Effects of the net efficiency of roller skiing on cross-country ski racing performance using the diagonal stride

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Abstract
A roller skiing test in the field that uses mechanical efficiency to assess cross-country skiing performance has not been established. Thus, in this study, the net efficiency, a definition of mechanical efficiency, during roller skiing was determined using the diagonal stride technique, and the net efficiency at racing speed was estimated to determine the relationship between net efficiency and racing performance in cross-country and roller skiing and to evaluate whether net efficiency could be a determinant of racing performance. Eight male collegiate cross-country skiers were assigned to high- and low-level groups (n = 4 each) based on their cross-county skiing performances. Two-dimensional kinematics and oxygen uptake were determined for the skiers while they were diagonally roller skiing at various speeds on a level track. The net efficiency was calculated from the total mechanical work rate, which is comprised of the rates of internal and external work, and thenet energy expenditure. The rates of total mechanical work and net energy expenditure at racing speed were estimated by substituting the mean racing speed into individual regression equations obtained for the experiment, and the net efficiency at racing speed was calculated from the estimates. Racing performance during roller and cross-country skiing was found to be directly correlated (r = −0.915, p = 0.001). Net efficiency was higher throughout most of the speed range (p = 0.029) and at racing speed (p = 0.029) in the high-level group compared with the low-level group. These findings revealed that net efficiency is one factor that determines racing performance during cross-country and roller skiing and that higher net efficiency enhances racing performance. The diagonal roller skiing test on flat terrain, which was proposed in this study, could be a new field test for assessing the performance of cross-country skiers.

KeyWords: mechanical efficiency, internal work, external work, energy expenditure, field test

Introduction
Cross-country skiing generally requires endurance for racing performance. Investigations to date have thus focused on factors that are physiologically relevant to endurance as determinants of performance in cross-country skiing. Endurance performance capability has historically been determined for cross-country skiers using maximal oxygen uptake, which is accepted as an important determinant of aerobic endurance capacity. Rusko, Havu, and Karvinen (1978) and Ingjer (1991) indicated that cross-country skiing performance significantly depends on the maximal oxygen uptake during treadmill running, which has been extensively applied to assess the endurance of cross-country skiers. Other physiological parameters, such as lactate threshold (Baumgartl, 1990; Rundell, 1995; Rundell & Bacharach, 1995), anaerobic threshold (Larsson, Olofsson, Jakobsson, Burlin, & Henriksson-Larsen, 2002) and onset of blood lactate accumulation (Baumgartl, 1990; Larsson et al., 2002), have also been tested while running on a treadmill.

However, the type of motion pattern and musculature involved considerably differ between cross-country skiing and running. Several investigators have thus developed ski-specific tests involving roller skiing to evaluate cross-country skiers. Roller skiing was originally created as a training method for cross-country skiing during the off-season, and the movement patterns and endurance required in roller and cross-country skiing are now considered quite similar. Rundell (1995) first investigated the relationship between racing performance and physiological parameters during roller skiing on a treadmill and confirmed the validity of the treadmill roller skiing test as a method of assessing cross-country skiing performance. Subsequently, roller skiing tests using the double poling technique (Rundell & Bacharach, 1995; Staib, Im, Caldwell, & Rundell, 2000; Stögg, Lindinger, & Müller, 2006; Fabre, Ballestrieri, Leonardi, & Schema, 2010) and the diagonal stride technique (Staib et al., 2000; Fabre et al., 2010) on a treadmill were developed.

These tests require a wide, specific, motor-driven treadmill; however, most cross-country skiers have little opportunity to undergo such specific testing. Thus, roller skiing tests in the field appear more useful for evaluating the performance of cross-country skiers. Broussouloux, Lac, Rouillon, and Robert (1996) first conducted a roller skiing test using the diagonal stride in the field and found that peak physiological parameters are lower than those during a treadmill running test. Mahood, Kenefick, Kertzer, and Quinn (2001) and Stögg et al. (2006) determined time trial performance during maximal voluntary roller skiing using the double pole technique in the field and found that the 50-m (Stögg et al., 2006) and 1000-m (Mahood et al., 2001; Stögg et
al., 2006) times closely correlated with cross-country skiing performance. They both concluded that a roller skiing test in the field, especially when using time trials, is a more effective method of assessing cross-country skiing performance.

A previous study (Nakai, Ito, & Toyooka, 2009) examined oxygen uptake kinetics with increasing speed while diagonal roller skiing on a level track and then estimated the speed at maximal oxygen uptake, as described by Morgan, Martin, and Kohrt (1986). Consequently, the authors found that the 5-km uphill race times closely correlated with the speed at maximal oxygen uptake, which indicates the ratio of maximal aerobic capacity that is converted into roller skiing speed. This suggests that roller skiing performance depends on the ratio of chemical energy converted into mechanical energy, namely mechanical efficiency. Coyle (1999) also noted that mechanical efficiency is an important determiner of endurance performance; however, few studies have examined mechanical efficiency during roller skiing (Hoffman, Clifford, Watts, O'Hagan, & Mittelstadt, 1995; Nakai & Ito, 2011). Measuring oxygen uptake, which is essential for computing mechanical efficiency, is not feasible during an actual competition. Additionally, defining an uphill section that maintains the same slope angle to measure the steady-state oxygen uptake (0.4–1.2 km in the present study) is rather difficult in the field. Several investigators (e.g., Hoffman, Clifford, Foley, & Brice, 1990; Broussouloux et al., 1996; Fabre, Passeraguer, Bouvard, & Perrey, 2008) have conducted field tests on flat terrain to determine the physiological parameters during roller skiing using the diagonal stride technique, which has been applied in most sections of uphill roller skiing races. Accordingly, in this study, the kinematic and physiological parameters were measured while diagonal roller skiing on a level track and then, the net efficiency was estimated, which is a definition of the mechanical efficiency, at racing speed from the generated data.

Thus, the aims of this study were (a) to determine the net efficiency during diagonal roller skiing at various speeds on a level track, (b) to estimate the net efficiency at racing speed, and (c) to evaluate whether net efficiency in the field test using diagonal roller skiing is a determinant of racing performance in cross-country and roller skiing.

Material & methods

Participants

Eight male collegiate cross-country skiers with similar maximal aerobic capacities but different levels of cross-country and roller ski racing performance provided written, informed consent to participate in this study. The athletes were assigned to a high-level group or a low-level group (n = 4 each) based on their cross-country ski racing performance as described below. The physical characteristics of the athletes in each group are provided in Table 1. The Research Ethics Committee at Osaka University of Health and Sport Sciences, Osaka, Japan approved the study design and experimental protocols, which conformed to the 1975 Declaration of Helsinki (revised in 1983).

According to the methods of Rundell and Bacharach (1995), Staib et al. (2000), and Fabre et al. (2010), cross-country ski racing performance of the participants in this study is expressed using Ski Association of Japan (SAJ) points. These are the total number of points accumulated by the end of the season determined by SAJ based on the ranking system of the International Ski Federation. A lower score in this ranking system indicates better cross-country skiing performance. Racing performance during roller skiing was determined from the mean race speed during a 5-km uphill roller skiing race in which all of the participants had participated one month before this investigation, based on the approach of Alsobrook and Heil (2009).

Test protocols

All experiments in this study proceeded on a 400-m all-weather level track with two straight sections. The participants performed an incremental test to determine the maximal oxygen uptake while diagonal roller skiing and a sub maximal roller skiing test after the methods of Nakai and Ito (2011) on separate days. The sub maximal test comprised of 4 min of roller skiing using the diagonal stride technique at paced speeds of 1.67, 2.50, 3.33, 4.16, and

Table 1. Physiological characteristics and racing performances of the study participants

<table>
<thead>
<tr>
<th></th>
<th>High-level group</th>
<th>Low-level group</th>
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<tbody>
<tr>
<td>Number of skiers (n)</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Age (year)</td>
<td>19.0 (1.2)</td>
<td>19.8 (1.5)</td>
</tr>
<tr>
<td>Body height (m)</td>
<td>1.78 (0.05)</td>
<td>1.74 (0.08)</td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>66.3 (4.1)</td>
<td>63.9 (2.2)</td>
</tr>
<tr>
<td>Maximal oxygen uptake (mL·kg⁻¹·min⁻¹)</td>
<td>59.8 (2.6)</td>
<td>60.6 (10.9)</td>
</tr>
<tr>
<td>Mean racing speed (m·s⁻¹)</td>
<td>4.02 (0.07)</td>
<td>3.44 (0.43)β</td>
</tr>
<tr>
<td>SAJ points</td>
<td>92.89 (22.70)</td>
<td>203.40 (89.49)β</td>
</tr>
</tbody>
</table>

Note. Data are presented as M (SD), except for the number of the skiers in each group. SAJ points are indicators of cross-country skiing performance as established by the Skiing Association of Japan; lower scores indicate better performance. Mean racing speed expressed the roller skiing performance and was calculated from race times for 5-km uphill roller ski races one month before this study. βp<0.05.
5.00 m·s⁻¹ with 6-min rest intervals. All participants used the same pair of roller skis (V2-920; V2 Jenex Inc., Milford, NH, USA) equipped with load-adjusting devices and their own ski boots and poles throughout the study. The diagonal stride is generally applied in moderate to steep uphill sections for ski competitions. The movement characteristics of the diagonal stride executed with low-resistance roller skis on flat terrain were expected to differ somewhat from those on uphill terrain. Frictional loads were therefore applied to the roller skis using adjustment devices to bring the cycle characteristics on flat terrain closer to those on uphill terrain according to the method of the previous study (Nakai & Ito, 2011).

Measurements

Movement patterns in the sagittal plane of each skier over one complete cycle of the diagonal stride over a 10-m straight section of the track were rerecorded at 60 Hz using a digital video camera (DSR-PD150; Sony Corporation, Tokyo, Japan). One complete cycle was defined as beginning from the moment of ground contact to the start of the subsequent ground contact by the right roller ski (Fig.1). Mean oxygen uptake over each breath was measured during the last minute of a 4-min standing rest and during the last minute of each 4-min trial using a portable metabolic testing system (VO2000; Medical Graphics Corporation, St. Paul, MN, USA). The participant standing on both roller skis was towed by a motorcycle at the above five different speeds on the track, and the towing force was measured using a 200-N load cell (LUR-A-200NSA1; Kyowa Electronic Instruments, Tokyo, Japan) using the methods of Saibene, Cortili, Roi, and Colombini (1989) and Hoffman et al. (1995).

Data collection and analysis

The skier was represented as an 18-segment link segment model comprising three segments for each leg and for each arm, the head, and the trunk plus two roller skis and two ski poles (Fig.1). Video images over the cycle were digitized at 60 Hz using a motion analysis system (Frame-DIAS 3.22; DKH Inc., Tokyo, Japan). Coordinates of body landmarks corresponding to the above model were then computed using two-dimensional (2D) panning direct linear transformation. Each calculated coordinate was digitally filtered using a fourth-order Butterworth low-pass filter, and the best cut-off frequency was selected via residual analysis (Winter, 2005). The displacement and velocity of the center of mass of each segment and the angular velocity of all segments were calculated from the filtered coordinates. The roller skiing speed of the skier was calculated from the mean velocity of the center of the total body mass of the skier over the cycle. The mass and moment of inertia of each body segment were calculated using body segment inertia coefficients (Ae, 1996). The mass, moment of inertia, and the center of mass of one roller ski and of one ski pole were determined via actual measurements.

The mechanical work was determined from the internal work, which is defined as work done on body segments, and the external work, which is defined as work done on external loads based on the definition by Winter (1979). The internal work was calculated from the mechanical energy, assuming energy transfer within and between segments using the approach of Pierrynowski, Winter, and Norman (1980). Internal work in this study was calculated by the following procedures. Mechanical energy components that contain potential energy and translational and rotational kinetic energy were computed from the kinematic data obtained from the previous video image analysis. All of the mechanical energy components were summed in each segment at a specific time point. The total mechanical energy was then calculated by adding these energy components over all body segments, including the roller skis and ski poles, and plotted as a function of time. Internal work applied over the cycle was calculated as the summation of energy increase over the total mechanical energy curve. External work over the cycle was computed as the product of the cycle length of the skier and the towing force (i.e., the force required to overcome external loads). The net energy expenditure was calculated by subtracting the energy expenditure of standing rest from that of each trial. The measured oxygen uptake was converted into energy expenditure using the following biochemical formula, 1 L of O₂ = 20.93kJ; then, the net energy expenditure over the cycle was calculated.

Internal and external work and net energy expenditure were divided by cycle time and total mass, including the body mass of the skier and the mass of the roller skis, ski poles, ski boots, and instruments for measuring oxygen uptake to determine the rates of internal and external work and the rates of net energy expenditure, respectively. Mechanical efficiency during diagonal roller skiing was evaluated from the net efficiency, which is defined as the

![Fig.1. Motion pattern during one complete cycle of diagonal stride, expressed by 18-segment link segment model. Solid and broken lines, left and right body segments, respectively.](image-url)
ratio of work performed to the extra energy expended during movement. The total mechanical work rate was calculated by adding the internal and external work rates. Net efficiency over the cycle was then calculated by dividing the total mechanical work rate by the net energy expenditure rate.

Mognoni, Rossi, Gastaldelli, Canclini, and Cotelli (2001) determined the physiological parameters from experiments and estimated those during competition from the experimental data. Although some conditions, such as course incline, frictional resistance, and roller skis in the race, differed from those in the experiment in this study, here, the total mechanical work rate and net energy expenditure rate at racing speed were estimated based on the approach from Mognoni et al. The total mechanical work rate and net energy expenditure rate at racing speed were estimated by substituting the mean race speed of each skier into individual regression equations obtained from the experiment. The net efficiency at racing speed was then computed from the estimated total mechanical work rate and net energy expenditure rate via the same calculation described above.

**Statistical analyses**

The data from the high- and low-level groups are expressed as means and standard deviations. Each parameter was statistically analyzed using the Mann-Whitney U test between the groups. The relationship between SAJ points and mean racing speed was determined via linear regression analysis. All data were statistically analyzed using IBM SPSS Statistics 26 software (IBM Corporation, Armonk, NY, USA). The alpha level was set to 0.05 for all analyses.

**Results**

Maximal oxygen uptake, mean racing speed, and SAJ points for each group are listed in Table 1. Maximal oxygen uptake did not differ between the groups. Mean racing speed was faster for the high-level group than for the low-level group ($Z = −2.323$, $p = 0.029$, ES = −0.82), and SAJ scores were lower in the high-level group than in the low-level group ($Z = 2.021$, $p = 0.043$, ES = 0.72). Additionally, the mean racing speed decreased linearly with increasing SAJ points ($r = −0.915$, $p = 0.001$).

The total mechanical work rate, net energy expenditure rate, and net efficiency of each group plotted as a function of roller skiing speed are shown in Fig. 2. Figure 2a shows that the total mechanical work rate in both groups linearly increased with increasing speed, and the total mechanical work rates at each speed did not statistically differ between them. The data in Fig. 2b show that net energy expenditure rates increased exponentially with an increase in speed for both groups. The net energy expenditure rates at 2.50, 3.33, and 4.16 m·s$^{-1}$ were significantly lower in the high-level group than in the low-level group ($Z = 2.309$, $p = 0.029$, ES = 0.82, all comparisons). The parabolic-like curve in Fig. 2c similarly shows the variation in the net efficiency for each group. With increasing speed, net efficiency increased to a maximum of 42.0% and 32.6% in the high-level and low-level groups, respectively (Table 2) and then slowly decreased. The net efficiency was significantly higher in the high-level group than in the low-level group at 2.50 m·s$^{-1}$ or more ($Z = −2.309$, $p = 0.029$, ES = 0.82, all comparisons).

**Table 2. Estimated parameters at racing speed and maximum net efficiency for each group**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>High-level group</th>
<th>Low-level group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total mechanical work rate at racing speed (W)</td>
<td>4.89 (0.20)</td>
<td>4.03 (0.80)</td>
</tr>
<tr>
<td>Net energy expenditure rate at racing speed (W)</td>
<td>12.01 (0.86)</td>
<td>12.53 (2.54)</td>
</tr>
<tr>
<td>Net efficiency at racing speed (%)</td>
<td>40.9 (3.8)</td>
<td>32.2 (2.0)*</td>
</tr>
<tr>
<td>Maximum net efficiency (%)</td>
<td>42.0 (2.6)</td>
<td>32.6 (2.1)*</td>
</tr>
</tbody>
</table>

*Note. Data are presented as $M$ (SD). *$p<0.01.$
The data presented in Table 2 show the total mechanical work rates and net energy expenditure rates at racing speeds that were calculated from the equations described in the Methods section. The total mechanical work rate and the net energy expenditure rate at racing speed did not significantly differ between groups, whereas the net efficiency at racing speed and maximum net efficiency were significantly higher in the high-level group than in the low-level group ($Z = -2.309, p = 0.029, ES = 0.82, all comparisons$).

**Discussion**

This study showed that roller skiing performance and cross-country ski racing performance are directly related, and net efficiency was found to be higher in the high-level skiers than in the low-level skiers throughout the speed range, except for at low speed, including at racing speed. These findings demonstrate that net efficiency is one factor that determines racing performance during cross-country and roller skiing, that a higher net efficiency enhances the racing performance, and that a field test using diagonal roller skiing on flat terrain can be used to evaluate the performance of cross-country skiers. Although maximal oxygen uptake was quite similar, mean racing speed and SAJ points significantly differed between the two groups (Table 1). Mean racing speed was closely and negatively correlated with the SAJ scores. This indicated that the skiers in this study had the same level of maximal aerobic capacity but different levels of cross-country skiing and roller skiing performances, and that racing performance during roller skiing is directly associated with that during cross-country skiing. Thus, maximal oxygen uptake during diagonal roller skiing has little relevance to the performance during either roller or cross-country skiing, which agrees with the findings of Staib et al. (2000) and Fabre et al. (2010). Moreover, better performance during roller skiing improves the performance in cross-country skiing, and the results reconfirmed the value of roller skiing as an effective training method for cross-country skiing. Total mechanical work rates for both groups increased at a constant rate together with increasing speed and did not differ between groups at any of the tested speeds (Fig. 2a). Thus, an equivalent work rate (i.e., power) is required to maintain the same speed among skiers who have different performance characteristics. Net energy expenditure rates for both groups similarly varied exponentially as a function of speed, but the rates were significantly lower in the high-level group than in the low-level group for the middle speed ranges (Fig. 2b). These results closely agree with those of Mahood et al. (2001), which were obtained while roller skiing via the double pole technique. These results demonstrate that the low-level skiers expended more energy at the middle speed and expended even more energy to maintain higher speeds than the high-level skiers. Despite the difference in performance between the groups, the net efficiency of each similarly varied with increasing speed, but it was generally higher for high-level group than for low-level group (Fig. 2c). A higher net efficiency would confer an advantage upon high-level skiers, which would further enhance the endurance performance for the majority of speeds and accomplish better race outcomes. Thus, the net efficiency determined in the field test using diagonal roller skiing at a given speed can be used to evaluate performance during cross-country skiing as well as roller skiing. Individual parameters at racing speed were calculated from the mean racing speed of each skier and assessed in consideration of the skier’s racing performance. The ratio of net efficiency at racing speed to the maximum net efficiency was 98.1±3.1%, which suggests that all of the skiers in this study roller skied with a comparably high ratio of net efficiency compared to the maximum net efficiency during races. Net energy expenditure rates at racing speed were almost identical among the skiers. However, the net efficiency at racing speed was higher for the high-level skiers than for the low-level skiers (Table 2), which was consistent with the results that Norman and Komi (1987) obtained during a cross-country skiing race using the diagonal stride technique. Both the high-level and low-level skiers in the present study expended almost the same levels of energy to maintain their speeds during races; however, the high-level skiers maintained a higher speed (Table 1). Millet, Perrey, Candau, and Rouillon (2002) reported that the energy cost of roller ski skating is significantly related to the skiers’ performances and a significant part of the inter-individual differences in energy cost can be explained by the kinematic parameters of skiing locomotion. These observations indicate that high-level skiers could produce more chemical energy from oxygen delivered to the body, develop more musculature to transform chemical energy into mechanical energy (i.e., aerobic capability), advance their skiing skills to effectively transduce mechanical energy into skiing speed (i.e., technical capability), and perform cross-country and roller skiing with a higher net efficiency. Some of these issues, however, were not directly determined in this study, and investigations that are more detailed are thus required for confirmation.

**Conclusions**

This investigation determined the net efficiency among male collegiate cross-country skiers during diagonal roller skiing on a level track and then evaluated the relationship between net efficiency and racing performance in cross-country skiing and roller skiing. Racing performance was found to be directly associated between roller skiing and cross-country skiing, and the net efficiency was higher in high-level skiers than in low-level skiers through most of the entire speed range, including at racing speed. These findings revealed that net efficiency is a determinant of racing performance in cross-country and roller skiing, that a higher net efficiency improves racing performance, and that the diagonal roller skiing test on flat terrain can be used to assess the performance of cross-country skiers.
Conflicts of interest The author has no conflicts of interest directly relevant to the contents of this article.

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