Title

Changes in Straight Skating Motions in World-class Long-distance Speed Skaters during the
Ladies' 3,000-m Race

Running title

Changes in Straight Skating Motions during Ladies' 3,000-m

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Abstract

The present study aimed to investigate kinematic changes in the straight skating motions of world-class speed skaters during a ladies' 3,000-m race. Sixteen elite skaters who participated in the World Cup were included in the study. Three-dimensional motion analyses using 4 synchronized high-speed cameras (300 Hz) were performed on the straight skating motions at the initial, middle, and final stages of the race. As the race progressed, skating velocity decreased and the body center of mass (CM) height and the thigh angle increased. Shank outward tilting time exhibited a significant negative relationship with the official time for both the left and right strokes in the initial stage. In the final stage, skating velocity was significantly, positively associated with hip and knee angular velocity at the end of strokes. These results demonstrated that, in the ladies' 3,000-m race, although the air resistance increases with higher CM position and the skating velocity decreases as the race progressed, the straight skating motion of the excellent skaters was characterized by longer outward tilting of the shank in the initial stage contributes to maintaining skating velocity until the middle and final stages of the race.

Keywords: long-distance speed skating; three-dimensional motion analysis; kinematic parameters; technical issues for each race stage; elite athletes

1. Introduction

Long-distance events held during senior speed skating competitions include the men's 5,000-m, men's 10,000-m, ladies' 3,000-m, and ladies' 5,000-m. Several studies have investigated skating techniques in the men's 5,000-m race. For example, Yuda et al. (2003, 2007) analyzed curve skating motions in the men's 5,000-m during an international competition, revealing the importance of preventing the left shank from rising to maintain velocity in the second half of the race, and that elite skaters tilted more inward during curve skating than junior skaters. In a similar analysis of straight skating motions, Yuda et al. (2009b) revealed that the thigh was raised more in the second half than the first half of the race. In addition, Noordhof et al. (2013) performed a two-dimensional analysis of the straight skating motion in the men's 5,000-m during an international competition, reporting increases in the knee joint angle after the 4th lap.

However, the race pattern differs depending on the distance of the event. The maintenance rate of the lap time (after excluding the first lap, average lap time in the former half of the race divided by the average lap time in the latter half of the race) of the world's elite skaters were over 99% in the men's 10,000-m, men's 5,000-m and ladies' 5,000-m events, while in the ladies' 3,000-m, it was $95.1 \pm 1.9\%$ which indicated a large decrease in velocity in the latter half of the race (Kimura et al., 2020). Therefore, it is not appropriate to apply the above findings for the men's 5,000-m to the ladies' 3,000-m. However, previous studies of skating performance have analyzed only velocity and stroke number during the straight section of the ladies' 3,000-m (Kimura et al., 2020). Thus, further investigation of

the straight skating motion during a 3,000-m race is required to clarify optimal skating techniques and improve performance among elite skaters.

Furthermore, given the large decrease in velocity during the 3,000-m race, it can be also expected that skating motions and techniques will differ among the initial, middle, and final stages of the race. Thus, it is important to compare skating motions among three stages and to focus on the relationships between kinematic parameters in each stage and skating velocity or race performance. The present study aimed to investigate kinematic changes in the straight skating motion of world-class speed skaters during the ladies' 3,000-m race.

2. Methods

2.1. Data collection

The present study targeted ladies' 3,000-m races during the International Skating Union Speed Skating World Cup held in the Nagano Olympic Memorial Arena. Permission to collect data was requested in advance and obtained from the organizing committee through the Japan Skating Federation. This study was approved by the Ethical Review Committee of the Japan Institute of Sports Sciences. The target skaters for data collection were selected in advance from among the top 24 in the World Cup ranking, taking into account data storage capacity and the maximum number of individuals that can be captured at the same time during a quartet (four skaters') race with emphasis on the ranking. The measurement range consisted of a 4-m wide, 48-m long, and 1.25-m high area of the inner finishing straight lane. Four high-speed cameras (Phantom v1611, v310, and v311, Vision Research, USA) were

used to record the skaters from the front (stationary), back (stationary), and sides (panning). The skating motion was captured at 300 Hz with an exposure time of 1/1000 s. The videos were synchronized using a wireless LED synchronizer (PTS-168, DKH, Japan). In the 3,000-m race, the skaters start near the entrance to the second curve, diagonally opposite the finishing line, and complete seven and a half laps. In this study, the first lap was defined as the half lap from the start of the race to the first crossing of the finishing line, and the subsequent laps were defined as laps 2 through 8. Data were captured at the 2nd, 4th, and 6th laps (corresponding to approximately 550-m, 1,350-m, and 2,150-m, respectively) for skaters starting in the outer lane and at the 3rd, 5th, and 7th laps (corresponding to approximately 950-m, 1,750-m, and 2,550-m, respectively) for skaters starting in the inner lane. These laps were defined as the initial, middle, and final stages of the race, respectively. Among the top 24 skaters based on official times, 16 skaters (age: 26.31 ± 6.02 , height: 1.70 ± 0.07 m, body mass: 61.69 ± 5.57 kg) who were recorded were included in the analyses. The official time and the lap time of each lap were taken from the official results measured by the photoelectric tube measuring device installed on the finishing line.

2.2. Data processing

After excluding the first lap (i.e., the acceleration phase), the remaining laps were divided into former and latter halves and the percentage of the average lap time maintained in the latter half was calculated against the average lap time in the former half (hereafter referred to as maintenance rate of the lap time, Yuda et al., 2002). However, in the 3,000-m

race, due to the odd number of laps (excluding the acceleration phase), the 2nd–4th laps are counted as the former half of the race and the 6th–8th laps as the latter half.

On the captured images, 21 body endpoints and four blade edges were digitized at 50 Hz using specialized digitizing software (Frame-Dias IV, DKH, Japan). Digitizing was conducted manually by identifying anatomical points on the high-speed camera images (Figure 1-a). Three-dimensional coordinates of 25 points were obtained using a panning direct linear transformation technique and smoothed using a fourth-order Butterworth low-pass digital filter with a cutoff of 2.5–7.0 Hz, as determined using a residual method (Winter, 2005).

In this study, "blade-off" was defined as the moment when the entire bottom of the blade left the surface of the ice, while "blade-on" was defined as the moment when the bottom of the blade made even partial contact with the surface of the ice, and both were detected with a resolution of 300 Hz. In addition, the left stroke was defined as the period from right blade-off to left blade-off, while the right stroke was defined as the period from left blade-off to right blade-off (Yuda et al., 2009b). Two consecutive strokes were analyzed in the present study. The time taken for one stroke was defined as the stroke time. The strokes were divided into gliding and push-off phases based on the opposite side blade-on (van der Kruk et al., 2017) and the time required for each phase was calculated. The coordinates of the CM were calculated using the body segment inertial parameters for ladies' speed skaters provided by Yokozawa et al. (2015). Skating velocity was calculated by dividing the distance that the CM moved in a direction parallel to the course during a stroke by stroke time. Note

that the left and right strokes were analyzed separately in this study because the characteristics of changes in the straight skating motion as the race progress may differ between the left and right strokes due to the influence of the asymmetry of the curve skating motion.

A local coordinate system was set such that the horizontal component of the skating velocity was the y-axis, the vertically upward direction was the z-axis, and the cross product of the y-axis and z-axis was the x-axis. The CM height was defined as the z component of the coordinates of the CM. The thigh angle was defined as the angle between the thigh segment and the y-axis, and the shank angle was defined as the angle between the shank segment and the y-axis on the y-z plane (Figure 1-b). The shank tilt angle was defined as the angle between the shank segment and the z-axis on the x-z plane, with positive values indicating an inward tilt (Figure 1-c). Furthermore, shank outward tilting time was defined as the time from the beginning of the stroke until the shank tilt angle changed to a positive value. The hip, knee, and ankle joint angles were defined as the angles between the torso and thigh, thigh and shank, and shank and foot, respectively (Figure 1-d), and the angular velocity of each joint at the end of the stroke was calculated by time differentiation of each joint angle. Blade anteroposterior distance was calculated from the difference between the y-coordinate of the CM and the y-coordinate of the midpoint at both ends of the blade (Figure 1-e), and the values at the beginning and end of the stroke were calculated. The heel elevation angle was defined as the angle between the foot segment and blade at blade-off (Figure 1-e).

2.3. Statistical analysis

Differences in stroke parameters and kinematic parameters among race stages (initial, middle, and final) were examined using one-way repeated-measures analyses of variance (ANOVA). If the main effect was significant, a post hoc analysis was performed using Bonferroni's multiple comparison method.

In the ladies' 3,000-m race, it was confirmed that the difference in skating velocity between the top performers and the bottom performers greatly increased in the middle and final stages of the race (Kimura et al., 2020). Therefore, we investigated not only the relationships between the parameters and the skating velocity in the same stage, but also the relationships with the official time, and calculated the Pearson's product-moment correlation coefficients. Statistical analyses were performed using SPSS Statistics (ver. 24, IBM, USA). The significance level was set at 5%.

Time series data for the kinematic parameters were normalized to a single stroke. One-way repeated-measures ANOVA was conducted using the one-dimensional statistical parametric mapping (SPM1D) technique, which was used to evaluate differences in time series data among race stages. The SPM1D analyses were executed using the open-source software package spm1D version 0.4 (www.spm1d.org). If the main effect was significant, post hoc paired t-tests were used to examine differences among all three race stages (Pataky et al., 2015). The significance level was set at 5%. The significance level of the post hoc paired t-test was set at 1.67% based on Bonferroni correction.

3. Results

The average official time of the target 16 skaters was $247.78 \text{ s} \pm 2.78 \text{ s}$. The maintenance rate of the lap time was $96.71 \pm 2.31\%$ and exhibited a negative correlation with the official time ($r=-0.50$, $p=0.047$, Table 1).

The main effect of the race stages on the skating velocity, stroke time and gliding time for both left and right strokes was significant (Table 1). Skating velocity for both left and right strokes was greatest in the initial stage, followed by the middle and final stages (left stroke: $p=0.004$, right stroke: $p=0.023$). For both strokes, skating velocity exhibited a significant negative correlation with the official time in all race stages (left stroke: initial: $r=-0.63$, $p=0.009$, middle: $r=-0.81$, $p=0.000$, final: $r=-0.82$, $p=0.000$, right stroke: initial: $r=-0.51$, $p=0.044$, middle: $r=-0.83$, $p=0.000$, final: $r=-0.80$, $p=0.000$). Stroke time for both left and right strokes was greatest in the initial stage, followed by the middle and final stages (left stroke: $p=0.020$, right stroke: $p=0.003$). Gliding time for both the left and right strokes was significantly greater in the initial and middle stages than in the final stage (left stroke: $p=0.000$, right stroke: $p=0.000$). For the left stroke in the middle stage, skating velocity exhibited a significant positive relationship with stroke time and gliding time ($r=0.63$, $p=0.009$, $r=0.50$, $p=0.047$, respectively). The main effect of the race stages on the push-off time of the left stroke was not significant. There was a significant main effect for race stage with push-off time for the right stroke significantly greater in the initial stage than in the middle and final stages ($p=0.018$).

During both strokes, CM height gradually increased from the beginning of the stroke

and reached a peak at approximately 30% of the stroke (Figure 2). Then, the CM height gradually decreased until approximately 90% of the stroke, following which it increased again until the end of the stroke. For both strokes, the main effect of the race stages was significant, and CM height was significantly greater for the final stage than for the initial and middle stages at approximately 70-90% of the stroke.

The main effect of the race stages on the thigh, shank and shank tilt angles during both left and right strokes was significant (Figure 3). The thigh angle of each stroke increased gradually during the gliding phase and increased rapidly during the push-off phase (Figure 3-a). During both strokes, the thigh angle was significantly greater for the final stage than for the initial and middle stages at approximately 70-90% of the stroke. The shank angle of each stroke remained flat from the beginning of the stroke to approximately 60% of the stroke, following which it gradually decreased (Figure 3-b). The lowest shank angle was observed at approximately 90% of the stroke, following which it increased until the end of the stroke. During both strokes, the shank angle was significantly greater for the final stage than for the initial stage at approximately 0-10%, 40-50%, and 80-90% of the stroke. During both strokes, the shank was tilted outward at the beginning of the stroke and shifted to an inward tilt around 20-40% of the stroke (Figure 3-c). During the right stroke, the shank tilt angle was significantly greater for the final stage than for the initial and middle stages at approximately 20-40% of the stroke.

The main effect of the race stages on the hip and ankle angular velocity at the end of both left and right strokes was not significant (Table 2). In the final stage, skating velocity

exhibited a significant positive relationship with hip angular velocity at the end of both strokes (left stroke: $r=0.61$, $p=0.013$, right stroke: $r=0.56$, $p=0.025$). There was a significant main effect for race stage with knee angular velocity at the end of both left and right strokes significantly greater in the initial stage than in the final stage (left stroke: $p=0.047$, right stroke: $p=0.012$). There was a significant negative relationship between the official time and the knee angular velocity at the end of the left stroke in the middle and final stages ($r=-0.50$, $p=0.048$, $r=-0.52$, $p=0.040$, respectively). In the middle and final stages, skating velocity exhibited a significant positive relationship with knee angular velocity at the end of both strokes (left stroke: middle: $r=0.55$, $p=0.027$, final: $r=0.61$, $p=0.013$, right stroke: middle: $r=0.63$, $p=0.009$, final: $r=0.51$, $p=0.042$).

There was a significant main effect for race stage with the shank outward tilting time for both strokes was significantly greater in the initial and middle stages than in the final stage (left stroke: $p=0.013$, right stroke: $p=0.000$, Table 3). For the left stroke in the initial stage and right stroke in all race stages, the official time exhibited a significant negative relationship with shank outward tilting time (left stroke: initial: $r=-0.53$, $p=0.033$, right stroke: initial: $r=-0.57$, $p=0.020$, middle: $r=-0.62$, $p=0.010$, Final: $r=-0.57$, $p=0.022$). For the right stroke in the middle and final stages, skating velocity exhibited a significant positive relationship with shank outward tilting time ($r=0.58$, $p=0.019$, $r=0.56$, $p=0.025$, respectively).

The main effect of the race stages on the blade anteroposterior distance at the beginning of both left and right strokes was not significant (Table 3). There was a significant

main effect for race stage with the blade anteroposterior distance at the end of both strokes significantly greater during the final stage than during the initial and middle stages (left stroke: $p=0.028$, right stroke: $p=0.034$). There was a significant main effect for race stage at both blade-off with the heel elevation angle significantly greater during the final stage than during the initial stage (left stroke: $p=0.000$, right stroke: $p=0.001$). The heel elevation angle at the right blade-off exhibited a significant positive relationship with the official time in the final stage ($r=0.55$, $p=0.027$).

4. Discussion

In the present study, we investigated kinematic changes in the straight skating motion of world-class speed skaters during a ladies' 3,000-m race. As the race progressed, the skating velocity decreased and the CM height and the thigh angle increased. In addition, as the race progressed, the blade became more backward in relation to the CM at blade-off, and the heel elevated greatly at blade-off. Skaters with better official times performed a straight skating motion characterized by longer outward tilting of the shank during strokes in the initial stage of the race. In the final stage, skaters with larger skating velocity had larger hip and knee angular velocity at the end of the stroke.

4.1. Changes in skating motion during the race

The skating velocity decreased significantly as the race progressed (Table 1). In addition, there were strong negative correlations between the skating velocity and the official

time, especially in the middle and final stages of the race, and there was a significant negative correlation between the maintenance rate of the lap time and the official time. A previous study reported that, in the men's 5,000-m, there was no significant correlation between the maintenance rate of the lap time and the official time (Yuda et al., 2002). In the ladies' 3,000-m race, the importance of suppressing the decreases in skating velocity during the latter half of the race was demonstrated. In addition, the stroke time and gliding time of both left and right strokes decreased significantly as the race progressed (Table 1).

Notable changes in the skating motion as the race progressed included an increase in the CM height (Figure 2) and an increase in the thigh angle (Figure 3-a) in the latter half of the stroke for both left and right strokes. Since the timing at which the CM height increased as the race progressed was similar to that at which the thigh angle increased as the race progressed, these two parameters may be closely related to each other. Reducing air resistance is important for attaining a high velocity during speed skating (van Ingen Schenau, 1982). A previous study reported that a higher skating posture with a larger knee joint angle increases air resistance (11.5 N) when compared with a normal skating posture (Yuda et al., 2009a). Therefore, one factor contributing to decreases in skating velocity as the race progresses (Table 1) may be an increase in air resistance due to greater CM height. In addition, in a skating posture with a larger knee joint angle, the knee extension torque will be smaller, making it difficult to exert a large amount of power (Yuda et al., 2005). Therefore, the decrease in push-off power due to the higher knee joint angle as the race progresses may also contribute to progressive decreases in skating velocity during the race. Furthermore,

maintaining a low skating posture with a small knee joint angle has been reported to reduce oxygen saturation in the vastus lateralis and increase the concentration of lactate in the blood (Foster et al., 1999), which may make it more difficult to maintain a horizontal thigh position as the race progresses.

As the race progressed, the blade position at the beginning of the stroke did not change, but the blade became more backward in relation to the CM at the end of the stroke and the heel elevated greatly at blade-off for both left and right strokes (Table 3). Since the stroke times became shorter as the race progressed (Table 1), the blade would move further behind relative to the CM during strokes within a shorter time. In the final stage, such a movement of the blade further behind the CM will cause an increase in the range of motion to pull the lower limb forward after blade-off and result in extra energy expenditure. Furthermore, Yuki et al. (2000) indicated that the force applied to the blade is quite small in the heel-elevated phase owing to the characteristics of the klapskate. Thus, a large degree of heel elevation at blade-off does not contribute to increasing or maintaining skating velocity. For these reasons, these blade motions in the final stage may also contribute to decreases in skating velocity as the race progresses.

4.2. Relationship between skating motion in the initial stage and official time

The ladies' 3,000-m was characterized by a marked decrease in skating velocity as the race progressed. Therefore, in the initial stages of the race, the skater must be able to attain a certain skating velocity with maximal efficiency to maintain skating velocity in the

middle and final stages of the race (Kimura et al., 2020). In the initial stage, skaters with excellent official times exhibited longer shank outward tilting times for both left and right strokes (Table 3). The shank outward tilting time is similar to the time spent tilting the blade outward (Yuki et al., 1996). Skaters with excellent official times were likely to have spent more time with their shank and blade tilted outward in the initial stage. However, in the initial stage, there was no significant correlation between the shank outward tilting time and skating velocity for either left or right strokes (Table 3). Therefore, it is unlikely that a longer shank outward tilting time in the initial stage itself contributed to skating speed during this stage of the race. This suggests that straight skating with a long shank outward tilting time in the initial stage is an efficient motion that helps the skater maintain skating velocity in the middle and final stages. However, it is difficult to clarify this mechanism based on kinematic analysis alone. The outward tilting of the shank at the beginning of the stroke reflects the lateral shift of the CM due to push-off immediately preceding the stroke and may be related to a horizontal blade reaction force (Yuki et al., 1996). Future studies should aim to address this issue by measuring the blade reaction force during a time trial.

4.3. Skating motion to maintain skating velocity in the final stage

Skaters with higher skating velocity had higher hip and knee angular velocity at the end of both left and right strokes, even in the final stage of the race (Table 2). It is assumed that higher skating velocity enables skaters to attenuate decreases in skating velocity as the race progresses by performing push-off with emphasis on leg extension in the final stage of

the race. Regarding curve skating motion, it has been reported that the decrease in knee extension power during the push-off phase influences the decrease in skating velocity as the race progresses (Yuda et al., 2005). This suggests that a push-off motion that emphasizes hip and knee extension is also important for maintaining skating velocity during the straight in the final stage of the race. However, it should be prioritized to perform efficient skating motions in the initial stage (see Section 4.2), given that individual differences in the final stage appears to be influenced by the degree of fatigue that occurs in the initial and middle stages.

5. Conclusion

In the present study, we aimed to identify kinematic changes in the straight skating motion of world-class speed skaters during the ladies' 3,000-m race. Our findings indicate that, as the race progressed, the skating velocity decreased and the CM height increased as the thigh rose in the latter half of the stroke. The skaters with better official times performed a straight skating motion characterized by longer outward tilting of the shank during strokes in the initial stage of the race. The skaters maintain larger skating velocity performed push-off with emphasis on hip and knee extension, even in the final stage of the race. These results indicate that in the ladies' 3,000-m race, although the skating velocity decreased as the CM height increased as the race progressed, a straight skating motion characterized by longer outward tilting of the shank in the initial stage helps to maintain the skating velocity until the middle and final stages and contributes to good official times.

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Figure 1 Definitions of digitized points and kinematic parameters. a) twenty-one body endpoints and four blade edges for digitizing, b) thigh and shank angle, c) shank tilt angle, d) hip, knee, and ankle angle, e) blade anteroposterior distance and heel elevation angle. The cross-shaped circle indicates the position of the whole-body center of mass.

Figure 2 Average patterns of CM height during the left and right strokes in the initial, middle, and final stages. CM: whole-body center of mass.

Figure 3 Average patterns of the thigh, shank and shank tilt angles during the left and right strokes in the initial, middle, and final stages.

Table 1 Mean values of the maintenance rate of the lap time and the stroke parameters in the initial, middle, and final stages of the race (Initial, Middle, and Final, respectively) and correlations of these parameters with the official time/skating velocity.
r (time) indicates the correlation with the official time, while r (velocity) indicates the correlation with skating velocity.

		Mean	S.D.						
Maintenance rate of the lap time (%)		96.71	2.31						
	r (time)	-0.50	*						
		Initial		Middle		Final		Main effect	Significant difference
		Mean	S.D.	Mean	S.D.	Mean	S.D.	(Race phases)	(Race phases)
Left stroke	Skating velocity (m/s)	12.49	0.18	12.31	0.21	12.09	0.29	F=24.89 ***	Initial>>Middle>>>Final
		r (time)	-0.63 **	-0.81 ***		-0.82 ***			
		r (velocity)	-	-		-			
	Stroke time (s)	1.05	0.08	1.00	0.05	0.91	0.09	F=26.82 ***	Initial>Middle>>>Final
		r (time)	-0.48	-0.48		-0.21			
		r (velocity)	0.03	0.63 **		0.24			
	Gliding time (s)	0.82	0.08	0.78	0.06	0.69	0.08	F=25.77 ***	Initial, Middle>>>Final
		r (time)	-0.36	-0.40		-0.12			
		r (velocity)	0.13	0.50 *		0.27			
	Push-off time (s)	0.23	0.05	0.22	0.04	0.22	0.05	F=0.81 n.s.	n.s.
		r (time)	-0.16	0.02		-0.20			
		r (velocity)	-0.17	0.00		0.02			
Right stroke	Skating velocity (m/s)	12.43	0.19	12.27	0.21	12.06	0.29	F=17.85 ***	Initial>Middle>>>Final
		r (time)	-0.51 *	-0.83 ***		-0.80 ***			
		r (velocity)	-	-		-			
	Stroke time (s)	1.06	0.07	1.02	0.07	0.92	0.08	F=47.37 ***	Initial>>Middle>>>Final
		r (time)	-0.27	-0.43		-0.35			
		r (velocity)	-0.27	0.39		0.32			
	Gliding time (s)	0.84	0.08	0.81	0.08	0.72	0.08	F=29.38 ***	Initial, Middle>>>Final
		r (time)	-0.15	-0.40		-0.25			
		r (velocity)	-0.34	0.38		0.31			
	Push-off time (s)	0.23	0.04	0.21	0.03	0.20	0.03	F=10.18 **	Initial>Middle Initial>>Final
		r (time)	-0.20	-0.01		-0.29			
		r (velocity)	0.18	-0.03		0.05			

***, >>> : p<0.001, **, >> : p<0.01, *, > : p<0.05, n.s. : no significant

Table 2 Mean values of the joint angular velocity at the end of the stroke in the initial, middle, and final stages; and correlations of these parameters with the official time/skating velocity.

r (time) indicates the correlation with the official time, while r (velocity) indicates the correlation with skating velocity.

		Initial		Middle		Final		Main effect (Race stages)	Significant difference (Race stages)
		Mean	S.D.	Mean	S.D.	Mean	S.D.		
Left stroke	Hip angular velocity (deg/s)	144.95	29.92	154.95	37.11	144.50	38.53	F=0.84 n.s.	n.s.
		r (time)	-0.28	-0.28		-0.47			
		r (velocity)	0.19	0.10		0.61	*		
	Knee angular velocity (deg/s)	115.46	63.83	85.44	61.73	50.61	83.17	F=10.35 ***	Initial>>Final Middle>Final
		r (time)	-0.45	-0.50	*	-0.52	*		
		r (velocity)	0.33	0.55	*	0.61	*		
	Ankle angular velocity (deg/s)	166.29	62.44	161.26	65.95	176.11	66.78	F=0.58 n.s.	n.s.
		r (time)	-0.21	-0.10		-0.12			
		r (velocity)	0.47	0.03		-0.05			
Right stroke	Hip angular velocity (deg/s)	119.03	42.40	124.17	38.06	127.33	50.37	F=0.36 n.s.	n.s.
		r (time)	-0.43	-0.23		-0.42			
		r (velocity)	0.00	0.19		0.56	*		
	Knee angular velocity (deg/s)	111.82	76.35	77.23	88.07	48.26	109.45	F=8.18 **	Initial>Final
		r (time)	-0.43	-0.40		-0.27			
		r (velocity)	-0.21	0.63	**	0.51	*		
	Ankle angular velocity (deg/s)	188.55	44.33	190.10	51.25	189.81	52.09	F=0.01 n.s.	n.s.
		r (time)	0.16	-0.06		0.33			
		r (velocity)	0.02	0.10		-0.04			

*** : p<0.001, **, >> : p<0.01, *, > : p<0.05, n.s. : no significant

Table 3 Mean values of the shank outward tilting time and the blade anteroposterior distance at the beginning and end of stroke; the heel elevation angle in the initial, middle, and final stages; and correlations of these parameters with the official time/skating velocity. r (time) indicates the correlation with the official time, while r (velocity) indicates the correlation with skating velocity.

		Initial		Middle		Final		Main effect	Significant difference	
		Mean	S.D.	Mean	S.D.	Mean	S.D.	(Race stages)	(Race stages)	
Left stroke	Shank outward tilting time (s)	Mean	0.28	0.08	0.25	0.08	0.21	0.09	F=17.97 ***	Initial>>Middle>Final Initial>>>Final
		r (time)	-0.53	*	-0.38		-0.37			
		r (velocity)	0.19		0.40		0.39			
	Blade anteroposterior distance at the beginning of stroke (m)		-0.08	0.02	-0.08	0.02	-0.08	0.02	F=1.12 n.s.	n.s.
		r (time)	-0.09		-0.03		0.13			
		r (velocity)	-0.15		0.12		0.30			
	Blade anteroposterior distance at the end of stroke (m)		0.41	0.05	0.43	0.07	0.46	0.08	F=9.52 ***	Initial<<Final Middle<Final
		r (time)	0.07		0.00		-0.03			
		r (velocity)	-0.16		-0.13		0.03			
	Heel elevation angle (deg)		16.55	6.29	21.04	5.83	22.09	6.85	F=20.88 ***	Initial<<<Middle, Final
		r (time)	0.28		0.24		0.33			
		r (velocity)	0.02		-0.32		-0.41			
Right stroke	Shank outward tilting time (s)	Mean	0.37	0.08	0.34	0.09	0.29	0.08	F=25.39 ***	Initial, Middle>>>Final
		r (time)	-0.57	*	-0.62	*	-0.57	*		
		r (velocity)	-0.08		0.58	*	0.56	*		
	Blade anteroposterior distance at the beginning of stroke (m)		-0.08	0.03	-0.09	0.03	-0.09	0.03	F=3.06 n.s.	n.s.
		r (time)	-0.13		0.12		0.01			
		r (velocity)	-0.08		0.06		0.01			
	Blade anteroposterior distance at the end of stroke (m)		0.40	0.05	0.41	0.05	0.45	0.05	F=13.35 ***	Initial<<<Final Middle<Final
		r (time)	0.09		0.09		-0.19			
		r (velocity)	-0.01		-0.24		0.15			
	Heel elevation angle (deg)		19.50	6.95	22.37	6.94	24.72	6.81	F=9.73 ***	Initial<<Final
		r (time)	0.45		0.33		0.55	*		
		r (velocity)	0.01		-0.45		-0.48			

***, >>> : p<0.001, >> : p<0.01, *, > : p<0.05

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Main Works

Kimura, Y., Yokozawa, T., and Yuda, J. (2020). Characteristics of female world-class skaters associated with changes in skating speed and stroke parameters in the straight section for 3,000 m speed skating race. *Journal of High Performance Sport*, 6: 74-87. (in Japanese).

Membership in Learned Societies

Japan Society of Physical Education, Health and Sport Sciences

Japanese Society of Biomechanics

Japanese Society of Physical Fitness and Sports Medicine

Japanese Society of Physical Therapy