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Diagonal technique of cross country skiing on 50km classical race in FIS Nordic World Ski Championships 2007

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Key-Words: kinematics, skiing speed, gliding length, and kicking

Abstract

This study investigated kinematic changes in the skiing motion of the diagonal stride technique during a world-class 50km classical cross-country skiing competition.

Data were collected from a men's 50 km classical mass start race during the FIS Nordic World Ski Championships 2007 on a 12.5-km circuit course. Skiers were videotaped by cameras (60 Hz) set perpendicular to the uphill section at the 16.8-km and 46.8-km points of the course. Six skiers who were within 20 seconds from the leader at 20-km point and more than 5 minutes behind the leader at the 35-km point were selected as subjects, containing Japanese. The skiing motion of six the

subjects at the 16.8-km and 46.8-km points were compared.

In an analysis with paired t-tests, the skiing speed ($t = 5.56$, $p < 0.05$) and the ski gliding length ($t = 4.11$, $p < 0.05$) at the 16.8-km point were significantly greater than those at the 46.8-km point. The long ski gliding length may result from the high ski gliding speed, which was affected by the high recovering speed in the final part of the ski recovery phase with the high kicking speed of the centre of gravity.

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I. INTRODUCTION

Performance in cross-country skiing is constrained by numerous biomechanical factors such as gravity, aerodynamic drag, aerodynamic lift, hydrodynamic drag and friction (Frederick, 1992). Complicated relationships among these constraints in actual cross-country skiing races make it difficult to investigate the mechanics of such events in the field.

Although analysing skiing mechanics during an actual competition is difficult, Norman et al. (1985, 1989), Norman and Komi (1987) and Yoshimoto et al. (1998) analysed the classical skiing techniques during the World Championships and Olympic Games. Furthermore studies of other official classical races with a lower performance level, were conducted by Marino et al. (1980), Norman et al. (1985), Bilodeau et al. (1996) and Hoga and Sambongi (2010). In addition, Dal Monte et al. (1980), Dufek and Bates (1987), Komi and Norman (1987), Bilodeau et al. (1991, 1992) and Boulay et al. (1995) analysed the classical technique in experiments conducted on snow. All these studies except Yoshimoto et al. (1998) analysed the diagonal stride technique, the most common skiing technique used in the uphill section of classical technique (Nilsson et al, 2004).

Bilodeau et al. (1996) measured the change in speed, cycle rate and cycle length for all competitors in an official 50 km race in the uphill and flat sections of four laps. The authors divided competitors into four groups according to the final result of the competition. The time difference among the groups increased in the uphill section but not in the flat section. The speed among competitors did not vary in the flat section, but the speed in the uphill section decreased in successive laps.

As the authors of the studies mentioned above, fatigue was one factor causing a decrease in speed among competitors in successive laps, and the skiing motion in the uphill section may have changed from the initial part of the competition to its final part. Lindinger et al. (2009) conducted a laboratory experiment on roller skiing and reported that the stride length, leg swing and gliding length are related to the time until exhaustion in the uphill diagonal stride technique. Changes in skiing motion during competition have not hitherto been investigated in either skating or classical technique. However, findings related to the change of motion during an official race will provide useful knowledge that may enable competitors to increase their performance.

As Lindinger et al. (2009) reported, skiers showing a high performance in competitions may maintain their stride and gliding lengths by means of their specific techniques. Bilodeau et al. (1996), referring to Norman et al. (1985), reported that a larger stride in the diagonal stride technique resulted from a higher leg swing and greater use of gravitational force as a supplement to muscle force in the leg swing.

However, these authors have reached these conclusions without actual analysis of the leg swing motion and its relationship to the stride length. Thus, an investigation dealing changes in the leg swing motion during an official race will provide useful information to skiers, enabling them to improve their performance.

This study investigated kinematic changes in the diagonal stride technique used by world class skiers who declined speed according to distance completed during an official classical 50km cross-country ski event, in order to clarify why the reduction of skiing speed occurs during races.

II. METHODS

1. Data collection

Data were collected from a men's 50 km classical mass start race during the FIS Nordic World Ski Championships 2007 on a 12.5-km circuit course. The air temperature was 5°C, and the snow temperature was 0.5°C. Skiers passing through the uphill sections of the course (4.1°) were videotaped at 60 Hz with videotape recording (VTR) cameras (TRV-50, Sony INC., Japan) positioned at the 16.8-km and 46.8-km points. Each camera was placed 15.7 m away from the left of the course to reconstruct the two-dimensional coordinates of the skiers' motion. Calibration was performed by measuring the distance between the supporting poles for the advertising boards (**Figure 1**: 4.04 m) and vertical poles set outside the course to establish the absolute horizontal and vertical coordinates. To compensate for the vertical coordinate ratio to the horizontal coordinate, one-metre height poles were placed vertically and videotaped in the same positions after the race. The distance between the advertising boards and the nearest track lane, that among the four track lanes and that between the camera and the nearest track lane were measured to compensate for the distances from the calibration markers to the track where the skiers were racing. After the last skier completed the competition's final event, the course was opened to the public and the distance from the tracks and boards were measured. The track in which each skier ran was identified by the bib number on the images of a video camera placed diagonally to the analysed area.

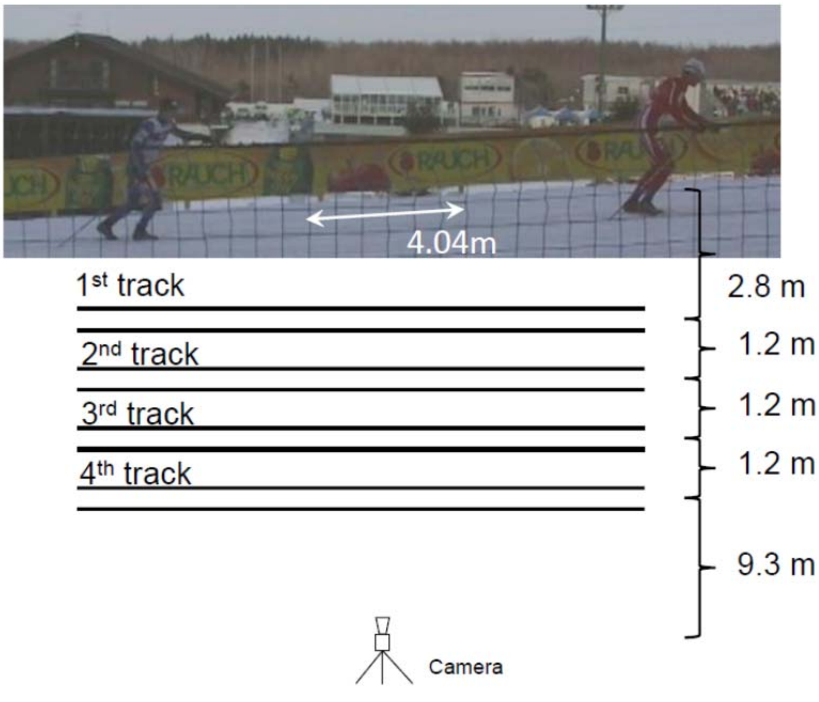
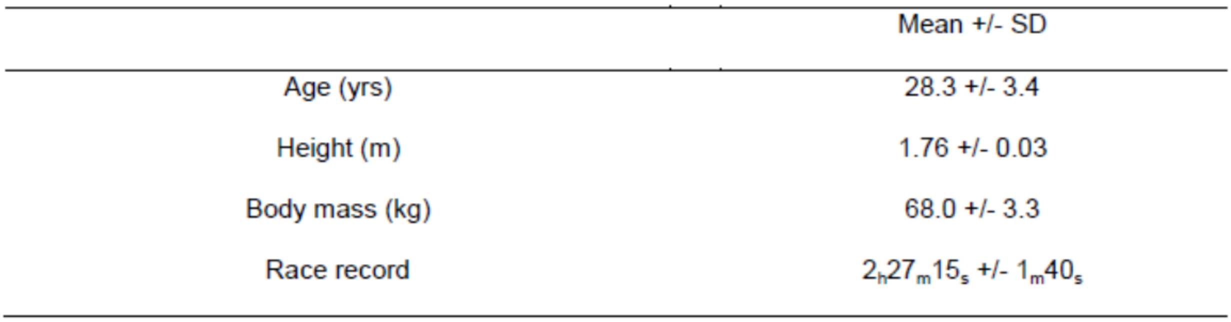


Figure 1 Camera position

All participants passed through the uphill section using the diagonal stride technique. Six skiers who were within 20 seconds from the leader at 20-km point and more than 5 minutes behind the leader at the 35-km point were selected as subjects, containing Japanese. Characteristics of subjects, as provided on the FIS web-site (The International Ski Federation, 2007, May 1), are listed in **Table 1**.

Table 1 Characteristics of the subjects (*N* = 6)



	Mean +/- SD
Age (yrs)	28.3 +/- 3.4
Height (m)	1.76 +/- 0.03
Body mass (kg)	68.0 +/- 3.3
Race record	$2_h27_m15_s$ +/- 1_m40_s

2. Data processing

The segment endpoints of the subjects and endpoints of the poles and skies of each subject were digitized at 60 Hz throughout one skiing cycle from VTR images according to an 18-segment body model including poles and skies by using digitizing software (Frame-DIAS II, DKH INC., Japan). Before digitizing, AVI files of 720 X 480 resolutions were captured from VTR images to this software. To digitize the endpoints of the body segments, planes of joint centres of the human body as defined by Dempster (1955) were referenced (Plagenhöf et al., 1983). Coordinates of the digitized points were converted to real two-dimensional coordinates and smoothed using a Butterworth low-pass digital filter. Optimal cut-off frequencies were determined by the residual error method proposed by Wells and Winter (1980). The optimal cut-off frequencies for the leading and the trailing group ranged 1.8-5.4 Hz for the horizontal coordinates and 1.8-5.4 Hz for the vertical coordinates.

The distance from the advertising board to the track lanes was compensated for by multiplying the converted coordinates with the ratio of the distance between the camera and the track lane to that between the camera and the advertising board.

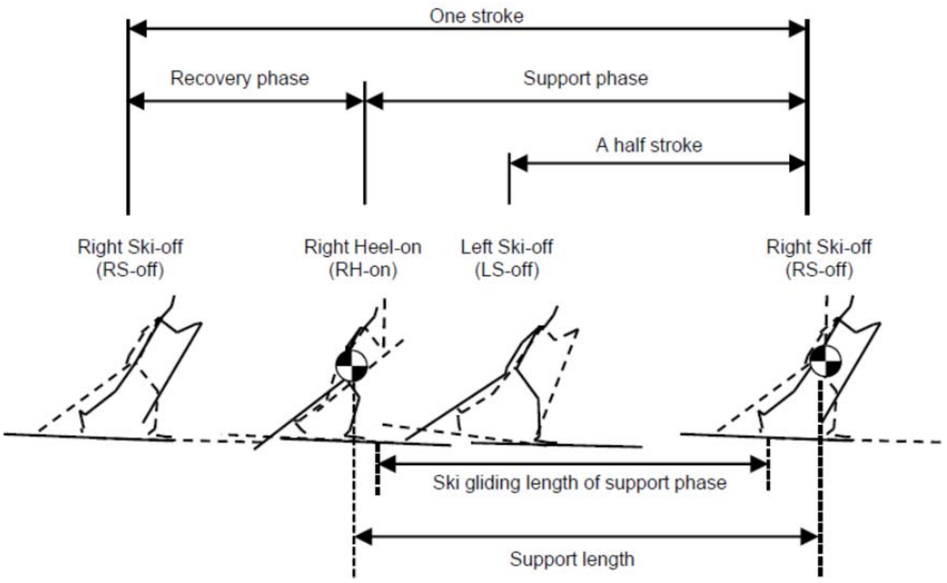
Because the most of subjects on this study ran at the 2nd track, the length of the track on the captured image was about 15m with the compensation of the camera distance. The horizontal distance among pixels should be about 0.02m, which might be enough to process the analysis on this study.

A two-dimensional, 18-segment model was used to calculate the linear and angular kinematics of the joints, the centres of mass and the body segments.

Locations of the centres of mass and body masses of the subjects' body segments were estimated from the body segment parameters (BSP) of Ae et al. (1992).

Although BSP of Ae et al. (1992) were derived from Japanese athletes, same parameters of these parameters (Ae, 1996) were applied to world elite athletes of various disciplines (Enomoto et al., 1999, distance running; Yuda et al., 2007, Speed skating; Marquez et al., 2009, volley ball; Yokozawa et al., 2009, triathlon; Shibayama et al., 2011, sprint hurdle), which contains Japanese and non-Japanese athletes. The mass of the poles and skies of each competitors were calculated as 0.15 kg for the pole and 1.3kg for the ski. This calculation was based on catalogue data for one representative competitor, assuming that all subjects used poles and skies with the same mass (Salomon Sports, 2007, May 1).

Cycle length was determined as the horizontal displacement of the whole body centre of gravity (CG), including the poles and skies progressed during one cycle from the instant of one right ski-off (RS-off) to that of the next RS-off in the slope-fixed coordinate system (**Figure 2**). RS-off was identified as the frame in which the ski tail was lifted from the ski gliding lane. A cycle length was divided into a recovery phase and a support phase. The recovery phase was defined as the right ski recovery phase from the instant of the RS-off to the instant of the right heel on (RH-on). The support phase was defined as the right ski support phase from RH-on to RS-off. RH-on was identified as the frame in which the right heel of the boot touched the gliding ski. The ski gliding length was defined as the horizontal displacement of the right toe during the support phase.



Kicking length = Support length – Ski gliding length

Figure 2 Definition of the support phase in one stroke, ski gliding length and kicking length. Solid line: Right extremities, Dotted line: Left extremities.

Ski gliding speed was calculated as a horizontal velocity of the right toe in the slope-fixed coordinate system during the support phase. Kicking-speed was calculated as a relative horizontal velocity of the CG to the right toe during the support phase. Recovering speed was calculated as a horizontal velocity of the right toe during the recovery phase. Relative ski recovering speed was calculated as a horizontal velocity to the left (gliding) toe during the (right ski) recovery phase.

Relative CG speed to the gliding toe was calculated as a horizontal velocity to the left (gliding) toe during the (right ski) recovery phase.

Segment angle was determined as the anti-clockwise angle between the vector from the proximal to the distal end of the segment and that from the upside to the downside (**Figure 3**). The vector for the shank angle was from the knee joint to the ankle joint, and that for the thigh angle was from the hip joint to the knee joint.

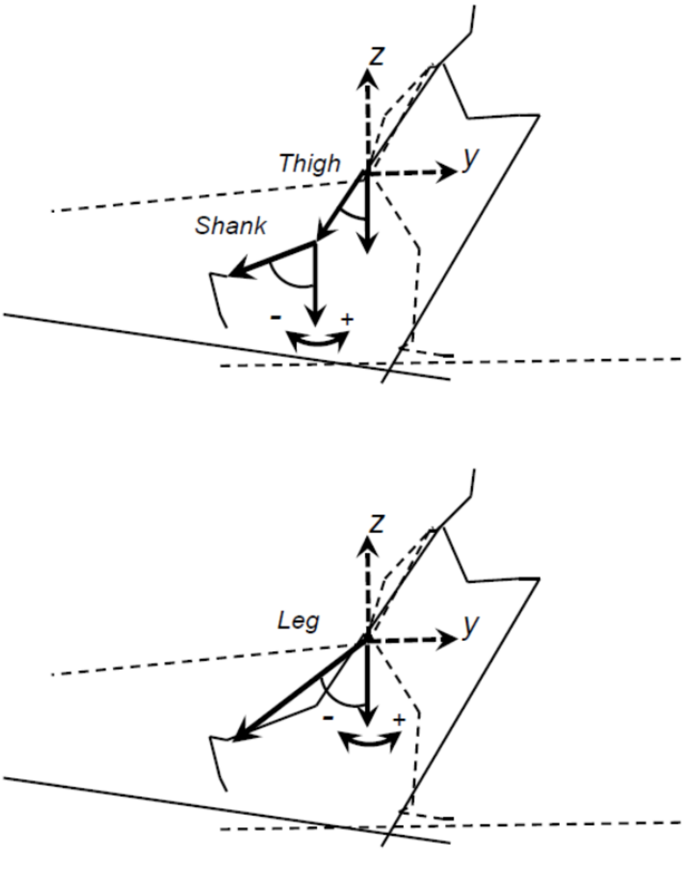


Figure 3 Definitions of ‘Thigh ‘, ‘Shank’ and ‘Leg ’ angles

The leg angle was also determined in the same manner as the segment angles. The vector for the leg angle was from the hip joint to the ankle joint. Angular velocities for these three angles were calculated by the time differentials.

The ’Kicking Angle’ was determined as the clockwise angle from the horizontal vector directing backwards to that from the supporting toe to the CG (**Figure 4**). The distance between the supporting toe to the CG was determined as the ’Kicking length’. Further, the ’ Kicking Angular Velocity’ was calculated by the time differential of the ’Kicking Angle’, and the ’Kicking Velocity’ was calculated by the time differential of the ’Kicking Length’.

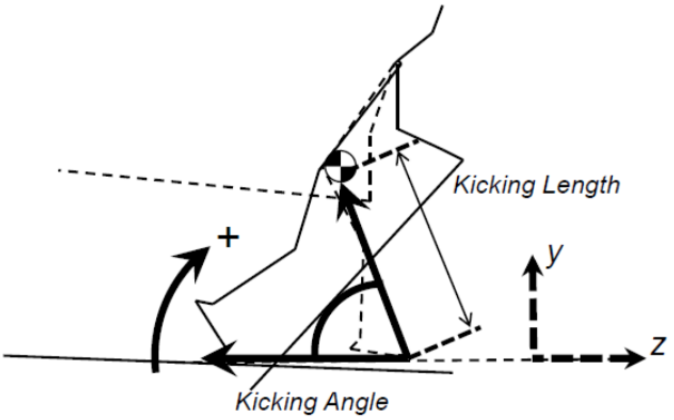


Figure 4 Definitions of ‘Kicking Angle’ and ‘Kicking Length’

Time series data were normalized by the time of the recovery and support phases, which was defined from RH-on to RS-off for the support phase to compare magnitudes and patterns between the two points. A paired (distance) t-test was performed to compare data patterns. The significance level for all statistical tests was set at 5%.

III. Results

1. Cycle analysis

The skiing speed for the subjects at the 16.8-km point was significantly greater than that at the 46.8-km point. The cycle length, support length and gliding length for the subjects at the 16.8-km point were significantly larger than those at the 46.8-km point.

2. Speed of ski and centre of gravity

Although not shown in the figures, the skiing speeds of the subjects at the 16.8-km point were maintained at a constant rate during the entire support phase, and their speed at the 16.8-km point was significantly greater than that at the 46.8-km point for all phases.

The ski gliding speed for the subjects at the 16.8-km point (7.10 ± 0.34 m/s) was significantly greater ($t = 2.73$, $p < 0.05$) than that at the 46.8-km point (6.29 ± 0.29 m/s) at RH-on (**Figure 5a**). The ski gliding speed at both points decreased gradually from RH-on to 30% of the support phase and there was a significant difference between the two points during this phase until 10% of the support phase.

The ski gliding speed at the 16.8-km point remained about 4 m/s from 30% to

50% of the support phase and decreased to 0 m/s until 70% of the support phase. The ski gliding speed at the 46.8-km point remained about 3.6 m/s from 30% to 40% of the support phase and decreased to 0 m/s until 70% of the support phase. Thus, a significant difference was found between the two points, from 30% to 40% and from 50% to 70%, of the support phase. Although the ski gliding speed at both points increased from 90% of the support phase to RS-off, no significant difference was observed between the two points.

The negative kicking speed at both the 16.8-km and 46.8-km points increased gradually from RH-on and changed to positive from 30% of the support phase (**Figure 5b**). After being maintained at 0 from 20% to 50% of the support phase, the kicking speed increased to almost 4 m/s from 50% to 80% of the support phase and decreased to RS-off. The kicking speed at the 16.8-km point was significantly greater than that at the 46.8-km point from 80% to 90%. The ski gliding speed at the 16.8-km point remained about 4 m/s from 30% to 50% of the support phase and decreased to 0 m/s until 70% of the support phase.

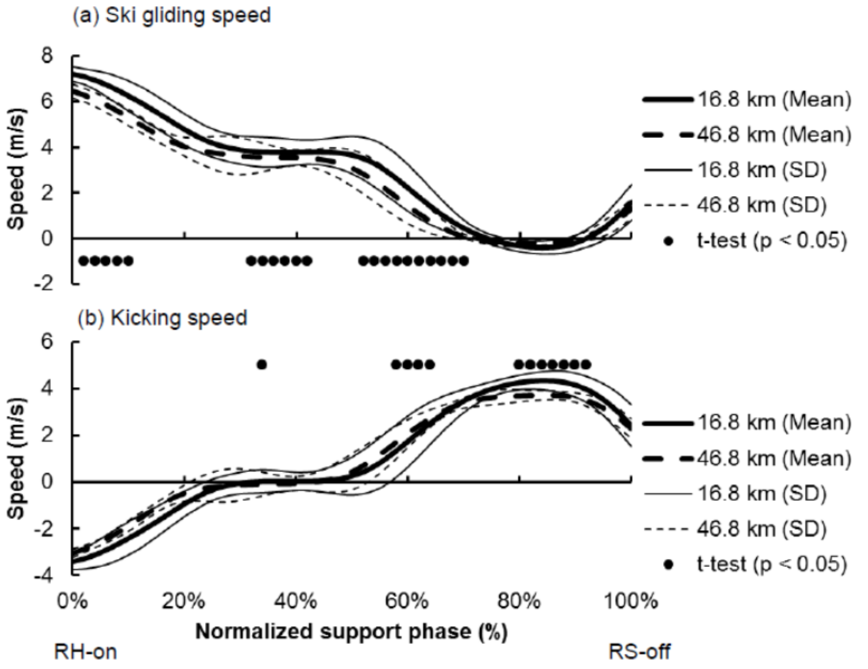


Figure 5 Patterns of (a) ski gliding speed and (b) kicking speed during support phase during the right ski recovering phase at the 16.8-km and 46.8-km points. Significant differences between the two points are indicated ($p < 0.05$).

The ski recovering speed for the subjects increased steeply from RS-off to 80% of the recovery phase and decreased moderately from 80% to RH-on at both points (**Figure 6a**). The ski recovery speed at the 16.8 km point from 3% to 70% of the recovery phase and from 80% to RH-on was significantly greater than that at the 46.8-km point.

The relative right ski recovering speed to the gliding left toe was negative at RS-off (**Figure 6b**). However, it changed to positive at 20% of the recovery phase and increased to RH-on. The relative right ski recovering speed for the trailing group at 16.8-km point was significantly greater than that at 46.8-km point from 90% of the recovery phase to RH-on.

The relative CG speed to the gliding left toe was almost zero from RS-off to 40% of the recovery phase and increased to RH-on (**Figure 6c**). The relative CG speed for the subjects at 16.8km point was significantly greater than that at the 46.8- km point from 90% of the recovery phase to RH-on.

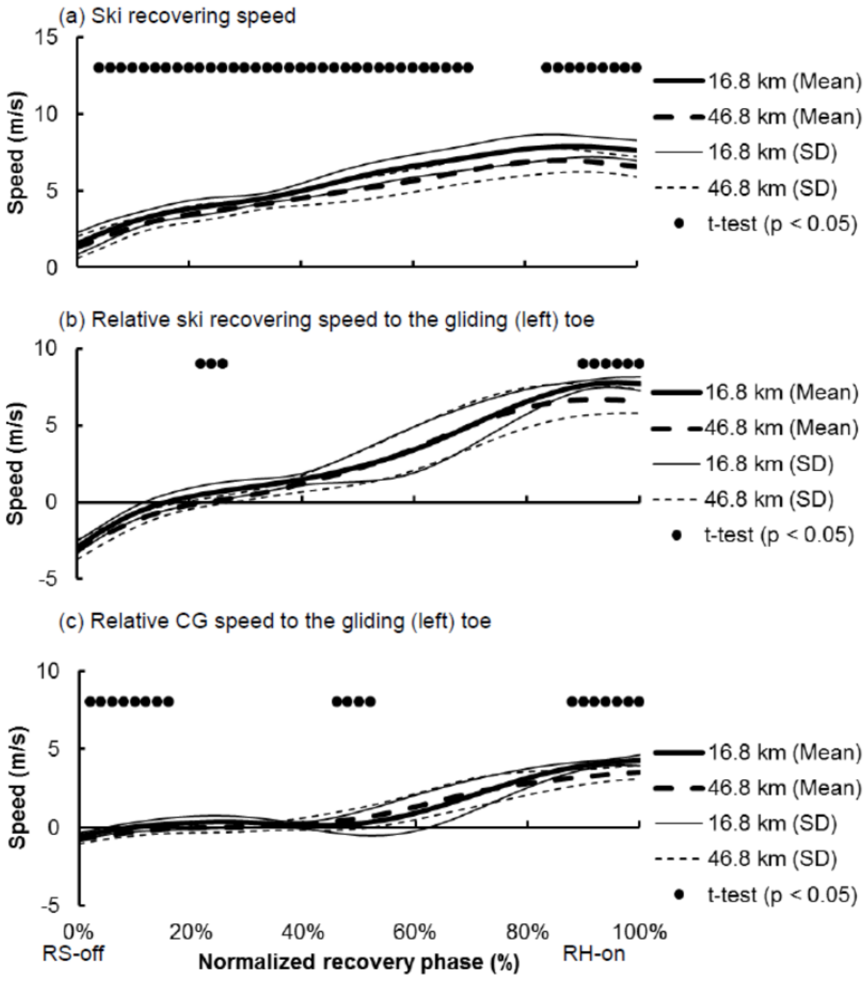


Figure 6 Patterns of (a) ski recovering speed, (b) relative ski recovering speed to the gliding (left) toe, and (c) relative CG speed to the gliding (left) toe, during the recovery phase at the 16.8-km and 46.8-km points. Significant differences between the two points are indicated (p < 0.05).

3. Recovering leg motion

The shank angular velocity of the right leg for the subjects at both 16.8- km and 46.8-km points decreased from RS-off to 20% of the recovery phase, increased to 50 % of the recovery phase and maintained the same magnitude to RH-on (**Figure 7**a). There was no significant difference between the angles at the two points.

Further, the thigh angular velocity for

the subjects increased from RS-off to 80% of the recovery phase at the 16.8-km point and to 65% at the 46.8-km point (Figure 7b).

From 75% to 85% of the recovery phase, the angular velocity of the recovery thigh at the 16.8-km point was greater than that at the 46.8-km points.

The right leg angular velocity was negative at RS-off and changed to positive at 30% of the recovery phase (Figure 7c). This velocity increased to 80% of the recovery phase. There was no significant difference between the 16.8-km and 46.8-km points.

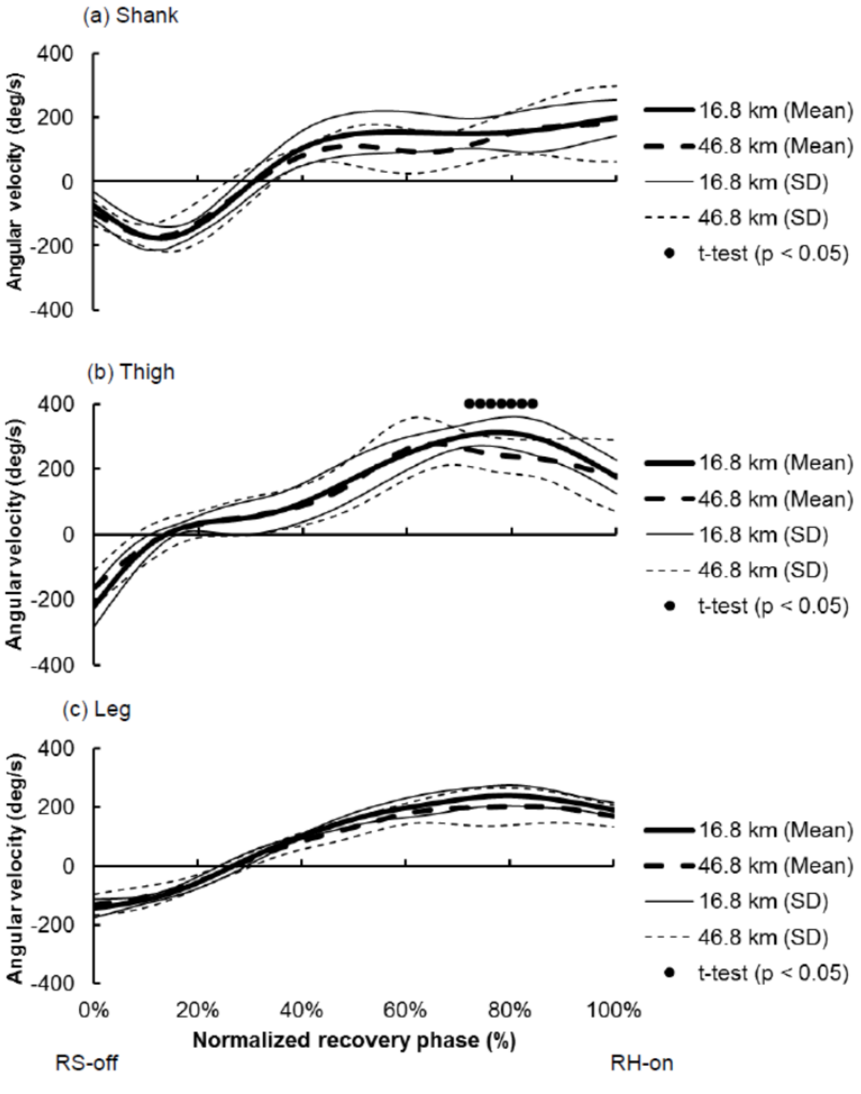


Figure 7 Patterns of the angular velocity of (a) shank, (b) thigh and (c) leg during the recovery phase at the 16.8-km and 46.8-km points. Significant differences between two conditions are indicated ($p < 0.05$).

4. Kicking motion

The Kicking angular velocity was almost zero from RS-off to 50% of the recovery phase and increased to RH-on (**Figure 8a**). This velocity was greater at the 16.8-km point than at the 46.8-km point from 90% of the recovery phase to RH-on.

Further, the positive Kicking velocity

decreased to negative at 20% of the recovery phase and changed to positive at 80% of the recovery phase (**Figure 8b**). Although, the negative kicking velocity at the 16.8-km point was significantly smaller than that at the 46.8-km point, there was no significant difference between the 16.8-km and 46.8-km points from 90% of the recovery phase to RH-on.

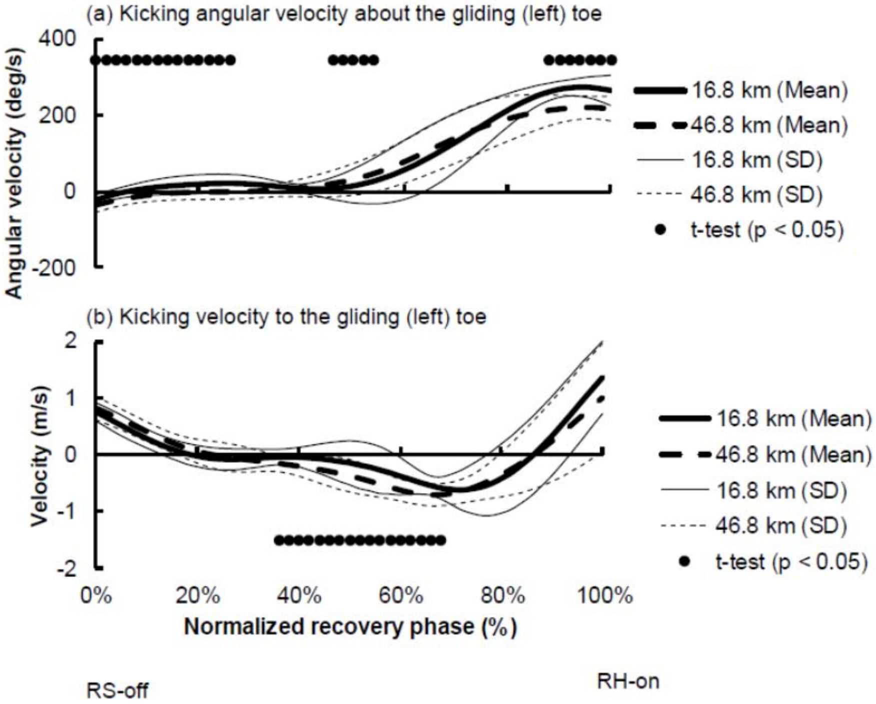


Figure 8 Patterns of the (a) Kicking angular velocity and (b) Kicking velocity to the gliding left toe during the right leg recovery phase at the 16.8-km and 46.8-km points. Significant differences between the two conditions are indicated ($p < 0.05$).

IV. Discussion and Implications

The main findings of this study on the kinematic changes in the diagonal stride technique throughout the race distance for participant in a world class 50 km race were the following: 1) The ski gliding length in the final part of the race for a subjects who decreased skiing speed was shorter than that in the initial part. 2) The reduction in the ski gliding length came from a reduction in the ski gliding speed during the initial phase of the support phase. The reduction in ski recovering speed during the overall recovery resulted in a reduction in the ski gliding speed during the initial phase of the support phase. 3) The decreased kicking leg motion of the support leg resulted in a decreased forward recovery speed of the recovering ski. A detailed discussion is presented below.

1. Cycle analysis

Abbiss and Laursen (2008) reviewed pacing strategies for endurance exercises and reported that an average pacing strategy tends to be adapted by competitions ranging from 2 minutes to 4 hours. All the competitors in this study finished the 50km cross-country event in over 2 hours and within 3 hours. It is important to analyse the change in skiing speed and skiing motion by comparing the skiing motion at initial and final part of the race because the change in skiing motion during the second part of the race may influence the difference in skiing speed during that phase.

Significant differences between the two points of the race were shown in the cycle length and gliding length in the support phase. This implies that skiers reduced the cycle length by short gliding as reported Bilodeau et al. (1996) in their study of a 50km classical race. Hoga and Sambongi (2010) investigated the difference in the skiing motion of the diagonal stride technique on different grades of uphill slope. In moderate conditions, where the skiing speed was greater than that in steep conditions, they found that the cycle length and gliding length were larger than those in steep conditions. These results are in accordance with the difference in the cycle analysis in this study.

2. Speed of ski during the support and recovery phase

Hoga and Sambongi (2010) reported that the difference in the ski gliding speed of the diagonal stride technique comes from the difference in the ski gliding speed after heel contact with the gliding ski, from 20% to 50% of the support phase.

As reported in previous studies (Saibene et al., 1989; Frederick, 1992; Street and Gregory, 1994; Vähäsöyrinki et al. 2008), friction between ski and snow is an important factor influencing ski gliding.

However, in this study, the ski gliding speed in the middle of the support phase (from 30% to 70%) where there was a significant difference between the 16.8- km and 46.8-km points was very small. It may be that the significant difference between the two points in the initial part of the support phase influenced the ski gliding length between the two points. A significantly greater ski recovering speed at the 16.8-km point may have affected the greater gliding speed during the initial phase of the support phase.

The ski recovering speed consists of the ski gliding speed of the opposite side ski, the relative CG speed to the gliding ski of the opposite side and the relative recovering ski speed to the CG. The relative recovering ski speed to the CG was affected by the recovering leg motion. However, the angular velocities of the recovering leg at both 16.8-km and 46.8-km points were almost the same. These results indicate that the recovering leg motion had no significant influence on the difference in the recovering ski speed between the two points. The greater angular velocity of the kicking leg in the final part of the recovery phase may affect the greater relative CG speed to the gliding toe. This greater relative CG velocity may come from the greater angular velocity of the support leg.

The results of this study suggest that the kicking leg motion may be important in obtaining a high skiing speed in the diagonal technique in the uphill section. The high ski gliding speed was obtained by the high ski recovering speed, which comes from the high kicking speed.

The fact that the subjects of the present study showed a decrease in both skiing speed and gliding length with the reduction in the kicking leg angular velocity, explains that maintaining kicking leg motion throughout the race distance is important for avoiding a reduction in the skiing speed.

V. Conclusion

This study investigated the kinematic changes at different distances in the diagonal stride technique of cross-country skiing by world-class skiers during an official 50 km race.

The ski gliding length after heel contact on the ski in the initial phase of the competition for subjects who reduced the skiing speed was greater than that in the final phase of the competition.

The large ski gliding length was obtained by a high ski gliding speed in the initial part of the support phase. The high ski gliding speed, in turn, was affected by the large kicking angular velocity via the relative CG speed and recovering ski to the gliding ski.

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