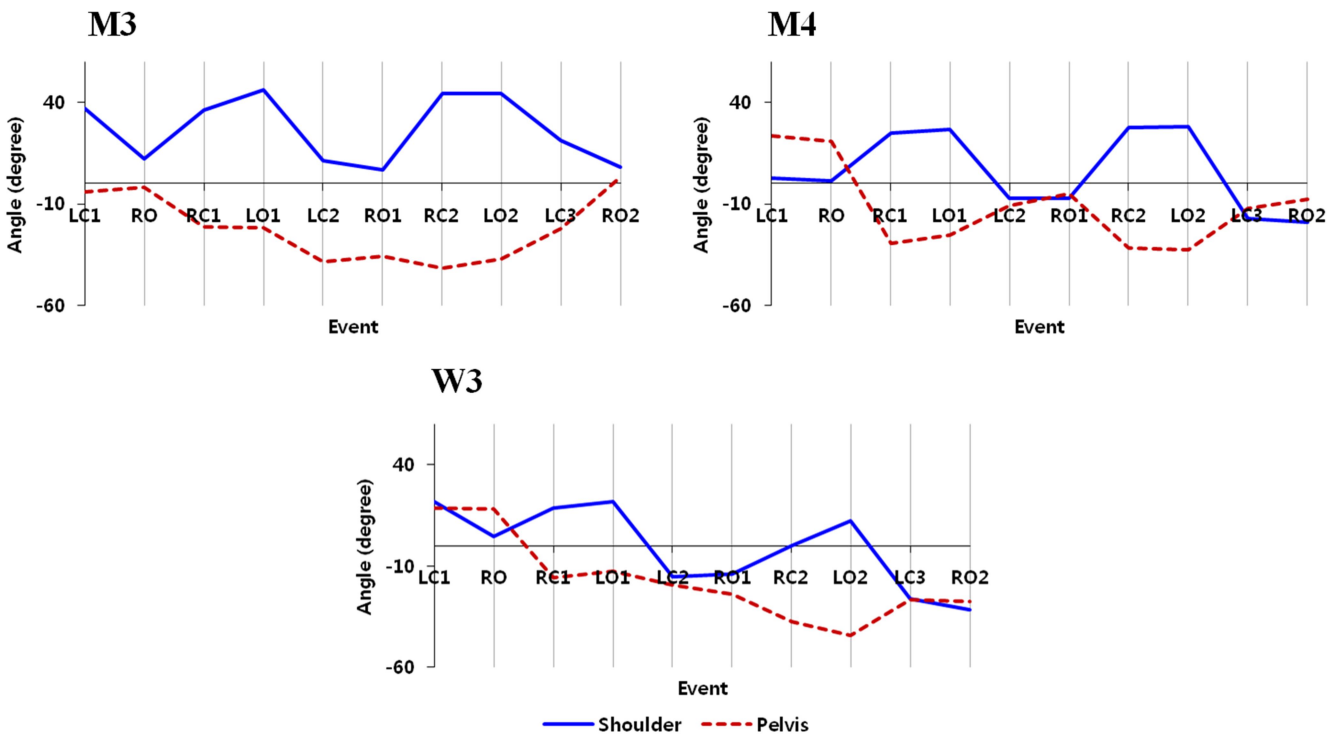

Figure 6. Shoulder and pelvis rotation angles in the horizontal plane of skaters starting from out-course

the curve phase.

First, athletes who stayed as close as possible to the inside line and appropriately exited the curve phase and changed course according to the circumstances of the race not only showed fast speeds in the curve phase but also accelerated more than 20 m/s to enter the straight phase at a fast velocity. Second, athletes with a fast curve phase speed showed a powerful push-off with a knee extension angle of over 160°, and maintained a constant trunk angle, with a change of less than 10°, which minimizes air resistance. Third, skaters whose pelvis was facing anteriorly and who showed appropriate pelvis movements coinciding with blade contact and lifting (e.g., anterior rotation of the left pelvis on right blade contact) showed faster average curve phase velocity, while skaters whose left pelvis was overall rotated posteriorly showed slower speeds.

M1 and M2, who started from the in-course, stayed very close to the inside line during the curve phase and entered the straight phase simultaneously with exiting the curve phase. These athletes not only showed a fast velocity during the curve phase but also accelerated over 30 m/s before entering the straight phase. Conversely, W1 entered the straight phase earlier than the out-course skater but continued to keep a course close to the inside line during entry into the straight phase, and was thus unable to produce sufficient acceleration. The strategy of shifting course while entering the straight phase is thought to enable entry to the straight phase at a faster velocity, by utilizing the centrifugal force generated in the curve phase.

M2, W1, and M4, who showed fast curve phase speeds, maintained a near-constant trunk angle, changing less than 10°, and this is thought to be a strategy to minimize air resistance. Flexing the trunk to form an angle of 15° relative to the horizontal plane is, aerodynamically, the optimal angle to skate at high speeds (van Ingen Schenau, 1982). The mean trunk angle for the skaters was varied, ranging from 15.65° to 24.21°. In a race where every one-hundredth of a second matter, athletes who skate with a mean trunk angle of over 20° could minimize air resistance and skate faster by reducing their trunk angle.

Several previous studies have reported that near-complete knee extension of approximately 171° at push-off can generate the most power (de Boer, Ettema, Faessen, Krekels, Hollander, de Groot & van Ingen Schenau, 1987a; Allinger & van den Bogert, 1997; Houdijk, de Koning, de Groot, Bobbert & van Ingen Schenau, 2000). The maximum knee angles for the left and right knees of the skaters with the fastest curve phase speed were, respectively, 159.64° and 165.82° for M2, 165.01° and 171.28° for M4, 164.25° and 166.53° for W1, and 172.78° and 165.34° for W3, demonstrating ample knee extension at push-off. In addition, the difference between the right and left maximum knee extension angles was less than 10° for all these athletes. Meanwhile, the maximum left and right knee angles for M1 were 120.03° and 137.42°, and for M3 were 134.08° and 160.89°, meaning that these athletes did not achieve sufficient extension of both knees, and also showed considerably imbalance in the movements of the two knees. Therefore, it is essential to extend the left knee sufficiently while generating a powerful push-off.

M2, M4, and W1 skated with the pelvis facing anteriorly in the horizontal plane and showed faster speeds than athletes who skated with the left pelvis rotated posteriorly. The faster athletes also showed the appropriate timing of pelvis movements in line with the lower limb segments, with the pelvis rotating anteriorly upon blade contact and posteriorly upon blade lifting.

Furthermore, increasing the stroke frequency with repeated, short strokes in the curve phase can increase skating speed (de Boer et al., 1987b), and because a small knee angle at the start of push-off enables a large extension range of motion, the work per stroke increases, producing more power (van Ingen Schenau, 1983). Training based on the technical factors we identified in this study can be expected to improve speed in the curve phase. Moreover, since the power generated by athletes is greatly affected by physiological factors, such as aerobic and anaerobic capacity, in addition to technical factors (van Ingen Schenau & Cavanagh, 1990; van Ingen Schenau, de Koning & de Groot, 1990; Konings, Elferink-Gemser, Stoter, van der Meer, Otten & Hettinga, 2015), accompanying this technical training with physical training should help to improve overall technique.

CONCLUSION AND SUGGESTION

In the present study, we compared major kinematic variables in the curve phase of 500-m races by elite speed skaters, with the aim of providing basic data to identify curve phase technique and to improve training programs. The major technical factors we identified in the curve phase were as follows: first, skating as closely as possible to the inside line and attempting the change course in accordance with the race circumstances; second, maintaining a constant trunk angle with less than 10° of movement, and extending the knee joint at least 160° during push-off; third, keeping the pelvis facing anteriorly, and rotating the pelvis appropriately with blade contact and lifting.

For skaters with good race times but slow curve phase speed, improving these factors would enable even faster times. On the other hand, many skaters show fast average curve phase speed but low rankings in tournaments. The overall race performance for these athletes is likely to be affected by start technique, straight phase skating characteristics, or physical conditioning. Therefore, these skaters could improve their race times by practicing starting movements, including reaction time, minimizing deceleration and air resistance in the straight phase, and improving physical stamina so that they can complete 500 m in peak condition.

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