A Comparison of Skating Economy On-Ice and On the Skating Treadmill


Abstract

The purpose of this study was to compare skating economy and oxygen uptake (VO₂) on-ice and on the skating treadmill (TM). Male varsity hockey players (n = 15, age = 21.0 yr) performed skating tests on a TM and on-ice. The subjects skated for 4 min at each of 3 submaximal velocities (18, 20, and 22 km · h⁻¹), separated by 5 min of passive recovery. A VO₂ max test followed the submaximal tests and commenced at 24 km · h⁻¹ with the velocity increasing by 1 km · h⁻¹ every minute until volitional fatigue. VO₂ was 39.7, 42.9, 46.0, and 53.4 ml · kg⁻¹ · min⁻¹ at 18, 20, 22, and maximum speed (km · h⁻¹) on the TM. VO₂ was significantly lower (p < .05) 31.5, 36.9, and 42.7 ml · kg⁻¹ · min⁻¹ at 18, 20, and 22 km · h⁻¹ on-ice. The on-ice VO₂ max (54.7 ml · kg⁻¹ · min⁻¹) was similar to TM. Stride rate, stride length and heart rate (HR) were significantly different on-ice compared to TM. These results show that at submaximal velocities, VO₂, HR, and stride rate are higher on TM compared to on-ice. VO₂ max was similar while HR max was higher on the skating treadmill compared to on-ice.
universitaire de hockey (n = 15, âge = 21.0 ans) ont effectué une épreuve de patinage sur un tapis roulant et sur la glace. Les sujets ont patiné durant quatre minutes à chacune des trois vitesses sous-maximales (18, 20 et 22 km · h⁻¹), entrecoupées de cinq minutes de récupération passive. Suite à l’épreuve de patinage sous-maximale, un test pour évaluer le VO₂max était réalisé. Celui-ci débutait à une vitesse de 24 km · h⁻¹ et la vitesse était augmentée de 1 km · h⁻¹ à chaque minute jusqu’à épuisement. Les VO₂ obtenus sur le tapis roulant étaient de 39.7, 42.9, 46.0, et de 53.4 ml · kg⁻¹ · min⁻¹ à 18, 20, 22 (km · h⁻¹) et à vitesse maximale. Le VO₂ était significativement plus bas sur la glace (p = 0.05) 31.5, 36.9 et 42.7 ml · kg⁻¹ · min⁻¹ à 18, 20, et 22 km · h⁻¹. Le VO₂max sur la glace (54.7 ml · kg⁻¹ · min⁻¹) était similaire à celui mesuré sur le tapis roulant. Les données cinématiques (vitesse et longueur des enjambées) ainsi que la fréquence cardiaque étaient significativement différentes sur la glace comparativement aux résultats obtenus sur le tapis roulant. Ces résultats démontrent qu’à vitesse sous-maximale, le VO₂, la fréquence cardiaque ainsi que la vitesse des enjambées sont plus élevées sur le tapis roulant que sur la glace.

Introduction

Physiological data have been reported for ice hockey players on cycling ergometers (Cox et al., 1993; Rhodes et al., 1986), running treadmills (Cox et al., 1988; Montgomery and Dallaire, 1986), and on-ice (Carroll et al., 1993; Ferguson et al., 1969; Léger et al., 1979). Skating movements are not mirrored by either bicycle or treadmill tests and therefore may not adequately reflect the specific aerobic power developed by ice hockey players (Smith et al., 1982). When selecting a modality for testing, sport specificity is important (MacDougall and Wenger, 1991). Recently a skating treadmill (TM) has been introduced to assess the skating performance of ice hockey players. This treadmill consists of a parallel series of polyethylene slats creating a surface permitting subjects to perform wearing their own ice skates. A hockey-specific VO₂max protocol was developed by Dreger and Quinney (1999). They found no significant difference in VO₂max between TM and cycle ergometer protocols.

Due to the recent innovation of the TM, there is a paucity of literature describing the bioenergetics and the biomechanics of skating on this ergometer. Hinrichs (1994) examined the difference between treadmill skating and on-ice skating from a muscle activity perspective. There were few differences in EMG activity of the lower leg muscles between the two modes.

Economy of motion has been defined for running (Daniels, 1985) and ice skating (Riby, 1994) as the steady-state VO₂ at submaximal velocities. A linear relationship exists between VO₂ (ml · kg⁻¹ · min⁻¹) and velocity of both running (Conley and Krahenbuhl, 1980; Daniels, 1985) and skating (Riby, 1994). The inter-individual variability in skating at a given velocity is larger than running (Montgomery, 1988). The coefficient of variation at 20 km · h⁻¹ has been reported at 15% during skating compared to 5–7% when running at similar intensities (Riby, 1994).

Before the skating treadmill can become a laboratory tool to evaluate the effects of various modifications to the skate, it is important to understand the similarities and differences compared to on-ice skating. There is a need to compare both kinematic and physiological responses while skating at similar submaximal and maximal velocities on the two surfaces. Maximal capacities are important for performance to the elite ice hockey player. Information on the submaximal
performance of skaters is important to equipment manufacturers since it is easier to evaluate design changes to skates during submaximal skating in the laboratory compared to an on-ice setting. Thus, the purpose of this study was to compare skating economy and VO$_2$ max on-ice and on the skating treadmill.

Methods

Based on previously reported data on VO$_2$ values of ice hockey players skating at two submaximal velocities (Carroll et al., 1993; Montgomery and Cartwright, 1994; Riby, 1994), an effect size was calculated in accordance with the criteria outlined by Cohen (1988). It was estimated that 11 subjects were needed to obtain statistically significant differences in this study. Fifteen male university ice hockey players volunteered to participate in this study. These subjects were selected as they represent highly-skilled skaters. Informed consent was obtained with all procedures approved by the ethics committee of the university. Anthropometric measurements of height, weight, and skinfolds (biceps, triceps, subscapula, iliac crest, chest, abdomen, thigh, medial calf) were made and percent fat was calculated (Yuhasz, 1966).

Each subject participated in two skating sessions described as TM and on-ice. Both skating sessions were performed during the competitive phase of the season with the on-ice test performed four weeks after the TM test. The availability of ice time and the K4b$_2$ portable system necessitated this sequence. A random assignment would have improved the experimental design. For both skating protocols, subjects wore the same skates (Bauer 7000 or Nike Quest), hockey gloves, track suit, and carried a hockey stick.

The TM test was performed on a skating treadmill (Acceleration Canada, Calgary, AB). Subjects performed a minimum of three 30 min familiarization sessions on the treadmill during the two weeks prior to testing. The familiarization sessions provided adequate time for the player to skate efficiently, comfortably, and confidently on the skating treadmill. The skating treadmill has a skating surface area of 3.20 m$^2$ (1.80 m wide $\times$ 1.78 m long). The surface is covered with a series of parallel polyethylene slats attached to a rubber belt, which rolls over two drums. Prior to each test, the surface was sprayed with silicone oil to reduce friction between the skate blade and the polyethylene surface. During the test, subjects wore a safety harness that was attached to an overhead track as a precaution if a fall occurred. Figure 1 illustrates the skating treadmill, safety harness, and metabolic gas collection system.

Skating economy was measured at three submaximal velocities (18, 20, and 22 km · h$^{-1}$) with performance in a progressive manner beginning with the slowest velocity. These velocities were selected to represent on-ice skating intensities estimated at 55 to 75% of the VO$_2$ max of a typical varsity hockey player and were anticipated to be aerobic intensities for these players. Subjects skated for 4 min at each velocity with physiological data averaged for the last 2 min. A plateau was achieved at these velocities since there was no difference in VO$_2$ between the 3rd and 4th minutes at each velocity. Subjects had 5 min of passive recovery between each skating bout. Heart rate data suggest that 5 min of recovery was adequate as values were below 120 beats · min$^{-1}$ prior to starting the next skate. Following the third skating economy test, a VO$_2$ max test was completed. The test was initiated at
4 km · h⁻¹ with increments of 1 km · h⁻¹ each minute until maximal volitional exhaustion was reached. Grade was 0% for the skating economy and maximal tests. $\text{VO}_2$ and respiratory exchange ratio (RER) were averaged every 20 s using a 2900 metabolic cart (SensorMedics). Physiological data were examined to confirm that RER remained below 1.00 for each skating economy test and above 1.10 for the VO₂ max test. Heart rate (HR) data were collected every 5 s using a Polar Accurex Plus HR monitor (Polar Electro, Kempele, Finland). Temperature in the laboratory ranged from 20 to 23 °C.

The on-ice test was performed on a 140-m oval track with a similar protocol that was used on the skating treadmill. The track was set using 10 pylons with 4 markers specifically positioned every 35 m for the purpose of pacing. Velocity was controlled via an audio tape system. For each velocity an audio signal was emitted at a rate of four beeps per lap. The hockey players synchronized their speed with the audio signals and the four pylons. Subjects skated for 4 min at 18, 20, 22 km · h⁻¹ with 5 min of recovery between each test. The VO₂ max test was initiated at 24 km · h⁻¹ with increments of 1 km · h⁻¹ each min until maximal volitional exhaustion was reached. A test-retest correlation of 0.94 for on-ice VO₂ max measurements has been reported (Ferguson et al., 1969).

The on-ice physiological data were collected using a breath-by-breath portable gas exchange system (Cosmed K4b², Italy). The K4b² system weighed 600
grams. Gas measurements were averaged every 20 s throughout the tests. Physiological data were telemetered to a receiver located in the press box above the ice surface. The accuracy and the reliability of the K4b2 system have been reported (Hausswirth et al., 1997; Palange et al., 1996). Recently, Doyon et al. (2001) observed excellent agreement between the K4b2 breath-by-breath system and a mixing box system across a wide range of VO2 when tested outdoors (2 ºC) and indoors. RER remained below 1.00 for each skating economy test and exceeded 1.10 at the end of the VO2max test. Heart rate data were averaged every 5 s during the on-ice test. The temperature in the hockey arena ranged from 0 to 5 ºC.

It was necessary to use two metabolic systems in this study since the K4b2 system was only available for the on-ice portion of the study. The K4b2 system has been validated and compared to other metabolic measurement systems (McLaughlin et al., 2001) with similar measurements of VO2 over a wide range of exercise intensities.

During the skating economy tests, stride rate was measured by counting the number of skating strides in 58 to 60 s. A skating stride was defined as one cycle, beginning at push-off of the right skate to push-off of the same skate. This definition includes the three components of the skating stride (push-off, glide, and recovery). A stop watch was started beginning at push-off of the right skate and stopped at the beginning of a push-off. For example, 39 strides in 58.9 s was converted to a rate of 39.7 strides · min–1. Stride length was calculated as:

\[
\text{Stride length (m} \cdot \text{stride}^{-1}) = \frac{\text{Velocity (m} \cdot \text{min}^{-1})}{\text{Stride Rate (strides} \cdot \text{min}^{-1})}
\]

One-way repeated measures ANOVAs were used to examine differences in VO2, HR, and stride rate on the 2 surfaces (TM and on-ice), and the 4 velocities (18, 20, 22 km · h–1, and maximum). When appropriate, post hoc analyses were performed using a Tukey honest significant difference (HSD) test. For all statistical analyses, α was set at P < .05.

**Results**

Physical characteristics of the subjects are included in Table 1. These values are typical of varsity university players. Table 2 shows the VO2 results for the TM and on-ice skating economy and VO2max tests. The linear relationship between VO2

**Table 1  Characteristics of the Subjects (n = 15)**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>S.D.</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yr)</td>
<td>21.0</td>
<td>1.4</td>
<td>19–24</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>179.5</td>
<td>8.3</td>
<td>164.3–193.8</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>83.5</td>
<td>6.7</td>
<td>68.0–92.5</td>
</tr>
<tr>
<td>Percent fat (%)</td>
<td>10.6</td>
<td>1.5</td>
<td>8.4–14.1</td>
</tr>
<tr>
<td>Sum of 8 skinfolds (mm)</td>
<td>85.3</td>
<td>17.1</td>
<td>59.4–122.8</td>
</tr>
</tbody>
</table>
and velocity is illustrated in Figure 2. The on-ice \( \text{VO}_2 \) was significantly \( (P < .01) \) lower than TM values at 18, 20 and 22 km · h\(^{-1} \). The mean \( \text{VO}_2 \text{max} \) was similar on-ice (54.7 ml · kg\(^{-1} \) · min\(^{-1} \)) and TM (53.4 ml · kg\(^{-1} \) · min\(^{-1} \)).

Table 2 also shows the HR results for the TM and on-ice skating economy and \( \text{VO}_2 \text{max} \) tests. The on-ice submaximal HRs were significantly \( (P < .01) \) lower than TM values at all three velocities. The mean HR\text{max} was significantly lower \( (P < .01) \) on-ice (187.9 beats · min\(^{-1} \)) compared to TM (193.3 beats · min\(^{-1} \)).

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### Table 2 \( \text{VO}_2 \) and HR on the Skating Treadmill and On-Ice

<table>
<thead>
<tr>
<th>Velocity km · h(^{-1} )</th>
<th>Treadmill Mean</th>
<th>Treadmill S.D.</th>
<th>On-Ice Mean</th>
<th>On-Ice S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{VO}_2 ) (ml · kg(^{-1} ) · min(^{-1} ))</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>39.7</td>
<td>2.8</td>
<td>31.5</td>
<td>3.3</td>
</tr>
<tr>
<td>20</td>
<td>42.9</td>
<td>2.2</td>
<td>36.9</td>
<td>4.2</td>
</tr>
<tr>
<td>22</td>
<td>46.0</td>
<td>2.3</td>
<td>42.7</td>
<td>4.2</td>
</tr>
<tr>
<td>Maximum</td>
<td>53.4</td>
<td>2.3</td>
<td>54.7</td>
<td>3.6</td>
</tr>
<tr>
<td>Heart rate (beats · min(^{-1} ))</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>159.3</td>
<td>11.3</td>
<td>134.4</td>
<td>12.9</td>
</tr>
<tr>
<td>20</td>
<td>166.5</td>
<td>11.3</td>
<td>149.5</td>
<td>13.4</td>
</tr>
<tr>
<td>22</td>
<td>173.3</td>
<td>10.8</td>
<td>165.1</td>
<td>11.1</td>
</tr>
<tr>
<td>Maximum</td>
<td>193.3</td>
<td>6.6</td>
<td>187.9</td>
<td>5.8</td>
</tr>
</tbody>
</table>

**Figure 2.** Comparison of 4 studies measuring \( \text{VO}_2 \) on-ice and on TM.
Table 3 shows the results for stride rate and stride length on the TM and on-ice during the skating economy and VO$_2$ max tests. The on-ice stride rates were significantly ($P < .01$) lower than TM values. Stride rates were similar at 18, 20, and 22 km · h$^{-1}$ during the TM tests. On-ice stride rate significantly increased from 32.0 strides · min$^{-1}$ at 18 km · h$^{-1}$ to 39.3 strides · min$^{-1}$ at 22 km · h$^{-1}$.

**Discussion**

Although, treadmill skating is believed to simulate on-ice skating, few studies have compared the physiological responses between the two modalities. The purpose of this study was to compare skating economy and VO$_2$ max on-ice and on the skating treadmill. Figure 2 illustrates the linear relationship between VO$_2$ and on-ice skating using data from four studies. The subjects for these studies were also male varsity hockey players. Our on-ice data using the K4b$^2$ system were similar to VO$_2$ measurements using Douglas bags (Carroll et al., 1993; Ferguson et al., 1969; Montgomery and Cartwright, 1994; Riby, 1994). Carroll et al. (1993) used a 110-m oval course with measurements at 12.5, 16.5 and 20 km · h$^{-1}$. The other three studies used a 140-m oval course with velocities ranging from 20 to 23 km · h$^{-1}$ (Montgomery and Cartwright, 1994; Riby, 1994), and 21 to 26 km · h$^{-1}$ (Ferguson et al., 1969).

At 20 km · h$^{-1}$, our VO$_2$ was 36.9 ml · kg$^{-1}$ · min$^{-1}$ on-ice while Carroll et al. (1993) reported a value of 33.8 ml · kg$^{-1}$ · min$^{-1}$ at this velocity. On the TM, our VO$_2$ was 6.0 ml · kg$^{-1}$ · min$^{-1}$ higher. At 20 km · h$^{-1}$, the intensity relative to the maximum value for each modality was 67.5% on-ice compared to 80.3% on the TM. Heart rate values confirm the higher intensity when skating on the TM compared to on-ice. At 20 km · h$^{-1}$, the HR was 17 beats · min$^{-1}$ higher on the TM.

Only one other study has compared TM and on-ice physiological demands during submaximal skating. The experimental design utilized by Hinrichs (1994)...
compared TM and on-ice heart rates as well as EMG activity while skating at three
stride frequencies (42, 49.5, and 54 strides \cdot \text{min}^{-1}) described as slow, medium, and
fast skating. At each stride frequency, the speed of the TM was significantly slower
than the on-ice velocity. The “fast” condition was only 16.5 km \cdot \text{h}^{-1} on the TM
versus 25.0 km \cdot \text{h}^{-1} on-ice. There were no significant differences in muscular acti-
vation patterns between TM and on-ice. The HR for the “fast” condition was 175
beats \cdot \text{min}^{-1} on the TM. The higher HRs in the study by Hinrichs may be attributed
to the protocol, which included a treadmill grade of 2.5%. By using similar stride
frequencies on the TM and on-ice, Hinrichs was able to equate the physiological
demands of skating on the two surfaces. In order to achieve a similar HR response
our subjects skated at a higher velocity on the TM. During the skating economy
test at 22 km \cdot \text{h}^{-1}, the mean HR was 173.3 beats \cdot \text{min}^{-1} on the TM and 165 beats \cdot
\text{min}^{-1} on-ice.

At similar velocities, stride rate and VO\text{2} were significantly greater on TM
compared to on-ice. The different physiological and kinematic patterns observed
on-ice versus TM might be attributed to two factors – the coefficient of friction of
the two skating surfaces and the skating task. The TM test was performed using
only forward strides in a linear direction whereas the on-ice test was performed on
an oval course necessitating forward crossover strides. Hinrichs (1994) also ob-
served increased stride frequencies on the TM compared with on-ice skating. Dur-
ing on-ice speed skating at high velocities, the frictional component is mainly due
to air resistance (deKoning et al., 1992). On the TM, surface friction is much greater
while air resistance is minimal. When skating on the TM there is increased drag on
the player’s skate effectively reducing the glide phase of the stride compared with
on-ice skating (Dreger, 1997).

The glide phase of ice-skating is possible because of a low coefficient of
friction. The on-ice coefficient of friction ranges from \(\mu = 0.003\) (deKoning et al.,
1992; Kobayshi, 1973) to \(\mu = 0.030\) (Zatsiorski et al., 1987). The coefficient of
friction for the artificial surface of the skating treadmill has yet to be determined
and it is probably higher than that which is reported for ice. The following theories
have been suggested to describe the mechanics of skating on-ice: frictional heat-
ing of the ice (Colbeck, 1995), pressure melting (van Ingen Schenau, 1989),
and intrinsic properties of the ice surface (deKoning et al., 1992; Pearsall et
al., 2000).

We found that VO\text{2max} was similar on the TM compared to on-ice. The
protocol for the TM test was continuous with grade remaining constant at 0%.
Dreger and Quinney (1999) found a similar VO\text{2max} when TM results were com-
pared to cycle ergometer. They used a discontinuous protocol with a constant speed
of 14.4 to 16.0 km \cdot \text{h}^{-1} with grade increasing by 2% every 2 min. Their protocol
permitted 2 min of recovery between stages.

We observed a higher maximal HR on the TM (193.3 beats \cdot \text{min}^{-1}) com-
pared to on-ice (187.9 beats \cdot \text{min}^{-1}) despite having similar maximal oxygen up-
takes. We have no physiological explanation for this observation but note that
others have reported the same response. A higher HRmax was also recorded dur-
ing a TM protocol compared to a cycle ergometer test even though both modes of
exercise resulted in similar VO\text{2max} values (Dreger and Quinney, 1999). Our results
are supported by Léger et al. (1979) who also tested varsity hockey players on-ice and
in the laboratory. HRmax was 185.9 beats \cdot \text{min}^{-1} during treadmill running and
significantly lower (175.7 beats · min$^{-1}$) during on-ice skating. Montgomery and Cartwright (1994) found lower HRs while skating on-ice compared to in-line skating at similar submaximal velocities.

Since the physiological demand was greater during submaximal skating on the TM compared to on-ice, we expected that the subjects would achieve a higher peak velocity during the maximal on-ice protocol. However, the average peak velocity during the final stage was 29.6 km · h$^{-1}$ on the TM compared to 28.0 km · h$^{-1}$ on-ice. We attribute the difference to two factors - the cornering effect of skating on the oval course and the procedure for measuring the oval course. On the oval course, greater physical effort is probably required when performing crossover strides (i.e., skating on the corners) as compared to only forward skating on the TM. We have no data to verify this statement but observed that most players increased the stride frequency on the corners versus the straight sections of the course. Our 140-m oval was measured on the inside of the track. Using the markings on the ice we measured the total distance skated per lap. At peak velocities, the subjects traveled approximately 146 m per lap. If the maximum on-ice velocity is calculated using a 146-m oval, then the peak velocity would have been 29.1 km · h$^{-1}$ compared to 28.0 km · h$^{-1}$.

In summary, these results showed that at submaximal velocities, VO$_2$, HR, and stride rate were higher on the skating treadmill compared to on-ice. VO$_2$ max was similar while HRmax was higher on the skating treadmill compared to on-ice. This study has implications for individuals using the skating treadmill to evaluate the effect of design changes in skates, skating mechanics, and physical training. The differences in physiological response between on-ice and treadmill skating are greatest at slow velocities. At VO$_2$max, the velocity obtained on the skating treadmill is similar to that obtained when skating on a 140-m oval course. Trainers of hockey players can use this information to design work-outs for athletes who desire additional training.

References


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