Influence of Body Mass on Energy Cost of Roller Skiing

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A theoretical analysis was used to evaluate the effect of body mass on the mechanical power cost of cross-country skiing and roller skiing on flat terrain. The relationships between body mass and the power cost of overcoming friction were found to be different between cross-country skiing on snow and roller skiing. Nevertheless, it was predicted that the heavier skier should have a lower oxygen cost per unit of body mass for roller skiing, as is the case for snow skiing. To determine whether the theoretical analysis was supported by experimental data, oxygen consumption measurements were performed during roller skiing by six male cross-country ski racers who spanned a 17.3-kg range in body mass. The theoretical analysis was supported by the experimental findings of decreases in oxygen consumption for each kg increase in body mass of approximately 1.0% for the double pole technique, 1.8% for the kick double pole technique, and 0.6% for the V1 skate technique.

Body dimensions have an obvious impact on performance in many sports. As a result, an attempt is frequently made to equalize competitions by matching individuals based upon body mass (e.g., wrestling, rowing). However, the influence of body size on performance capability in cross-country skiing is not inherently obvious, nor has it received much scientific attention. Bergh (1987) recently presented a dimensional analysis of the effect of body mass on the power costs of cross-country skiing. He reasoned that heavier skiers have a larger ratio of capacity for power production to mechanical power cost for cross-country skiing under all terrain conditions except steep uphills. Thus it was suggested that the heavier skier has an advantage over the lighter skier when skiing across level, downhill, and mild uphill terrain.

Unfortunately, experimental measurements to independently evaluate the influence of body mass on metabolic cost of cross-country skiing are technically...
difficult because the power cost of overcoming friction between ski and snow is subject to considerable variation with changes in temperature, humidity, snow characteristics, ski characteristics, and ski base preparation. Because of these potentially confounding variables, it was reasoned that a better controlled study could be performed during roller skiing. The purpose of this study, then, was to use a theoretical model to predict the effect of body mass on the mechanical power cost of roller skiing on flat terrain, determine whether the predicted relationship between mechanical power cost and body mass is supported by experimental measurements of the metabolic cost of roller skiing, and use these results to expand the understanding of the effects of body mass on performance in cross-country skiing.

Methods

Theoretical Model

This theoretical model assumes that the major mechanical power costs associated with snow skiing and roller skiing on flat terrain are accounted for by changes in potential energy ($P_p$), translational kinetic energy ($P_{kt}$), rotational kinetic energy ($P_{kr}$), overcoming air resistance ($P_s$), and overcoming friction ($P_f$). These factors are described by the following equations:

\[
    P_p = m \cdot g \cdot h \cdot f \\
    P_{kt} = 1/2 \cdot m \cdot (v_1^2 - v_0^2) \cdot f \\
    P_{kr} = 1/2 \cdot m \cdot r^2 \cdot (\omega_1^2 - \omega_0^2) \cdot f \\
    P_s = K \cdot A \cdot \nu^3 \\
    P_f = m \cdot g \cdot \mu_k \cdot \nu
\]

where $m$ = mass, $g$ = acceleration of gravity, $h$ = vertical displacement of the center of mass, $f$ = cycle frequency, $v_1$ and $v_0$ = extreme velocities during the cycle, $\nu$ = mean velocity of the center of mass, $\omega_1$ and $\omega_0$ = extreme segmental angular velocities during the cycle, $r$ = length of segment, $A$ = frontal area, $K$ = a constant, and $\mu_k$ = dynamic friction coefficient.

This model neglects the power costs that might result from energy transfer between body segments and between different forms of energy. As pointed out by Bergh (1987), the interchanges of potential and kinetic energy and the energy transfer between body segments are probably not affected by body dimensions. Since this analysis is concerned with the relationships of the mechanical power costs with body mass, these factors can appropriately be neglected. It was also presumed that the effects of storage and recovery of elastic energy are not affected by body dimensions.

This theoretical analysis is also based on the assumptions that the subjects are equally skilled at cross-country skiing and are geometrically similar with the variables in the mechanical power cost equations being related to body mass in the following manner (Astrand & Rodahl, 1986; Günther, 1975; McMahon, 1975): height $\propto m^{1/3}$; length $\propto m^{1/3}$; velocity $\propto m^0$; area $\propto m^{2/3}$; frequency $\propto m^{-1/3}$.

Experimental Study

Subjects. Six male cross-country ski racers participated in the experimental study. They were selected from a pool of skiers participating in other studies and were included in this analysis because of their very similar cross-country ski
racing performances in the 2 years prior to the study. Each subject was provided
an explanation of the procedures and potential risks of participation, and signed
a consent form approved by the Human Research Review Committee.

All subjects had at least 5 years of cross-country skiing experience and had
been racing and using the ski skating techniques for at least 3 years. The subjects
were proficient in all cross-country skiing techniques and had a history of placing
well in classical and freestyle citizen races at the local and regional level. How-
ever, they did indicate that the majority of their recent training on roller skis had
been spent using freestyle techniques. For comparison of the subjects’ recent
racing performances, the American Birkebeiner was identified as the race that
was most consistently entered by all subjects. This is a freestyle ski race of
approximately 55 km that has several thousand participants each year and is part
of the Worldloppet circuit. Each subject had finished in the top 200 in the Ameri-
can Birkebeiner races during the two seasons that preceded this study, and there
was generally less than 5% variation among the finishing times of the six subjects.

Table 1

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age (yrs)</th>
<th>Mass (kg)</th>
<th>Height (cm)</th>
<th>Ponderal index</th>
<th>Body fat (%)</th>
<th>(\dot{V}O_2)max (ml/kg/min)</th>
<th>(\dot{V}O_2)max (ml/min/kg(^{0.75}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>32</td>
<td>69.0</td>
<td>180</td>
<td>22.8</td>
<td>10.5</td>
<td>58.08</td>
<td>238.3</td>
</tr>
<tr>
<td>B</td>
<td>18</td>
<td>69.6</td>
<td>178</td>
<td>23.1</td>
<td>4.6</td>
<td>59.24</td>
<td>243.6</td>
</tr>
<tr>
<td>J</td>
<td>34</td>
<td>71.5</td>
<td>180</td>
<td>23.1</td>
<td>7.8</td>
<td>62.68</td>
<td>260.1</td>
</tr>
<tr>
<td>A</td>
<td>40</td>
<td>76.8</td>
<td>185</td>
<td>23.0</td>
<td>10.8</td>
<td>58.02</td>
<td>246.6</td>
</tr>
<tr>
<td>K</td>
<td>39</td>
<td>78.4</td>
<td>183</td>
<td>23.4</td>
<td>11.4</td>
<td>62.69</td>
<td>268.4</td>
</tr>
<tr>
<td>M</td>
<td>36</td>
<td>86.3</td>
<td>183</td>
<td>24.1</td>
<td>15.4</td>
<td>52.70</td>
<td>232.9</td>
</tr>
<tr>
<td>M</td>
<td>33</td>
<td>75.3</td>
<td>182</td>
<td>23.2</td>
<td>10.1</td>
<td>58.90</td>
<td>248.3</td>
</tr>
<tr>
<td>SD</td>
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<td>6.6</td>
<td>3</td>
<td>0.5</td>
<td>3.6</td>
<td>3.71</td>
<td>13.5</td>
</tr>
</tbody>
</table>

Other characteristics of the subjects are shown in Table 1. The subjects
were between 18 and 40 years of age. Body mass spanned a 17.3 kg range from
69.0 to 86.3 kg. The model of geometric similarity assumes that body height is
proportional to body mass to the 1/3 power. Therefore, body geometry can be
characterized by a ratio of the cube root of body mass to body height. However,
a more conventional value used to describe body physique is the ponderal index
(PI) defined by the equation

\[ PI = 3 \sqrt{\frac{m}{h}} \times 1000 \]

where body mass (m) is in kg and body height (h) is in cm. The subjects in this
study showed a variation in ponderal index ranging from 22.8 to 24.1. Percent
body fat, as estimated by the sum of seven skinfolds (Pollock, Wilmore, & Fox, 1984), ranged from 4.6 to 15.4%.

Maximal Oxygen Uptake Determination. Maximal oxygen uptake (\(\dot{V}O_2\text{max}\)) was determined for each subject during uphill running on a motor driven treadmill (Quinton Q55). After an initial warmup and accommodation period of 5–10 minutes at about 9.0 km/h and no elevation, the treadmill speed was increased to 12.9 or 13.7 km/h and the grade was increased 1% every minute until the subject was exhausted. Maximal efforts were achieved at grades of 9–12%. Oxygen consumption was measured each minute by open circuit spirometry. Oxygen and carbon dioxide concentrations were measured by calibrated electronic oxygen (Applied Electrochemistry S-3A) and carbon dioxide (Sensor Medics LB-2) analyzers, and inspiratory volumes were measured with a calibrated dry gas meter (Parkinson Cowan). The mean (\(\pm SD\)) \(\dot{V}O_2\text{max}\) for the subjects was 58.90 ± 3.71 ml/kg/min (Table 1).

Theoretical and experimental evidence suggests that the expression of \(\dot{V}O_2\text{max}\) relative to body mass to the \(2/3\) power provides a better measure for comparison of fitness level for individuals of different body masses (Astrand & Rodahl, 1986; Bergh, 1987). For the group of subjects in this study, expression of \(\dot{V}O_2\text{max}\) in ml/min/kg\(^{2/3}\) (rather than in ml/kg/min) lowered the coefficient of variation within the group from 6.3 to 5.4.

Roller Skiing Tests. The roller skiing tests were performed on the outside lanes of a flat, oval running track composed of rubberized asphalt that allowed for excellent ski pole purchase. The center of the skiing area measured 432 m in length and the radii of the turns were 37 m. The same pair of ratcheted two-wheeled roller skis (Pro-Ski Roadline Dual Technique) were used for all roller skiing tests. The subjects also used similar ski poles (Exel Avanti) of their chosen lengths (\(M\pm SD = 170\pm 3\) cm). Each subject roller skied using the double pole, V1 skate, and kick double pole techniques. The double pole technique was performed twice by each subject. The order of performance for each study condition was randomized. Each technique was performed in continuous graded bouts with 4-min stages paced at mean speeds of 14.6, 16.4, and 18.0 km/h. Velocity was controlled with an ultrasonic Doppler speed measuring device (Nike Monitor) mounted on the pacing vehicle. Velocity was independently determined by timing each lap and the standard deviations for the three study speeds were not greater than 0.4 km/h. All subjects completed each condition, except for two subjects who were unable to complete the kick double pole technique at 18.0 km/h due to difficulty in performing the technique at this velocity on the turns.

Oxygen uptake (\(\dot{V}O_2\)) was determined during the final minute of each stage by collection of expired gases into 120-liter meteorological balloons through an expiratory tube that was directed into the pacing vehicle. Oxygen and carbon dioxide content in the collected gases were determined immediately with calibrated electronic oxygen (Beckman OM-11) and carbon dioxide (Beckman LB-2) analyzers, and volume was measured with a calibrated dry gas meter (Rayfield). Wind velocity was monitored during each bout with an anemometer (Dwyer Instruments). The average maximal wind velocity throughout all tests was less than 5 km/h. The air temperature during the tests ranged from 17 to 33 °C.

Measurement of Dynamic Friction Coefficient. Since the subsequent dimensional analysis develops expressions for each power cost as a function of body mass, it is important to define the relationship between body mass and the
dynamic friction coefficient for the roller skis ($\mu_k$). The $\mu_k$ is determined from the force required to pull a known mass positioned on the roller skis according to the equation

$$\mu_k = \frac{F}{mg}$$

where $F =$ drag force, $m =$ mass riding on the roller skis, and $g =$ acceleration of gravity. A technique for determining the $\mu_k$ of roller skates has been described by de Boer, Vos, Hutter, de Groot, and van Ingen Schenau (1987). With this technique, $F$ was measured while towing a weighted sledge (roller skates mounted under a board) or a subject wearing the skates. However, their data show a variability in $F$ of as much as 20%, probably due to difficulties in maintaining a constant velocity with the towing vehicle and inconsistencies in the ground surface. Saibene, Cortili, and Colombini (1989) have since reported similar difficulties in measuring the $\mu_k$ of cross-country skis on snow using a comparable technique.

In view of these apparent problems with this technique, we reasoned that measurements on a level motorized treadmill might provide more useful information regarding the relationship of the $\mu_k$ with mass. While this relationship may be dependent upon the rolling surface, the approach used in this study seemed justifiable since any variation in the $\mu_k$ for the roller skis as a result of mass was thought to be due to deformation of the wheels and/or skiing surface, and in this case the track surface appeared to be harder and less likely to be deformed than the roller ski wheels. Thus the assessment of the $\mu_k$ was made on a level motorized treadmill (Quinton Q55) by measuring the drag force of one of the investigators standing with his mass distributed evenly between both roller skis. The drag force was measured with a calibrated 23-kg load cell (Sensotec 311430) and instrument (Sensotec HH). The $\mu_k$ was determined across a mass range of 70 to 100 kg by adding mass to the investigator with a loaded backpack. All measurements were made with the treadmill at a constant velocity of 8.1 km/h after allowing adequate time for the roller ski bearings to warm up as assessed by a stable $F$ reading. The slower treadmill speed relative to the roller skiing velocities was used to avoid damage to the treadmill belt from friction. Limited preliminary testing up to 18 km/h showed no evidence of velocity dependency for $\mu_k$.

**Statistical Analysis.** The best power curve fits ($y = kx^n$) were determined for the plots of oxygen consumption and dynamic friction coefficient against body mass. The relationship describing the friction coefficient as a linear function of mass was determined with linear regression analysis. A p-value of 0.10 was chosen as the level of statistical significance for these relationships.

**Results**

**Dynamic Friction Coefficient of the Roller Skis**

The dynamic friction coefficient for the roller skis on the treadmill was defined by the linear regression equation

$$\mu_k = 0.0094 + 7.1 \times 10^{-5} \text{ m} \ (r=0.94, \ p<0.05)$$

where $m$ is the mass in kg. In other words, $\mu_k$ was not a constant and increased slightly with increasing body mass. Across the mass range of the subjects in this
study, the dynamic friction coefficient ranged from about 0.014 to 0.016. The equation defining \( \mu_k \) as a power function of mass was

\[
\mu_k = 0.0026 \cdot m^{0.40} \quad (r=0.94, \ p<0.05).^1
\]

**Theoretical Analysis**

The power cost equations and the assumptions in the model of geometric similarity allow for description of the relationships of the various mechanical power costs as functions of body mass. Bergh's (1987) theoretical analysis for cross-country skiing on flat snow has previously demonstrated these relationships: \( P_p \propto m^1; P_{kt} \propto m^{2/3}; P_{kr} \propto m^{2/3}; P_s \propto m^{2/3}; P_\mu \propto m^{1/3}. \)

Summation of these factors indicates that the mechanical power cost of cross-country skiing on flat terrain is proportional to body mass raised to an exponent of between 1/3 and 1. In other words, a given increase in body mass should theoretically result in a proportionally smaller increase in the mechanical power cost. Although there are biomechanical differences between roller skiing and snow skiing (Dillman & Dufek, 1983; Gervais & Wronko, 1988; Pinchak, Hancock, Hagen, & Hall, 1987; Yudin & Fedotov, 1975), the theoretical relationships of \( P_p, P_{kt}, P_{kr}, \) and \( P_s \) with body mass should not differ between these two activities. However, there does appear to be an important difference for \( P_\mu \).

The power cost for overcoming friction is defined by the following equation:

\[
P_\mu = m \cdot g \cdot \mu_k \cdot v.
\]

Bergh's (1987) analysis suggests that \( \mu_k \propto m^{-2/3} \) for snow skiing, and it has been experimentally determined that \( \mu_k \propto m^{-0.86} \) (Eriksson, 1949; Westergren, quoted in Bergh, 1987). Therefore, since \( g \) and \( v \) are independent of body mass, the theoretical analysis suggests that

\[
P_\mu \propto m^1 \cdot m^{-2/3} \text{ or } P_\mu \propto m^{1/3}
\]

and the experimental evidence suggests that

\[
P_\mu \propto m^1 \cdot m^{-0.86} \text{ or } P_\mu \propto m^{0.14}.
\]

In contrast, the friction coefficient for the roller skis in the present study was described by the relationship \( \mu_k \propto m^{0.40} \). Therefore,

\[
P_\mu \propto m^1 \cdot m^{0.40} \text{ or } P_\mu \propto m^{1.40}.
\]

Thus the power cost of overcoming friction with the roller skis used in this study was proportional to body mass raised to an exponent of 1.40 rather than 1/3 or 0.14, as previously demonstrated for snow skiing. With this modification, the theoretical analysis suggests that the mechanical power cost of roller skiing with the roller skis used in this study is proportional to body mass to a power between 2/3 and 1.40.

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1 To distinguish between theoretical and experimental results, the convention is used of expressing theoretically determined exponents as whole fractions and experimentally determined exponents as decimal fractions.
Use of an analysis similar to that applied by Frederick (1987) to carriage of the biathlon rifle during cross-country skiing suggests that the magnitude of the sum of $P_{kr}$, $P_{kr}$, and $P_a$ are considerably greater than the sum of $P_p$ and $P_n$ for movement of the body mass during cross-country skiing. Therefore it is reasonable to expect the overall exponent for body mass to be greater than 2/3 but less than 1. This means that a given increase in body mass should also result in a proportionally smaller increase in the mechanical power cost of roller skiing, as was predicted for cross-country skiing on snow.

**Oxygen Consumption During Roller Skiing**

The oxygen consumption for the three skiing techniques and three velocities are shown in Figures 1, 2, and 3. In each of these figures, $\dot{V}O_2$ has been plotted against body mass. $\dot{V}O_2$ has been expressed in ml/kg/min since this is the common unit of representation. The power functions have been determined for each technique and speed. Since the dimensional analysis above describes the absolute power cost rather than the power cost relative to body mass, it is of interest to also describe the oxygen cost in absolute terms. The following relationship is considered:

$$\dot{V}O_2 \propto m^n \Rightarrow \dot{V}O_2 \propto m^n \cdot m^1 = m^{n+1}.$$  

Therefore the addition of 1 to the exponent on body mass describing the power function of $\dot{V}O_2$ in ml/kg/min (relative $\dot{V}O_2$) with body mass will yield the appropriate exponent for the power function for the relationship of absolute $\dot{V}O_2$ with body mass.

![Figure 1 — Effect of body mass on oxygen consumption during roller skiing with the double pole technique at 14.6 (□), 16.4 (△), and 18.0 km/h (○). The power curves are defined by the following equations: 14.6 km/h, $y = 677.0 \times x^{-0.74}$ ($r = 0.87, p<0.05$); 16.4 km/h, $y = 1410 \times x^{-0.87}$ ($r = 0.87, p<0.05$); 18.0 km/h, $y = 1264 \times x^{-0.82}$ ($r = 0.76, p<0.05$).](image-url)
Figure 2 — Effect of body mass on oxygen consumption during roller skiing with the kick double pole technique at 14.6 (□), 16.4 (△), and 18.0 km/h (○). The power curves are defined by the following equations: 14.6 km/h, \( y = 5488 x^{-1.17} \) \( (r = 0.73, p < 0.1) \); 16.4 km/h, \( y = 12,490 x^{-1.33} \) \( (r = 0.74, p < 0.1) \); 18.0 km/h, \( y = 116,100 x^{-1.82} \) \( (r = 0.99, p < 0.05) \).

Figure 3 — Effect of body mass on oxygen consumption during roller skiing with the V1 skate technique at 14.6 (□), 16.4 (△), and 18.0 km/h (○). The power curves are defined by the following equations: 14.6 km/h, \( y = 256.6 x^{-0.48} \) \( (r = 0.37, \text{nonsignificant}) \); 16.4 km/h, \( y = 199.4 x^{-0.39} \) \( (r = 0.49, \text{nonsignificant}) \); 18.0 km/h, \( y = 264.3 x^{-0.42} \) \( (r = 0.37, \text{nonsignificant}) \).
Figures 1 through 3 reveal a tendency for relative \( \dot{V}O_2 \) to decrease with increasing body mass for each technique and speed. The magnitude of the decrease in relative \( \dot{V}O_2 \) for each kg increase in body mass averaged 1.0\% for the double pole technique, 1.8\% for the kick double pole technique, and 0.6\% for the V1 skate technique. For the double pole technique, significant correlations were found for the power curves for all three speeds (Figure 1). The exponents for these functions ranged from \(-0.74\) to \(-0.87\) and averaged \(-0.81\). Therefore, for the double pole technique the absolute \( \dot{V}O_2 \) was proportional to body mass raised to a power of about \(-0.81 \pm 1\) or 0.19.

The kick double pole technique showed weaker power curve fits (Figure 2). For this technique the exponent for relative \( \dot{V}O_2 \) ranged from \(-1.82\) to \(-1.17\). In other words, absolute \( \dot{V}O_2 \) was proportional to body mass to the power of \(-0.82\) to \(-0.17\). The V1 skate technique showed even more variability, with none of the power curve fits demonstrating significant correlations (Figure 3).

**Discussion**

This study compared the oxygen uptakes for roller skiing among six cross-country skiers with comparable race performance records, and body weights that spanned a 17.3 kg range. The experimental findings of this study demonstrate a tendency for the relative oxygen cost of roller skiing on flat terrain to decrease with increasing body mass. In other words, the heavier skiers tended to have lower oxygen requirements per unit body mass than the lighter skiers. The magnitude of this effect across all techniques and speeds averaged about 1\% per kg body mass.

The experimental findings of the present study compare well with the data of Bergh (1987) on world-class cross-country skiers during cross-country skiing on level snow. His data demonstrated that the oxygen cost, expressed relative to transported mass, decreased 0.8–1.2\% for each kg increase in mass. In an earlier study, Statin and Lindahl (quoted in Bergh, 1982) evaluated the metabolic cost of cross-country skiing on flat terrain with skiers wearing a loaded weight vest. They also demonstrated that the oxygen cost per kg transported mass decreased with an increase in transported mass, although the magnitude of the effect was considerably less than found by Bergh. As Bergh has suggested, a more comparable effect probably would have been observed if Statin and Lindahl’s subjects had matched the ski stiffness for the transported mass rather than using the same skis regardless of mass.

The theoretical analysis presented here suggests that the mechanical power cost of roller skiing with the roller skis used in this study is proportional to body mass raised to a power less than 1. The value of this exponent depends upon the quantitative importance of the various mechanical power costs. Differences in the relative contribution of the various mechanical power cost factors should result in each skiing technique and speed having somewhat different exponents. Experimentally, the best relationships between the oxygen cost and body mass were found for the double pole technique. For this technique the absolute \( \dot{V}O_2 \) was proportional to body mass raised to a power between 0.13 and 0.24.

These values are smaller than was predicted by the theoretical analysis for the relationship of mechanical power cost with body mass (i.e., 2/3 to 1). If metabolic cost directly reflects the mechanical power cost, then exponents derived from the theoretical analysis should be similar to those determined experi-
mentally. The different findings between the theoretical analysis of mechanical power cost and experimental study of metabolic cost probably reflect limitations on both the theoretical and experimental aspects of the study.

The experimental findings were limited by less than perfect geometric similarity of the subjects, the small number of subjects, and their modest weight range. Another limitation of the study is probably due to differences among the subjects’ skill at the different techniques. Experimentally, the best relationships between oxygen consumption and body mass were found with the double pole technique. To some extent this may have been the case because there were twice as many data points for the double pole technique compared with the other techniques. However, the double pole technique is less difficult to master than either the kick double pole or V1 skate techniques, and since the double pole technique is basic to both classical and freestyle cross-country skiing, the subjects presumably had the greatest experience with this technique.

We would hypothesize that the greater variability in oxygen consumption with the kick double pole and V1 skate techniques is due to differences in skill level that are reflected as differences in economy. This is probably the most important factor accounting for the experimental finding that absolute VO2 for the kick double pole technique was proportional to body mass raised to an exponent less than 1. It is interesting that even with this group of skilled skiers with similar performance characteristics, there seems to be considerable variability in economy with the more skilled techniques.

The theoretical analysis is limited by the possibility that it does not fully or accurately account for all of the mechanical power cost factors. For instance, the theoretical relationship between body mass and the power cost of overcoming friction was oversimplified. The drag force of a roller ski during actual roller skiing is rarely equal to the force measured with full body mass equally distributed between two flat roller skis. Even with the double pole technique there is considerable fluctuation in the vertical force applied to the skis through each cycle (Ekstrom, 1981). Certainly for the V1 skate technique, where the normal force on the rolling roller ski may be as high as two times body mass (Street, 1988) and the roller ski is not flat during the entire weight-bearing phase, the drag force of the roller skis is underestimated by the procedures in this study. Furthermore, the assumptions made with regard to energy transfer between body segments and different forms of energy may not be fully accurate.

The theoretical analysis of mechanical power costs reveals an important difference between roller skiing and cross-country skiing on snow. This difference is in the relationship of body mass with the power cost of overcoming friction. For snow skiing, Bergh’s analysis (1987) suggests that $P_F$ is proportional to body mass to the 1/3 power. Experimentally, this exponent was shown to be 0.14 (Eriksson, 1949; Westergren, quoted in Bergh, 1987). Both the theoretical analysis and experimental findings indicate that as body mass is increased, there is a smaller proportional increase in the power cost of overcoming friction in snow skiing. In contrast, the power cost of overcoming friction for the roller skis used in this study was experimentally determined to be proportional to body mass raised to a factor of 1.40. In other words, an increase in body mass resulted in a greater proportional increase in the power cost of overcoming friction with the roller skis. Thus, with regard to the power cost of overcoming friction on flat terrain, the heavier skier has the advantage over the lighter skier for snow skiing, but the situation seems to be reversed for roller skiing.
To assess the effect of body mass on performance during roller skiing and snow skiing, it is necessary to compare the relationships of physical capacity and power costs with body mass. Maximal aerobic power appears to be a major determinant of physical capacity for cross-country skiing (Bergh, 1987) and is suggested by both theoretical and experimental evidence to be proportional to body mass to the $2/3$ power (Åstrand & Rodahl, 1986). This means that a given increase in body mass results in a smaller proportional increase in maximal aerobic capacity. Of the power costs, $P_{kt}$, $P_{kr}$, and $P_a$ are also theoretically proportional to body mass to the $2/3$ power. Therefore a given increase in body mass should produce increases in $P_{kt}$, $P_{kr}$, and $P_a$ that are offset by a comparable increase in $V_O^{max}$. However, for $P_p$ the exponent is 1, and for $P_n$ the exponent is experimentally 0.14 for snow skis and 1.40 for the roller skis in the present study. Therefore the effect of body mass on performance will be determined by the influence of body mass on $P_p$ and $P_n$ and the quantitative importance of these two factors.

Comparison of the pattern and magnitude of the normal forces applied to skis shows that there are considerable differences with the various techniques (Ekstrom, 1981; Street, 1988). This would suggest that the relative contribution of $P_n$ to the total power cost of skiing would also differ among the techniques. Saibene et al. (1989) have provided some experimental evidence supporting this concept and suggest that the proportion of total energy expenditure devoted to overcoming friction is greatest for the skating technique compared with the double pole and diagonal stride techniques. This is logical since the average normal forces applied to the skis during the gliding phase are probably greater with the skating techniques than the other techniques. In any case, Bergh (1987) has reasoned that $P_n$ is generally greater than $P_p$ for cross-country skiing on snow. Therefore, if $P_p \propto m^{0.14}$ and $P_n \propto m^1$, an elevation in body mass results in a greater proportional increase in the maximal aerobic capacity than the total mechanical power cost. Thus the heavier skier theoretically has the advantage in snow skiing on level terrain.

In contrast, for roller skiing $P_n$ and $P_p$ both appear to be proportional to body mass to a power greater than $2/3$. Thus, a given elevation in body mass will theoretically result in a proportionally smaller increase in the maximal aerobic capacity than in the total mechanical power cost. As a result, the lighter skier should have the advantage at roller skiing on flat terrain. Nevertheless, since the magnitude of the sum of $P_{kt}$, $P_{kr}$, and $P_a$ are considerably larger than the sum of $P_p$ and $P_n$, the overall influence of body mass on cross-country skiing or roller skiing performance is minimized.

This investigation provides theoretical evidence for differences in the effect of body mass on the mechanical power cost of cross-country skiing on flat snow and roller skiing on flat terrain. The greatest difference between these two activities seems to be in the relationship of body mass with the power cost of overcoming friction. Relative to the power cost of overcoming friction, the heavier skier appears to have an advantage for snow skiing while the situation is reversed for roller skiing. Yet, because the power cost of overcoming friction is a small component of the total mechanical power cost for roller skiing, the heavier skier still has a lower total mechanical power cost relative to body mass for roller skiing on flat terrain. This is supported by our experimental findings that relative oxygen cost for roller skiing decreases at the rate of about 1% for each kg increase in body mass. In contrast, when considering the theoretical effect of
body mass on mechanical power cost of cross-country skiing relative to its effect on maximal aerobic capacity, the lighter skier should have a slight advantage when roller skiing on level terrain and the heavier skier should have a slight advantage when skiing on flat snow.

References


The authors would like to thank Dr. E.C. Frederick for his valuable suggestions and review of the manuscript, the Milwaukee Public Schools for the use of their facilities for conducting this study, and Nordic Equipment, Inc., and Exel, Inc., for providing skiing equipment used in the study.