Skating Economy of Ice Hockey Players

by

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Dedicated to

my Grandmother, Mother, and Pary

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Abstract

The purpose of this investigation was to describe skating economy in terms of physiological and simple kinematical variables in ice hockey players. Furthermore, an attempt was made to identify a possible relationship between skating economy and skating ability with the use of a subjective rating system. The subjects (n=13; VO_2 max=60.5 ml.kg^{-1}.min^{-1}) were volunteers from the McGill University Varsity Redmen Hockey Team. Subjects performed three 4-minute skating bouts at 336, 357, and 381 m.min^{-1} around a 140 meter oval course. The dependent variables were: oxygen consumption, blood lactate concentration, heart rate, stride rate and stride length. The skating economy results were: 38.6±5.5 at 336 m.min^{-1}, 44.4±5.1 at 357 m.min^{-1}, and 55.2 at 381 m.min^{-1} (r = 0.79, $p<0.01$). The mean stride rate values for velocities of 336, 357, and 381 m.min^{-1} were 79.0, 85.2 and 96.6 stride.min^{-1} (r = 0.71, $p<0.01$), respectively. The mean stride length values for velocities of 336, 357, and 381 m.min^{-1} were 4.4, 4.2 and 4.0 m.stride^{-1} (r = -0.36. $p<0.05$), respectively. The Spearman rank order correlation of skating economy and skating ability for velocities of 336, 357 and 381 m.min^{-1} were 0.21, 0.10 and 0.29 ($p>0.05$), respectively. The Spearman rank order correlation across the three velocities was 0.30 ($p>0.05$). It was concluded that skating economy at velocities between 336 and 381 m.min^{-1} may be described by a linear regression equation. Additionally, skating economy does not have predictive and diagnostic value to determine skating ability in ice hockey players.

Résumé

Le but de cette étude visait à décrire l'économie des patineurs de hockey par rapport à certaines variables physiologiques et kinématiques. De plus, l'un des objectifs visait à établir un rapport entre l'économie des patineurs et leur aptitude au patinage en utilisant un système d'évaluation subjectif. Les sujets (n=13; VO_2 max=60.5 $ml.kg^{-1}.min^{-1}$) étaient des membres de l'Equipe de Hockey de l'Université McGill qui ont participé volontairement. Les sujets ont patiné trois séquences de 4-minutes à 336, 357, et 381 $m.min^{-1}$ sur un circuit oval de 140 mètres. Les variables mesurés étaient les suivantes: la consommation d'oxygen (VO_2), la concentration d'acide lactique sanguine, le rythme cardiaque, le rythme de poussées et la longueur des poussées. Les résultats pour l'économie du patinage étaient: 38.6±5.5 à 336 $m.min^{-1}$, 44.4±5.1 à 357 $m.min^{-1}$, et 55.2±5.2 à 381 $m.min^{-1}$ ($r=0.79$, $p<0.01$). Les rythmes moyens des poussées étaient de 79.0, 85.2, et 96.6 $poussées.min^{-1}$ ($r=0.71$, $p<0.01$). Les rythmes moyens de longueur des poussées étaient de 4.4, 4.2, et 4.0 $m.poussées^{-1}$ ($r=-0.36$, $p<0.05$). Le Spearman rank order correlation entre l'économie du patinage et l'aptitude au patinage pour les vitesses de 336, 357 et 381 $m.min^{-1}$ étaient de 0.21, 0.10 et 0.29 ($p>0.05$). Le Spearman correlation sur les trois vitesses était de 0.30 ($p>0.05$). Les conclusions sont les suivantes: l'économie au patinage à des vitesses entre 336 et 381 $m.min^{-1}$ correspond à une équation linéaire; et l'économie du patinage ne constitue pas une valeur à fin d'établir l'aptitude des patineurs de hockey.

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CHAPTER I

Introduction

Data on the efficiency of human movement have been accumulating steadily for the last sixty-five years (Hill & Lupton, 1922). Technological advancements in data collection apparatus, measurement techniques, greater understanding of human physiology, the emergence of exercise as a legitimate area of scientific study and the increasing zenith of athletic exploits have all contributed to the further understanding of efficiency during human movement. The preponderant data available on human movement involve the activity of running. This should not be surprising, since running, or "jogging", is practised world-wide on a continuum ranging from recreational to highly competitive, and has witnessed the emergence of a billion dollar sporting market.

Many significant contributors to successful running performance have been identified and investigated. These include: maximal aerobic power, fractional utilization of VO_2 max, lactate threshold, skeletal muscle fibre type, muscle respiratory capacity, and fuel supply. However, research in the last twenty years has left little doubt about the significant predictive and diagnostic value of running economy relative to running performance. In his review of running economy, Daniels (1985, p. 332), defined and implied the importance of efficient running as "the relationship between work done and energy expended, and minimizing or eliminating unwanted or counter-productive muscular movement is a desirable goal for any distance runner".

From its simple beginnings as a speculative area of study, researchers have since taken a genuine multidisciplinary approach in an attempt to understand the phenomenon. Input from the biomechanical, physiological, and psychological realms have all served to increase our understanding of running economy. A multitude of factors, which include physiological, environmental, biomechanical and psychological, have all been shown to have a notable effect on running economy. Despite the significant progress made in the understanding of running economy, research in the economy of other activities is lacking (Daniels, 1985; Morgan & Craib, 1992).

The sport of ice hockey has also received much attention from the scientific community. From its modest beginnings on the grounds of McGill University in 1877 (The McGill Gazette, 1877), organized hockey has evolved into one of the most popular sports in North America and Europe. It is a professional and Olympic sport, and is played recreationally by both young and old alike.

Skating mechanics, the energetics of skating, and energy expenditure during skating are but a few of the many areas of study in ice hockey. The hockey athlete is becoming more specialized, as the specific demands of the game are further understood and described by exercise physiologists. Specific annual training regimes are now common for athletes wishing to compete at the higher levels of the game. Periodic fitness testing sessions comprised of highly specific tests, are now routine in professional leagues. Biomechanists are increasing the skill and speed of players through a greater understanding of skating kinematics and equipment development. In addition, sport psychologists have been called upon to help improve the hockey player's mental approach to the game. Coaches, often physical educators themselves, are becoming more aware of the potential to improve individual and team performances by utilizing the knowledge of the scientific community. But similar to running, many areas of ice hockey remain unexplored or poorly understood.

1.1 Nature and Scope of the Problem

VO_2 max ($ml.kg^{-1}.min^{-1}$) is one of the most commonly utilized indicators of potential success in activities of aerobic nature. A myriad of both laboratory and field tests exist, which enable the athlete and coach alike to measure VO_2 max (MacDougall et al., 1982). Numerous studies (Brandon & Boileau, 1987; Costill, 1967; Davies & Thompson, 1979; Hagan et al., 1981; Maron et al., 1976; Saltin & Åstrand, 1967) have emphasized the importance of an elevated VO_2 max to achieve successful performances in long-distance running events. However, while not dismissing the importance of a high VO_2 max, some authors (Brandon & Boileau, 1987; Daniels et al., 1978b; Pollack et al., 1980) have suggested that other influential variables exist which may have an equally significant effect on running performance. For instance, some studies (Allen et al., 1983; Farrell et al., 1979; Lehmann et al., 1983) have reported higher correlations between running performance and blood lactate variables than with VO_2 max. Velocity at VO_2 max (vVO_2 max), derived by combining the relative contributions of VO_2 max and submaximal VO_2 (economy), has exhibited a significant ability to determine successful running performance (Daniels, 1985; Morgan et al., 1989a). Body composition, skeletal muscle fibre type and efficiency, and fuel supply and utilization have also been determined to have a significant effect on running performance (Morgan et al., 1989b).

The significant contribution of running economy in terms of successful running performance is well documented (Bransford & Howley, 1977; Conley & Krahenbuhl, 1980; Daniels, 1985; Daniels & Daniels, 1992; Morgan et al., 1989b). Daniels (1985, p. 336) stated that "within a homogenous group of runners (relative to performance), running economy has the potential of being the most important characteristic in the determination of success". The neverending quest to improve on personal best times and World and Olympic records, may lead coaches and athletes to pay greater attention to running economy. By carefully manipulating the factors hypothesized to affect running economy, athletes may be able to improve their athletic performances (Baily & Pate, 1991).

Based on the available literature of ice hockey, several physiological and biomechanical variables may also be hypothesized to have a potential effect on the hockey player's performance. Skating mechanics (Marino & Weese, 1979), body composition

(Montgomery, 1982), accumulation and subsequent utilization of lactate (Watson & Hanley, 1986), and anaerobic power and endurance (Green, 1978) are but a few. Psychological factors such as motivation, as well as environmental factors (MacDougall, 1979) may also have a positive or negative effect on the hockey athlete. Considering the running economy results reported in the literature, one may speculate that submaximal skating VO_2, or skating economy, is an important variable to predict skating ability.

1.2 Significance of the Study

Previous work (Ferguson et al., 1969) has resulted in the development of an on-ice maximal oxygen uptake test for hockey players. The reliability of the test was high ($r = 0.94$) and the interindividual variability of the VO_2 max scores was reported at ± 15%. Léger et al. (1979), duplicating the test of Ferguson et al. (1969), reported hockey players to be more efficient on the ice compared to runners, but less efficient than their running counterparts on the treadmill. Interindividual variability of the on-ice VO_2 max scores of the hockey players was similar (11.9 - 15.1%) to that reported by Ferguson et al. (1969). The large interindividual variability was attributed to the mechanical efficiency of skating.

Neither study examined nor described the skating economy of their hockey players, although Ferguson et al. (1969) did report a linear relationship between VO_2 and submaximal skating velocity.

If the effect of skating economy on skating ability and presumably performance is as important as running economy is for running performance, then hockey coaches should also measure this variable. The lack of research in ice hockey literature describing skating economy in hockey players therefore warrants further study.

1.3 Statement of the Problem

The aim of this study was to describe skating economy in terms of physiological and simple kinematic variables in ice hockey players. Players were evaluated while performing a forward skating on-ice task at three different velocities (336, 357, and 381 $m.min^{-1}$). Oxygen consumption (VO_2), heart rate, blood lactate, stride rate and stride length were measured in all players during the performance of the skating task. Furthermore, an attempt was made to identify a possible relationship between skating economy and skating ability with the use of a subjective rating system.

1.4 Hypotheses

This study tested the following hypotheses:

1.4.1 There will be a significant linear relationship between oxygen uptake and submaximal skating velocity.

1.4.2 There will be a significant linear relationship between skating velocity and stride rate.

1.4.3 There will not be a significant relationship between skating velocity and stride length.

1.4.4 The interindividual variability in oxygen uptake of skating will be greater than that of running economy.

1.4.5 There will be a significant relationship between skating economy and skating ability.

1.5 Operational Definitions

The following terms are operationally defined as follows:

Oxygen uptake (VO_2): An indirect estimate of energy metabolism based on oxygen consumption at rest and/or under steady-state exercise conditions. Expressed in both absolute ($l.min^{-1}$) and relative ($ml.kg^{-1}.min^{-1}$) terms.

Submaximal VO_2: An indirect measure of oxygen consumption ($ml.kg^{-1}.min^{-1}$) during steady-state aerobic exercise, representing an intensity less than maximum (VO_2 max). Intensities of approximately 65, 75, and 90% of skating VO_2 max were used in this study.

Running economy (RE): The steady-state VO_2 ($ml.kg^{-1}.min^{-1}$) required to run at a given standardized submaximal velocity.

Skating economy (SE): The steady-state VO_2 ($ml.kg^{-1}.min^{-1}$) required to skate at a given standardized submaximal velocity. This study used velocities of 338, 357, and 381 $m.min^{-1}$.

Submaximal velocity: A skating or running velocity ($m.min^{-1}$) representing an intensity less than maximum.

On-ice: All experimental activities which were conducted on the ice hockey surface by the players in skates.

Blood lactate concentration: A measurement ($mmol.l^{-1}$) from a single sample drawn prior to exercise (resting) and following an exercise bout (two minute post-exercise).

Skating stride: A complete stride represents the time of take-off from the ice surface of one skate to the point of take-off of the other skate (i.e. right stride = take-off right to take-off left).

Stride rate (SR): The number of strides required to complete one minute of skating around the 140 meter oval course ($strides.min^{-1}$).

Stride length (SL): The length in meters of one complete stride ($m.stride^{-1}$).

1.6 Delimitations

This study had the following delimitations:

1. All of the subjects in this investigation were male volunteers from the McGill University hockey team.
2. Conclusions regarding the skating velocity/oxygen uptake relationship are limited to velocities employed in this study.

1.7 Limitations

This study had the following limitations:

1. Although all of the subjects in this study were recruited from the same hockey team, some variation in physical fitness is inevitable.
2. The condition of the ice may not have been the same for each subject.

p. 11 missing

Daniels, 1992; Morgan et al., 1989a, 1990b). The use of indirect calorimetry is based on two assumptions outlined by Morgan et al. (1989b, p. 312). They stated "that the use of indirect calorimetry to accurately reflect metabolic rate during exercise assumes that the ATP requirement derives wholly from cell respiration, not from the phosphagen breakdown or the anaerobic degradation of carbohydrates; and that the contribution of protein and amino acid degradation to the active energy requirement is insignificant." Research by Magaria et al. (1963) supports the first assumption, particularly during submaximal steady-state exercise. However, during non-steady-state exercise, a percentage of energy is derived through anaerobic metabolism, especially during high intensity exercise bouts (Magaria et al., 1963). In their review of protein metabolism during exercise, Lemon and Nagle (1981) outlined that protein catabolism increases with the rigorousness of exercise, during prolonged exhaustive exercise, and in glycogen-depleted individuals. Given the submaximal character of running economy tests and their short duration, indirect calorimetry may provide a valid representation of the energy cost of running.

Running economy tests, which have an average duration of six to 10 minutes, have typically required subjects to run at pre-determined standardized speeds until achievement of a steady-state VO_2 (Conley & Krahenbuhl, 1980; Daniels et al., 1978a; Morgan et al., 1989a, 1990b; Pate et al., 1987). Typically, one to six exercise bouts are involved, each followed by a five to 10 minute resting period. Expiratory gases are generally monitored at some pre-determined point during the last two minutes of the running bout.

Achievement of a steady-state VO_2 condition is dependent upon VO_2 kinetics (Morgan et al., 1989b). Studies have demonstrated that VO_2 kinetics fluctuate with work intensity and fitness level (Hagberg et al., 1978; Whipp & Wasserman, 1972). Whipp and Wasserman (1972) reported that a steady-state condition was reached within three minutes at low and moderate work rates, and that while the attainment of a steady-state condition was slower at higher work loads, the VO_2 at any point prior to attainment of steady-state was higher in well-trained subjects. The determination of the anaerobic threshold (4 $mmol.l^{-1}$) and the existence of a respiratory exchange ratio (VCO_2/VO_2) less than 1.00 have also been used to identify the presence of a steady-state metabolic condition (Morgan et al., 1989b).

2.2 Relationship Between Running Economy and Performance

Early research on running economy involved subjects which were heterogeneous in VO_2 max and running performance (Apor et al., 1980; Costill, 1967; Costill et al., 1973; Daniels et al., 1977; Farrell et al., 1979; Foster et al., 1978). Because of the heterogeneous characteristic of their sample populations, these early studies reported a strong inverse relationship ($r = -0.82$ to -0.91) between VO_2 max and performance in long distance running events (Costill, 1967; Costill et al., 1973; Farrell et al., 1979;

Foster et al., 1978).

These early studies concluded that successful distance running was dependent on the economical utilization of a highly developed aerobic capacity, but that VO_2 at selected submaximal speeds was of little value in discriminating distance running ability (Conley & Krahenbuhl, 1980). The inclusion of heterogenous samples in the experimental design contributed in masking the significant predictive and diagnostic value of running economy in terms of performance, while exaggerating that of VO_2 max.

Research has since demonstrated that running economy is correlated with endurance performance, particularly within groups that are homogeneous in terms of maximal aerobic power (VO_2 max) and running performance (Bransford & Howley, 1977; Conley & Krahenbuhl, 1980; Conley et al., 1981a, 1984; Costill & Winrow, 1970; Krahenbuhl et al., 1989; Morgan et al., 1989a; Pate et al., 1987).

Early research by Costill and Winrow (1970) examined two middle-aged ultramarathon runners with similar VO_2 max values (65.1 vs 63.7 $ml.kg^{-1}.min^{-1}$). The more successful of the two subjects utilized substantially less oxygen at all competitive running speeds above 200 $m.min^{-1}$. The superiority of the more successful runner, despite having a slightly lower VO_2 max, may be a product of greater running economy.

Bransford and Howley (1977) measured running economy in four homogeneous groups of 10 subjects each, which included trained men, untrained men, trained women, and untrained women. The relationship between oxygen uptake and running speed was found to be linear for all four groups. The lowest correlation coefficient observed for any group was $r = 0.80$ (untrained women), and $r = 0.97$ for a single subject. The trained males were found to be the most economical of the four groups, as illustrated by a significantly lower slope ($p<0.05$). The slope of the trained females was significantly different ($p<0.05$) from that of the untrained females, and confirmed their more economical running style. The authors concluded that a well developed aerobic capacity and a low oxygen cost (better economy) of running are two variables which enhance success in endurance performance.

Conley and Krahenbuhl (1980) examined the relationship between running economy and distance running performance (10 km) using highly trained and homogeneous distance runners ($\bar{X}$ VO_2 max = 71.7 ± 2.80 $ml.kg^{-1}.min^{-1}$; $\bar{X}$ 10 km run time = 32.10 ± 1.00 min.). Based on their observations of 12 male runners, they reported coefficients of $r = 0.83$, 0.82, and 0.79 ($p<0.01$) for standardized running speeds of 241, 268, 295 $m.min^{-1}$ and their relationship to performance in a 10 km run. By averaging the three paces, 65.4% of the variation observed in 10 km performance could be explained by variation in running economy. Because of the high homogeneity of the group, the relationship between VO_2 max and performance in the 10 km run was nonsignificant ($r = -0.12$, $p>0.05$). These authors concluded that among highly trained and experienced runners of similar ability and VO_2 max, running economy explains a large and significant amount of the variation observed in a 10 km race.

Furthermore, they indicate that the relevancy of running economy may be expressed only when the performers are homogeneous in terms of ability and VO_2 max (Conley & Krahenbuhl, 1980).

Conley et al. (1981a) performed a longitudinal study (18 weeks) on a long-distance running champion. From the onset to the conclusion of the study period, the subject improved his VO_2 max from a pre-season low of 70.2 to 77.6 $ml.kg^{-1}.min^{-1}$. During the same period, the subject's running economy improved by 16, 13, and 9% for running speeds of 241, 268, and 295 $m.min^{-1}$, respectively. Over the 18 week study span, the relative utilization of maximal aerobic capacity decreased from 83.5 to 71.5%. Physiological improvements of this magnitude would have permitted the subject to run an additional 960 meters in a 30 minute run at his race pace intensity of 93% of VO_2 max. The authors concluded that among runners of homogeneous ability, a slight difference in economy may make a significant difference in the finishing time of races longer than 10 kilometres.

In later work, Conley et al. (1984) studied an American mile record holder over a period of nine months. During that period, the subject improved his VO_2 max from 74.4 to 80 $ml.kg^{-1}.min^{-1}$. Concurrently, his aerobic requirement to run at a 268 $m.min^{-1}$ (6 $min.mile^{-1}$) pace decreased from 48.5 to 45.9 $ml.kg^{-1}.min^{-1}$. A combination of improvement in maximal aerobic power and running economy decreased the relative intensity of running at 268 $m.min^{-1}$ from 65.1 to 57.3% of VO_2 max. These changes took place despite a body weight variation of less than 1 kg during the study period.

Pate et al. (1987) examined the cardiorespiratory and metabolic responses to submaximal and maximal running in elite women distance runners. They used two homogeneous groups of elite female runners ($\bar{X}$ VO_2 max = 67.1 ± 4.2 $ml.kg^{-1}.min^{-1}$; n=15) and good female runners ($\bar{X}$ VO_2 max = 58.6 ± 5.2 $ml.kg^{-1}.min^{-1}$; n=13). Based on the physiological responses at submaximal running speeds of 230 and 248 $m.min^{-1}$, the submaximal VO_2 max required to run was significantly lower for the elite runners than for the good runners (45.0 vs 47.9 $ml.kg^{-1}.min^{-1}$ at 230 $m.min^{-1}$, $p<0.01$ and 48.4 vs 51.2 $ml.kg^{-1}.min^{-1}$ at 248 $m.min^{-1}$, $p<0.05$), indicating that running economy was superior in the elite group.

Krahenbuhl et al. (1989) performed a seven year longitudinal study on adolescent boys, beginning when the subjects were 10 years old (n = 6). None of the subjects participated in regular training for distance running during the study period, but all participated in recreational and high school sports (i.e. swimming, wrestling, football). Despite no significant changes in VO_2 max (48.9 vs 47 $ml.kg^{-1}.min^{-1}$) during the seven year period, a significant decrease was noted in running economy (234.2 vs 202.8 $ml.kg^{-1}.km^{-1}$, $p<0.001$). Nine minute run distance was significantly increased (1637 vs 2115 m, $p<0.01$), as was the estimated percent of VO_2 max incurred during the nine minute run (85.9 vs 99.5%, $p<0.05$). Since VO_2 max remained stable, the authors concluded that the above increases appear to be imputable to better running economy, and to a greater proficiency in runs of fixed duration to perform at a higher relative percentage of VO_2 max.

Daniels (1985) proposed that velocity at VO_2 max (vVO_2 max) may be useful in explaining similarities and differences among well-trained runners who vary in VO_2 max and/or running economy (i.e. low VO_2 max and good economy vs high VO_2 max and poor economy). Morgan et al. (1989a, p. 81) defined vVO_2 max as "a composite variable which integrates VO_2 max and running economy". This interplay of VO_2 max and running economy is expressed by calculating the predicted running velocity at VO_2 max, and may be a useful predictor of running performance (Daniels, 1985; Morgan et al., 1989a).

To investigate the relationship between vVO_2 max and running performance, Morgan et al. (1989a) studied 10 trained runners exhibiting nearly identical VO_2 max values ($\bar{X}$ VO_2 max = 64.8 ± 2.1 $ml.kg^{-1}.min^{-1}$) and 10 km run times ($\bar{X}$ 10 km = 32.3 ± 1.27 min.). Their study found a strong inverse relationship ($r = -0.87$, $p<0.01$) between 10 km run time and predicted velocity at VO_2 max (vVO_2 max). The relationship was stronger than that exhibited by both VO_2 max ($r = -0.45$, $p>0.05$) and running economy ($r = 0.64$, $p<0.05$) with 10 km run time. This is in agreement with Daniels (1985), who has suggested that among runners homogeneous in VO_2 max, a significant relationship exists between distance running performance and vVO_2 max that appears to be moderated to a large degree by running economy. In conclusion, the authors suggested that among well-trained subjects unvarying in VO_2 max, a significant association exists between 10 km run time and vVo_2 max. Furthermore, vVO_2 max may be a sensitive predictor of running performance, and should receive additional attention from both physiological and biomechanical viewpoints (Morgan et al., 1989a).

Table 1 provides a summary of the relationship between running performance and both VO_2 max and running economy. Significant relationships are denoted by an asterisk (* $p<0.05$, ** $p<0.01$) and non-significant relationships by the initials ns ($p>0.05$).

2.3 Physiological Factors Affecting Running Economy

Many physiological factors are believed to affect running economy. However, according to Morgan and Craib (1992, p. 459), "despite growing interest in running economy as a legitimate area of study, many physiological issues lack consensus or remain to be explored in greater detail." Although numerous, the physiological factors examined in this review will be limited to intraindividual variability, training, and fatigue.

2.3.1 Intraindividual Variability in Running Economy

Knowledge of the daily stability of running economy is critical if the efficacy of a particular treatment (e.g., training, gait manipulation) on economy is to be assessed (Morgan & Craib, 1992; Morgan et al., 1989b; Morgan et al., 1991). Further understanding of the daily stability of running economy may help

Table 1 Relationship of VO_2 max ($ml.kg^{-1}.min^{-1}$) and Running Economy With Running Performance.

Study	VO_2 max Range	Test Race Distance (km)	Performance Range (min)	Relationship Between Performance & VO_2max	RE
Costill et al. 1973 (n=16)	54.8-81.6	16.1	48.3-68.2	-0.91	0.02
Farrell et al. 1979 (n=18)	46.3-73.7	15.0 9.7	45.9-73.6 28.4-44.3	-0.89^{*} -0.86^{*}	0.59^{*} 0.60^{*}
Conley & Krahenbuhl 1980 (n=12)	67.7-77.7	10.0	30.5-33.6	-0.12	0.81^{**}
Conley et al. 1981b (n=14)	53.0 ±4.1	10.0	39.4-48.6	-0.66^{**}	0.15
Powers et al. 1982 (n=9)	66.0-71.0	10.0	33.2-34.9	-0.38^{ns}	0.51^{ns}
Williams & Cavanagh 1987 (n=16)	67.1 ±5.5	10.0	30.4-38.3	-0.76	0.07
Fay et al. 1989 (n=13)	51.7-68.4	16.1 10.0	58.1-83.4 35.2-47.9	-0.88^{*} -0.92^{*}	0.62^{*} 0.57^{*}
Morgan et al. 1989a (n=10)	64.8 ±2.1	10.0	32.3±1.27	-0.45^{ns}	0.64^{*}
Cunningham 1990 (n=24)	50.0-78.0	5.0	N/A	-0.05	0.77^{**}

determine the number of tests required to obtain stable economy and gait measures (Morgan & Craib, 1992). Several variables, including small sample sizes and the limited number of test sessions, typically employed in variability studies limit the degree to which significant conclusions may be deduced regarding running economy stability (Morgan et al., 1989b; Morgan et al., 1991; Williams et al., 1991).

Daniels et al. (1984) assessed running economy in 10 well-trained male subjects. The purpose of the study was to determine variations in VO_2 during repeated identical submaximal runs on a treadmill. All of the subjects performed 15 treadmill tests (4 equally-spaced testing periods composed of 3 or 6 runs each) at 268 $m.min^{-1}$ over a seven month period. In their investigation they reported that individual stability in running economy varied by as much as 11% within a particular test period. The authors concluded that despite controlling for running speed, learning, footwear and testing material, significant differences ($p<0.01$) exist in the aerobic demands of running between and within well trained runners.

Morgan et al. (1987) examined the day-to-day stability in running economy of 10 elite male runners ($\bar{X}$ VO_2 max = 64.8 ± 2.2 $ml.kg^{-1}.min^{-1}$). The subjects performed four 6-minute treadmill running economy sessions at 230, 248, 268, 293 $m.min^{-1}$ on three separate days. The authors reported that daily variation in running economy ranged from 3 to 5% of the mean subject variation in economy at each speed, and that the largest within-subject variation in economy at each speed was 5 to 9% of mean VO_2 values.

The authors concluded that elite subjects exhibited a wide range of day-to-day variation in running economy.

These studies have been criticized by some authors (Morgan et al., 1989b; Morgan et al., 1991; Williams et al., 1991) since either a small number of running economy values were obtained for any one subject, or factors that are known or postulated to influence running economy (such as circadian fluctuation, fatigue, training status, treadmill accommodation, and footwear) were not adequately monitored.

Morgan et al. (cited in Morgan et al., 1989b), examined the daily stability of running economy in a homogeneous group of 16 male subjects. To control training effects, the subjects were instructed to refrain from road racing and to reduce their workout regime during the testing period. Each subject performed two 30-minute treadmill accommodation runs followed by two 10-minute economy tests at 200 $m.min^{-1}$, within a four day period. All of the trials were conducted in the same footwear and at the same time of day. When expressed as a percentage of the initial test value, intraindividual economy variation was 1.6% (range = 0.4% to 3.4%). This figure is much smaller than the 3 to 11% range reported by both Daniels et al. (1984) and Morgan et al. (1987). Furthermore, the mean intraclass economy correlation between the two testing periods was $r = 0.97$. The authors suggested that reliable running economy values may be obtained in trained male runners when potentially influential variables (e.g. treadmill accommodation, footwear, circadian fluctuation and training) are controlled.

Morgan et al. (1990a) examined the within-subject variation in running economy of two male ($\bar{X}$ VO_2 max = 67.0 ± 0.5 $ml.kg^{-1}.min^{-1}$) and four female ($\bar{X}$ VO_2 max = 59.2 ± 0.9 $ml.kg^{-1}.min^{-1}$) runners. All of the subjects completed 28 running economy sessions at the same time of day and in the same footwear, during a 6-week period. Running velocities of 188, 214, 241 $m.min^{-1}$, and 161, 188, 214 $m.min^{-1}$ were used for the males and females, respectively. The mean coefficient of variation (CV) for all subjects was 1.66% (range = 1.35 to 1.93%). Interestingly, 60% of the total variation was explained by variation in body mass and measurement error. As in the previous study, the authors demonstrated stable running economy values for both male and female subjects.

Morgan et al. (1991) examined the variability and reliability of running economy in a cohort of 17 trained male runners ($\bar{X}$ VO_2 max = 58.5 ± 4.4 $ml.kg^{-1}.min^{-1}$) during a 7-day period. Footwear and training during the study span were controlled. Prior to running economy data collection, each subject performed 60 minutes of treadmill accommodation. Within four days, each subject performed two 10-minute level treadmill runs at 200 $m.min^{-1}$. The runs were performed on different days, with a two day period separating each run. Expressed as a percentage of mean VO_2, the average day-to-day variation in economy was reported at 1.86% (range = 0.44 to 6.24%), while the mean coefficient of variation for economy was 1.32% (range = 0.30 to 4.40%). Further analysis demonstrated a high association between daily economy measures (r = 0.95). These results indicate that group measures of running economy remain stable across two treadmill running sessions, if controls for potentially influential extraneous variables are included in the experimental design. More importantly, the authors suggested that a stable gauge of running economy may be achieved via a single data collection session under appropriately controlled conditions.

Williams et al. (1991) measured total within-subject variation in running economy in a group of 10 moderately trained male subjects. Training effects, diet, circadian fluctuation, treadmill habituation, and footwear were all controlled. Each subject performed a pre-and-post VO_2 max treadmill test to verify that a training effect had not occurred over the testing period. Each subject was monitored during treadmill running five times a week for four weeks (20 running economy tests) at speeds of 161, 188, and 215 $m.min^{-1}$, which correspond to approximately 50, 60, and 70% of VO_2 max. Each running bout was six minutes in duration. Results indicated no significant differences ($p>0.05$) in the coefficient of variation between the three speeds. Reported coefficients of variation were 3.08, 2.60, and 2.48% for speeds of 161, 188, and 215 $m.min^{-1}$, respectively. The authors' conclusion regarding the stability of running economy as a physiological measure is in agreement with that of Morgan et al. (1989b; 1990a; 1991). Furthermore, they reported that reliable and stable measures of running economy may be obtained with two testing sessions, and that the more precise indication of variation obtained with additional testing does not warrant its time, effort and cost.

Based on the available literature, it may be concluded that if circadian fluctuation, footwear, fatigue level, and treadmill habituation are appropriately controlled, reliable and representative group economy measures may be obtained with a minimum of testing (Morgan & Craib, 1992).

2.3.2 Training and Running Economy

Little agreement exists regarding the effects of training on running economy. This lack of consensus may be due to the small number of longitudinal studies, and to limitations in experimental design (Morgan et al., 1989b). Regardless of these limitations, several studies have reported a wide range of improvement in running economy through various types of training regimes (Daniels & Oldridge, 1971; Daniels et al., 1978a; Patton & Vogel, 1977; Sjödin et al., 1982; Svendenhag & Sjödin, 1985).

Daniels and Oldridge (1971) and later Daniels et al. (1978a) conducted longitudinal studies to examine differences and changes in VO_2 among young boys during growth and running training. The authors studied a group of 20 young male runners between the ages of 10 to 18 for a period of 2 to 5 years. All of the subjects participated in a monitored middle and long distance running program throughout the study period. A significant linear increase in VO_2 max ($p<0.01$) was noted during the study. However, when the accompanying significant increase in body weight ($p<0.01$) was taken into consideration, there was essentially no change in VO_2 max

($p>0.01$). The studies also reported a significant linear decrease in VO_2 submax ($ml.kg^{-1}.min^{-1}$, $p<0.01$) in all age groups. The significant decrease ($p<0.01$) observed in both 1-and 2-mile run times, even in the absence of VO_2 max improvements, lends further credence to the benefit of improved running economy. The authors point out that even in the absence of VO_2 max improvements, the significant changes noted in submaximal VO_2 corresponded to noticeable changes in performance. The authors concluded that both growth and training may account for improvements in the running economy of their young subjects, as measured by 1-and 2-mile race times (1.6 - 3.2 kilometres).

Patton and Vogel (1977) examined the cross-sectional and longitudinal effects of a 6-month endurance training program (2 and 4 mile runs at an 8-to-9-minute mile pace, 5 times/week) on a large cohort of male military personnel (n=120). The average intensity of exercise was estimated at 75% of VO_2 max. Sixty of the subjects were new recruits (Group I), while Group II was composed of 60 subjects who had been participating in the experimental training program for a period of five to six months. Although there were no significant differences in VO_2 submax ($p>0.10$) between the two groups at pretest, Group II had a significantly higher VO_2 max ($p<0.05$). The 11% difference between the two groups in terms of VO_2 max may be attributable to the trained state of Group II. By the end of the study period, Group I had a similar VO_2 max value to that of Group II, which had showed no further improvement. However, submaximal VO_2 had decreased significantly in both groups upon retesting ($p<0.01$). Because VO_2 max was improved only in the untrained group, the authors suggested that a combination of training, improved mechanical efficiency, and treadmill habituation may have been associated with the recorded decrease in submaximal VO_2 observed in both groups (Morgan et al., 1989b).

Conley et al. (1981a, 1984) performed longitudinal (Study I = 18 weeks, 1981; Study II = 9 months, 1984) case studies of two elite male runners. Throughout the duration of the study span, both subjects used a combination of continuous and interval training, but emphasized greater interval work as the study progressed. By the end of the study period, both subjects had improved their running economy values ($ml.kg^{-1}.min^{-1}$) by 12.6% and 5% respectively. The authors pointed out that the largest improvement in running economy was noted during or immediately after weeks of increased interval training. It is important to note that since these were case studies, the external validity is questionable, and it is therefore not possible to generalize from these findings.

Sjödin et al. (1982) examined the effect of a supplemental one weekly 20-minute treadmill run at a velocity calculated to elicit a blood lactate concentration of 4 mmol X 1^{-1} (V_{OBLA}) on running economy. As pointed out in Jacobs (1986, p. 15), "several studies (Hollmann et al., 1981; Kindermann et al., 1979; Mader, 1980; Mader et al., 1976) have suggested that the exercise intensity which induces an optimal qualitative stimulus for adaptation to endurance training should elicit a steady-state lactate concentration of approximately 4 $mmol.l^{-1}$." The treadmill run was termed "supplemental" since the subjects continued their regular training regime throughout the study period. Eight well-trained middle and long distance male runners participated in the 14-week study. Despite no significant changes in VO_2 max (68.7 vs 69.9 $ml.kg^{-1}.min^{-1}$), the subjects significantly decreased their oxygen consumption while running at 15 $km.hr^{-1}$ (50.6 vs 49.2 $ml.kg^{-1}.min^{-1}$, $p<0.05$) and also relative to VO_2 max (73.8 vs 70.1%, $p<0.01$). Significant increases in velocity at OBLA (V_{OBLA} = 4.69 vs 4.89 $m.s^{-1}$, $p<0.01$) and VO_2 at OBLA (VO_{2OBLA} = 58.6 vs 60.6 $ml.kg^{-1}.min^{-1}$, $p<0.05$) were also reported. These changes may be due in part to improved running economy after training. The authors suggested that modifications in running style and improved intracellular oxidative capacity may have been accountable for the lower oxygen demand (Morgan et al., 1989b).

In later work, (Svedenhag & Sjödin, 1985) examined the seasonal variation in physiological characteristics of 16 elite male runners. Seasonal training modes varied throughout the year from slow distance running, uphill running, to intense interval running. Significant improvements in running economy were noted in the subjects at both 15 $km.hr^{-1}$ (VO_2 15, $p<0.05$) and 20 $km.hr^{-1}$ (VO_2 20, $p<0.01$), as measured by repeated economy tests over a mean of 22 months. The most economical values were recorded when seasonal training consisted predominantly of high intensity anaerobic training (i.e. short intervals, hill training). The authors suggested that even in elite runners, there may be small but continuous improvement in running economy. Finally, the authors suggested that the improvement in submaximal oxygen uptake of the subjects was due to improved running economy, and not to adaptations to the test procedure or growth.

Other studies have reported no change (Daniels et al., 1978b; Wilcox & Bulbulian, 1984) in running economy, while a study by Lake and Cavanagh (1990) actually reported a slight increase in running economy. It is important to note that all three studies involved training periods of short duration (6 to 8 weeks).

Daniels et al. (1978b) failed to demonstrate a significant improvement in the running economy of 15 well-trained recreational runners ($\bar{X}$ VO_2 max = 63.9 ± 4.1 $ml.kg^{-1}.min^{-1}$) following an 8-week program of continuous and interval running. The subjects increased their training mileage from 20-30 $km.wk^{-1}$ to 50-70 $km.wk^{-1}$ throughout the study span. Despite no change in pre and post VO_2 max measures, running performance improved significantly ($p<0.01$) as measured by 805m (880 yards) and 3218m (2 miles) run times. Mean VO_2 values recorded during a submaximal steady-state run at 230 $m.min^{-1}$, were 43.1, 44.1, and 43.4 $ml.kg^{-1}.min^{-1}$ for weeks one, five and nine, respectively. However, these submaximal values were not significantly different. The authors concluded that physiological alterations not incorporated in the VO_2 max test (e.g. skeletal muscle oxidative enzyme activity), or an amelioration in pacing ability, contribute to training induced improvements in running performance.

Similarly, Wilcox and Bulbulian (1984) noted no significant improvement in the running economy of seven competitive female cross-country runners, over an 8-week varsity season. Pre and post measures of VO_2 max revealed significant improvement (53.8 vs 58.3 $ml.kg^{-1}.min^{-1}$, $p<0.05$) throughout the season. Fractional utilization of VO_2 max (%VO_2 max) also showed significant improvement with reductions at two testing velocities (from 77 to 70% at 215 $m.min^{-1}$ and 87 to 79% at 241 $m.min^{-1}$, $p<0.05$). Despite these improvements in both physiological measures, running economy was not significantly lower at either 215 or 241 $m.min^{-1}$ ($p>0.05$). These authors concluded that an 8-week season of cross-country running and its accompanying intense training regime was not sufficient to improve running economy, despite improvements in VO_2 max and %VO_2 max.

In recent work, Lake and Cavanagh (1990) measured running economy in 15 recreationally active males. After completing various pre-experimental physiological measures, the subjects were randomly assigned to either a training group (n=8) or to a control group (n=7). The training group participated in a 6-week running training program (15-25 $miles.wk^{-1}$). As expected, no significant physiological changes were found in the control group. Contrary to Daniels et al. (1978b), the experimental group significantly improved their VO_2 max (57.3 vs 61.3 $ml.kg^{-1}.min^{-1}$, $p<0.01$). The trained subjects also decreased their fractional utilization of VO_2 max (71.6 vs 69.3%, $p<0.05$) and run time until exhaustion (10.9 vs 11.9 min, $p<0.01$). Despite these physiological improvements, running economy in the experimental group had in fact increased

(41.0 vs 42.4 ml.kg^{-1}.min^{-1}) post-training. These authors concluded that improvements in running performance in untrained subjects, as measured by treadmill run time until exhaustion, following a short-term 6-week running program, are the product of physiological alterations associated with an increase in VO_2 max, and not due to improvement in running economy.

Although more research is needed to clearly identify the exact mechanisms, running economy seems to improve with training due to better mechanical efficiency, treadmill habituation, modifications in running style and oxidative energy supply, and optimization of motor unit recruitment patterns (Morgan & Craib, 1992). Furthermore, Bailey and Pate (1991) suggested that alterations in the runner's training status may be the most promising route by which running economy may be improved.

When comparing trained runners with their untrained peers, Bransford and Howley (1977) reported significantly lower ($p<0.05$) running economy values in trained males when compared to the values obtained by untrained males, trained females, and untrained females. At 200 m.min^{-1}, the trained men utilized 37.0, the trained women 40.0, the untrained men 40.3, and the untrained women 41.1 ml O_2.kg^{-1}.min^{-1}. The trained women and untrained men also had significantly lower ($p<0.05$) running economy scores than the untrained females, but did not differ among each other ($p>0.05$). Although a gender role may seem to be responsible for the marked differences between the groups, the authors discounted that explanation. Rather, they proposeed training, genetics, superior mechanical efficiency (less vertical displacement), and a more proficient oxidative energy supply as plausible hypotheses.

Pollock et al. (1980) examined the submaximal VO_2 scores of 8 marathoners, 12 middle-long distance runners (all 20 subjects classified as elite) and 8 good runners. Their group VO_2 max mean scores were 74.1 ± 2.6, 78.7 ± 3.0 and 69.2 ± 3.7 $ml.kg^{-1}.min^{-1}$, respectively. Mean submaximal VO_2 scores were 62.7, 66.7, and 65.3 $ml.kg^{-1}.min^{-1}$ for the marathoners, middle-long distance runners, and the good runners, respectively. Furthermore, the elite runners as a group had a mean submaximal VO_2 of 65.5 $ml.kg^{-1}.min^{-1}$. Multiple analysis of variance confirmed that the three groups were significantly different from each other ($p<0.01$). It was also confirmed that the elite runners were significantly different from the good runners ($p<0.01$), and the marathoners were significantly different from the middle-long distance runners ($p<0.05$). Via discriminant function analysis, more efficient physiological adaptations (e.g. higher VO_2 max, lower percent fat values, higher %VO_2 max, and lower lactate accumulation) were hypothesized as reasons for the significant difference between the elite and good runners. Further analysis suggested that the lower lactic acid submaximal value of the marathoners and the higher VO_2 max value of the middle-long distance runners accounted for the significant metabolic difference between the two groups. In conclusion, the authors proposeed that differences in training regimes may account for some of the observed differences. The marathoners characteristically included more long-distance work in their training regime, as opposed to the more intense training of the middle-distance runners.

Dolgener (1982) studied the differences in running economy between untrained (UT, n=13), sprint trained (ST, n=13), and endurance trained (ET, n=12) women. The author ensured physiological homogeneity on the variables height, weight, and sum of skinfolds between the three groups. No significant differences ($p>0.05$) in running economy were reported between the three groups at either a walking speed of 80.2 $m.min^{-1}$ or a run speed of 160.4 $m.min^{-1}$. The author postulated several reasons for the reported non-significant economy values. It is suggested since the three groups did not differ in mechanical efficiency, no differences in running economy could be observed. Mechanical efficiency had been proposed by Bransford and Howley (1977) as a plausible mechanism for the differences observed between their trained and untrained women. The untrained subjects in the present study had participated in a two-week run training period prior to data collection. Finally, the possibility that the untrained subjects were working too close to their anaerobic threshold at 160.4 $m.min^{-1}$ and the use of improper statistical methodology were also advanced as possible reasons for the observed results.

Pate et al. (1987) examined differences in running economy between 15 elite and 13 good female distance runners (67.1 vs 58.6 $ml.kg^{-1}.min^{-1}$, $p<0.01$). The elite group was more economical at both running speeds of 230 $m.min^{-1}$ (45.0 vs 47.9 $ml.kg^{-1}.min^{-1}$, $p<0.01$) and 248 $m.min^{-1}$ (48.4 vs 51.2 $ml.kg^{-1}.min^{-1}$, $p<0.05$). Although the authors did not attempt to explain the better economy of the elite group, the significant superior ($p<0.01$) responses of other physiological variables, including $\%VO_2$ max, heart rate, and blood lactate, may partly explain the result.

2.3.3 Fatigue and Running Economy

Little research, and thus little consensus, exists on the effect of fatigue on running economy. What research exists is limited to studies involving male elite and recreational distance runners (Cavanagh et al., 1985; Morgan et al., 1990b; Wilcox et al., 1989).

Cavanagh et al. (1985) developed a comprehensive biomechanical profile for the evaluation of elite distance runners. Included in their profile was a description of selected metabolic measurements of two elite male distance runners. Both subjects performed a battery of tests, which included a running economy test, during separate 2-day test periods. It is however, important to note that both subjects were still recuperating from exhaustive competition (10 km race) prior to the testing sessions, hence the fatigued state of the subjects. The values obtained on the submaximal running economy test decreased over the two test days (subject A: 57.1 vs 54.5 $ml.kg^{-1}.min^{-1}$; subject B: 59.0 vs 56.7 $ml.kg^{-1}.min^{-1}$) The authors attributed the rapid decline in oxygen uptake, and thus what would seem as improved economy, to the immediate post-competitive state of the subjects (initially high VO_2 values).

However, the small sample and the methodological limitations inherent in the study, restrict the generalizability of these results.

Wilcox et al. (1989) examined the effects of delayed onset of muscular soreness (DOMS) on submaximal oxygen consumption. Eleven subjects (7 males, 4 females) were evaluated at two speeds of 7 and 8 mph and 6 and 7 mph for the male and female subjects, respectively. Measurements were taken before and 24, 48, and 72 hours subsequent to a 3-mile downhill (10% grade) treadmill run at a velocity eliciting 48% VO_2 max. VO_2 was significantly higher ($p<0.05$) for all three post-downhill measures when compared to the pre-downhill measure, although no differences were found between the three post measures. The authors concluded that fatigue, established by rates of perceived exertion of delayed onset of muscular soreness, caused an increase in the VO_2 of running for up to three days following a downhill run.

Morgan et al. (1990b) examined the effects of a prolonged maximal run (PMR) on running economy and running mechanics in 16 moderately trained male runners ($\bar{X}$ VO_2 max= 59.0 ±4.5 $ml.kg^{-1}.min^{-1}$). Subsequent to treadmill accommodation bouts, all of the subjects performed an initial 10-minute running economy test at 200 $m.min^{-1}$. Three days later, a second identical running economy test was performed. Five minutes upon completion of the second run, each subject performed a 30-minute treadmill run (PMR) at a velocity representing approximately 85 to 90% of predicted velocity at VO_2 max (vVO_2 max). The relative mean intensity of the PMR for all subjects was calculated at 89.0 ± 3.1% of VO_2 max ($ml.kg^{-1}.min^{-1}$). A 10-minute running economy test was then performed at one, two, and four days following the PMR. The authors reported no significant difference ($p>0.05$) in running economy (range = 42.5 - 42.6 $ml.kg^{-1}.min^{-1}$) following the PMR. The authors concluded that a 30-minute maximal run does not influence the running economy of moderately trained male runners for up to four days following the run. The prolonged maximal running protocol incorporated in the study to elicit a fatigued state, would tend to increase the validity of the results.

2.4 Relationship Between Temperature and Running Economy

Little consensus exists regarding the effects of increased core temperature on VO_2. Some studies have demonstrated an increase in VO_2 (MacDougall et al., 1974; Saltin & Stenberg, 1964), some no change (Rowell et al., 1969), and others a decrease (Dill, 1965; Maron et al., 1976) while exercising under various thermal conditions.

In Saltin and Stenberg (1964), four male subjects performed 180 minutes of treadmill and bicycle ergometer exercise at an intensity representing approximately 75% of VO_2 max (range = 72-76%). Room temperature was 19°C, and a fan was placed behind the exercising subjects. A 5% increase in oxygen uptake was recorded throughout the 180 minute period with a synchronous increase in core temperature (range = 38.0 to 38.6°C).

MacDougall et al. (1974) examined the physiological responses to exhaustive treadmill running under three thermal conditions: normal, hyperthermal, and hypothermal. Six male subjects participated in the study ($\bar{X}$ VO_2 max = 57.5 ± 7.8 $ml.kg^{-1}.min^{-1}$). All subjects were required to run to exhaustion at a constant speed calculated to elicit approximately 70% of VO_2 max. The three thermal conditions were achieved using the experimental design of Rowell et al. (1969) (see p. 38), and ambient room temperature was held constant at 23 ± 1°C throughout the study span. Run times to exhaustion were 48.3, 75.0, and 90.8 minutes for the hyperthermal, normal, and hypothermal conditions, respectively. VO_2 increased throughout the run in all three thermal conditions. The highest increase in VO_2 was recorded under the hyperthermal condition, whereas the lowest increase occurred under the hypothermal condition. The hyperthermal VO_2 value was significantly higher ($p<0.05$) than both hypothermal and normal conditions. The hypothermal condition was also significantly lower than the normal condition. The authors suggested that exercise induced hyperthermia may cause a limitation in running performance. The rise in VO_2 may be attributable to heat dissipation mechanisms: an increased energy demand for peripheral circulation, increased sweat gland activity, and hyperventilation. A decrease in the efficiency of energy metabolism due to hyperthermia is also suspected.

Brooks et al. (1970) and later Brooks (1971) examined rat skeletal and liver mitochondria in vitro to further understand the relationship between temperature and oxygen consumption. Based on their observations, these authors postulated that exercise-induced hyperthermia may cause a decrease in mitochondrial respiration efficiency, leading to the need for greater amounts of oxygen to synthesize a given amount of ATP. Therefore, the long-term elevated basal levels of oxygen consumption, characteristically observed upon cessation of exercise, may be in part due to the increased temperature (Q_{10} effect) on cell metabolism; particularly on mitochondrial energetics (Gaesser & Brooks, 1984).

Rowell et al. (1969) conducted three different experimental protocols to determine whether VO_2 is increased or decreased in hyperthermic men. Fifty four healthy male subjects (range = 21 - 36 yrs) were randomly assigned to participate in one of three experimental protocols. Hyperthermic conditions were achieved by raising room temperature or through a form-fitting water-perfusable suit. Several findings were reached during the study span. No significant differences ($p>0.01$, $n=7$) were found when comparing VO_2 measures taken during prolonged submaximal exercise (range = 41.0 - 54.0% of VO_2 max) at 25.6 and 48.9°C. Rapid skin temperature changes at three 30-minute intervals and a fourth 15-minute period during continuous exercise (total duration = 105 min.) at three different intensities (14.4, 17.2, and 29.8 $ml.kg^{-1}.min^{-1}$; 26.0 - 64.0% of VO_2 max) failed to significantly alter VO_2 ($n=16$). Temperature changes progressed from approximately 33, 38, 26 (30-minute intervals), and 39°C (15-minute interval). Finally, when comparing the VO_2 response to four 15-minute periods of intermittent graded submaximal exercise under 25.6 and 43.3°C thermal conditions, the latter condition exhibited an average reduction of 3% or 1.6 $ml.kg^{-1}.min^{-1}$ (range = 1.4 - 5.9 $ml.kg^{-1}.min^{-1}$, $p<0.01$, n=27). These authors concluded that the suggested additional costs of working under hyperthermic conditions such as increased cardiac output, ventilation, and sweating as reported by MacDougall et al. (1974) are too negligible to significantly raise VO_2. Rather, they attributed the relative uniformity of VO_2 in hyperthermic conditions to an increased mechanical efficiency of the working muscles, significant enough to offset temperature effects.

Evidence suggesting a decrease in VO_2 during activity are presented by Dill (1965) and Maron et al. (1976). Dill (1965), in a case study of marathon runner, Clarence DeMar, reported a significant decrease in VO_2 over a 20-minute treadmill run at constant speed. Maron et al. (1976) measured the VO_2 of two elite marathon runners during an actual marathon race at approximately three intervals. Both runners exhibited a decrease in VO_2 during the course of the run, which was independent of a reduction in speed or slope, despite a recorded increase in core temperature. In agreement with Rowell et al. (1969), these authors suggested that the decrease in VO_2 characterized by an increase in core temperature represents an increase in the efficiency of muscle metabolism. The generalizability of these findings should be done with caution, due to the small number of subjects and the methodological constraints of each study. Clearly more research is needed on the topic.

In a recent review, Bailey and Pate (1991) suggested that both schools of thought may be valid and operating simultaneously. They felt that submaximal VO_2 may decrease at the onset of activity as muscle temperature increases above resting values, but increases as the body's heat dissipation system is called into play. The validation of such a theory may justify the relevance of a warm-up prior to exercise.

2.5 Biomechanical Considerations for Running Economy

Far less research is available in the literature documenting the relationship between running economy and biomechanical factors when compared to physiological factors (Morgan et al., 1989b). Nevertheless, there is sufficient literature documenting the significant contribution of various biomechanical factors on running economy to warrant its inclusion in this review (Baily & Pate, 1991; Cavanagh et al., 1985; Cavanagh & Kram, 1985; Martin & Morgan, 1992; Morgan et al., 1989b; Williams & Cavanagh, 1987). While not overlooking the important contribution of physiological variables, Williams and Cavanagh (1987), in an extensive study examining the relationship between running mechanics and running economy, reported that 54% of the observed variation in running economy could be linked to selected biomechanical variables. Covered biomechanical factors in this review include: body mass, body and segment mass distribution, running speed, and stride length.

2.5.1 Body Mass and Running Economy

Biomechanical factors are believed to play an important role in the commonly observed interindividual differences in running economy. In order to better control the potential effects of body mass on inter-subject variability during running economy tests, values are normalized and reported relative to body mass ($ml.kg^{-1}.min^{-1}$). This procedure assumes that body mass is independent of the aerobic demand of performing (Martin & Morgan, 1992; Morgan et al. 1989b).

Davies (1980), in examining earlier work researching the aerobic performance of ultramarathon athletes (Davies & Thompson, 1979), reported no difference in running economy between light-weight men and their heavier peers, in a group of 13 subjects.

Skinner et al. (1973) compared the VO_2 response during treadmill walking in lean (weight = 65.7 ± 7.6 kg, body fat = 7.6 ± 2.6%; n=8), obese (weight = 106.8 ± 10.9 kg, body fat = 28.2 ± 1.3%; n=8) and lean subjects fitted with a weighted vest and belt, to equal the weight of a matched obese counterpart. The average amount of weight required to match the lean with the obese subjects was 19.0 kg (range = 16.8 - 22.0). All subjects were required to walk at a speed of 5.6 $km.hr^{-1}$, while the treadmill grade was increased 2.5% every two minutes until volitional exhaustion. Oxygen intake was nearly identical for all three groups throughout the economy test, regardless of room temperature (24°C and 32°C).

Williams and Cavanagh (1986), on the other hand, demonstrated an inverse relationship ($r = -0.39$) between body mass and submaximal VO_2 for a group of 13 elite male distance runners. It is interesting to note that anthropometric variables related to body size (i.e. leg length, pelvic width, and foot length) showed higher correlations with submaximal VO_2 (range = -0.55 to -0.68) than ground reaction force and kinematic data (i.e. knee and ankle angles) typically employed to describe running mechanics. In later work, Williams et al. (1987) further demonstrated a significant modest inverse relationship ($r= -0.52$, $p<0.05$) between running economy and body mass in a group of 14 elite female runners. Of particular interest is the significant correlation ($r = -0.58$, $p<0.05$) found between running economy and maximal thigh circumference. Data from both studies would seem to indicate that heavier runners are more economical than their lighter counterparts.

In a recent study, Pate et al. (1992) examined running economy and its relationship to various physiological, anthropometric, and training variables. The study involved a large cohort of heterogeneous, habitual distance runners (n=188; 118 males, 69 females). Submaximal VO_2 data were collected using a standardized six minute treadmill run at 161 $m.min^{-1}$ (VO_2-6). VO_2-6 was found to be significantly and negatively correlated with weight ($p<0.001$), indicating that heavier runners were more economical than their lighter weight counterparts. In an earlier study, Pate et al.

(1989) reported a significant inverse relationship ($p<0.05$) between running economy and height.

Although more research needs to be performed, the available literature seems to indicate that heavier, and perhaps taller and stronger runners, are more economical than smaller individuals (Martin & Morgan, 1992). This marked difference is hypothesized to be due to weight-related differences in segmental mass distribution (Pate et al., 1992). Research has shown that lighter weight individuals tend to carry a larger percentage of their body mass in the extremities, when compared to their heavier peers (Zatsiorsky & Selvyanov, 1983).

2.5.2 Body and Segment Mass Distribution and Running Economy

As was the case with body mass, body mass distribution, more specifically segmental mass distribution, is hypothesized to be an important factor describing individual differences in movement economy (Bailey & Pate, 1991; Cavanagh & Kram, 1985; Martin & Morgan, 1992; Morgan et al., 1989b).

Hypotheses concerning the relationship between body and segment mass distribution and the energetic cost of locomotion have been proposed by functional morphologists examining terrestrial animal movement (Gray, 1968; Hildebrand, 1962; Howell, 1944; Smith & Savage, 1956). Simply stated, these studies suggest that individuals who carry a greater amount of mass at the distal aspect of the extremities, particularly the legs, require more work in moving the body segments during running than those carrying less mass in these regions. Furthermore, greater limb mass concentration closer to the main axes of rotation is also associated with reduced muscular efforts during running. However, in an oft cited study, Taylor et al. (1974) failed to identify significant differences in the oxygen cost of locomotion between three species (cheetah, goat and gazelle), despite their considerably different limb mass distribution. The limb mass distribution hypothesis has received indirect support from studies involving human subjects, through the use of simulated weight added to the body segments during locomotion.

Catlin and Dressendorfer (1979) examined the effect of shoe weight on the energy cost of running. Submaximal oxygen consumption was measured in seven marathon runners during treadmill running at their marathon racing speeds (range = 201 to 303 $m.min^{-1}$). Training and racing shoes were alternately worn under identical conditions. The weight of the shoes were 0.87 kg and 0.52 kg for the training and racing models, respectively. The mean energy expenditure was 0.51 $kcal.min^{-1}$ higher ($p<0.05$) while running with the heavier training shoe. The predicted total energy cost for the race duration (42.4 km) was 3.3% greater while performing with the heavier training shoe.

The results of Catlin and Dressendorfer (1979) were substantiated by Jones et al. (1984), who examined the effects of shoes versus boots on the energy cost of treadmill walking and running. Fourteen male subjects, six trained and eight untrained, participated in the study. Submaximal oxygen consumption measurements were collected, while walking and running at three different velocities, in athletic shoes and leather military boots with an average weight of 616g and 1776g per pair, respectively. A third experimental protocol required the subjects to exercise while wearing running shoes weighted with lead pellets to equal the weight of the boots. With the exception of the slowest walking speed (4 $km.hr^{-1}$), the energy cost of wearing boots was significantly greater ($p<0.05$) for all three speeds, when compared to wearing shoes. Similarly, the cost of wearing the weighted shoes was significantly greater ($p<0.05$) at all three running speeds, when compared to the shoes alone. Furthermore, the increase in oxygen uptake creditable to wearing boots as compared to shoes ranged from 5.9 to 10.2%, while that of shoes versus the weighted shoes ranged from 5.0 to 6.3%. On average, sixty percent of the increased energy cost of wearing heavy footwear may be attributable to the weight variable alone (Jones et al., 1984).

Martin (1985) conducted an extensive study examining the mechanical and physiological responses to lower extremity loading during running. Fifteen highly trained men performed 8-minute running bouts at 12 $km.hr^{-1}$ under five different experimental conditions. These included: a baseline condition (no load), 0.25 kg added to each thigh, 0.25 kg added to each foot, 0.50 kg added to each thigh, and 0.50 kg added to each foot. Submaximal VO_2 increased significantly ($p<0.05$) across all four conditions as the load magnitude was increased for both feet and thigh loading. As hypothesized, greater increases in oxygen consumption were recorded when artificial loading was in the feet in comparison with the thighs. Increases of 1.7 and 3.5%, as well as increases of 3.3 and 7.2%, in oxygen consumption with the addition of 0.25 and 0.50 kg of weight were reported for the thigh and feet loading conditions, respectively. These findings are in close agreement with those of Catlin and Dressendorfer (1979) and Jones et al. (1984), who reported a average increase in oxygen consumption values of 5.2 and 9.4%, respectively, under similar conditions. These findings exemplify the greater energy cost, as indicated by oxygen consumption, of carrying added mass at the distal end of the segment as opposed to a more proximal location to the axes of rotation. Based on observations of various kinematic variables and mechanical work, the author credits the increased metabolic demand under loaded conditions to increases in mechanical work required by the active musculature.

Myers and Steudel (1985) also examined the effects of altering segmental mass distribution, but also included the addition of weight to the waist of their subjects, as an experimental condition. Their experimental conditions included: no load, a 3.6 kg load around the waist, and a 1.8 kg load around each upper thigh, each upper shank, and each ankle. Four subjects (3 male, 1 female), all in good physical condition and of similar body mass (range = 62-74 kg), participated in the study. In an attempt to control the movement and acceleration of the limbs and centre of mass, subjects were required to maintain a constant stride frequency throughout all loading conditions during each run. The authors expressed their findings as an average percentage increase over the rate of energy consumption in unloaded runs. Average increases were of the magnitude of 3.7, 9.4, 12.1, and 24.3% for the waist, thigh, shank, and ankle loading conditions, respectively. All comparisons between the waist loaded condition and the three limb loaded conditions were significantly different (W-T: $p<0.01$; W-S: $p<0.01$; W-A: $p<0.001$). These findings illustrate the effect of adding extra weight to the distal aspects of the limbs on the energy cost of running, but furthermore, indicate that the cost of adding weight to the centre of mass (waist) is significantly less than adding it to the limbs.

2.5.3 Running Speed and Economy

It is well documented that as running speed is increased, the rate of oxygen consumption ($ml.kg^{-1}.min^{-1}$) simultaneously and systematically increases. Furthermore, research has demonstrated the relationship between running speed and economy (VO_2) to be linear in nature (Daniels, 1985).

Magaria et al. (1963), in early work examining the energy cost of running, reported the net energy cost of running when expressed relative to distance travelled ($kcal.kg^{-1}.m^{-1}$), to be constant and independent of speed. Thus, the amount of energy required to travel a specific distance is nearly identical whether it is run at a competitive or a recreational pace. These authors estimated the net cost of running at approximately 1 $kcal.min^{-1}.km^{-1}$ during level running. Furthermore, they reported superior mechanical efficiency in running of the magnitude of 5 to 7% for the trained subjects, when compared to their untrained peers.

In his review, Daniels (1985) noted that the linear relationship between running speed and VO_2 during submaximal running, is characteristically met through aerobic metabolism and measured via a limited range of running speeds. When examining this relationship, Daniels et al. (1977) collected data through the use of a large range of running velocities (150 - 268 $m.min^{-1}$). Their group of subjects exhibited a large variation in the slope of the regression lines, dependent upon the speeds chosen for analysis. The regression curves produced from the slower speeds were flatter than their steeper counterparts calculated from faster speeds. The data appeared to be most linear when the subjects ran at speeds which were self-described as most comfortable (generally 200 $m.min^{-1}$ and above). In conclusion, Daniels (1985) suggested that a departure from linearity at slower speeds, as well as faster speeds requiring anaerobic metabolism, is a plausible hypothesis worthy of further investigation.

2.5.4 Stride Length and Running Economy

Numerous studies have demonstrated that a deviation from a natural self-selected running stride length at a given speed may lead to an increase in aerobic demand (Cavanagh & Williams, 1982;

Heinert et al., 1988; Högberg, 1952; Knuttgen, 1961; Powers et al., 1982). Under these stride length manipulation conditions, the aerobic demand of running increases in a curvilinear fashion. As stride length is either lengthened or shortened from the preferred gait, runners become less economical, as substantiated by the resultant U-shaped stride length/rate-economy response. Morgan and Martin (1986) have reported the same phenomenon in a racewalking economy study.

In an early case study, Högberg (1952) demonstrated that increasing or decreasing the stride length of a well trained runner, led to increases in the aerobic demand of running. Stride lengths and corresponding oxygen uptake values at freely chosen running kinematics were 135cm and 3.35 $l.min^{-1}$ and 149cm and 3.87 $l.min^{-1}$ for velocities of 14 and 16 $km.hr^{-1}$, respectively. At 14 $km.hr^{-1}$, shortening the stride length (119cm) lead to a 6.0% increase in oxygen consumption, while lengthening the stride (153cm) resulted in an 11.9% increase. Similarly, at 16 $km.hr^{-1}$ increases in oxygen consumption of the magnitude of 4.13% (4.031 $l.min^{-1}$) and 19.4% (4.52 $l.min^{-1}$) were recorded for the shortening and lengthening conditions, respectively. The author concluded that an increase in stride length resulted in a larger increase in oxygen consumption compared to a shortening condition. Furthermore, runners tend to have an optimal stride length and rate at various speeds.

In a later study, Knuttgen (1961), using two well-trained runners, reported data which was in agreement with that of Högberg

(1952). Like Högberg's subject, large deviations from a self-selected stride length were more costly than smaller ones. Furthermore, the author described an increase in stride length with a concurrent slight decrease in stride rate, as the means for adjusting to the faster running velocities.

Emphasizing the need to generalize the results of the two previous studies to a larger population, Cavanagh and Williams (1982) examined the effect of stride length variation in 10 male runners ($\bar{X}$ VO_2 max = 64.7 ± 5.6 $ml.kg^{-1}.min^{-1}$). At a constant speed of 3.83 $m.s^{-1}$ (7 $min.mile^{-1}$), the following seven stride length conditions (stride length expressed as a percentage of leg length) were used to determine oxygen consumption: a self-selected stride length, and six values deviated by ± 6.7, ± 13.4, and ± 20% of leg length from the freely chosen stride length. Several findings were reported by the authors. Small changes in stride length only had a minor effect on oxygen uptake. Oxygen demand increased substantially as stride length was varied considerably from optimal values. Leg length was not a good predictor of optimal stride length as indicated by a correlation of r = 0.09 between the two variables. A large variation existed between subjects on the effect of shortening or lengthening the stride length. In contrast to Högberg (1952) and Knuttgen (1961), lengthening of the stride length did not necessarily lead to greater increases in VO_2 when compared to a shortening condition and vice versa. The most interesting finding was a small mean absolute deviation of only 0.2 $ml.kg^{-1}min^{-1}$ in oxygen uptake from the predicted optimal velocity, when running at freely chosen gait patterns. This represented a mean inefficiency of only 0.5%. The authors concluded that well trained runners are more likely to perform with a stride length and frequency combination which closely matches their optimal condition, as assessed by economy measures.

To determine if the previous studies were applicable across gender, Powers et al. (1982) examined the effect of stride length manipulation in a group of 12 trained female runners ($\bar{X}$ VO_2 max = 49.0 ± 3.0 $ml.kg^{-1}.min^{-1}$). The authors investigated the effect of treadmill running on VO_2 consumption at a constant speed of 175 $m.min^{-1}$ with both a 15% increase and decrease from a freely chosen stride length. As reported by Cavanagh and Williams (1982), oxygen consumption was significantly lower ($p<0.05$) when subjects ran at their freely chosen stride when compared to both the longer and shorter imposed strides. Furthermore, oxygen consumption was not statistically different ($p>0.05$) when comparing the shorter versus the longer stride. The markedly different anatomical structures of male and females (i.e. pelvis width), did not seem to result in any differences in the response of oxygen consumption, when altering stride length 15% from the subjects' comfortable and freely chosen stride.

Because many long-distance races involve some degree of uphill and downhill running, Heinert et al. (1988) examined the effect of stride length changes during graded (4%) treadmill running at 230 $m.min^{-1}$. The effect on VO_2 of an 8% increase and decrease from a freely chosen stride length, in conjunction with both a level and

4% running grade was examined. Sixteen trained male subjects participated in the study ($\bar{X}$ VO_2 = 74.0 ± 4.4 $ml.kg^{-1}.min^{-1}$). The freely chosen stride lengths were greater at 0% than 4% grade (133.5 vs 131.5, $p<0.05$). As expected, significant oxygen consumption increases were reported across all three stride conditions when running with a 4% grade rather than on a level surface ($p<0.05$). The mean increases in oxygen consumption were 26.7, 27.1, and 25.2% for the shorter, chosen, and longer stride conditions, respectively. The increases in VO_2 for both altered stride conditions (± 8%) at both grades (0 and 4%) were significantly different ($p<0.05$) from the freely chosen condition. However, no significant differences were found between the short and long stride conditions ($p>0.05$). As reported by Cavanagh and Williams (1982) some variation existed between the subjects, as some subjects exhibited better economy with shorter or longer variations from their freely chosen stride length.

The literature leaves no doubt that runners who alter their stride length from a self-selected stride generally exhibit increases in VO_2. Although the exact mechanisms which may account for this decrease in economy are not known, several hypotheses have been suggested. They include poor foot placement during the running stride in relation to the centre of gravity, increased rates of muscular contractions resulting in increased energy expenditure, and inefficient recruitment of active muscle fibres (Powers et al., 1982). Clearly, future research should attempt to identify the exact mechanisms which are responsible for the economy response, and whether they are predominantly a rate-based or length-based experience.

To conclude this section on biomechanical factors and running economy, the available literature indicates that some structural and biomechanical variables significantly affect running economy. Despite the notable progress made in the understanding of this relationship, Martin and Morgan (1992, p. 472) stated that "the relationships that have been observed between economy and individual descriptors of body structural and gait mechanics have generally been weak and inconsistent from study to study".

2.6 A Review of Ice Hockey

A vast amount of literature is available documenting the physiological and biomechanical parameters of ice hockey. In his review of the physiology of ice hockey, Montgomery (1988) provides a thorough summary of the many facets of the sport. For practical purposes, this review will limit itself to a review of skating mechanics, the energetics of skating, the effect of added mass, and energy expenditure during a game.

2.6.1 Skating Mechanics

Marino and Weese (1979) described the ice skating stride as consisting of three distinct phases: glide during single support, propulsion during single support, and propulsion during double support. Observations based on university varsity players determined average stride duration at maximal velocity to be .283 seconds, and consisting of 82% single support time and 18% double support time (Marino & Weese, 1979).

The classic stride pattern begins with deceleration during the initial stage of the single support component. This initial phase consists of a glide period with deceleration due to the resistant forces of drag and friction (Marino & Weese, 1979). Approximately halfway through the single support phase, acceleration is initiated and is characterized by an outward rotation of the thigh, and extension of both the hip and knee (Marino & Weese, 1979). Halliwell (as cited in Montgomery, 1988) described the quadriceps muscle group as generating the largest contractile force during acceleration, with the hamstring and gastrocnemius acting as stabilizers. The predominant role of the quadriceps femoris in the hockey skating thrust was further exemplified by Halliwell and Rhodes (1979), who determined peak forces of 302, 124, and 54 kg for the quadriceps, hamstrings, and gastrocnemius muscle groups, respectively. The skating stride ends with a short double support period in which acceleration is continued with hyperextension of the hip, complete extension of the knee, and plantar flexion of the ankle.

Marino (1977) attempted to identify the effects of velocity on the different components of the skating stride. Skating velocity was increased from a mean slow speed of 3.75 to 6.13 and 6.92 $m.sec^{-1}$ for speeds described as medium and fast, respectively. The increase in skating velocity was accomplished by a significant increase in stride rate, and significant decreases in both single and double support times across all three speeds ($p<0.05$). On the other hand, no significant changes were discerned for stride length. The data indicated the importance of quicker strides at greater velocities with greater power applied per stride. Coefficient of determination revealed that nearly 60% of the variation in velocity could be attributed to variations in stride rate ($r = 0.76$), whereas the contribution of stride length was insignificant ($r = 0.05$). This finding is in contrast to running, where both stride rate and length play a significant role as velocity is increased (Högberg, 1952; Knuttgen, 1961). The existence of the glide phase in the skating stride may account for this marked difference between the two activities (Marino, 1977).

Later, Marino (1983) attempted to determine the significant mechanical factors associated with front skate acceleration in ice skating. The author examined the time required to skate a distance of 6.0 meters from a stationary position, as well as the final instantaneous velocity at completion of the task. Only the first three strides were used for analysis. Using a large heterogenous group of subjects ($n=69$), several significant correlations ($p<0.01$) were determined. As expected, a high correlation ($r = 0.93$) existed between acceleration over the 6.0m distance and final velocity. Based on the statistical analysis, significant determinants for the time required to skate the 6.0m distance were: single support time ($r = 0.33$), stride rate ($r = -0.37$), knee angle at push-off (r = -0.38), and lean angle at touchdown (r = 0.48). Final velocity was significantly correlated to the toe to hip distance at touchdown (r = -0.38). The author concluded that a stride pattern characterized by a high rate of acceleration and a minimum skating time from a static position includes : a high stride rate, significant forward lean at the point of landing of the recovery skate, short single support phases, and placement of the recovery skate almost directly below the body at the end of the single support period (Marino, 1983).

2.6.2 Energetics of Skating

In order to design a sport-specific protocol, Ferguson et al. (1969) developed a maximal oxygen uptake test which required its participants (n=17) to skate around a 140 meter oval course. Oxygen consumption was measured by an open-circuit gas collection apparatus. The testing protocol, which was progressive and discontinuous, consisted of three minute skating periods interspersed by five minute rest periods. The test consisted of velocities of 350, 382, 401, 421 and 443 $m.min^{-1}$, producing lap times of 24, 22, 21, 20 and 19 seconds, respectively. The velocities represented increases of 300 $ml.min^{-1}$ for each one second decrease in lap time. Subjects were expected to skate until volitional exhaustion.

Test-retest correlation was determined to be highly reliable (r = 0.94), with mean VO_2 max values of 54.7 ± 5.1 and 55.3 ± 5.8

$ml.kg^{-1}.min^{-1}$ for trials I and II, respectively. Based on the slope of the regression equations, heart rates (183 - 208 bpm), and minute ventilations (114 - 172 $l.min^{-1}$) obtained at the highest VO_2 values, most subjects would seem to have reached their maximum aerobic capacity. The relationship between VO_2 and submaximal skating velocity was linear, which is agreement with the running economy literature (Daniels, 1985).

Léger et al. (1979) examined the VO_2 max response of runners and hockey players on various maximal VO_2 max tests. The four testing protocols used were: continuous treadmill run, 20m shuttle skate with ($20m^+$) and without equipment ($20m^-$), and a 140m oval course (test of Ferguson et al., 1969). The study revealed several interesting findings. Runners had a greater mechanical efficiency on the treadmill than the hockey players, who in turn were more efficient on the ice surface. Mechanical efficiency is calculated by measuring the oxygen cost of skating or running at a set velocity:

$$\text{Efficiency} = \frac{\text{Velocity } (m.min^{-1})}{VO_2 \ (ml.kg^{-1}.min^{-1})} \times 100$$

The coefficient of variation of the VO_2 max scores for the hockey players on the 140m oval course was 15.1, compared to scores of 12.3 and 10.9% for the 20m shuttle skate test with and without equipment, respectively. The coefficient of variation of the mechanical efficiency of the runners on the treadmill (6.9%) was lower than that of hockey players on the three ice skating tests (140m = 14.0%, $20m^+$ = 10.3%, $20m^-$ = 9.8%). The high coefficient of variation of the mechanical efficiency of skating may be attributable to differences in skating skills amongst the hockey players. It is interesting to note that such a variation in skating skills exists despite the fact that all of the subjects played at the same competitive level (i.e. university hockey).

2.6.3 Effect of Added Weight

The detrimental effect of added weight on running economy has been well documented (Cureton & Sparling, 1980; Cureton et al., 1978). Expressing a lack of research, Montgomery (1982) constructed an experimental design similar to that of Cureton et al. (1978), to investigate the effect of added weight on skating performance. Using the Repeat Sprint Skate Test (RSS) developed by Reed et al. (1979), subjects (n=11) were tested under four conditions: normal body weight, 5% added body weight, 10% added body weight, and 15% added body weight. The added weight was securely fastened to the waist and shoulders of the subjects, and did not interfere with skating mobility. The weighted vest was designed to duplicate unnecessary adipose tissue or equipment weight. Results indicated a significant ($p<0.05$) decrease in both the speed and anaerobic endurance components of the test across all three added weight conditions, when compared to the normal body weight condition. No significant differences were noted in recovery heart rate across all four conditions since the subjects exercised at maximum intensity in each condition. The author concluded that surplus weight in the form of body fat or unnecessary equipment will negatively affect performance, since both speed and anaerobic endurance are critical factors in ice hockey playing performance (Green, 1978, 1979; Green et al., 1978a, 1978b; Montpetit et al., 1979). This study illustrates the benefits of playing at a leaner weight and with lighter protective equipment.

Léger et al. (1979) had previously demonstrated the potentially negative effect of skating with extra weight in the form of protective equipment. In their study, 10 subjects performed a 20m shuttle skating test wearing complete hockey equipment and without any equipment, with the exception of a helmet. Despite similar VO_2 max's (58.6 ± 6.4 vs 59.9 ± 7.4 $ml.kg^{-1}.min^{-1}$, $p>0.05$) for the equipment and no equipment conditions, respectively, the duration of the test was reduced by 20.3% (6.4 vs 5.1 minutes, $p<0.05$). Furthermore, the final skating speed (7 $m.min^{-1}$) was decreased by 2.9% ($p<0.5$) and skating mechanical efficiency by 4.8% ($p<0.05$) when skating with the 7.3 kg of equipment.

Chomay et al. (1982) examined the relationship between segmental mass distribution and performance in the RSS. Through experimental alterations in skate weight, the subjects (n=11) performed the test under three conditions: with normal skate weight, 227g of added weight to each skate, and 555g of added weight to each skate. As reported in the running economy literature by Catlin and Dressendorfer (1973), Jones et al. (1974), Martin (1985) and Myers and Steudel (1985), significant ($p<0.05$) decrements in performance were noted, as depicted by slower speed and anaerobic endurance times.

Hoshizaki et al. (1982), in investigating the effect of added mass and fatigue on the ice hockey skating pattern, required their subjects (n=11) to perform under three conditions: with normal skate weight, 448g of weight attached to each ankle, and 896g of weight attached to each ankle. Video analysis revealed that fatigue resulted in a decrease in stride velocity caused by a decrease in stride rate, with no accompanying decrease in stride length. This trend is in agreement with that reported by Marino (1977). Furthermore, fatigue induced strides were characterized by a slower extension of the leg and a larger gliding period.

2.6.4 Energy Expenditure During a Game

Because of the impracticality of gas collection materials to measure oxygen consumption during actual competitive games, little data are available on the topic. To help shed light on the subject, simulated "model" training games have been used (Seliger et al., 1972), as well as heart rate telemetry readings during actual competitive games (Green et al., 1976; Paterson, 1977).

Seliger et al. (1972) examined energy expenditure in 13 elite hockey players during one period of a model game. Each player had six shifts of approximately one minute duration separated by three minute rest periods. Following the last shift, 21 minutes of recovery were allotted after which oxygen samples were collected for analysis. Based on oxygen consumption during the last shift and the lengthened recovery period, they estimated the energy requirement of hockey to be met predominantly by anaerobic metabolism (69%), with some involvement from aerobic metabolism (31%). Oxygen consumption during the shift averaged 32.0 $ml.kg^{-1}.min^{-1}$, which represented 66% of VO_2 max during the simulated game.

This study has received criticism by some researchers (Green et al., 1976; Montgomery, 1988). Based on contemporary views of lactate metabolism and post-exercise VO_2, estimating anaerobic energy requirements from oxygen consumption measures may be misleading (Gaesser & Brooks, 1984). Anaerobic metabolism, but also various other factors which include catecholamine concentration, circulating fatty acids, calcium ions, increased body temperature (Q_{10} effect), and substrate cycling are all believed to have an indirect effect on post-exercise VO_2 consumption (Gaesser & Brooks, 1984). This methodological flaw may have underestimated the role of aerobic metabolism in ice hockey (Montgomery, 1988).

Green et al. (1976) attempted to estimate the relative contribution of the anaerobic and aerobic energy systems during an actual university varsity hockey game. The authors utilized heart rate telemetry readings recorded during a game on eight subjects. By comparing the game heart rate readings to those obtained during a laboratory treadmill VO_2 max test, it was estimated that the subjects averaged 87 to 92% of their maximal heart rate. Based on the linear HR/VO_2 relationship, average on-ice energy requirements were estimated at 70 to 80% of VO_2 max. Utilizing the same experimental protocol as Green et al. (1976), Paterson et al. (1977) estimated the energy expenditure and aerobic and anaerobic involvement of ice hockey, in 28 ten year old boys. These authors estimated the average on-ice heart rate values at 185 bpm, or 93.5% of maximal values. These figures indicate that the youngsters were playing at an average intensity of approximately 85% of their VO_2 max. However, the authors point out the inherent dangers of using heart rate readings to estimate energy expenditure during nonsteady-state work performed on an intermittent basis, such as in ice hockey (Paterson et al., 1979).

Although beyond the scope of this review, other methods which have been used to estimate energy expenditure and/or exercise intensity during a hockey game include: time motion analysis (Thoden & Jetté, 1975), muscle glycogen depletion patterns (Green, 1978), and lactate accumulation measures (Green et al., 1978b). Based on the available literature, ice hockey may be described as an intermittent, high intensity activity, requiring optimal development of both the athlete's aerobic and anaerobic systems.

Chapter III

Methods and Procedures

3.1 Subjects

A total of 13 subjects volunteered for this study. The subjects were all male varsity athletes from the McGill University Hockey Team. The age of the subjects ranged from 18 to 24 years, with playing experience ranging from first to fifth year players.

3.2 Treatment of Subjects

Prior to testing, the subjects were informed of the experimental procedure and the inherent risks of each test. After briefing, the subjects signed an individual consent form (Appendix B) confirming their willingness and physical readiness to perform the tests, as well as their understanding of the procedures and related risks.

Each subject participated in two testing sessions within a three week span, at the half-way mark of the season. The first testing session was conducted in the McGill University Human Performance Laboratory, while the second testing session was conducted on-ice at the McGill University McConnell Arena.

The subjects were asked to refrain from eating, smoking, and drinking (except water), for two hours prior to each testing session, and to present themselves well rested. To standardize the procedures, each subject performed a warm-up consisting of stretching and a light jog/skate prior to testing. The subjects were refamiliarized with the experimental procedure prior to each test. Personnel were available for trouble shooting during the procedures, to record data, and to provide verbal feedback and encouragement to enhance maximal performance.

3.3 Laboratory Testing Protocol

Body composition and maximal oxygen uptake (VO_2 max) values were collected for each subject as folows.

3.3.1 Body Composition

The height and weight of each subject was determined with the subject dressed in shorts and socks. Standing height was measured to the nearest 0.5cm using a wall mounted stadiometer. Body weight was determined using a balance beam medical scale (Detecto Scales Inc.), and recorded to the nearest kilogram. Five skinfolds (triceps, biceps, subscapular, iliac crest, and medial calf) were assessed using the procedure outlined in the Canadian Standard Test of Fitness Operations Manual (1986) using a Harpenden caliper. The results were recorded as the sum of the five skinfolds.

3.3.2 Treadmill VO_2 max Test

VO_2 max, VE max, and heart rate max were determined using a continuous, progressive loading running protocol. Prior to the VO_2 max test, a brief treadmill accommodation bout was performed to familiarize the subjects with the treadmill and to serve as a warm-up.

The protocol began with a brisk horizontal walking pace (4 mph), and was subsequently increased every two minutes until a maximal running speed of 8 mph was attained. Afterwards, while maintaining a steady running pace, treadmill inclination was increased two degrees every two minutes until achievement of maximal oxygen consumption. VO_2 max was generally attained between minutes 12 to 17. The protocol is outlined in Table 2.

Table 2 Treadmill VO_2 max Protocol.

Time (min)	Speed (mph)	Speed ($m.min^{-1}$)	Inclination (degrees)
0 - 2	4	106.7	0
2 - 4	6	160.0	0
4 - 6	8	213.3	0
6 - 8	8	213.3	2
8 - 10	8	213.3	4
10 - 12	8	213.3	6
12 - 14	8	213.3	8
14 - 16	8	213.3	10
16 - 18	8	213.3	12

Subjects were required to run until volitional exhaustion, at which point they terminated the test by straddling the treadmill belt. Peak VO_2 was determined as the highest minute value attained for VO_2 during the maximal exercise. Heart rate and respiratory exchange ratio were monitored throughout the test to confirm attainment of VO_2 max.

3.4 <u>On-ice Skating Economy Test</u>

The on-ice skating economy test took place on a 140 meter oval course set up on a regulation size hockey surface (200ft X 85ft). The arena air temperature was a constant -4°C throughout the entire testing period. Ten cones were strategically placed at an equidistant 14 meters apart to delineate the course. To measure oxygen uptake, subjects were required to skate at velocities of 336, 357, and 381 $m.min^{-1}$, which corresponded to lap times of 25, 23.5, and 22 seconds, respectively. The skater's velocity was controlled via an audio tape system. For each velocity, an audio signal was emitted at a rate of five signals per lap. The subjects monitored their pace according to the audio signal, and were expected to synchronize their speed with every second cone. If the subject was ahead or behind the cone at the signal, the speed was adjusted to match the desired velocity. By the second lap of skating, the subjects were usually right on pace and rarely varied by more than ± one stride. The ice surface was flooded anew following every second subject.

Each testing session began with a resting blood lactate measure and was followed by a review of the procedures while the subject warmed up. A skate sharpening machine was available in the event that blade sharpening adustments were required prior to testing. The subject was then fitted with the gas collection apparatus which included: a 3-way respiratory valve with mouthpiece, headgear, plastic tubing, nose clip, and neoprene Douglas bag. The subject skated with a hockey stick, hockey gloves and a properly fitted athletic suit. Only Bauer 3000 and Micron Mega 10-90 skate models were used by the subjects throughout the skating bouts. The weight of each skate model as reported by the manufacturer was 1054.6 and 1052.9g for the Bauer 3000 and Micron 10-90 models, respectively. The subjects were required to skate for four minutes, at which point a steady-state was assumed to have been achieved. The on-ice instructor indicated the four minute mark to the subject, who would then adjust the respiratory valve to direct air flow into the Douglas bag. Following the required gas collection time, the on-ice instructor signalled the subject to turn the valve again, returning expired air to the atmosphere. For the two slowest velocities (336 and 357 $m.min^{-1}$), gas samples were collected from minute four to five. At a velocity of 381 $m.min^{-1}$, gas samples were collected for 30 seconds from the four minute mark. Each skating bout was interspersed by a five minute rest period in the dressing room. Two minute post-exercise fingertip blood lactate samples were drawn after each velocity. Each subject's heart rate was monitored throughout the duration of the on-ice skating economy test.

3.5 Collection of Data

3.5.1 VO_2

A Collins treadmill with variable speed and grade was used for the VO_2 max test. Both the treadmill speed and grade were set by electronic remote control and verified by a meter counter. Subjects wore a traditional lightweight plastic headpiece apparatus that supported a mouthpiece, turbine, one-way valves, and a low resistance flexible hose. Subjects wore a noseclip during the test. Volume of inspired air was measured to the nearest tenth of a litre by a low resistance turbine, which conveys electrical signals to a Morgan ventilometer. Expired air was analyzed in an 8.5 litre mixing chamber of a Roxon Metabolic Cart. Applied Electrochemistry oxygen and carbon dioxide analyzers continuously sampled the contents of the mixing chamber. All of the gas moisture was removed by drierite. Standard gases were used prior to each test to calibrate the gas analyzers. Percent oxygen and carbon dioxide were measured to the nearest one-hundredth of a percentage point. An Apple IIe microcomputer, using S & M Instruments Company (1983) software, calculated VE, VO_2, VCO_2, and RQ. The expired air measurements were analyzed every thirty seconds and displayed on an Okidata micro-82A printer.

On-ice oxygen consumption was measured using an open-circuit gas collection apparatus. The same lightweight plastic headpiece was used as in the VO_2 max test, with the exception of a 3-way respiratory valve system. The respiratory valve was adjustable and securely held in place to the headpiece. The valve was connected to a 100 litre neoprene Douglas bag. The Douglas bag was firmly fastened to the subject's back with a velcro and belt system. The gas collection apparatus was designed to minimize wind resistance and did not interfere with the fluid skating movements of the subjects.

While skating prior to attainment of a steady-state VO_2, the respiratory valve was set to direct expired air to the atmosphere. During gas collection, the subjects turned the valve, rerouting the expired air into the Douglas bag. Upon completion of the gas collection period, the bag was removed, sealed, and left to reach room temperature. The gas volume was measured with a Parkinson-Cowan dry gasometer and then directed into the Roxon Metabolic Cart for oxygen and carbon dioxide analysis. The gasometer was calibrated using a Tissot tank.

3.5.2 Heart Rate

The subjects' heart rates were monitored continuously using a Polar Electro Sport Tester (model PE 3000). The accessory consists of a watch type receiving unit worn around the wrist, and a telemetry transmission unit strapped to the subjects chest at heart level. Maximal heart rate was recorded for the VO_2 max test.

During the on-ice skating test, heart rates were recorded throughout the test duration, and stored in the memory of the receiving unit. Upon completion of each skating bout, the mean steady-state heart rate was reported in beats.min^{-1}.

3.5.3 Blood Lactate

Peripheral fingertip blood samples were drawn during recovery between skating bouts. Blood sample sizes of 50-100 ul were drawn using an Ames Glucolet with Monolet sterile lancets, and collected in heparinized capillary tubes. No storage or erythrocyte lysing agents were used. Whole blood samples were injected with a 25 ul syringepet into a YSI (Yellow Springs Analyzer) Model 27 industrial L-lactate analyzer. The apparatus employed an enzyme electrode method, described by Clark et al. (1984), for lactate analysis. Duplicate, and when needed, triplicate analysis were made from each blood sample. The instrument was calibrated prior to each testing session using 5.0 mmol and 15.0 mmol standards.

3.5.4 Stride Rate and Stride Length

Kinematic data were collected for each subject at every skating velocity. A stride was defined as the full skating cycle of one skate, from push-off of one skate to push-off of the other skate. This methodology ensured that all three components of the skating stride were involved. Stride rate was counted for three complete turns of the circuit once the subject had synchronized his skating velocity with the prescribed pace. Data were recorded as the mean stride rate per lap for the three laps, and converted into the number of strides per minute. Stride length was calculated as: Stride length = Velocity ($m.min^{-1}$) ÷ Stride Rate ($strides.min^{-1}$).

3.6 Experimental Design and Statistical Analysis

The independent variable under study was skating velocity, reported in meters per minute ($m.min^{-1}$). The dependent variables being examined were: VO_2 ($ml.kg^{-1}.min^{-1}$), heart rate (bpm), blood lactate concentration ($mmol.l^{-1}$), stride rate ($strides.min^{-1}$) and stride length ($m.stride^{-1}$). The experimental design for hypotheses 1.4.1, 1.4.2 and 1.4.3 is outlined in Table 3.

3.6.1 Descriptive Statistics

The mean, standard deviation, range, and standard error of the mean were recorded for height, weight, and sum of five skinfolds. Descriptive statistics were also calculated for the following dependent variables: VO_2, blood lactate, heart rate, stride rate, and stride length. The coefficient of variation was calculated to determine the interindividual variability. Tabular and graphic representation of all pertinent variables was used where appropriate.

3.6.2 Linear Regression Analysis

Linear regression analysis of skating economy at the three submaximal velocities (336, 357, and 381 $m.min^{-1}$) was performed between skating velocity and submaximal VO_2. Linear regression was also calculated between velocity and both stride rate and length.

3.6.3 Validity

In an attempt to determine if skating economy measures were related to skating ability, a Spearman rank order correlation was calculated between the head coach's subjective rating of each players skating ability with the results from the skating economy measure. The coach was unaware of the purpose of the rating in the present study and was instructed to rank each player according to his assessment of forward skating ability only. The assessment was based on the following five components of the forward skate: stance, extension of the hip, knee, and ankle in a lateral thrust, recovery of the propelling leg, use of arms, and overall fluidity of motion (as described by Canadian Hockey Amateur Association, 1986).

Table 3 Experimental Design for Hypotheses 1.4.1, 2 and 3.

	Velocity ($m.min^{-1}$)		
Subjects	336	357	381
1			
2			
3			
.			
.			
.			
13			

Table 4 Summary of Research Hypotheses and Statistical Analyses.

Research Hypothesis	Statistical Analysis
1. There will be a significant linear relationship between oxygen uptake and submaximal skating velocity.	Linear regression analysis
2. There will be a significant linear relationship between skating velocity and stride rate.	Linear regression analysis
3. There will not be a significant relationship between skating velocity and stride length.	Linear regression analysis
4. The interindividual variability in oxygen uptake of skating will be greater than that of running economy.	Coefficient of variation
5. There will be a significant relationship between skating economy and skating ability.	Spearman rank order correlation

Chapter IV

Results

The purpose of this study was to describe skating economy in terms of physiological and simple kinematic variables. The dependent variables under study were: oxygen uptake, blood lactate, heart rate, stride rate, and stride length.

Tables 5 through 11 provide descriptive statistics for the physical characteristics of the subjects, treadmill VO_2 max test, and the five dependent variables across all three skating velocities (where applicable). The descriptive statistics for all the tables include measures for the mean, standard deviation (SD), standard error of the mean (SEM), and range.

4.1 Subject Characteristics

Among the 13 members of the McGill University Varsity Redmen Hockey Team, the mean age, height, weight, and sum of five skinfolds were 20.9 years, 179.7 cm, 79.9 kg, and 40.0 mm, respectively. Descriptive statistics of the physical characteristics of the subjects are presented in Table 5.

Table 5 Physical Characteristics of the Subjects.

Subject	Age (yrs)	Height (cm)	Weight (kg)	Sum of Skinfolds (mm)
1	20	185.0	81.0	41.3
2	20	170.0	70.0	27.0
3	21	175.0	75.0	38.7
4	21	178.0	80.0	31.1
5	20	178.0	83.0	47.8
6	18	180.0	78.0	40.1
7	23	194.0	97.0	48.9
8	24	176.0	84.0	36.2
9	19	183.0	75.0	42.2
10	23	174.5	75.0	31.4
11	22	180.0	87.0	53.0
12	19	178.0	73.0	40.6
13	22	185.0	81.0	41.2
MEAN	20.9	179.7	79.9	40.0
SD	1.8	6.0	7.0	7.4
SEM	0.5	1.7	1.9	2.1
MIN	18	170.0	70.0	27.0
MAX	24	194.0	97.0	53.0

4.2 Treadmill VO_2 max Data

Individual results for the treadmill VO_2 max test are presented in Table 6. Maximal oxygen uptake (VO_2 max) was measured as the peak minute VO_2 value during the maximal treadmill test. Maximum heart rate (beats per minute) represents the highest heart rate recorded during the maximal aerobic test. Time (minutes) represents the time on the treadmill from the initiation of the maximal aerobic test until volitional exhaustion. The mean VO_2 max, heart rate, and time on treadmill were 60.5 $ml.kg^{-1}.min^{-1}$, 195 bpm, and 14.2 minutes, respectively.

Table 6 Treadmill VO_2 max Test.

Subject	VO_2 max ($l.min^{-1}$)	VO_2 max ($ml.kg^{-1}.min^{-1}$)	VE max ($l.min^{-1}$)	HR max (bpm)	Time (min)
1	5.25	64.8	167.5	202	16.0
2	4.93	70.3	137.8	190	17.0
3	5.02	66.9	147.7	193	15.0
4	4.14	51.8	118.8	191	13.0
5	4.84	58.3	146.9	205	14.0
6	4.44	56.9	134.8	200	14.0
7	5.60	57.9	145.6	185	12.5
8	4.79	57.0	162.1	190	14.0
9	4.86	64.8	140.5	205	15.0
10	4.27	56.9	125.9	198	12.5
11	5.05	60.3	134.7	186	13.0
12	4.64	63.5	139.7	205	16.0
13	4.71	57.4	139.9	186	12.5
MEAN	4.81	60.5	141.7	195	14.2
SD	0.39	5.1	13.1	8	1.5
SEM	0.11	1.4	3.6	2.2	0.4
MIN	4.14	51.8	118.8	185	12.5
MAX	5.60	70.3	167.5	205	17.0

4.3 Descriptive Statistics of the Skating Economy Test

The descriptive statistics used to describe skating economy in terms of physiological and simple kinematic variables in ice hockey players are presented in this section.

4.3.1 Skating Economy Data

Skating economy data for the experimental velocities of 336, 357, and 381 $m.min^{-1}$ are presented in Tables 7 through 9. For each velocity, VO_2 is presented in both absolute ($l.min^{-1}$) and relative ($ml.kg^{-1}.min^{-1}$) terms. Heart rate is reported in beats per minute (bpm). The mean VO_2's for velocities of 336, 357, and 381 $m.min^{-1}$ were 38.6, 44.4, and 55.2 $ml.kg^{-1}.min^{-1}$, respectively. Mean heart rate values for the three submaximal skating velocities were 161, 172, and 180 bpm, respectively.

4.3.2 Blood Lactate Data

Blood lactate concentration values are reported in Table 10. Lactate concentrations were analyzed at all three skating velocities and are reported in millimoles per litre ($mmol.l^{-1}$). Mean lactate concentration values for skating velocities of 336, 357 and 381 $m.min^{-1}$ were 2.17, 3.19, and 4.04 $mmol.l^{-1}$, respectively. Mean resting blood lactate was 1.67 $mmol.l^{-1}$.

Table 7 Skating Economy at 336 meters per minute.

Subject	VO_2 ($l.min^{-1}$)	VO_2 ($ml.kg^{-1}.min^{-1}$)	HR (bpm)
1	3.65	45.1	164
2	2.87	40.9	160
3	3.06	40.8	145
4	2.60	32.5	160
5	3.00	36.1	162
6	3.55	45.6	174
7	3.59	37.1	169
8	2.78	33.1	144
9	2.33	31.0	173
10	3.44	46.5	159
11	3.22	38.5	161
12	2.25	30.8	165
13	3.64	44.4	162
MEAN	3.08	38.6	161
SD	0.49	5.7	9
SEM	0.14	1.6	2.5
MIN	2.25	30.8	144
MAX	3.65	46.5	174

Table 8 Skating Economy at 357 meters per minute.

Subject	VO_2 $(l.min^{-1})$	VO_2 $(ml.kg^{-1}.min^{-1})$	HR (bpm)
1	4.16	51.3	173
2	2.94	41.9	165
3	3.90	52.0	161
4	3.29	41.1	173
5	3.34	40.2	174
6	3.98	51.1	185
7	4.01	41.5	181
8	3.51	41.8	152
9	2.61	34.8	183
10	3.51	47.5	170
11	3.72	44.5	171
12	2.91	39.9	173
13	4.01	49.0	174
MEAN	3.53	44.4	172
SD	0.49	5.3	9
SEM	0.14	1.5	2.5
MIN	2.61	34.8	152
MAX	4.16	52.0	185

Table 9 Skating Economy at 381 meters per minute.

Subject	VO_2 ($l.min^{-1}$)	VO_2 ($ml.kg^{-1}.min^{-1}$)	HR (bpm)
1	5.25	64.9	177
2	3.69	52.6	172
3	4.21	56.2	174
4	4.42	54.6	181
5	5.00	60.2	183
6	4.37	56.0	189
7	4.68	48.4	187
8	3.75	44.7	162
9	4.35	58.0	189
10	4.32	58.3	177
11	4.88	58.4	184
12	3.93	53.9	182
13	4.24	51.7	183
MEAN	4.39	55.2	180
SD	0.47	5.2	8
SEM	0.13	1.4	2.2
MIN	3.69	44.7	162
MAX	5.24	64.9	189

Table 10 Blood Lactate Concentration ($mmol.l^{-1}$) at Rest and at Three Skating Velocities.

	Velocity ($m.min^{-1}$)			
Subject	Rest	336	357	381
1	1.83	2.41	3.85	5.17
2	1.88	2.43	3.63	5.08
3	2.03	2.04	3.29	4.83
4	1.50	1.24	2.85	4.52
5	1.78	2.09	3.34	4.22
6	1.27	3.61	4.72	5.23
7	1.60	2.04	2.77	3.19
8	1.12	1.27	1.66	1.69
9	2.04	2.04	2.65	3.04
10	1.76	2.73	3.20	3.73
11	0.88	2.17	3.47	4.71
12	2.16	2.16	2.92	3.67
13	1.81	2.01	3.17	3.50
MEAN	1.67	2.17	3.19	4.04
SD	0.38	0.60	0.71	1.04
SEM	0.11	0.17	0.20	0.29
MIN	0.88	1.24	1.66	1.69
MAX	2.16	3.61	4.73	5.23

4.3.3 Kinematical Data

Stride rate and stride length data for all three skating velocities are presented in Table 11. Stride rate is reported as the number of strides performed in one minute ($strides.min^{-1}$), whereas stride length depicts the length in meters of one stride ($m.stride^{-1}$). A stride was defined as the time of push-off of one skate to push-off of the other skate.

4.4 Coefficient of Variation of the Submaximal Oxygen Uptake Data

The coefficient of variation (%) in oxygen uptake for the three submaximal skating velocities is presented in Figure 1. The coefficient of variation is the ratio of the standard deviation to the sample mean, and is a statistical description of interindividual variability. Coefficient of variation values for velocities of 336, 357, and 381 $m.min^{-1}$ were 14.8, 11.9, and 9.4%, respectively.

Table 11 Kinematical Analysis of Skating at Three Velocities ($m.min^{-1}$).

	Stride Rate ($stride.min^{-1}$)			Stride Length ($m.stride^{-1}$)		
	336	357	381	336	357	381
Subject						
1	81.6	87.1	102.0	4.1	4.1	3.7
2	81.6	96.9	108.9	4.1	3.7	3.5
3	81.6	86.7	98.0	4.1	4.1	3.9
4	86.4	76.5	98.0	3.9	4.7	3.9
5	86.4	86.7	92.5	3.9	4.1	4.1
6	91.2	96.9	108.9	3.7	3.7	3.5
7	72.0	81.6	92.5	4.7	4.4	4.1
8	76.8	86.7	92.5	4.4	4.1	4.1
9	67.2	76.5	87.1	5.0	4.7	4.4
10	72.0	81.6	98.0	4.7	4.4	3.9
11	72.0	76.5	81.6	4.7	4.7	4.7
12	76.8	81.6	92.5	4.4	4.4	4.1
13	81.6	91.8	103.4	4.1	3.9	3.7
MEAN	79.0	85.2	96.6	4.4	4.2	4.0
SD	7.0	7.0	8.0	0.4	0.3	0.3
SEM	1.9	1.9	2.2	0.1	0.1	0.1
MIN	67.2	76.5	81.6	3.7	3.7	3.5
MAX	91.2	96.9	108.9	5.0	4.7	4.7

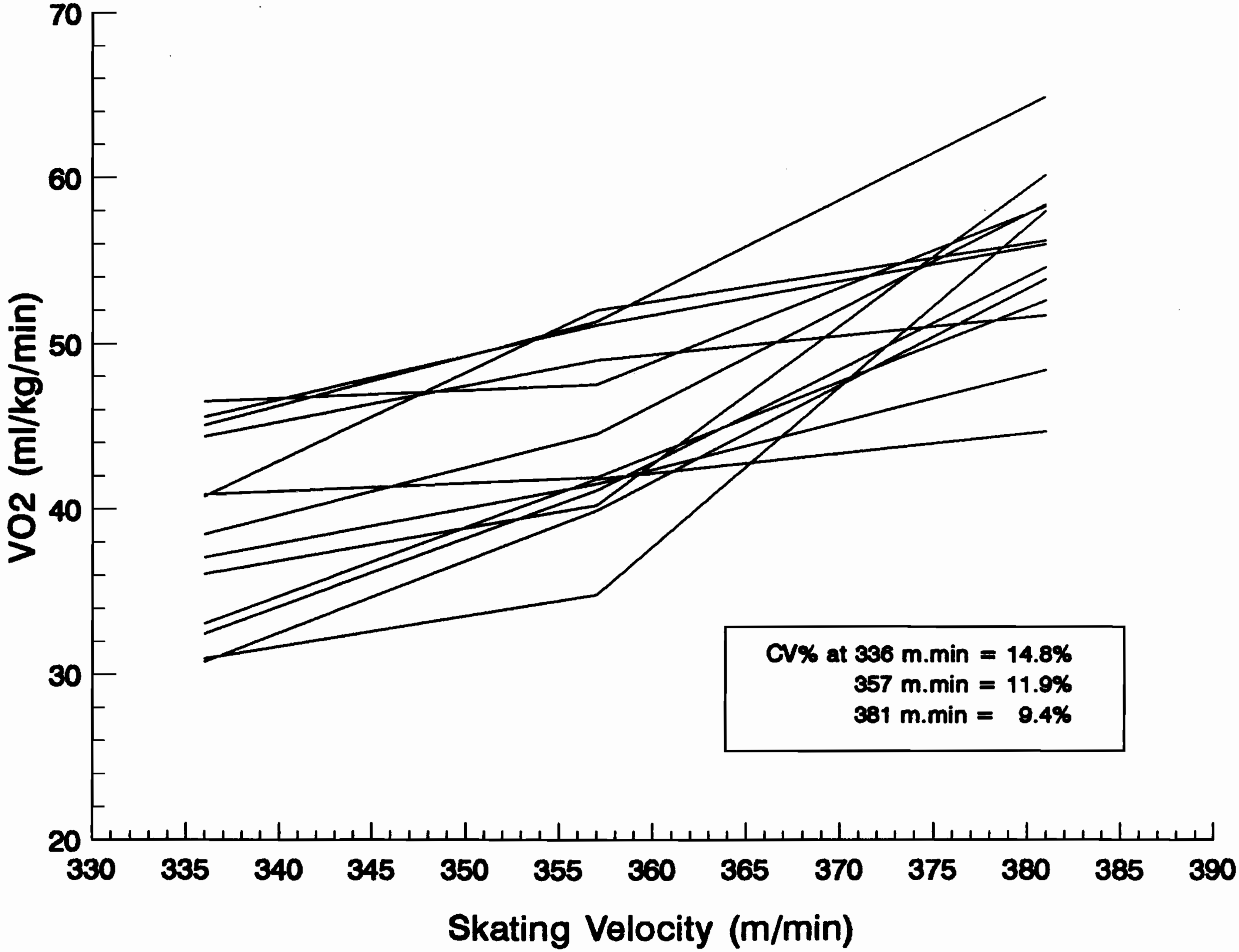

Figure 1 Relationship between velocity and oxygen uptake (VO2) at three skating velocities.

4.5 Linear Regression Analyses

The linear regression analysis of skating velocity and oxygen uptake at the three experimental velocities is presented in Figure 2. The relationship between the two variables is represented by the formula:

$$Y = 0.370X - 86.520$$

where Y = oxygen consumption ($ml.kg^{-1}.min^{-1}$)

X = velocity ($m.min^{-1}$)

The standard error of estimate is 5.44 ($ml.kg^{-1}.min^{-1}$).

A significant correlation ($p<0.01$) of $r = 0.79$ was determined between the two variables.

The linear regression analysis of skating velocity and stride rate is presented in Figure 3. The relationship between the two variables is represented by the formula:

$$Y = 0.393X - 53.757$$

where Y = oxygen consumption ($ml.kg^{-1}.min^{-1}$)
X = stride rate ($m.stride^{-1}$)

The standard error of estimate is 7.31 ($ml.kg^{-1}.min^{-1}$).

A significant correlation ($p<0.01$) of $r = 0.71$ was determined between the two variables.

The linear regression analysis of skating velocity and stride length is presented in Figure 4. The relationship between the two variables is represented by the formula:

$$Y = -0.007X + 6.766$$

where Y = oxygen consumption ($ml.kg^{-1}.min^{-1}$)
X = stride length ($m.stride^{-1}$)

The standard error of estimate is 0.36 ($ml.kg^{-1}.min^{-1}$).

A significant correlation ($p<0.05$) of $r = -0.36$ was determined between the two variables.

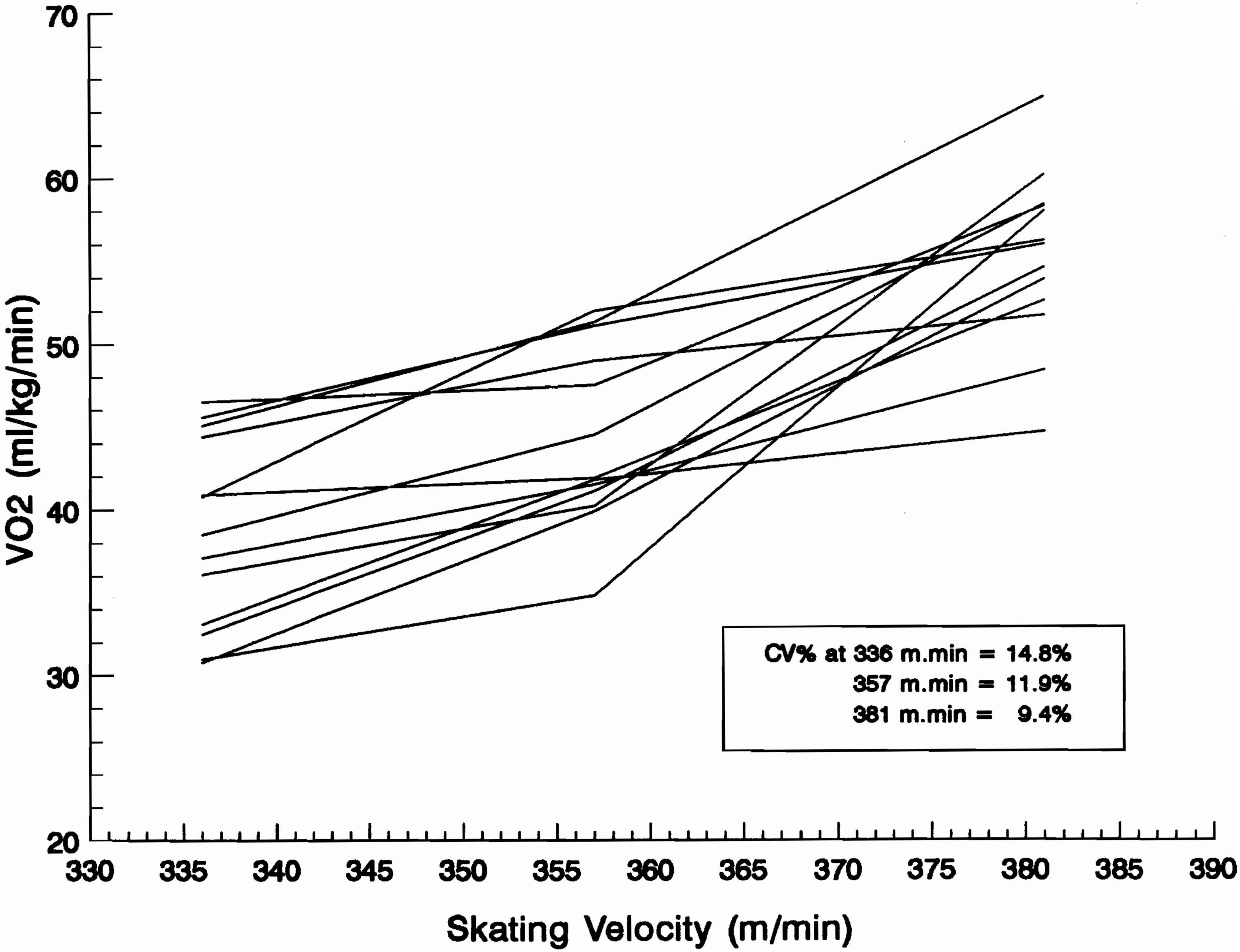

Figure 1 Relationship between velocity and oxygen uptake (VO2) at three skating velocities.

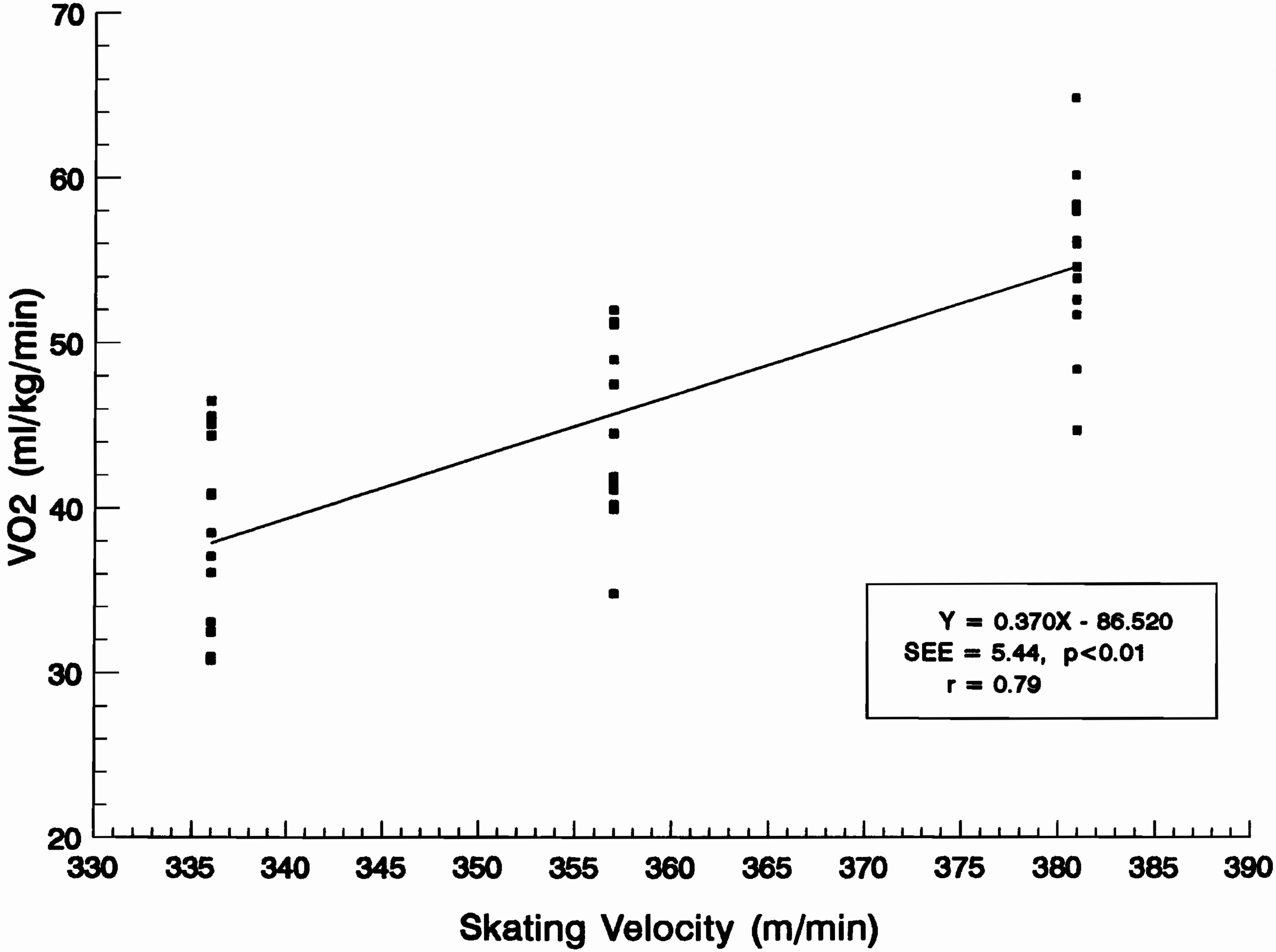

Figure 2 Linear regression analysis of velocity and oxygen uptake (VO2) at three skating velocities.

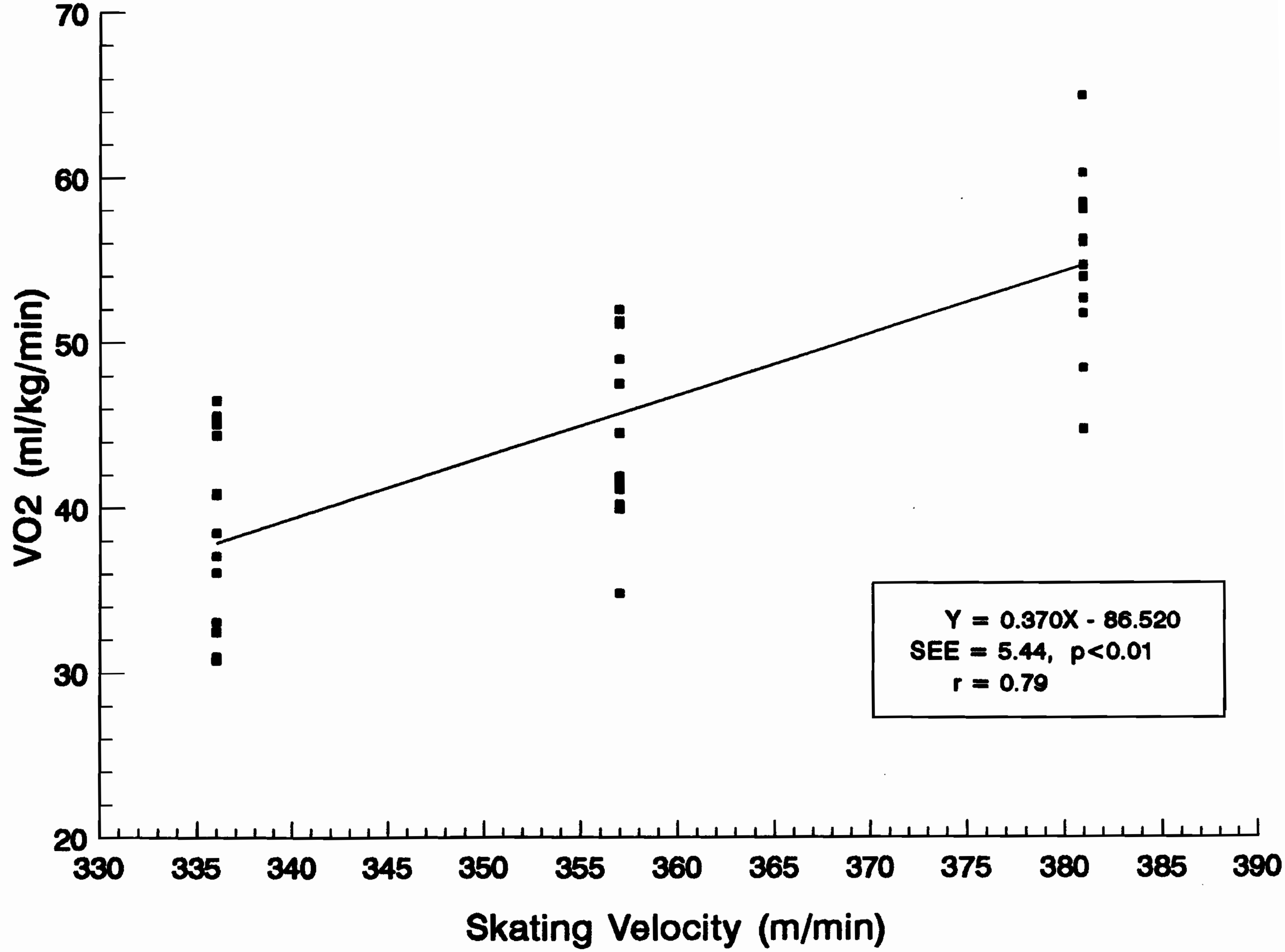

Figure 2 Linear regression analysis of velocity and oxygen uptake (VO2) at three skating velocities.

4.6 Spearman Rank Order Correlation of Skating Economy and Skating Ability

The Spearman rank order correlation analyses data are presented in Table 12. The coach's subjective rating of each player's skating ability as well as their mechanical efficiency (economy) ranking is presented. Lower oxygen consumption values are representative of a more efficient skating style, and are therefore indicated by a better ranking. The Spearman rank order correlations for velocities of 336, 357, and 381 $m.min^{-1}$ were 0.21, 0.10, and 0.29, respectively. The Spearman rank order correlation across all three velocities was 0.30. None of the four correlations was significant ($p>0.05$).

Table 12 Spearman Rank Order Correlation Between Skating Economy ($ml.kg^{-1}.min^{-1}$) and Skating Ability.

Subject	Skating Ability Rating	Economy Rank (336)	Economy Rank (357)	Economy Rank (381)	Overall Economy Rank
1	11	11	12	13	13
2	7	9	7	4	6
3	6	8	13	8	10
4	1	3	4	6	5
5	12	5	3	12	7
6	13	12	11	7	12
7	3	6	5	2	4
8	5	4	6	1	1
9	10	2	1	9	2
10	4	13	9	10	11
11	2	7	8	11	8
12	8	1	2	5	3
13	9	10	10	3	9
r		0.21	0.10	0.29	0.30

4.7 Testing of Research Hypotheses

Linear regression analyses were calculated to test hypotheses 1, 2, and 3. A Spearman rank order correlation was calculated to test research hypothesis 5. The results supported hypotheses 1 and 2, but did not support hypotheses 3 and 5. Results of the research hypotheses testing are presented in Table 13.

Table 13 Results of Research Hypotheses Testing.

Research Hypotheses	Results of Statistical Analyses
1. There will be a significant linear relationship between oxygen uptake and submaximal skating velocity.	$r = 0.79$, $p<0.01$
2. There will be a significant linear relationship between skating velocity and stride rate.	$r = 0.71$, $p<0.01$
3. There will not be a significant relationship between skating velocity and stride length.	$r = -0.36$, $p<0.05$
4. The interindividual variability in oxygen uptake of skating will be greater than that of running economy.	CV% at 336 = 14.8% CV% at 357 = 11.9% CV% at 381 = 9.4% (see discussion)
5. There will be a significant relationship between skating economy and skating ability.	336 $m.min^{-1}$, $r = 0.21$ 357 $m.min^{-1}$, $r = 0.10$ 381 $m.min^{-1}$, $r = 0.29$ $p>0.05$

CHAPTER V

Discussion

It has been demonstrated that running economy is a reliable predictor of endurance running performance, particularly among individuals of similar VO_2 max (Morgan et al., 1989b). On the other hand, no data on skating economy exist in the ice hockey literature. Therefore, the purpose of this study was to describe skating economy in a group of university ice hockey players and to establish a possible relationship between skating economy and skating ability.

5.1 Subject Characteristics

The hockey players in this study were similar in age to those reported in previous studies. The present subjects were taller and heavier than the subjects in studies dating prior to 1986 (Green et al., 1976; Green et al., 1979; Jones & Green, 1984; Romet et al., 1978; Song et al., 1979), and of similar stature to those of more recent studies (Gamble & Montgomery, 1986; Koziris, 1991; Montgomery et al., 1990). The mean value of 79.9 kg found in this study is indicative of the trend in recent years to ice bigger hockey players. The hockey players comprising of the professional hockey team are taller and heavier than the present subjects, which is typical of the ice hockey literature (Montgomery, 1988).

Appendix C permits a comparison of the mean physical characteristics of the subjects in the present study, with those of previous studies using hockey players from the Canadian University level. Also included in the table for comparison purposes are recent data on the physical characteristics of a professional hockey team (NHL).

The sum of five skinfolds (40.0 mm) for the present group of hockey players placed them at the 60^{th} percentile among Canadian males of similar age (CSTF, 1986). The typical Canadian hockey player, when compared to elite athletes in other sports, tends to carry some excess fat weight (Marcotte & Hermiston, 1975; Montgomery, 1988). The excess adipose tissue may be beneficial in the form of extra protection during the frequent collisions with opponents and boards, characteristic of elite hockey games.

5.2 <u>Maximum Oxygen Uptake</u>

The mean treadmill and on-ice VO_2 max value of 60.5 $ml.kg^{-1}.min^{-1}$ recorded for the present group of subjects, is higher than most of the average figures reported in the literature. The high VO_2 max value of the study group may be attributable to the implementation of a year-round strength and conditioning program. Because of the intermittent nature of ice hockey and its high glycolytic involvement, a well developed aerobic system may facilitate ATP and CP resynthesis following bouts of intense skating activity, characteristic of elite level hockey games.

The measurement of VO_2 max permitted to calculate average submaximal oxygen uptakes of 65, 75, and 90% of VO_2 max for the experimental skating velocities of 336, 357, and 381 $m.min^{-1}$, respectively.

The mean maximum laboratory oxygen uptake value collected in this study is compared with those reported in the literature in Appendix D. The mean maximum on-ice oxygen uptake value is also presented, along with available comparisons. All of the data is from studies involving Canadian University hockey players.

5.3 Blood Lactate Concentration

Only a handful of studies have examined blood lactate accumulation patterns in Canadian University ice hockey players during skating tasks. Blood lactate concentration values have typically been examined through either competitive hockey games (Green et al., 1978a) or various maximal (Léger et al., 1979) and submaximal (Daub et al., 1983) skating tasks.

Despite the limited number of studies, results have been consistent throughout. Mean blood lactate concentration values have ranged from 2.2-4.1, 4.2-6.8, and 10.7-14.7 $mmol.l^{-1}$ for submaximal, competitive games, and maximal testing protocols, respectively. The results of the present study are in agreement with those of previous studies which utilized a continuous submaximal skating protocol (Daub et al., 1983; Green, 1978). Caution should be exercised when considering these results, since ice hockey energy expenditure studies have described the game as a high intensity intermittent activity (Seliger et al., 1972; Green et al., 1976, 1978a, 1978b). The higher blood lactate concentration values obtained via competitive ice hockey game protocols tend to indicate that continuous submaximal skating tasks underestimate the degree of anaerobic involvement of an actual ice hockey game. A large anaerobic involvement has been characteristically observed while examining elite ice hockey players during game situations (Green, 1979, 1987; Paterson, 1977). However, the measured blood lactate concentration values of 2.17, 3.19, and 4.04 $mmol.l^{-1}$ for skating velocities of 336, 357, and 381 $m.min^{-1}$ respectively, confirm that the subjects were exercising at submaximal intensities, which would be desirable when attempting to measure skating economy.

Appendix E provides a comparison of mean blood lactate accumulation studies of Canadian University ice hockey players through various testing protocols.

5.4 The Oxygen Uptake and Skating Velocity Relationship

The significant linear relationship observed between steady-state oxygen uptake and running velocity is well documented in the running economy literature (Bransford & Howley, 1977; Conley & Krahenbuhl, 1980; Daniels, 1985; Daniels et al, 1977; Hagan et al., 1980). This relationship has been observed in many activities of an aerobic nature which include cycling (Hagberg et al., 1978), rowing (Carey et al., 1974) and swimming (Bonen et al., 1980). Furthermore, this relationship is observed in both trained and untrained subjects (Bransford & Howley, 1977).

Skating, similar to other aerobic type activities such as running, cycling, and rowing, calls upon the large muscle groups of the body and may significantly tax the cardiorespiratory system (Montgomery, 1988). A study by Green et al. (1978b) indicated that the active musculature and glycogen depletion patterns observed during skating closely resemble those of cycling.

As previously discussed, it is assumed during steady-state exercise that energy requirements are met predominantly through cell respiration, with minimal glycolytic involvement or protein catabolism (Daniels, 1985; Morgan et al., 1989b). Based on research by Whipp and Wasserman (1972), approximately three minutes are required for the attainment of a steady-state condition during submaximal work.

A significant linear relationship ($r = 0.79$, $p<0.01$) was determined between steady-state oxygen uptake and the three submaximal skating velocities in the present study. The slope of the group regression line was +0.370, and the mean standard error of estimate was 5.44 $ml.kg^{-1}.min^{-1}$. This relationship may be considered valid for several reasons. The subjects were skating at mean intensities of 65, 75, and 90% of VO_2 max. Submaximal running intensities ranging from 50 to 90% are typically employed in running economy research (Bransford & Howley, 1977; Conley & Krahenbuhl, 1980; Costill et al., 1973; Morgan et al., 1991; Pate et al., 1992). Furthermore, the four to five minute skating bouts were of sufficient duration to allow the subjects to achieve steady-state oxygen consumption without undue fatigue. Thus, all of the subjects were able to complete the three skating bouts. A respiratory exchange ratio (RER) of less than unity has also been used to identify the presence of a steady-state condition (Bransford & Howley, 1977; Conley & Krahenbuhl, 1980). RER values of 0.88, 0.91, and 0.96 were observed for velocities of 336, 357, and 381 $m.min^{-1}$, respectively (see Appendix F). The values obtained indicate that all of the subjects were in steady-state for the gas collections at each velocity. Finally, the protocol and method of data collection had been determined to be valid and reliable by Ferguson et al. (1969) and later by Léger et al. (1979).

Based on the results of this study, these data support the hypothesis that the relationship between the oxygen requirements of skating and the skating velocities between 336 and 381 $m.min^{-1}$ are adequately described by a linear regression equation.

5.5 The Interindividual Variability of Skating Versus Running

It was hypothesized that the interindividual variability between subjects, as measured by the coefficient of variation (CV% = SD/X * 100) in mechanical efficiency, would be greater in skating than in running. The skating mechanical efficiency was calculated as follows: Efficiency = (Velocity ÷ VO_2) X 100

where velocity ($m.min^{-1}$) is a pre-determined submaximal pace and VO_2

is the achieved steady-state oxygen consumption ($ml.kg^{-1}.min^{-1}$) elicited by the exercise. Skating mechanical efficiency is an indication of the movement and energy requirements of skating at a specific velocity (Montgomery, 1988). Measuring the amount of oxygen consumed during steady-state skating permits the evaluation of the differences between individuals in expenditure of energy when covering a specified distance at a specified velocity.

The mean coefficients of variation in the skating mechanical efficiency of the subjects in the present study were 15.1, 12.3, and 9.9% for velocities of 336, 357, and 381 $m.min^{-1}$, respectively. The mean coefficient of variation in mechanical efficiency for both skating and running from the literature, in which raw data were available for computation (see Appendix G), is presented in Table 14.

Data from both the present study and that of Ferguson et al. (1969) exhibit larger coefficients of variation in mechanical efficiency (range = 6.8-15.1%) than those of the three running studies (range = 3.6-5.7%). Green (1979) reported a substantial interindividual variability in the skating efficiency of elite ice hockey players. Léger et al. (1979) reported mean coefficients of variation in mechanical efficiency of 6.9% for treadmill runners and 14.0% for skaters performing the protocol of Ferguson et al. (1969). Montgomery (1988), in his review of ice hockey literature, reported that the interindividual variability in VO_2 of skaters (±15%) is substantially greater than that of runners (5-7%).

Table 14 Coefficients of Variation in the Mechanical Efficiency ($m.ml^{-1}.kg^{-1}$) of Running and Skating.

n	Velocity ($m.min^{-1}$)	VO_2±SD ($ml.kg^{-1}.min^{-1}$)	Running Mechanical Efficiency	CV%	Reference
16M	215	39.0±2.1	552.7±30.2	5.5	Costill
	241	45.6±1.9	529.1±21.2	4.0	et al.
	268	51.7±1.9	518.8±18.8	3.6	(1973)
	295	59.0±2.3	501.0±19.1	3.8	
15M	188	36.5±2.1	516.6±28.6	5.5	McGruer
	215	40.8±2.3	528.7±30.1	5.7	(1989)
	241	45.9±1.9	526.2±21.5	4.1	
	268	51.9±2.4	517.0±24.1	4.7	
10M	161	31.8±1.8	504.0±28.3	5.6	Williams
	188	37.3±1.9	505.2±26.2	5.2	et al.
	215	42.9±2.0	501.9±23.1	4.6	(1991)

n	Velocity ($m.min^{-1}$)	VO_2±SD ($ml.kg^{-1}.min^{-1}$)	Skating Mechanical Efficiency	CV%	Reference
13M	336	38.6±5.7	887.6±134.1	15.1	Present
	357	44.4±5.3	815.9±99.9	12.3	Study
	381	55.2±5.2	695.9±68.9	9.9	
17M	350	41.1±2.9	856.9±57.8	6.8	Ferguson
	382	47.1±4.5	814.7±73.9	9.1	et al.
	401	50.8±4.6	795.1±69.6	8.8	(1969)
	421	54.7±4.9	775.5±65.5	8.4	

Three plausible mechanisms may explain the greater interindividual variability in skating efficiency. First, ice skating is a highly technical activity which require many years of dedicated practice to develop (Green, 1979; Marcotte & Hermiston, 1975; Marino, 1984; Montgomery, 1988). Skaters must master the propulsive, turning, stopping, and balancing intricacies of the skating stride. The contact surface of the skate is very small when compared to the contact surface of a running shoe. Skating, unlike the two dimensional movement of running, is a three dimensional motion which is characterised by an outward rotation of the thigh (Marino & Weese, 1979). Second, although the present sample of ice hockey players were all considered trained skaters and played for the same team, considerable differences probably existed in their skating skills. Third, the testing surfaces, namely, the treadmill and ice surfaces, clearly represent two significantly different surfaces. The treadmill surface is smooth and will remain intact throughout an entire testing session. On the other hand, an ice hockey surface is generally less uniform and is often marred with chips and gashes as use increases. Furthermore, the ice surface will deteriorate from one skating bout to the next until flooding renews its surface. Greater energy expenditure is required to overcome the frictional forces of skating as the ice surface deteriorates from one skating bout to the next. Players who benefit from a freshly flooded skating surface may therefore require less energy to skate, when compared to their counterparts who inherit a rougher ice surface.

5.6 Skating Economy and Simple Kinematic Variables

The changes in stride rate and stride length which accompany changes in running velocity are well documented (Boje, 1944; Hogberg, 1952; McCardle et al., 1986). As velocity increases from slow to medium, runners adapt by significantly increasing their stride length while maintaining a relatively stable stride rate. As velocity further increases from medium to fast, a levelling off in stride length and a synchronous increase in stride rate is exhibited. Ice hockey studies that were designed to study the effect of velocity on the gait pattern of skaters have established a significant relationship with stride rate and a non-significant correlation with stride length (Marino, 1977). It has been hypothesized that the existence of a glide phase in the skating stride may account for the observed differences in stride pattern between running and skating (Marino, 1977).

The skaters in the present study displayed a different stride pattern to that of runners, as skating velocity was increased from 336 to 381 $m.min^{-1}$. A significant linear relationship was determined for both stride rate ($r = 0.71$, $p<0.01$) and stride length ($r = -0.36$, $p<0.05$) with skating velocity. The slope of the group regression lines, and mean standard error of estimates, for stride rate and stride length were +0.393 and 7.31 and -0.007 and 0.36 $ml.kg^{-1}.min^{-1}$, respectively.

The significant increase in stride rate is in agreement with Marino's (1977) observations on skating kinematics in a group of ten subjects. Marino (1977) reported a significant relationship ($r = 0.76$, $p<0.05$) between skating velocity and stride rate. However, in contrast to the present study, Marino (1977) reported a non-significant relationship ($r = 0.05$, $p>0.05$) between stride length and skating velocity. Although the relationship between stride length and skating velocity in the present study reached significance, it accounted for only 13% of the variation in velocity.

Differences in sample populations may explain the discrepancy between the two studies in terms of stride length. The subjects in the present study were classified as trained skaters. On the other hand, Marino's (1977) subjects ranged in ability from highly skilled to moderately low skilled. It may not be unreasonable to hypothesize the existence of differences in the skating pattern response to increases in velocity between trained and untrained skaters. Furthermore, caution must be taken when comparing the two studies, due to the differences in velocities utilised. The present study used three pre-determined submaximal velocities. The subjects in Marino's (1977) study skated at self-selected velocities estimated to represent slow, medium, and maximal speeds. Regardless, it would seem that stride pattern responses to increases in skating velocity are more dependent upon changes in stride rate than to stride length.

5.7 Relationship Between Skating Economy and Skating Ability

It was hypothesized that skating economy would be a valid indicator of an individual's fluidity, or ease of movement, during skating. If such were the case, then perhaps skating economy could also serve as a valid predictor of skating ability. The running economy literature has highlighted the predictive and diagnostic value of running economy in predicting performance in running events of 10 kilometres and more (Conley & Krahenbuhl, 1980; Daniels, 1985; Morgan et al., 1989a, 1989b).

A subjective rating system based on the fundamental skills of skating, as described by the Canadian Hockey Amateur Association (1986), was used to evaluate each subject's skating ability. The rating was performed by the subjects' coach, a veteran of 14 years in the National Hockey League, who was knowledgeable of each subject's skating ability. Because of the rater's expertise and knowledge of the subjects, a rating system was deemed appropriate as a measure of skating ability.

Spearman rank order correlations of 0.21, 0.10, and 0.29 were calculated for skating velocities of 336, 357, and 381 $m.min^{-1}$, respectively. A correlation of 0.30 was calculated across all three skating velocities. None of the correlations reached significance ($p>0.05$).

The low correlation between skating economy and skating ability may be attributed to the heterogenous nature of the sample population in terms of VO_2 max. Running economy studies utilizing groups with large variations in VO_2 max, have typically reported low correlations between running economy and performance (Apor et al., 1980; Costill, 1967; Costill et al., 1973; Daniels et al., 1973; Farrell et al., 1979; Foster et al., 1978). On the other hand, studies utilizing subjects homogeneous in VO_2 max have reported a significant relationship between the two variables (Conley & Krahenbuhl, 1980; Daniels, 1985; Morgan et al., 1989a, 1989b). Although all of the subjects played for the same hockey team, a large discrepancy in their cardiorespiratory fitness level seems to have existed (range = 51.8-70.3 $ml.kg^{-1}.min^{-1}$).

The skill complexity involved in skating may also help explain the non-significant correlations between skating economy and skating ability. Many physiological variables (Morgan & Craib, 1992), including running economy, as well as biomechanical variables (Martin & Morgan, 1992) are known to significantly influence running performance. Similarly, several factors are also known to affect skating performance. Variables such as skating mechanics (Marino, 1977), body weight (Montgomery, 1988) and lactate metabolism (Green et al., 1978b) may all influence skating ability to varying degrees. In fact, blood lactate concentration levels, although non-significant ($p>0.05$), correlated higher with skating ability than submaximal oxygen consumption measures. Spearman rank order correlations were 0.37, 0.42, and 0.25 for skating velocities of 336, 357, and 381 $m.min^{-1}$, respectively. A correlation of 0.36 was calculated across all three velocities (see Appendix H). Jacobs (1986), in his review of blood lactate implications for sport performance, suggests that blood lactate may be a more sensitive predictor of performance than traditional oxygen consumption measures (i.e. VO_2 max). Furthermore, in an activity as complex as skating, skating mechanics, ground reaction forces, and mechanical power are all biomechanical factors which may account for a large variance in determining skating ability (Morgan & Craib, 1992; Williams & Cavanagh, 1987). Clearly, other variables along with submaximal oxygen consumption, may be responsible for determining an individual's skating ability.

Finally, the subjective nature of the rating system may partly account for the low correlations. Although the descriptors of what constitutes skating ability were well defined and the rater demonstrated expertise in the area, there are always inherent risks to internal validity when employing subjective rating scales.

Chapter VI

Summary, Conclusions, and Recommendations

6.1 Summary

The predictive and diagnostic value of running economy in terms of running performance in endurance events is well documented (Bailey & Pate, 1991; Conley & Krahenbuhl, 1980; Conley et al., 1981a; Daniels, 1985; Morgan et al., 1989a, 1989b; Morgan & Craib, 1992). Although the efficiency of movement has been examined in other sport activities (i.e. cycling & rowing), there exists a lack of research examining the skating economy of ice hockey players. Thus, the purpose of this study was to describe skating economy in terms of physiological and simple kinematic variables in ice hockey players. Furthermore, an attempt was made to identify a possible relationship between skating economy and skating ability with the use of a subjective rating system.

The subjects in the study were 13 male varsity hockey players. All of the subjects completed three 4-minute continuous, submaximal skating bouts at progressively increasing velocities. Oxygen uptake, blood lactate, heart rate, stride rate and stride length were monitored.

The first hypothesis was that a significant linear relationship would exist between submaximal skating velocity and oxygen uptake. Linear regression analysis revealed a correlation of r = 0.79 ($p<0.01$). Hypothesis 1 was accepted.

The second hypothesis was that a significant relationship would exist between skating velocity and stride rate. Linear regression analysis revealed a correlation of r = 0.71 ($p<0.01$). Hypothesis 2 was accepted.

The third hypothesis predicted a nonsignificant relationship between skating velocity and stride length. Linear regression analysis revealed a correlation of -0.36 ($p<0.05$). Hypothesis 3 was rejected.

The fourth hypothesis predicted that the interindividual variability in oxygen uptake of skating would be greater than that reported in the running economy literature. Data provided in Table 14 and in Appendix I lend support to hypothesis 4.

The fifth hypothesis was that a significant relationship would exist between skating economy and skating ability. Spearman rank order correlations of 0.21, 0.10, and 0.29 were calculated for velocities of 336, 357, and 381 $m.min^{-1}$, respectively. A correlation of r = 0.30 was calculated across the three velocities. Because none of the correlations were significant ($p>0.05$), hypothesis 5 was rejected.

Additional analysis revealed that blood lactate concentration correlated higher with skating ability than oxygen uptake. Spearman rank order correlations were 0.37, 0.42, and 0.25 for skating velocities of 336, 357, and 381 $m.min^{-1}$, respectively. A correlation of 0.36 was calculated across the three velocities. However, none of the relationships was significant ($p<0.05$).

6.2 Conclusions

Within the limitations and delimitations of this study, the following conclusions are justified:

1. Skating economy at velocities between 336 and 381 $m.min^{-1}$ may be described by a linear regression equation.
2. The relationship between oxygen uptake and stride rate may be described by a linear regression equation.
3. The relationship between oxygen uptake and stride length may be described by a linear regression equation.
4. The interindividual variability of skating in terms of oxygen consumption is greater than that elicited during running.
5. Skating economy does not have predictive and diagnostic value to determine skating ability in ice hockey players.

6.3 Recommendations

The following recommendations are proposed for future investigations:

1. A future study should use a group of ice hockey players that is homogeneous in terms of VO_2 max.
2. Valid and reliable objective skating tests, such as those described by Chouinard and Reardon (1984), Larivière et al. (1976), and Reed et al. (1979) may be used to further examine the predictive and diagnostic value of skating economy in terms of skating ability.
3. Future studies may incorporate previously utilized biomechanical assessment techniques (Marino, 1983) to assist in the development of a linear regression equation, which may adequately predict skating ability.

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McGILL UNIVERSITY

FACULTY OF EDUCATION

CERTIFICATE OF ETHICAL ACCEPTABILITY FOR RESEARCH INVOLVING HUMAN SUBJECTS

A review committee consisting of:

a) Professor H. Perrault
b) Professor J. Derevensky
c) Professor S. Nemiroff

has examined the application for certification of the ethical acceptability of the project titled:

Skating Economy of Ice Hockey Players

as proposed by:

Applicant's Name: Stephen Riby

Supervisor's Name: Rene Turcotte

Applicant's Signature: [signature]

Supervisor's Signature: René Turcotte

Granting Agency nil

The review committee considers the research procedures, as explained by the applicant in this application, to be acceptable on ethical grounds.

(Signed)

a) H. Perrault [signature]
b) [signature]
c) S. G. Nemiroff [signature]

Associate Dean (Academic) [signature]

Date: Jan 4/94

Research Ethics Committee of
The Faculty of Education

Statement of Ethics of Proposed Research in the Faculty of Education

It is assumed that the responses to the questions below reflect the author's (or authors') familiarity with the ethical guidelines for research with human subjects that have been adopted by the Faculty of Education.

1. **Informed Consent of Subjects**

Explain how you propose to seek informed consent from each of your subjects (or should they be minors, from their parents or guardian). Informed consent includes comprehension of the nature, procedures, purposes, risks, and benefits of the research in which subjects are participating. Please append to this statement a copy of the consent form that you intend to use.

All of the subjects will be informed verbally in writing regarding procedures to be administered during the experiment. Prior to the study, an educational information session will be held for all the athletes so that they understand the purpose of the experiment and all procedures.

2. **Subject Recruitment**

2.1 Are the subjects a "captive population" (e.g., residents of a rehabilitation centre, students in a class, inmates in a penal establishment)?

The subjects are male university hockey players.

2.2 Explain how institutional or social pressures will be applied to encourage participation.

All of the subjects will participate in the study on a volunteer basis only.

2.3 What is the nature of the inducement you intend to present to prospective subjects to persuade them to participate in your study?

Since the principal researcher is a member of the coaching staff, all of the subjects will be given a day off from practice after participating in the study.

2.4 How will you help prospective participants understand that they may freely withdraw from the study at their own discretion and for any reason?

All of the subjects will be informed verbally and in writing about their right to withdraw from the study at their own discretion. The consent from will inform the subjects of this right.

3. Subject Risk and Wellbeing

What assurance can you provide this committee (as well as the subjects) that the risks, physical and/or psychological, that are inherent to this study are either minimal or fully justifiable given the benefits that these same subjects can reasonably expect to receive?

Only healthy ice hockey athletes aged 18-24 will be tested in the study. Furthermore, these athletes habitually exert themselves at intensities much higher than is required of them during the testing sessions in the experiment.

4. Deception of Subjects

4.1 Will the research design necessitate any deception to the subjects?

No

4.2 If so, what assurance can you provide this committee that no alternative methodology is adequate?

N/A

4.3 If deception is used, how do you intend to nullify any negative consequences of the deception?

N/A

5. Privacy of Subjects

How will this study respect the subjects' right to privacy, that is, their right to refuse you access to any information which falls within the private domain?

This study does not require the subjects to divulge any information which may potentially fall within the private domain. Data will be presented anonymously. Thus, no names are associated with any of the data.

6. Confidentiality/Anonymity

6.1 How will this study ensure that (a) the identity of the subjects will be concealed and (b) the confidentiality of the information which they will furnish to the researcher or their surrogates will be safeguarded?

Strict confidence between tester and subjects will be maintained. Any technicians, graduate students, etc., that participate in data collection will also be advised that results are confidential. The subjects will be listed with a numerical symbol known only to the supervisors of the research project which will be used to present the data.

6.2 Further, will the data be aggregated in such a way that even should the identify of the participants become know, no reasonable inference could be made about the performance, competence, or character of any one of these participants?

This data in no way reflects the players' potential for performance on the ice. Since the project is exploratory in nature, it will be impossible to draw any conclusions about any of the players from this data.

Signature of researcher: ______________________

If this project has been submitted to another ethics committee, please note the particulars:

____

____

____

Appendix B Informed Consent Form for Skating Economy Study

I, __________________________, have listened to the researchers and understand all of the procedures related to the study in which I am a subject. I understand that I will be required to perform three skating bouts of four minutes in duration, interspersed by five minute rest periods. Furthermore, I am aware that the three skating velocities will represent intensities for which I have been screened and deemed capable of performing without undue risk to my physical health. Finally, I am aware that the research protocol has been established as safe through anteriorresearch projects, as well as by the directors of the present study. Thus, the description of the purpose and procedures is satisfactory and I have had the opportunity to inquire about procedures of which I was uncertain. It is my understanding that I may ask questions or request further explanations or information about the procedures of the study at any time.

I am aware of the risks involved and the procedures by which the researchers have minimized these risks. In addition, I know that I can withdraw from the study or discontinue a procedure at any time without question.

________________ Date

________________________ Signature of Participant

________________________ Signature of Witness

Appendix C Mean Physical Characteristics of Ice Hockey Players.

n	Age (y)	Height (cm)	Weight (kg)	Body Fat (%)	Reference
13	20.9	179.7	79.9	*40.0	Present study
8	21.0	177.3	75.9	8.6	Green et al. (1976)
18	21.0	178.0	78.1	10.5	Romet et al. (1978)
19	21.5		77.6	10.7	Green et al. (1979)
17	20.4	177.2	77.1		Song & Reid (1979)
8	21.7	177.4	78.8		Jones & Green (1984)
17	21.5	183.2	83.8		Gamble & Montgomery (1986)
19	20.8	179.9	82.0	*49.2	Koziris (1991)
17	21.5	183.2	83.8		Montgomery et al. (1990)
27		180.2	88.4	10.5	Professionals (1990-91)

* Sum of five skinfolds (CSTF)

Appendix D Mean Maximum Oxygen Uptake Values for Canadian University Ice Hockey Players.

Testing Protocol	n	Weight (kg)	VO_2 max ($ml.kg^{-1}.min^{-1}$)	Reference
<u>Treadmill</u>				
	13	79.9	60.5	Present study
	8	75.9	53.4	Green et al. (1976)
	8	77.9	60.8	Green et al. (1978a)
	19	77.6	58.9	Green et al. (1979)
	9	80.9	56.3	Hutchison et al. (1979)
	10	72.8	61.4	Léger et al. (1979)
	8	70.5	58.1	Montpetit et al. (1979)
	9	77.0	60.3	Green et al. (1980)
	11	79.5	56.4	Montgomery (1982)
<u>Cycling ergometer</u>				
	9	77.1	53.2	Hermiston (1975)*
	18	78.1	55.2	Romet et al. (1978)
	21	79.8	58.4	Krotee et al. (1979)
	5	79.5	54.3	Daub et al. (1983)
	8	78.8	51.1	Jones & Green (1984)
<u>Skating</u>				
	13	79.9	60.5	Present study
	17	73.7	55.0	Ferguson et al (1969)
	8	78.7	52.8	Green (1978)
	10	72.8	62.1	Léger et al (1979)
	5	79.5	52.1	Daub et al (1983)

* cited in Marcotte & Hermiston, 1975

Appendix E Mean Blood Lactate Concentration Values for Canadian University Ice Hockey Players.

n	Testing Protocol	Blood Lactate ($mmol.l^{-1}$)	Reference
13	Continuous skating		Present study
	60% of VO_2 max	2.2±0.6	
	75% of VO_2 max	3.2±0.7	
	90% of VO_2 max	4.1±1.9	
11	Repeat Sprint Skate Test (RSS)	10.7±2.3	Montgomery et al. (1990)
8	Intermittent maximal 45 sec. sprints	12.2±0.8	Watson & Hanley (1985)
10	30 min. continuous skating at 75-80% of VO_2 max.	3.1±1.0	Daub et al. (1983)
10	Protocol of Ferguson et al. (1969)	14.1±1.6	Léger et al. (1979)
	20m shuttle skate (Simard, 1975)	14.7±2.0	
8	30 min. continuous skating at 60% of VO_2 max.	2.8±0.3	Green (1978)
	60 min. continuous skating at 60% of VO_2 max.	2.7±0.5	
	30 min. intermittent maximal skate sprints	10.9±2.1	
	60 min. intermittent maximal skate sprints	13.3±0.6	
8	Competitive hockey game	4.2±0.8	Green et al. (1978a)
12	Competitive hockey game	4.9±1.8	Green et al. (1978b)
8	Competitive hockey game	6.8±1.0	Green et al. (1976)

Appendix F Calculation Data for the Respiratory Exchange Ratios (RER) of the Three Experimental Skating Velocities. Calculation for 336 $m.min^{-1}$.

Subject	VO2 ($l.min^{-1}$)	VO2 ($ml.kg^{-1}.min^{-1}$)	VE ($l.min^{-1}$)	VC02 ($l.min^{-1}$)	RER
1	3.65	45.1	77.2	3.68	1.01
2	2.87	40.9	59.5	2.61	0.91
3	3.06	40.8	55.9	2.68	0.88
4	2.60	32.5	47.0	2.20	0.85
5	3.00	36.1	67.0	2.59	0.86
6	3.55	45.6	86.3	3.57	1.01
7	3.59	37.1	78.5	3.15	0.88
8	2.78	33.1	57.8	2.38	0.86
9	2.33	31.0	53.9	1.96	0.84
10	3.44	46.5	81.4	3.15	0.92
11	3.22	38.5	65.4	2.99	0.93
12	2.25	30.8	46.2	1.87	0.83
13	3.64	44.4	74.0	2.30	0.63
MEAN	3.08	38.6	65.4	2.70	0.88
SD	0.49	5.7	13.2	0.58	0.09

Calculation for 357 $m.min^{-1}$.

Subject	VO2 ($l.min^{-1}$)	VO2 ($ml.kg^{-1}.min^{-1}$)	VE ($l.min^{-1}$)	VC02 ($l.min^{-1}$)	RER
1	4.16	51.3	88.3	4.26	1.02
2	2.94	41.9	56.4	2.66	0.90
3	3.90	52.0	71.2	3.56	0.91
4	3.29	41.1	58.6	2.94	0.89
5	3.34	40.2	65.4	2.93	0.88
6	3.98	51.1	94.0	4.09	1.03
7	4.01	41.5	77.3	3.46	0.86
8	3.51	41.8	69.6	3.00	0.85
9	2.61	34.8	47.3	2.18	0.84
10	3.51	47.5	82.3	3.15	0.90
11	3.72	44.5	71.7	3.48	0.94
12	2.91	39.9	50.7	2.57	0.88
13	4.01	49.0	94.8	3.66	0.91
MEAN	3.53	44.4	71.3	3.23	0.91
SD	0.49	5.3	15.6	0.60	0.06

Calculation for 381 $m.min^{-1}$.

Subject	VO2 ($l.min^{-1}$)	VO2 ($ml.kg^{-1}.min^{-1}$)	VE ($l.min^{-1}$)	VC02 ($l.min^{-1}$)	RER
1	5.25	64.9	126.5	5.55	1.06
2	3.69	52.6	70.7	3.36	0.91
3	4.21	56.2	101.9	4.35	1.03
4	4.42	54.6	94.1	4.15	0.94
5	5.00	60.2	105.8	4.33	0.87
6	4.37	56.0	122.9	4.66	1.07
7	4.68	48.4	105.2	4.28	0.91
8	3.75	44.7	75.9	3.23	0.86
9	4.35	58.0	75.8	3.75	0.86
10	4.32	58.3	116.6	4.16	0.96
11	4.88	58.4	114.0	5.15	1.05
12	3.93	53.9	83.5	3.81	0.97
13	4.24	51.7	99.8	3.96	0.93
MEAN	4.39	55.2	99.4	4.21	0.96
SD	0.47	5.2	18.5	0.65	0.08

Appendix G VO_2 ($ml.kg^{-1}.min^{-1}$) Data for Efficiency Calculations.

		Running Velocity ($m.min^{-1}$)				
Study	Subject	160	188	215	241	268
Costill et al. (1973)	DBL			38.0	44.0	49.5
	EH			37.5	44.0	50.7
	RB			39.0	45.5	52.6
	JB			35.5	44.5	54.8
	FP			41.2	47.6	53.1
	DL			37.0	43.8	54.4
	BS			39.2	45.0	50.6
	DB			36.0	42.4	48.4
	DO			38.0	46.3	52.8
	GE			42.8	47.5	52.1
	MP			39.6	43.6	51.5
	JF			39.5	46.3	49.3
	DG			38.2	45.7	49.7
	BP			42.5	47.3	52.7
	HP			38.5	45.7	52.8
	PS			41.6	49.7	52.6
McGruer (1989)	1		35.6	38.7	44.9	48.7
	2		33.7	37.2	42.4	47.6
	3		35.7	39.8	45.6	52.9
	4		35.9	40.9	45.6	52.9
	5		35.9	41.5	46.3	51.9
	6		35.4	40.3	43.4	51.3
	7		36.1	40.3	45.7	50.8
	8		36.0	41.7	47.5	54.9
	9		39.0	41.4	49.2	55.5
	10		38.4	43.5	46.9	52.9
	11		40.3	44.3	48.9	53.6
	12		35.7	43.9	45.9	51.5
	13		35.0	39.2	46.0	53.7
	14		34.1	36.6	43.6	48.0
	15		40.7	42.5	46.2	52.9
Williams et al. (1991)	1	34.6	40.1	45.8		
	2	33.4	39.1	45.0		
	3	31.3	36.9	42.4		
	4	29.1	34.1	39.5		
	5	31.1	35.8	40.7		
	6	30.9	37.0	43.3		
	7	33.1	38.5	44.0		
	8	30.1	36.0	42.3		
	9	33.9	39.5	44.3		
	10	30.9	36.0	41.8		

Study	Subject	Skating Velocity ($m.min^{-1}$)			
		350	382	401	421
Ferguson et al. (1969)	JD		45.0	47.0	50.5
	RL		48.6	51.5	57.0
	RD		41.5	45.6	50.7
	YG		46.2	51.0	54.4
	MP		42.4	47.7	50.9
	RD		40.4	45.6	48.3
	AL		47.3	50.0	54.7
	JL		50.3	51.5	55.4
	AM	38.7	45.2	48.8	50.5
	RB	39.6	47.4	52.1	51.2
	NM		48.5	56.6	61.5
	CM	38.7	44.9	49.7	54.0
	JL	40.5	44.1	48.4	50.7
	PB		52.7	56.5	58.6
	ML	46.6	55.9	58.4	61.2
	GC	39.5	45.0	44.0	
	RC	43.5	55.6	59.4	65.1

Appendix H Spearman Rank Order Correlation Analysis of Blood Lactate Concentration ($mmol.l^{-1}$) and Skating Ability at Three Skating Velocities ($m.min^{-1}$).

Subject	Skating Ability Ranking	Lactate Rank (336)	Lactate Rank (357)	Lactate Rank (381)	Overall Lactate Rank
1	11	10	12	12	12
2	7	11	11	11	11
3	6	8	10	10	9
4	1	1	4	8	4
5	12	7	9	7	7.5
6	13	13	13	13	13
7	3	5	3	3	3
8	5	2	1	1	1
9	10	5	2	2	2
10	4	12	7	6	7.5
11	2	9	10	9	10
12	8	8	5	5	6
13	9	3	6	4	5
SPEARMAN		0.37	0.42	0.25	0.36

Appendix I Running and Skating Economy Data.

Running Study	n	Velocity ($m.min^{-1}$)	Running Economy Data VO_2±SD	Range	CV%
Costill et al. (1973)	16M	215	39.0±2.1	35.5-42.8	5.4
		241	45.6±1.9	42.4-49.7	4.2
		268	51.7±1.9	48.4-54.8	3.7
		295	59.0±2.3	55.1-63.5	3.9
Daniels et al. (1977)	10M	202	36.2	32.0-39.0	
		215	39.0	35.0-42.0	
		241	44.6	41.0-47.0	
		268	50.5	47.0-53.0	
	10F	202	38.0	31.0-42.0	
		215	40.7	34.0-45.0	
		241	46.0	40.0-50.0	
		268	51.5	46.0-55.0	
Farrell et al. (1979)	18M	268	52.9±7.2	40.6-64.5	13.6
Conley & Krahenbuhl (1980)	12M	241	44.7		
		268	50.3		
		295	55.9		
Conley et al. (1981b)	14F	177	33.9		
		196	37.7		
		215	41.8		
Powers et al. (1983)	9M	243	48.1±1.0	43.2-53.5	2.1
Armstrong & Costill (1985)	4M	170	32.6±2.5		7.7
		200	39.3±3.1		7.9
		230	46.0±3.4		7.4
Morgan et al. (1987)	10M	230	41.5±2.2		5.3
		248	44.7±2.0		4.5
		268	49.3±1.8		3.7
		293	55.3±1.9		3.4

William & Cavanagh (1987)	16M	214	39.0±2.1		5.1
Pate et al. (1987)	15F	230	45.0±2.1	41.1-49.2	4.7
		248	47.9±3.3	41.7-54.0	6.9
	13F	230	48.4±2.3	45.0-53.3	4.8
		248	51.2±3.8	42.2-56.2	7.4
Fay et al. (1989)	13F	196	38.6±2.3	35.5-41.9	6.0
		215	42.8±2.0	40.5-46.1	4.7
		241	47.3±3.1	42.6-53.3	6.6
McGruer (1989)	15M	188	36.5±2.1	33.7-40.7	5.8
		215	40.8±2.3	36.6-44.3	5.6
		241	45.9±1.9	42.4-49.2	4.1
		268	51.9±2.4	47.6-55.5	4.6
Cunningham (1990)	24F	215	47.4±3.2	42.0-55.0	6.8
Williams et al. (1990)	10M	161	31.8±1.8	29.8-34.5	5.7
		188	37.3±1.9	34.1-40.1	5.1
		215	42.9±2.0	39.5-45.8	4.7

Skating Study	n	Velocity ($m.min^{-1}$)	Skating Economy Data VO_2±SD	Range	CV%
Ferguson et al. (1969)	17M	350	41.1±2.9	38.7-46.6	7.1
		382	47.1±4.5	40.4-55.9	9.6
		401	50.8±4.6	44.0-59.4	9.1
		421	54.7±4.9	48.3-65.1	9.0
		442	54.6±4.3	51.9-64.1	7.8
Present Study	13M	336	38.6±5.7	30.8-46.5	14.8
		357	44.4±5.3	34.8-52.0	11.9
		381	55.2±5.2	44.7-64.9	9.4