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A Comparison of Oxygen Consumption and Selected Kinematics between and within the 1-skate, 2-skate and Offset Techniques.

by

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Presented to the School of Kinesiology, Lakehead University, in partial fulfillment
for the requirements of the Master of Science in Coaching Theory degree.

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Abstract

The 1-skate, 2-skate and offset techniques are the three most prevalent skate-skiing techniques used during cross-country ski racing. Although kinematic differences at maximum velocity have been observed between techniques (Bilodeau et al., 1991, 1996), physiology based criteria for choosing between techniques during a race have not been examined.

The primary purpose of this study was to determine any differences in oxygen consumption between the 1-skate, 2-skate and offset when performed by highly trained cross-country ski racers over flat terrain at a submaximum velocity of 5.4 $m{\bullet}s^{-1}$. The secondary purpose was to identify the kinematic parameters that may be associated with economical skiing for each of the techniques by examining correlations between kinematic variables and economy for each of the techniques under the same conditions.

Eleven male sub-elite cross-country skiers skied behind a snow-machine at a submaximal velocity of 5.4 $m{\bullet}s^{-1}$ using the 1-skate, 2-skate or offset exclusively. Oxygen consumption was measured throughout each trial (KB1-C, AeroSport Inc.) to assess economy. Three-dimensional videography (Peak Performance Technologies) was used to measure kinematic parameters. A randomized block ANOVA and Scheffé's test was used to assess differences in oxygen consumption between techniques. Correlation coefficients between economy (expressed as percentage of VO_{2Max} and HR_{Max}) and selected kinematic parameters were examined to determine the kinematic performance variables associated with the economical performance of each technique.

Minute ventilation was observed to be lower ($p<0.05$) during performance of the 2-skate (84.77 L •min^{-1}) than the 1-skate (91.37 L•min^{-1}). This difference was attributed to the increased poling demands of the 1-skate. Although no other significant physiological differences were observed between techniques, small differences in oxygen consumption between the 1-skate and 2-skate, representing 2.5% of VO_{2Max}, could potentially be manifested in performance discrepancies at higher, race-specific velocities. Correlations observed between oxygen consumption and the kinematic parameters suggest that increased gliding time and more vigorous application of propulsive forces characterize more economical performance of the 2-skate. Economical performance of the 1-skate appears to feature more sustained poling and increased side-to-side movement of the centre of mass.

Future study of between and within group differences for the 1-skate and 2-skate should be completed at velocities approaching race pace. Few clear findings were observed with the offset and in the future it should be examined on uphill terrain where it is typically performed.

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CHAPTER 1

Introduction

Cross-country skiing has undergone a radical transformation over the past 15 years with the proliferation of skate-skiing at all levels of racing. Skate-skiing, which resembles ice-skating, is performed on a flat groomed trail instead of on the prepared tracks that the traditional classic technique typically requires. In 1986 the Fédération Internationale de Ski (F.I.S.) acknowledged the legitimacy of skate-skiing by equally dividing World Cup competition into its current format of "freestyle" and "classic" technique races. Distinct technique variations of skate-skiing have rapidly evolved from their initial forms of the skate-turn and the marathon skate, into the 1-skate, 2-skate and offset techniques performed today (Smith, Nelson, Feldman & Rankinen, 1989; Svensson, 1994). The question of technique selection during race situations has been inadequately addressed. Biomechanists have compared the maximum achievable velocity and other maximum velocity kinematic variables between techniques. (Bilodeau, Roy & Boulay, 1991; Boulay, Rundell & King, 1994). However, cross-country ski races vary in duration from approximately 15 minutes (5 km) to 2 hours (50 km) and therefore cannot be performed entirely at maximum intensity. This duration also dictates that the majority of metabolic energy required for cross-country ski racing must be derived aerobically. A comparison of the differences in both kinematic parameters and physiological responses, specifically oxygen consumption (VO_2), between the 1-skate, 2-skate and offset may provide more appropriate answers for the question of technique selection during racing.

Rationale for the Study

The determination of which skate-skiing technique(s) to select during the various portions of a race has not been definitively established. Direct comparisons of either biomechanical or physiological performance variables between the 1-skate, 2-skate and offset to verify technique selection has received little attention. In a series of studies directed by Bilodeau (1991,1992) and Boulay (1994), no differences in velocity or heart rate (HR) were observed between techniques during performance on slight downhill and flat terrains at both maximum and sub-maximum efforts. However, the offset was faster for climbing steep slopes (Boulay et al., 1994) and the 2-skate was slower on moderate (Bilodeau et al., 1992) to steep (Boulay et al., 1994) uphill terrain. The heart rates recorded during Boulay's study were lower during performance of the offset than for the 1-skate or 2-skate on steep uphills. Since the skiers in these studies performed at maximum intensity, different performance velocities were achieved based on individual differences between skiers and therefore a comparison of heart rate between techniques would not have been valid. The authors addressed this issue of individual differences by suggesting that technique selection was determined more by an "athlete's fitness and ability.... and less by the attainable speed of each technique" (Bilodeau et al., 1992, p. 924). Boulay et al., (1994) also cautioned that the "possible variable efficiency of skiers between techniques" (p.285) needs to be considered when comparing techniques. In other words, although two techniques yield the same top speed one may require less oxygen consumption for a particular athlete due to their fitness and/or their ability to efficiently perform a certain technique. The emergent problem appears to be the selection of technique(s) that allows the skier to perform at a desired velocity with the lowest possible oxygen consumption. Smith and Heagy (1994) suggested that:

> "Further studies may elucidate the trade-offs skiers face in the choice of technique and how mechanical and physiological demands of the skating technique affect performance" (p.87).

To the researcher's knowledge no study has been published which compares the three main skate-skiing techniques on the basis of oxygen consumption. Presumably, it should be advantageous during an event that lasts longer than 10 minutes and requires between 85-98% contribution from the aerobic energy systems (Eisenman, Johnson, Bainbridge & Zupan, 1989) to choose the technique(s) that require the least oxygen consumption in order to spare high energy metabolic reserves for the duration of the race (Norman & Komi, 1987; Norman, Ounpuu, Fraser & Mitchell, 1989). Previous correlations between specific kinematic variables and maximum achievable velocity provide insight into the mechanical demands of faster skiing using a particular technique. However, these analyses did not address the underlying energy requirements, represented by oxygen consumption, of performing a specific technique. Holding the velocity constant across subjects and techniques allows for the identification of between-subject differences in oxygen consumption against an equal workload (i.e., velocity). Determining if one technique requires less oxygen consumption than another (i.e., is more economical) would help to answer the question of technique selection for races.

Secondly, to the researcher's knowledge, no published study of skate-skiing exists which correlates 1-skate, 2-skate and offset kinematic parameters with values for oxygen consumption recorded during the performance of each technique. Differences in technique selection between skiers may exist due to individual differences in fitness and/or the technical ability to perform each technique. Cavanagh and Kram (1985) defined economy as the submaximum oxygen consumption per unit of body weight required to perform a given task. In previous research, differences in maximum performance velocities (i.e., task requirements) across athletes prevented the identification of differences in economy between athletes. Determining correlations between oxygen consumption and kinematic variables measured at an equal submaximum velocity could help to determine the preferred movement patterns associated with the economical performance of the 1-skate, 2-skate and offset. This information could help an athlete to improve their performance of a specific technique and help to establish individual criteria for technique selection during races.

Purpose

The primary purpose of this research was to compare physiological performance variables, in particular oxygen consumption but also VE, RQ and HR, between three skate-skiing techniques, the 1-skate, 2-skate and offset, performed by highly-trained cross-country ski racers over flat terrain at a controlled constant velocity of $5.4 m \bullet s^{-1}$. The intention was to determine which technique(s) was the most economical (i.e., lowest oxygen consumption) and to explore the question of technique selection by examining any differences in oxygen consumption, VE, RQ or HR in the context of any observed kinematic differences between techniques.

The secondary purpose was to determine kinematic differences between techniques and to describe the relationships between kinematic variables and the oxygen consumption required to perform the 1-skate, 2-skate and offset techniques at a controlled constant velocity of $5.4 m \cdot s^{-1}$. The objective was to assess which movement patterns were associated with either increasing or decreasing the oxygen demand on flat terrain at a submaximum intensity on each of the three techniques.

Hypotheses

It was hypothesized that the 1-skate and 2-skate techniques would be observed to have lower values for oxygen consumption than the offset on flat terrain, regardless of snow conditions. These techniques have been observed to have proportionally longer cycle lengths than the offset due to a longer duration for the gliding phase (Bilodeau et al., 1992). Additionally, since the prevailing snow conditions on the test day were "fast", lower values for oxygen consumption were expected for the 2-skate compared to the 1-skate. A skier's velocity should tend to be maintained during these favourable gliding conditions with less mechanical work (i.e., poling) required for the 2-skate technique.

Finally, it was hypothesized that an inverse relationship between oxygen consumption and cycle lengths for each technique would be observed. According to Bilodeau (1992) longer cycle lengths are associated with longer glide phases. At a controlled velocity, less mechanical work is required during these glide phases and it was therefore anticipated that lower oxygen consumption values would be observed.

Delimitations

The scope of this analysis was delimited to:

1. Eleven highly trained male cross-country ski-racers ranging in age from 20 - 27 years.
2. The performance of three distinct skate-skiing techniques: the 1-skate, 2-skate and offset.
3. Kinematic measures taken from a single average or composite trial compiled from three-dimensional co-ordinates of three cycles of each technique acquired by digitizing two separate but synchronized video images of each subject.
4. Oxygen consumption values recorded by a portable metabolic system during the performance of each technique.
5. The accuracy of the researcher to manually digitize the anatomical points of the computer-generated spatial model from video images of each subject.
6. The use of a centre of mass calculated from estimated segmental parameter values.
7. A controlled constant skiing velocity of $5.4 m \bullet s^{-1}$.

Limitations

This study was conducted under the following limitations:

1. A relatively small sample of highly-trained male ski-racers.

2. The ability of the snow-machine operator to maintain a constant velocity of $5.4 m \bullet s^{-1}$ for each subject and throughout each trial.

3. The variation in snow temperature (-6.5° to -5.5°C), air temperature (-6° to -3°C), humidity (39.6 – 70%) and general weather conditions (overcast and breezy early to clear and calm later) throughout the day such that each subject may have performed over different snow conditions.

Definitions

Physiology

Economy is defined as the submaximum oxygen consumption per unit of body weight (i.e., $VO_{2Submax}$) required to perform a given task (Cavanagh & Kram, 1985) such that the lower the oxygen consumption, the more economical is the movement.

Skate-skiing Techniques

The *1-skate* technique, also referred to as the V-2, is comprised of one double-symmetrical pole plant for each leg stride or skate (Bilodeau et al., 1992). The *2-skate*, also referred to as the Gunde skate (Boulay et al., 1994), V-1 alternate or open field technique (Smith & Heagy, 1994), consists of one double-symmetrical pole plant for every second leg stride (Bilodeau et al., 1996). The side of the body on which poling occurs was denoted as the "poling side" and the other side was referred to as the "non-poling side". The *offset* technique, commonly referred to as the V-1, has nonsymmetrical leg strides with asynchronous pole plants (Bilodeau et al., 1996). The poling and non-poling sides for the offset were referred to in a similar manner as the 2-skate.

CHAPTER 2 – REVIEW OF LITERATURE

Physiological Responses

Comparison Between Skating and Diagonal Stride

Several researchers have examined the differences in metabolic cost between the diagonal stride and skating techniques by comparing various physiological responses between the two disciplines at maximum and submaximum intensities. Physiological measures observed have included HR, VO_2, $[La^-]$, and minute ventilation (VE).

"Skating" (quotation marks used when specific skating technique was not indicated) has been observed to be faster than the diagonal stride at maximum intensity without differences between techniques for heart rate (Karvonen et al., 1987, 1989), blood lactate (Karvonen et al., 1987, 1989; Saibene, Cortili, Roi, & Colombini, 1989) or oxygen consumption (Saibene et al., 1989). Karvonen and colleagues (1989) observed HR values that were, on average, 20 beats•min^{-1} lower during "skating" compared to the diagonal stride at equal submaximum velocities. Zupan, Sheperd, and Eisenman (1988) reported 9.9% lower oxygen consumption values, 14.2% lower HR values and 5.6% lower VE values for the offset compared to the diagonal stride at equivalent submaximal velocities. Similarly, Saibene and colleagues (1989) reported that oxygen consumption and blood lactate values at equivalent submaximum velocities were 15 - 35% lower for "skating" compared to diagonal stride.

Hoffman and Clifford (1990) examined HR, VO_2 and VE between all variations of classic and skating technique that existed at that time at submaximum intensities. Lower HR (5%), VO_2 (19%) and VE (36%) values were observed for the offset and marathon skate techniques compared to the diagonal stride. Hoffman and Clifford attributed these differences to the lower dynamic frictional coefficient for skate-skis without kick-wax and the shorter time available for force application during the diagonal stride.

Rusko and colleagues (1992) incorporated a moderate hill climb into their examination of VO_2, HR and $[La^-]$ responses between offset and diagonal stride performed at maximum intensity. Until that point in time all comparisons between skate-skiing and diagonal stride had been performed on flat terrain. These researchers also initiated the use of a portable metabolic measurement system (Cosmed K-2) to measure VO_2 and HR. No differences in VO_2, HR or $[La^-]$ between the two techniques were observed. Maximum velocities for each technique were not reported so it is unclear if the offset was faster and therefore more economical than the diagonal stride as reported in Hoffman and Clifford's research (1990) on flat terrain. Correlations between VO_2 and velocity($r = 0.47$, $p<0.05$) for diagonal stride were reported for both the entire sample and the subgroup of subjects (n=5) who's training emphasized classic skiing (r=0.95, $p<0.05$). A similar relationship for the offset was not observed. Although discussion regarding this finding was not reported it seems to suggest that, unlike the diagonal stride, maximum achievable velocity for the offset may have been related to factors other than oxygen consumption, such as technical differences between skiers, which were not examined by Rusko and colleagues.

Several studies comparing physiological responses between classic and skate-skiing performed on rollerskis have also been performed. On-snow testing is typically complex because of the constant variations in the frictional drag of the ski associated with changes in air and snow temperatures, snow quality and grooming. Although rollerskis cannot replicate the frictional conditions of the snow-ski interface, the variation between subjects resultant from changing ambient conditions can be eliminated by studying skiing when performed on rollerskis (Hoffman, 1992). In comparison to on-snow research these studies have yielded some contradictory results. Stray-Gundersen and Ryschon (1987) observed higher VO_2, HR and [La^-] values for "skating" compared to the diagonal stride when performed at equivalent treadmill velocities on rollerskis. The authors suggested that the absence of kick-wax and the greater capacity to use the arm and trunk musculature for propulsion might explain the superior "skating" performances typically observed on-snow.

The reasons provided in the literature for the higher economy (i.e., lower oxygen consumption) consistently observed for skating techniques over the diagonal stride on both level and moderate uphills tend to be mechanical in nature. It has been speculated that the propulsive forces, both kicking and poling, applied during skating are greater than those applied during diagonal stride (Hoffman & Clifford, 1990; Karvonen et al., 1987, 1989; Saibene et al., 1989; Zupan et al., 1988). This improved propulsion for skate-skiing has been related to greater horizontal pole angles observed during the poling action (Karvonen et al., 1989) and greater propulsive forces exerted by the legs during the lateral push-off (Zupan et al., 1988). The increased trunk flexion at the hips and the lower trunk position inherent to skate-skiing apparently facilitate the application of these larger forces (Karvonen et al., 1987; Hoffman, 1992) while also reducing the force of wind drag against the skier (Karvonen et al., 1989; Saibene et al., 1988). It has also been suggested that skate-skiing is more efficient than diagonal stride because of reduced frictional drag on the ski due to the absence of kick-wax and the application of glide wax along the full length of the ski base (Hoffman & Clifford, 1990; Karvonen et al., 1989; Zupan et al., 1988). Furthermore, it has been speculated that frictional drag is also reduced in skating because only one ski is in contact with the snow during the glide phase instead of two, as is the case with the diagonal stride technique (Karvonen et al., 1987).

It is interesting that all of the reasons provided for the physiological differences between the two techniques were essentially mechanical in nature yet little research that examined both physiological and biomechanical factors simultaneously was completed.

Comparisons Between Different Skating Techniques

The direct scientific comparison of the 1-skate, 2-skate and offset techniques has only recently been undertaken. Currently, the literature offers less than complete comparisons of physiological responses between skate-skiing techniques.

Bilodeau et al. (1991) compared heart rates between 1-skate, 2-skate and offset techniques. Ten elite male cross-country ski racers performed each technique exclusively at maximal intensity or "competition speed" on a 3.04 km loop which contained demarcated sections of flat, 5° uphill and 3° downhill terrain. Heart rates were recorded and oxygen consumption values for each trial was estimated from individual HR-VO_2 curves calculated for each athlete from a previously completed treadmill running VO_{2Max} test. There were no differences observed for velocity, HR or estimated VO_2 between any of the skating techniques over each section of terrain. The order of terrains was not randomized across subjects such that each was skied in the same order as part of the loop. This potential methodological shortcoming was indicated by the significantly higher HR recorded for all techniques on the last section of the loop: the downhill section. Presumably the VO_2 required to ski this easier terrain was affected by the demands of skiing the rest of the loop. The authors explained this "surprising" finding by suggesting that athletes may have pushed harder on the downhill section to increase speed (Bilodeau et al, 1991).

Boulay and colleagues (1994) recorded HR while comparing the effect of different slopes on maximal attainable velocity for the offset, 1-skate and 2-skate techniques. Nine top-level junior ski racers (2 females and 7 males) performed each technique over slopes of -1, 0, 6, 9 and 12°. The sections of terrain ranged in distance from 120 to 200 m. The duration of the trials ranged from 26 to 60 seconds. Performance intensities reportedly ranged from 88-93% of $HR_{Max.}$ As slope increased HR increased for the 2-skate and 1-skate but not the offset. The offset also produced faster velocities than the 1-skate and 2-skate techniques on the steeper grades. Finally, despite the production of similar velocities, heart rate for 1-skate was significantly higher than 2-skate on the 9° slope. The authors were cautious, however, in inferring the apparent effectiveness and efficiency of the offset for generating faster velocities on moderate to steep uphill terrain. They cited the potential variable efficiency of each skier between techniques and/or the variation in anaerobic demands between terrains as likely contributors to the offset's faster velocities (Boulay et al., 1994). There were no reported differences in HR or velocity between techniques on the flat terrain suggesting that technique selection was of "minor importance in maintaining maximal velocity" (Boulay et al., 1994, p. 285).

A brief summary of these two studies suggests that, at maximum intensity, performance of the 1-skate, 2-skate or offset over flat, mild uphill (5-6°) or slight downhill (-1 to -3°) terrain produces similar velocities with equivalent heart rates (Bilodeau et al., 1991; Boulay et al., 1994). The validity of Bilodeau and colleague's 1991 findings is questionable due to their failure to control the confounding effects of one terrain upon another by not randomizing the order in which the different terrains were skied. The offset has been observed to be both faster and more economical (i.e., lower HR) than the 1-skate or 2-skate on moderate to steep (9-14°) uphill grades (Boulay et al., 1994). Finally, the 1-skate is more economical than the 2-skate on moderate (9°) uphills although it is still slower at maximum intensity than the offset (Boulay et al., 1994).

It appears that the comparison of economy between skate-skiing techniques based on oxygen consumption requires further investigation. This type of research has historically been restricted by the physical inability to continuously measure oxygen consumption in the field. Several methodologies have been used to measure or estimate oxygen consumption during the performance of cross-country skiing. Some researchers have used open circuit spirometry towards the end of a trial to collect expired air into either neoprene Douglass bags (MacDougall, Hughson, Sutton & Moroz, 1979) or meteorological balloons (Bedford, 1991; Hoffman & Clifford, 1990; Hoffman et al., 1990; Hoffman et al., 1991; Saibene et al., 1989; Zupan et al., 1988). Other researchers have recorded heart rates during skiing and used HR-VO_2 curves from treadmill running to predict VO_2 (Bilodeau et al., 1991; Boulay et al., 1994). Oxygen consumption has also been estimated from the kinematic analyses of film of elite competitors (Norman & Komi, 1987; Norman et al., 1989). To the researcher's knowledge only one study (Rusko et al., 1992), has used a portable metabolic system to directly measure oxygen consumption during the performance of cross-country skiing. Recent advancements in this type of technology would seem to warrant its further use in the scientific investigation of cross-country skiing.

Kinematic and Temporal Research

Kinematics of Skate-skiing

The majority of the biomechanical research of skate-skiing has sought to describe the unique kinematic and temporal characteristics of the offset technique.

Smith et al., (1988) filmed elite male skiers performing the offset up a 7° hill at a World Cup race in Oslo, Norway. Three-dimensional parameters were calculated for the analysis of 10 racers who were distributed across the entire performance range. A correlation (r=0.85, p<0.05) between cycle length (CL) and race velocity was observed. Faster skiers had longer cycle lengths than slower skiers while maintaining similar cycle rates (CR). As well, the horizontal path of the faster skiers' centre of mass (CM) tended to be aligned more with the forward direction vector (i.e., less mediolateral movement). Finally, the faster skiers tended to place the "weak" side ski (i.e., non-poling side ski) more directly up the slope (i.e., less laterally). The authors concluded that the specific combination of longer CL and the ability to consistently direct motion in the forward direction were "distinguishing characteristics" of more successful world class skiers.

Smith et al., (1989) filmed male and female skiers in the 50 km and 20 km (respectively) freestyle races at the 1988 Calgary Olympics and completed three-dimensional analyses of the offset on "moderate" (6 to 7°) and "steep" (10 to 11°) uphills. The major finding in this study was that as grade increased skiers tended to maintain or increase cycle rate while decreasing cycle length. Associated with these uphill cycle adaptations was an increase in the duration of the propulsive phase and a decrease in the relative duration of the recovery or gliding phase. The authors concluded that there were two apparent strategies for maintaining velocity on steeper slopes. The first entailed emphasizing CL and glide. The increase in required mechanical energy would be manifest by the increased lateral motion of the CM. The second strategy involved emphasizing CR and minimizing CM motion by changing pole orientations to a more forward direction. The increase in mechanical energy requirements for this approach would likely be related to the increase in muscular effort required by the arms. Males used both strategies while females mainly used the tactic that emphasized increased CR (Smith et al., 1989). Aro and colleagues (1990) used data from Smith's 1989 study to complete three-dimensional kinematic analyses of offset on 5-6° and 10-11° uphill slopes and observed a similar increase in CR for males with concurrent decreases in CL and CV in response to steeper grades. These changes were related to increases in poling and non-poling side ski-edging angles, forward step displacement, and the skiers' stance width and a decrease in lateral CM movement. Also, increases in poling and non-poling side ski angles (i.e., the angle of the ski to the forward direction of travel vector) were observed. The researchers suggested that this non-poling side ski angle increased because, in lieu of a poling force, the skier attempted to maximize glide and velocity on this side by maintaining a relatively laterally oriented ski.

Gregory and colleagues (1994) performed a three-dimensional kinematic analysis of the offset performed by 16 female Olympians skiing over flat terrain during the 30 km freestyle race at the 1992 Albertville Olympics. The movement patterns of eight finishers from the top half ("more successful skiers") were compared with eight from the bottom half ("less successful skiers"). Cycle length was correlated with cycle rate (r=-0.82, p<0.05) for the entire sample. Not surprisingly, the more successful skiers had faster cycle velocities, a finding which was attributed to larger poling and skating forces indicated by greater flexion of the trunk non-poling side elbow and knee (Gregory et al., 1994). No speculation was offered regarding the effect on oxygen consumption of generating larger propulsive forces. Humphreys and colleagues (1993) produced a three-dimensional kinematic analysis of the offset technique on a gradual uphill (no grade provided) from competitors in the same race. A 0.4m longer CL ($p<0.05$) with equivalent CR was noted as the distinguishing characteristic of a group of faster skiers over a group of slower skiers. Like Gregory's 1994 study, the longer CL was attributed to greater propulsion, illustrated by greater ($p<0.05$) R.O.M. of the trunk (27° versus 23°) and non-poling side knee (38° versus 31°).

Rundell and McCarthy (1996) perfomed a kinematic analysis of women performing the offset up an 11-12° grade on two successive laps of a 10km freestyle race at the 1995 U.S. National Championships. Once again, cycle length was observed to be positively correlated ($r=0.78$, $p<0.05$) with velocity. Slower race velocities observed during the second lap were associated with lower cycle rates. The shorter cycle lengths exhibited by the slower competitors, particularly during the second lap, was attributed to a relative lack of fitness, specifically upper body muscular endurance (Rundell & McCarthy, 1996).

In a similar offset study, Viitasalo, Norvapalo, Laakso, Leppävuori and Salo (1997) examined the effects of a 50km race distance on kinematic parameters from three-dimensional data of five world-class skiers performing the offset up an 8° incline over three consecutive laps of the 1993 World Championships 50 km freestyle race. A decrease in cycle velocity, correlated with a reduction in cycle length accompanied successively lower lap times. Additionally, with each subsequent lap, greater mediolateral movement of the CM was observed. A similar systematic increase in the vertical movements of the

CM did not occur as the authors had hypothesized. The authors suggested, "energy at the end of the competition was wasted more in sideward movements than at the beginning" (Viitasalo et al., 1997, p. 95).

Smith and Nelson (1990), who investigated the effect of increased velocity on kinematic parameters, further corroborated the similar results of these offset studies. Subjects were filmed skiing up a 7° pitch at three different perceived exertion levels: "training pace", "marathon pace" and "5 kilometre (race) pace". Three-dimensional co-ordinates for pole plant locations and displacement between pole plants were determined and CV, CR, and CL were calculated. Consistent with previous race-study findings (Smith et al., 1988; Smith et al., 1989) cycle rate was similar across subjects with the fastest skiers within each intensity condition producing the longest cycle lengths. Faster velocities were achieved, however, by increasing cycle rate and maintaining cycle length (Smith & Nelson, 1990).

In summary, the offset was one of the first commonly used skate-skiing techniques and it has received the most research attention. Most biomechanical investigation of this technique has described the kinematic factors that are most closely related to the production of faster velocities. The most often reported correlate of velocity for the offset technique was cycle length, on both flat terrain (Bilodeau et al., 1992; Bilodeau et al., 1996; Gregory et al., 1994; Humphreys et al., 1993) and uphills (Bilodeau et al., 1992; Bilodeau et al., 1996; Boulay et al., 1994; Rundell & McCarthy, 1996; Smith et al., 1988; Smith & Nelson, 1990; Viitasalo et al., 1997). It has been reported that this correlation weakens as the terrain becomes steeper (Aro et al., 1990; Smith et al., 1989). Longer cycle lengths were generally attributed to the application of larger and more efficient (i.e., more direct line of application) propulsive forces indicated by the correlation of velocity with increased flexion of the weak-side elbow (Gregory et al., 1994), weak-side knee and trunk (Gregory et al., 1994; Humphreys et al., 1993). Additionally, the path of the CM for the fastest offset performances tends to be more closely aligned with the forward direction (i.e., less mediolateral displacement of the CM) (Smith et al., 1988; Viitasalo et al., 1997). Several studies have examined the changes in kinematic variables for the offset that occur as a skier encounters an increase in grade or slope. The most salient finding from these studies has been that faster skiers tend to maintain or increase their cycle rate (Bilodeau et al., 1992; Smith & Nelson, 1990) while generally reducing cycle length (Aro et al., 1990; Smith et al., 1989) in order to maintain velocity. This maintenance of velocity apparently requires the skier to increase the poling phase of each cycle (Bilodeau et al., 1992; Smith et al., 1989). Other kinematic adaptations inherent to skiing faster while performing the offset uphill included a greater angle of the skis to the forward direction vector (Aro et al., 1990; Smith et al., 1989), increased ski edging angles (Aro et al., 1990), increased forward step distance (Aro et al., 1990) and a wider stance width (Aro et al., 1990).

2-skate

Smith and Heagy (1994) produced a three-dimensional kinematic analysis of the 2-skate performed on flat terrain during the men's 50 km freestyle race at the 1992 Albertville Olympics. Similar to the offset, the fastest skiers had the longest CL (r=0.76, p<0.05). Poling side knee extension was correlated with CL (r=0.51, p<0.05) leading the researchers to suggest that this "more vigourous knee extension" was indicative of larger propulsive forces and therefore longer cycle lengths for the faster skiers (Smith & Heagy, 1994, p.79). There was also an elevation of the skier's CM at the end of the glide phase just prior to the poling action. There was a drop of the CM during the offset technique just prior to the poling action (Smith & Heagy, 1994). It was suggested that the energy required for this upwards movement of the CM during the 2-skate may be associated with increased energy demands (i.e., higher oxygen consumption) compared to the offset technique (Smith & Heagy, 1994).

1-skate

The researcher is not aware of any published studies that solely describe the kinematics of the 1-skate. However, McPherson (1991) in a technical report based on the analysis of the top finishers in the World Nordic Championships described the movements involved in the performance of the 1-skate. Two-dimensional video recordings and a short field width made quantification difficult in this study.

Comparisons Between 1-skate, 2-skate and Offset

Several studies have been published that compared kinematic parameters of the 1-skate, 2-skate and offset techniques (Bilodeau et al., 1991, 1992; Boulay et al., 1994).

Bilodeau et al., (1991) appear to be the first researchers to have directly compared the different skating techniques over various grades of terrain. The maximum achievable velocities for the 1-skate, 2-skate and offset were compared over flat, uphill (8°) and downhill (-5°) grades. Differences in maximum velocity between techniques were not observed over any of the terrains and no discussion concerning these findings was provided.

Bilodeau et al., (1992) compared the relative durations of the gliding and propulsive phases between the 1-skate, 2-skate and offset techniques. Nine provincial and national level skiers were videotaped skiing at a self-prescribed 80% of maximum intensity using each of the techniques on flat and "low grade" uphill (5°) pitches. Cycle lengths were calculated from video analysis and times through a measured field were used to calculate velocities. Similar to previous findings (Aro et al., 1990; Smith et al., 1988; Smith et. al., 1989; Smith & Nelson, 1990), faster velocities were correlated with longer cycle lengths on flats (r=0.34, p<0.05) and uphills (r=0.87, p<0.05). Similar to the findings of Smith and Nelson (1990), an increase in cycle rate and not cycle length was required to maintain velocity on a steeper grade for all three skating techniques. This increase in CR on uphills was accompanied by an increase in the duration of the propulsive phase with a concurrent decrease in relative gliding time. Differences in velocity between the three techniques were not observed on flat terrain. However, a difference in cycle length between techniques was observed with the 1-skate producing the longest CL and the offset the shortest. A similar difference was noted for the uphill condition. The 2-skate elicited a slower velocity than either the 1-skate or offset on the uphill section. Regarding technique selection, it was suggested that the 2-skate was not well suited for uphill skiing as a slower velocity accompanied an increase in the duration of the propulsive phase (Bilodeau et al., 1992). No other recommendations for technique selection during racing were presented. However, it was suggested that fitness, technical ability, terrain profile and snow quality likely influenced technique selection more than a technique's maximum attainable speed and that further research was required to "fully document the efficiency of the skating techniques" (Bilodeau et al., 1992, p.925).

Boulay and colleagues (1994) examined the effect of slope variation upon maximal attainable velocity during performance of the 1-skate, 2-skate and offset techniques. Nine junior ski racers were videotaped skiing at maximal velocity using each of the techniques over slopes of -1, 0, 6, 9, and 12°for analysis. Cycle lengths and CR were different ($p<0.01$) between techniques with the 1-skate producing the longest CL followed by the 2-skate and offset. The inverse was found for cycle rate with the offset having the fastest and 1-skate the slowest values. Maximum velocity was related to CL but not CR for all three techniques. A reduction in cycle length and maintenance of cycle rates was observed as the incline increased. There were no differences in velocity reported for any of the techniques over the -1, 0 and 6° grades. However, the offset technique was observed to be faster than the 1-skate and 2-skate on the 9 and 12° uphills. The 1-skate was also faster than the 2-skate on the 9° ascent. The authors identified these differences as the study's novel findings although they cautioned that confounding variables not examined nor controlled for including the "possible variable efficiency of skiers between techniques" (Boulay et al., 1994, p. 285) might have partially contributed to the faster speeds observed during performance of the offset.

Comparisons between the three skate-skiing techniques have revealed that there are no differences in the maximal achievable velocity over flats, downhills or moderate uphills (Bilodeau et al., 1991; Boulay et al., 1994). Self-prescribed submaximal intensity velocities were also reported to be equivalent on flat terrain (Bilodeau et al., 1992). Maximum velocity is positively correlated with cycle length for all three techniques (Bilodeau et al., 1996; Boulay et al., 1994) with the 1-skate producing the longest CL followed by the 2-skate and then offset on flats, uphills (Bilodeau et al., 1992, Boulay et al., 1994) and downhills (Boulay et al., 1994). Similarly, the quickest cycle rates were observed during performance of the offset and the slowest during the 1-skate (Boulay et al., 1994). The 2-skate is slower at maximum velocity compared to the 1-skate on uphill terrain (Bilodeau et al., 1992; Boulay et al., 1994). Finally, the offset technique is significantly faster at maximum intensity on steep (9 -12°) uphills (Boulay et al., 1994).

There appears to be only a few suggestions provided in the literature for selecting a skate-skiing technique for racing based on kinematic factors. The 1-skate is preferred over the 2-skate on moderate to steep uphills although the offset is apparently preferable to both for steeper climbs. A comparison of findings from Smith and Heagy's 1994 examination of the 2-skate with results from the previously discussed comparative studies reveals two particularly interesting points. First, compared to the offset, a larger vertical displacement of the CM was observed throughout one cycle of the 2-skate. Second, the duration of skating phases for the 2-skate in two separate studies were practically the same: 55.0% of the cycle time (Smith and Heagy, 1994) and 54.1% of the cycle (Bilodeau et al., 1992). These values are greater than the 46.1% glide phase time reported for the offset by Bilodeau and associates (1992). Little speculation was offered in either study as to whether the greater vertical movement of the CM or the relatively longer gliding phase time offered the 2-skate a potential economical advantage or disadvantage over the offset. This problem could be addressed by comparing the oxygen consumption required for each technique at equal velocities. An examination of kinematic variables from the three skate-skiing techniques performed at a constant velocity over flat terrain could potentially answer some questions regarding technique selection for races. Additionally, potential solutions to the technique selection question could be found if the kinematic parameters unique to each technique were simultaneously examined and compared with the required oxygen consumption.

CHAPTER 3 – METHODOLOGY

Subjects

Eleven (11) highly trained male cross-country ski racers between the ages of 20-27 years, living and training in Thunder Bay, served as volunteer subjects. Seven subjects were members of Thunder Bay's National Training Centre Development Team. All subjects were training 1-2 times per day (a minimum of 400-700 training hours per year). Descriptive data for the subject pool is presented in Table 1. The mean VO_{2Max} of 65.7 $ml \bullet kg^{-1} \bullet min^{-1}$ is considerably less than the average value of 83.8 $ml \bullet kg^{-1} \bullet min^{-1}$ for elite Swedish skiers reported by Bergh (1987). In this context the subjects can be characterized as highly trained although below the elite level. Each subject signed written informed consent documents after having the purpose of the study, their role as subjects and any potential personal risks and/or discomforts associated with their participation in this study explained to them (see Appendices 1,2 & 10). Prior to recruiting subjects ethical approval for this study was obtained from Lakehead University's Ethics Advisory Committee.

Table 1 – Descriptive statistics for participating subjects.

Variable	Range	Mean
Age (years)	20 - 27	21.9
Skiing Experience (years)	3 – 19	9.8
Height (cm)	169.9 – 190.0	177.2
Weight (kg)	67.6 – 86.6	74.2
VO_{2Max} ($ml \bullet kg^{-1} \bullet min^{-1}$)	58.9 – 73.5	65.7

General Field Procedures

Each subject skied in a counter-clockwise direction around a flat oval track (≈500 m in length) groomed for skating in the stadium at the Lappe Nordic Ski

Centre in Thunder Bay, Ontario. Three consecutive trials were performed using 1-skate, 2-skate or offset exclusively for each trial. The order of techniques was randomly assigned and counterbalanced across subjects. Subjects maintained a constant velocity of 5.4 $m \cdot s^{-1}$ by following a snow-machine equipped with a speedometer. The value of this velocity was determined in consultation with the coach of the National Training Centre Development Team to ensure that all subjects could maintain the constant speed and stay below 70% of maximum intensity while using each of the techniques. Criteria for selecting this velocity included snow and weather conditions combined with the submaximum intensity requirement. Weather conditions over the 9 hour testing period remained remarkably static with the air temperature ranging from -6 to -3°C and the snow temperature ranging from -6.5 to -5.5°C. This relatively small range did not appear to cause changes in the structure or quality of the snow and therefore weather appeared to have no appreciable impact on any of the study's predictor or outcome variables.

Each skier warmed-up individually for 20 minutes before his first trial. Each trial lasted 5 to 6 minutes. There was a 5 minute rest period between each trial to download data and recalibrate the portable metabolic system. Air and snow temperatures as well as ambient humidity were recorded prior to beginning each trial. The total time required to perform all three trials was between 20 and 25 minutes per subject.

All subjects were instructed to abstain from consuming caffeine, food and alcohol 2 hours prior to their testing time. Subjects were also requested to avoid strenuous exercise 24 hours prior to testing. Additionally, subjects were requested to wax their skis with the same wax and using the same ski preparation techniques according to the day's prevailing snow and environmental conditions.

Measurement of Oxygen Consumption

Throughout each trial, each subject breathed into a portable metabolic measurement system (KB1-C, AeroSport Inc., Ann Arbor, MI). The KB1-C measures and records VO_2, VCO_2, heart rate (HR), respiratory exchange ratio (RQ) and minute ventilation (VE). The system includes a facemask to collect expired air, a sensor system to measure ventilation, O_2 and CO_2 concentrations, as well as a transmitter, a wireless heart rate electrode, rechargeable battery and receiver. The sensor system and gas sampler are connected to the facemask and harnessed to the subject's back (total weight approximately 1.0 kg). Continuous proportional sampling, basically a variation of open circuit spirometry that eliminates the need for a large gas-mixing chamber, is constantly performed within the unit to determine the gas concentrations of the expired air (AeroSport Inc., 1995). The capacity of the technology utilized by the KB1-C to provide reliable and valid measurements of VO_2 at submaximum and maximum exercise intensities has been established (Melanson, Freedson, Hendelman & Debold, 1996; Novitsky, Segal, Chatr-Aryamontri, Gukakov & Katch, 1995; Segal, Chatr-Aryamontri & Gukakov, 1994).

The variable flow pneumotach on the KB1-C was set to the "high" flow rating throughout the entire testing process. The high flow setting operates at a VE $_{(STPD)}$ range between 25 and 200 L•min^{-1} and is the manufacturer's recommended setting for higher intensity exercise studies (AeroSport Inc., 1995). A flow calibration performed on the pneumotach using a 3 L syringe just before testing was accurate within ±3%. A gas calibration performed on the KB1-C with a calibration gas of 16% O_2 and 4% CO_2 prior to testing was accurate to within less than ±1%. Immediately following the performance of each subject's third and final technique an AutoCal (AeroSport Inc., 1995) was performed on the unit to purge all remaining expired air from the system and reset the sensors to the calibration settings.

Immediately following each trial the KB1-C was unhooked from the gas lines connected to the facemask. The physiological data from the trial was downloaded to a printer and quickly assessed to ensure that each subject had achieved and maintained steady state metabolism for the last 2 minutes of the trial. The KB1-C was programmed to record average values every 20 seconds, the lowest interval available. Steady state metabolism was defined as less than 3% variation in VO_2 values (i.e., approximately ±120 ml). The steady state VO_2 values used for statistical analyses were calculated for each trial by averaging the values over the last minute of each trial. Following each download of physiological data the previously described AutoCal procedure was performed against ambient air. Subjects continued to wear the facemask between trials and were permitted to perform some light skiing if they desired.

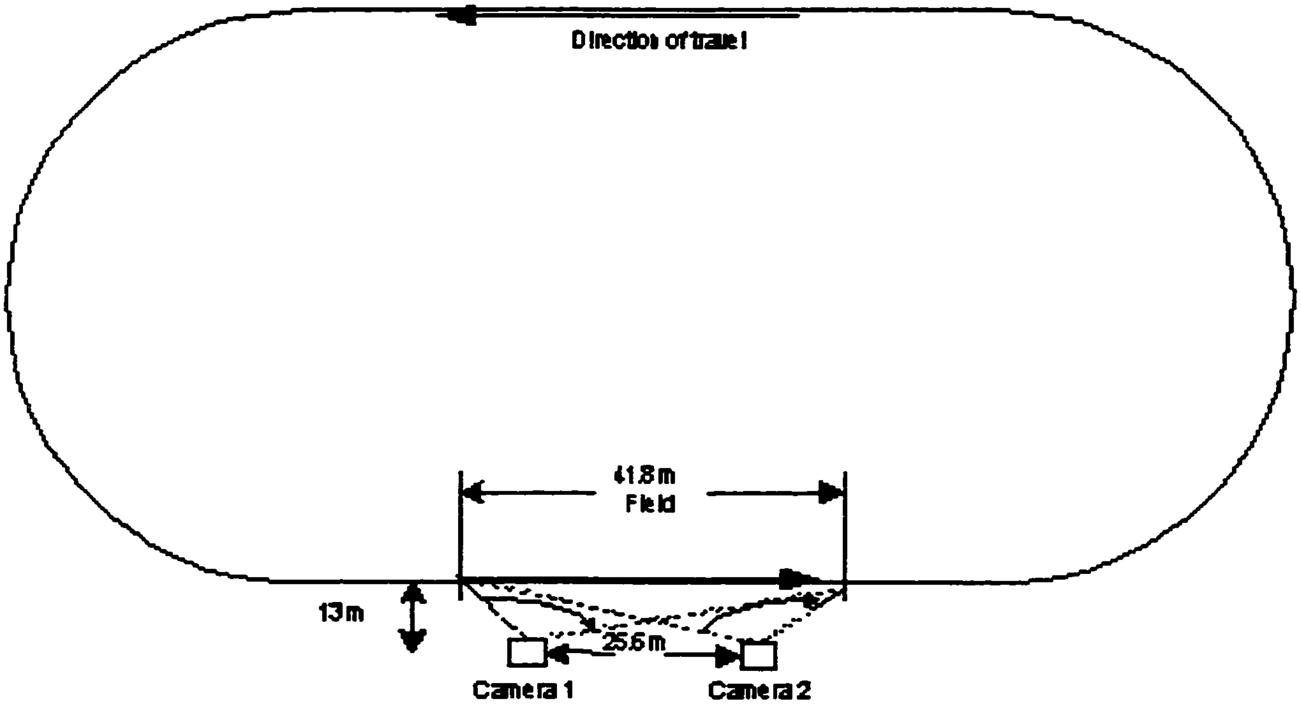
Laboratory Procedures

Within one week of the on-snow testing each subject completed a treadmill-running continuous graded-intensity VO_{2Max} test. The KB1-C was used to measure all expired gases for this procedure. The high setting on the pneumotach was utilized and the same calibration and verification procedures described for the on-snow testing were used prior to and following each VO_{2Max} test. Subjects warmed up on the treadmill for ten minutes at either the initial speed employed for the test or just below. Each subject began the test running at 3.74 $m \bullet s^{-1}$ on a level treadmill bed. The velocity was increased 0.29 $m \bullet s^{-1}$ each minute until a velocity of 5.76 $m \bullet s^{-1}$ was reached. After this the incline of the treadmill bed was increased 2° every minute until the subject achieved volitional exhaustion. VO_{2Max} was determined as the highest 20 second VO_2 value at the point where VO_2 values stopped increasing. The entire test lasted 9 to 13 minutes in duration.

Kinematic Data Capture

Each skier was videotaped throughout each trial as he passed through a demarcated 41.8 m field. Two digital video cameras (Panasonic CL-350) were positioned 25.6 m apart from one another and 13 m from the track (see Figure 1).

Figure 1 – Overhead diagram of video camera set-up.



The cameras were genlocked to ensure that the recorded video images were synchronized in time. Each camera was affixed to a pan and tilt head (Peak Performance Technologies Inc., Englewood, CO) that was in turn attached to a tribrach via a fixed tribrach adapter. The tribrach, mounted on a surveying tripod, was used to level the pan and tilt heads in the horizontal and vertical planes. Skilled camera operators panned and tilted each camera to videotape the skier as he passed through the field. A fixed focal length for each camera was determined prior to videotaping by having the tallest subject stand on the track where the camera's focal axis was perpendicular to the track (i.e., at the point closest to the camera or where the subject's image size would be the largest during panning). The focal length was zoomed in or away from the subject until his image occupied roughly two-thirds of the vertical aspect of the camera's viewing field. A previous pan and tilt pilot study of skate-skiing confirmed that this was the largest possible image size that allowed the camera operator to consistently follow the athlete without inadvertently cropping an essential distal portion of the image. Video images were captured at a speed of 30 Hz with a shutter speed of 1/1000 seconds, the fastest that the prevailing ambient light permitted.

Prior to being recorded on videotape, video signals from each camera passed through a Digital Encoding Unit (DEU). The DEU, connected to the pan and tilt head, digitally imprinted the camera's angular position (i.e., pan and tilt co-ordinates) on each video picture in the form of a bar code. This data was decoded and stored with the digitized data during the digitization process. The video signal also passed through a Time Code Generator (TCG) that imprinted a SMPTE time code window on each field of each picture of the videotape.

Subjects wore dark form fitting clothing to promote accurate digitization of the video pictures. Additionally, white contrasting tape was applied to the subjects' clothing over the following joint centres: i) lateral epicondyle of the right knee, ii) right hip at the greater trochanter, iii) dorsal aspect of the right wrist, iv) lateral epicondyle of the right elbow, v) acromion process of the right shoulder, vi) medial epicondyle of the left knee, vii) anterior surface of the left wrist and viii) medial epicondyle of the left elbow. Additionally, black contrasting tape was applied on subjects' ski boots over the lateral malleolus of the right foot and the medial malleolus of the left foot to facilitate digitization of the ankle joints.

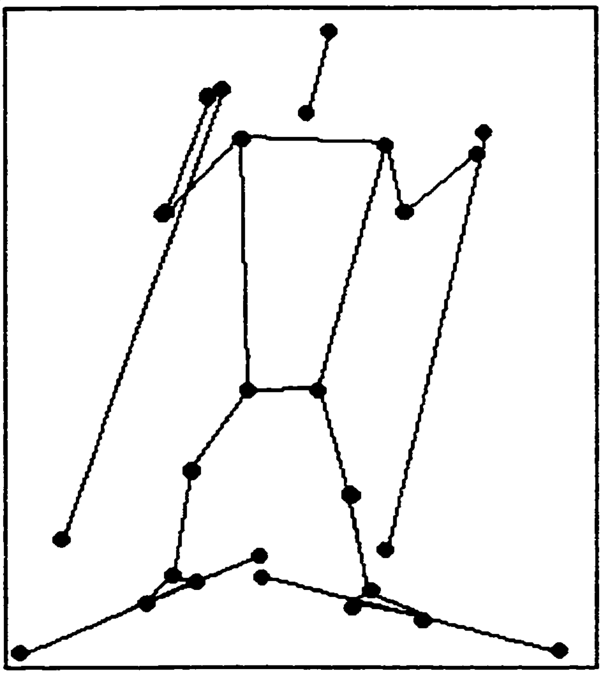
Immediately following completion of all trials four 365.76 cm surveying calibration rods were erected vertically using a level 10 m apart. The distance between the two furthest distinguishable vertical points on each rod was determined and videotaped for calibration purposes. The points were later digitized. The co-ordinates of these known interpoint distances were used to calculate the three dimensional image space and its associated co-ordinate system (Peak5 User's Reference Manual, 1995).

Kinematic Data Analysis

Analysis of each subject's technique entailed digitizing of the recorded video pictures using the Pan & Tilt module of the Peak5 System (Peak Performance Technologies Inc., Englewood, CO). Three full cycles of each technique were digitized from each camera view. For the 1-skate technique analysis of the cycle began and ended with pole plants on the right aspect of the skier, the side that was adjacent to the cameras. In this way one cycle of 1-skate included two pole plants and two leg strides, one on each side (Bilodeau et al., 1992). For the 2-skate technique, analysis of the cycle began and ended with successive pole plants (Bilodeau et al., 1992). For the offset technique analysis of one cycle began and ended with successive pole plants on the poling side (Bilodeau et al., 1996). Critical events were identified for each cycle during the digitizing process. These included the initiation and release of pole contact with the snow for each pole as well as the beginning and end of ski-snow contact for each ski.

Video pictures were digitized at a sampling rate of 30 Hz (i.e., only the first field of each video frame). A 26-point 16-segment model was digitized (see Figure 2) which included the head, neck, shoulders, elbows, wrists, hips (greater trochanter), knee, ankles, heels, toes, ski tips, ski tails, top of pole grips and pole baskets. Hinrichs' revised body segment parameter data (1990), modified to account for ski, boot and pole masses, were used to calculate the body's centre of mass (CM). The raw data was smoothed using a Butterworth digital filter at a cut-off frequency determined by spectral analysis and a follow-up visual comparison of raw and smoothed data. The cut-off frequency varied according to the rate of movement of the specific point and ranged between 3 to 7 Hz. Three extra pictures were digitized at the beginning and end of each cycle to minimize end point effects with the Butterworth algorithm during the smoothing process (Smith & Heagy, 1994). The Peak5 analysis software used the direct linear transformation method (DLT) to calculate the 3-D co-ordinates from the two conditioned trials. The three cycles of each technique were subsequently "averaged" using the Trial Averaging Module of the Peak5 system, a process that generates a representative or "average" cycle. This computation essentially reduces the deleterious statistical effects of any kinematic "abnormalities" present during the performance of a particular cycle and produces a cycle that is more representative of each subject's technique (Peak5 User's Reference Manual, 1995). This average cycle was used to calculate all kinematic variables and temporal phases.

Figure 2 - 26-point spatial model.



Kinematic Variables

The kinematic variables investigated included cycle length, cycle time and cycle rate. For the 1-skate technique the cycle began and ended with the pole plants on the side of the skier that was adjacent to the cameras (i.e., right side). In this way one cycle of 1-skate included two pole plants and two leg strides, one on each side (Bilodeau et al., 1992). For the 2-skate technique, the cycle began and ended with successive pole plants (Bilodeau et al., 1992). For the offset technique, a cycle began and ended with successive pole plants on the poling side (Bilodeau et. al., 1996). Cycle length was measured as the distance each skier's centre of mass (CM) travelled in the forward direction. Cycle time was measured as the time in seconds to complete one cycle and cycle rate, expressed in hertz (Hz) was calculated as the number of cycles completed per second.

In addition to these basic cycle characteristics, several temporal measures were calculated, specifically the relative durations of the propulsive and gliding phases for one cycle of each technique. The propulsive phase was defined as the portion of the skating cycle that included poling and/or knee extension of the leg applying a skate force. The glide phase was defined as the period of the cycle that included gliding on the leading ski without any concurrent propulsive activity. Critical events were identified for each cycle during the digitizing process. These included the initiation and release of pole contact with the snow for each pole as well as the beginning and end of ski-snow contact for each ski. The elapsed time between these events was used to calculate the relative timing of the glide and propulsion phases for each technique for each subject.

The joint angles measured included the minimum, maximum and range of motion (ROM) during: flexion/extension of the elbows (see Figure 3) and shoulder extension during poling; flexion and extension of the trunk, at the hips, relative to the horizontal plane during poling (see Figure 6); and flexion/extension of the knees and ankles (see Figure 4) as well as abduction/adduction of the hips (see Figure 5) during the skating phase. The ankle flexion/extension was defined as the as the angular displacement between the tibia and the segment between the malleolus and the toe. The ski angle, measured as the angle between the ski and the forward direction of travel vector, as the ski touched down to initiate the glide phase (see Figure 7) and just prior to the release of the ski from the snow were recorded. The vertical pole inclinations as poling was initiated were also measured in both the sagittal (see Figure 8) and transverse planes. The vertical and lateral displacements as well as the horizontal acceleration of the skier's centre of mass (CM) throughout one complete cycle were calculated for each technique. The average angle of the forward velocity vector was calculated as the angle between the resultant vector between cycle length and lateral displacement and cycle length. A smaller average angular displacement of the forward velocity vector would therefore be indicative of a tendency to direct the body more in the forward direction and less from side to side throughout each cycle.

Figure 3 - R.O.M. at both poling and non-poling side elbows during poling.

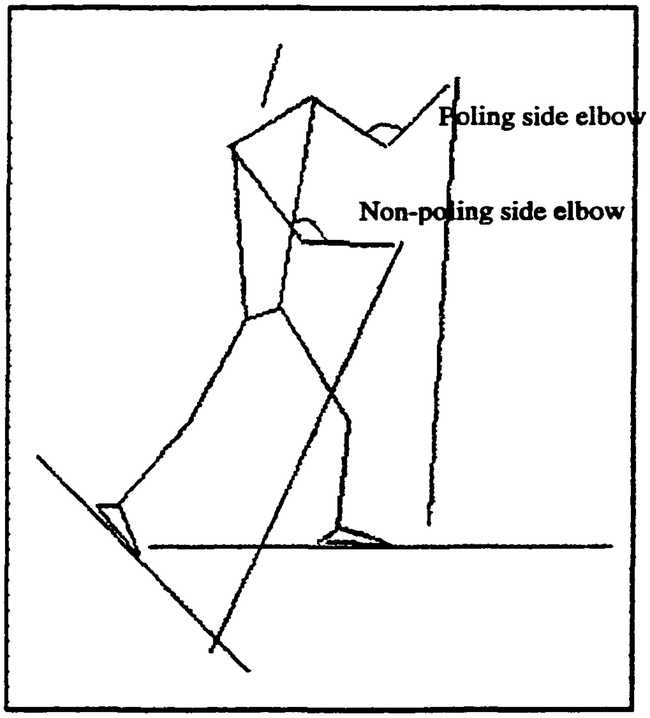


Figure 4 – R.O.M. at both poling and non-poling side knees (flexion/extension) and ankles (dorsiflexion).

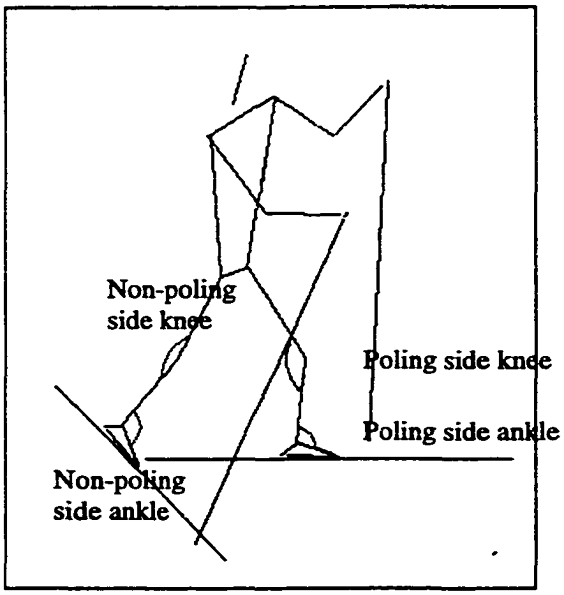


Figure 5 – Non-poling side hip abduction, measured between the thigh and the sagittal plane.

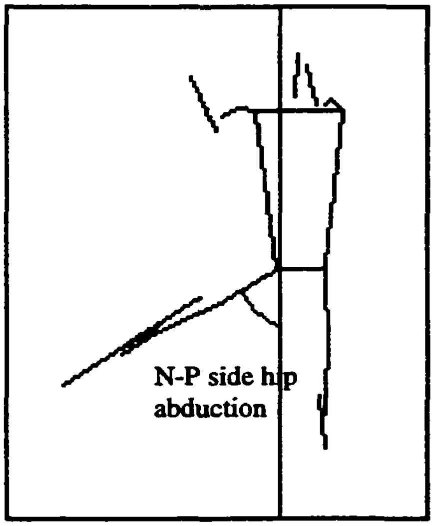


Figure 6 – Trunk flexion at the hip, measured as the angle between the trunk and the horizontal plane.

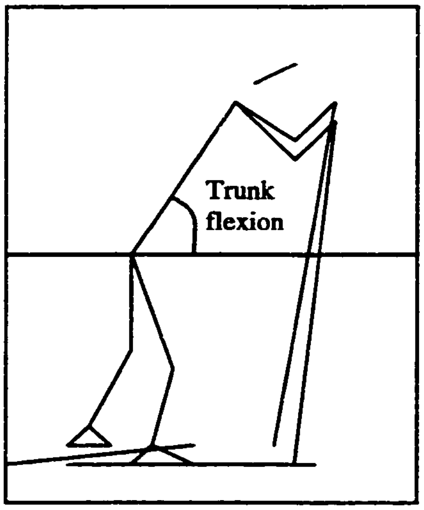


Figure 7 – Angle between the poling-side ski and the forward direction of travel vector as the ski touches down to initiate the glide phase.

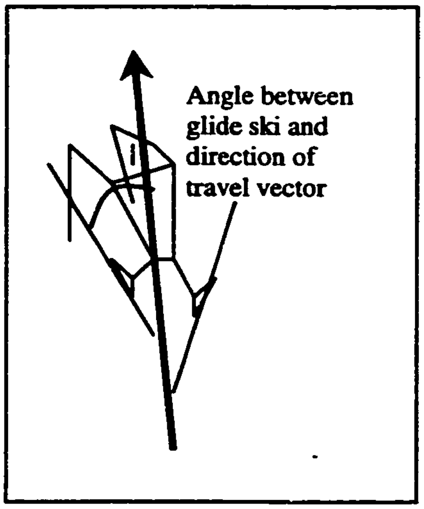
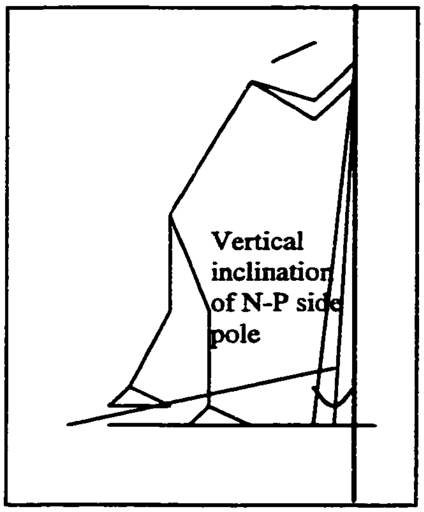


Figure 8 – Vertical pole inclinations at the initiation of poling.



Statistical Analyses

Between Techniques

A randomized block analysis of variance (ANOVA) was used to determine differences in VO_2 between the three techniques. The F-ratio was adjusted using a Greenhouse-Geisser epsilon to control for within-subject effects across techniques. Scheffé's Test ($p < .05$) was selected as the post hoc test to isolate significant differences.

Within Techniques

Bivariate correlations were calculated between oxygen consumption and heart rate (expressed as percentages of VO_{2Max} and HR_{Max}) and all kinematic performance variables to assess the strength of relationship between kinematic performance factors and those physiological response variables that represented economy. Additional correlation coefficients between economy and aerobic fitness, represented by VO_{2Max} were also calculated to determine the relationship between fitness and the economical performance of each technique.

CHAPTER 4 - RESULTS

Between Techniques

The descriptive statistics for the physiological variables for each skate-skiing technique are presented in Table 2. Minute ventilation for the 2-skate (84.77 l•min^{-1}) was lower (p<0.05, see Table 3) than the 1-skate (91.37 L•min^{-1}). All other physiological variables, including relative VO_2, VO_2 as a percentage of treadmill running VO_{2Max}, heart rate and RQ were not significantly different between techniques.

Table 2 - Physiological variables: descriptive statistics for 1-skate, 2-skate and offset.

Variable	1-skate		2-skate		Offset	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
O_2 consumption (ml•kg^{-1}•min^{-1})	44.89	2.49	43.23	1.63	43.77	4.77
O_2 consumption (%VO_2max)	68.51	4.54	66.04	4.52	66.60	5.36
CO_2 production (ml•kg^{-1}•min^{-1})	38.46	3.31	35.80	2.35	36.61	2.26
Heart rate (beats•min^{-1})	157.1	14.52	156.7	13.27	157.7	13.57
Heart rate (%HR_{Max})	81.1	7.43	80.9	7.15	80.9	7.11
*Minute ventilation (L•min^{-1}, BTPS)	91.37	9.67	84.77	6.68	88.05	6.65
Respiratory Quotient (VCO_2/VO_2)	.84	.05	.83	.04	.84	.05

*Significant difference between techniques, see Table 3.

Table 3 – ANOVA summary for minute ventilation.

Source of Variation	Sum of Squares	df (Corrected)*	Mean Square	F	Sig.
Between Techniques	266.417	1.560	170.760	5.89	.016†
Within Techniques	497.512	17.162	28.989		
Total	763.929				

*Greenhouse-Geisser epsilon = .780
†VE 2-skate less than 1-skate (p<0.05)

Kinematic and cycle characteristics for the 1-skate, 2-skate and offset are presented in Table 4. The 1-skate had both the longest average cycle length and cycle time, the 2-skate the next longest, and the offset the shortest. Inversely, the slowest cycle rate was observed during performance of the 1-skate, followed by the 2-skate with the offset requiring the fastest cycle rates. All observed between-technique differences were significant at the $p<0.05$ level.

Table 4 – Kinematic and cycle characteristics for 1-skate, 2-skate and offset.

Variable	1-skate		2-skate		Offset	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
Cycle length (m)	13.4[1]	1.32	9.93[1]	0.97	8.01[1]	0.84
Cycle Rate (Hz)	0.41[1]	0.03	0.54[1]	0.06	0.69[1]	0.06
%cycle time gliding	55.63	4.86	55.64	4.50	43.85[2]	10.55
%cycle time poling	27.88[1]	3.13	19.16[1]	2.09	23.22[1]	2.29
%cycle time skating	21.10[1]	3.35	27.59[1]	3.68	35.41[1]	7.63
%cycle time in propulsion	44.37	4.70	44.36	4.50	56.15[2]	10.55
Gliding time (s)	1.36[1]	0.19	1.04[1]	0.18	0.64[1]	0.19
Poling time (s)	0.68	0.06	0.35	0.04	0.34	0.02
Skating time (s)	0.49	0.08	0.51	0.05	0.52	0.12
Total propulsion time (s)	1.08[3]	0.09	0.82	0.07	0.82	0.15
Net vertical displacement of CM (m)	0.20	0.03	0.18	0.03	0.12[2]	0.04
Net lateral displacement of CM (m)	0.70[1]	0.17	0.55[1]	0.13	0.37[1]	0.17
Average forward velocity vector (º)	3.0	0.55	3.2	0.56	2.6[4]	0.84
Weight shift toward poling side (m)	0.08	0.04	0.11	0.03	0.08	0.05
Weight shift toward nonpoling side (m)	---	---	0.17[4]	0.04	0.24	0.05

[1] *differences exist between all three techniques ($p<0.05$)*
[2] differences exist between offset and 1-skate, offset and 2-skate ($p<0.05$)
[3] differences exist between 1-skate and 2-skate, 1-skate and offset ($p<0.05$)
[4] difference exists between 2-skate and offset ($p<0.05$)

The relative durations of each phase of the skating cycle for the three techniques are further illustrated in Figure 9. The percent duration of cycle time engaged in gliding was lower ($p>0.05$) for the offset compared to the 1-skate and 2-skate, which were practically equal. Consequently, a greater percentage of cycle time was required for propulsion during the offset compared to the 1-skate and 2-skate. The nature of this propulsion was observed to differ between techniques (see Table 4, Figure 9). The duration of cycle time engaged in poling was greatest for the 1-skate and smallest for the 2-skate. The offset was seen to require the greatest percent of cycle time for application of skating forces with the 1-skate requiring the least. All differences between techniques in percent cycle durations for application of propulsive forces were significant at the $p<0.05$ level.

Figure 9 - Relative phase durations for the 1-skate, 2-skate and offset techniques.

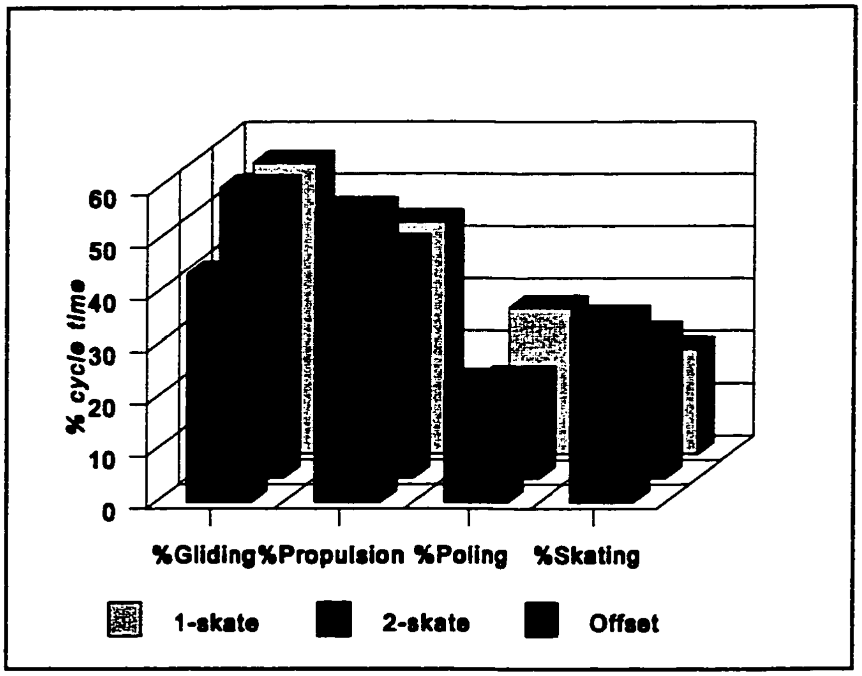
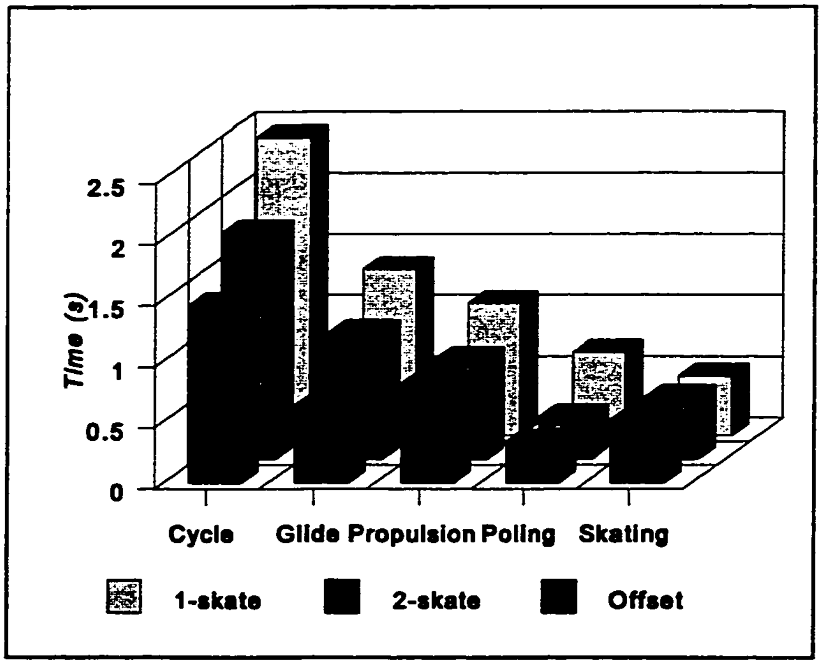


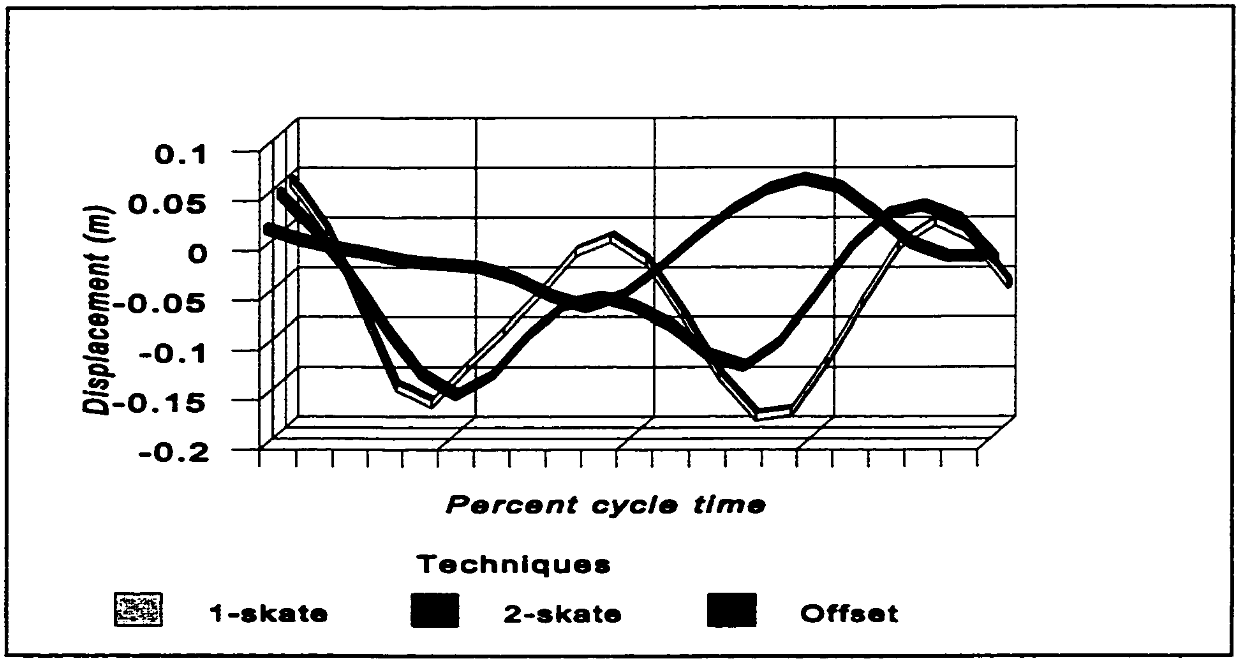
Figure 10 – Absolute phase durations for the 1-skate, 2-skate and offset.



Absolute cycle times and absolute phase durations are illustrated in Figure 10. Glide time was observed to be the longest ($p<0.05$) for 1-skate (1.36 s.), followed by 2-skate (1.04 s.) and offset (0.64 s.). The 1-skate required more time for propulsion per cycle then the 2-skate and offset techniques, which were observed to demand almost equal propulsion time (see Figure 10). Similarly, poling demanded approximately twice as much time per cycle of 1-skate (0.69 s.) as either 2-skate (0.34 s.) or offset (0.35 s.). Finally, all three techniques utilized similar amounts of time per cycle to apply skating forces (see Figure 10 and Table 4).

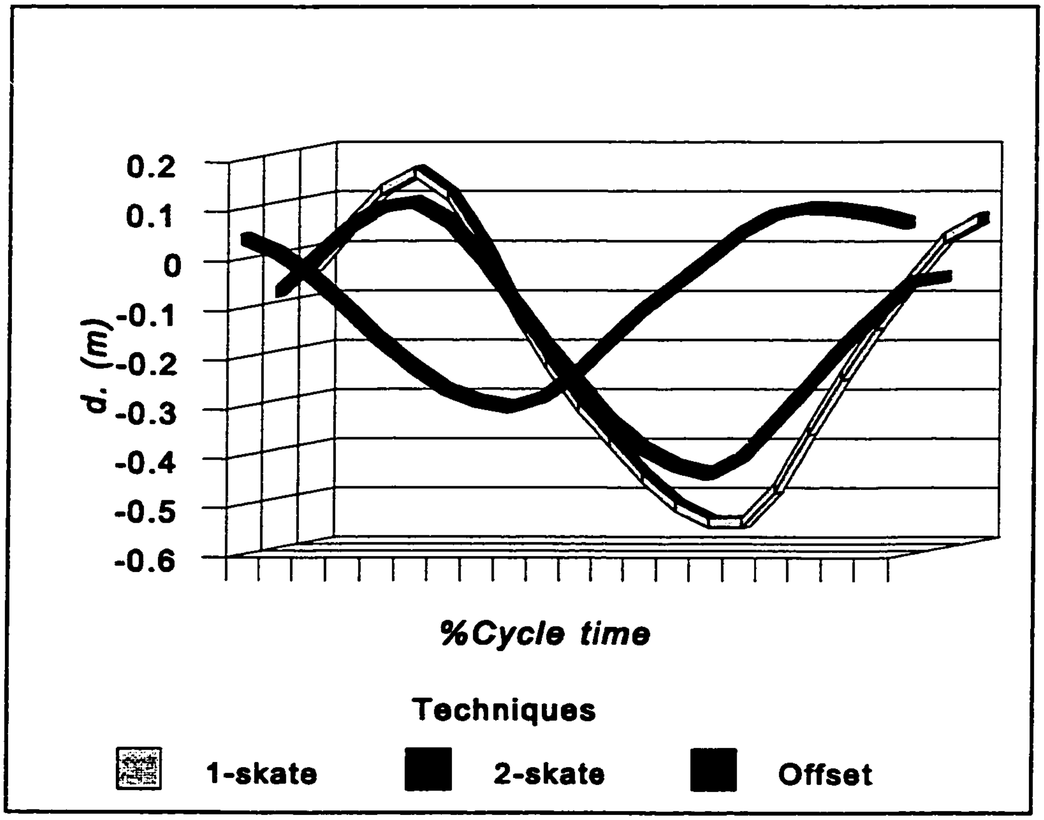
The net vertical displacement (see Figure 11) of the skier's centre of mass was less ($p<0.05$) during performance of the offset (12 cm) compared to either the 1-skate or 2-skate, which were not significantly different from one another (20 and 18 centimetres respectively).

Figure 11 – Vertical displacement of the CM versus %cycle time for the 1-skate, 2-skate and offset techniques.



The mediolateral CM was observed to be different ($p<0.05$) between all three techniques (see Figure 12). Performance of the 1-skate elicited the greatest lateral displacement and off set the least.

Figure 12 – Medio-lateral CM displacement versus %cycle time for the 1-skate, 2-skate and offset techniques.



Within Techniques

Significant ($p<0.05$) Pearson product correlations between %VO_{2Max} and %HR_{Max} and kinematic performance variables as well as fitness variables are presented in Tables 5 (1-skate), 6 (2-skate) and 7 (offset).

Table 5 – Significant correlations between physiological variables and kinematic performance/fitness variables for the 1-skate technique.

Physiological Variable	Kinematic Performance/Fitness Variable	r (p<0.05)
$\%VO_{2Max}$	VO_{2Max} (l•min^{-1})	-.68
	$VO_{2\,Max}$ (ml•kg^{-1}•min^{-1})	-.60
	PS poling time (s)	-.74
	Total poling time	-.64
	PS max. elbow flexion while poling on preferred side (°)	-.68
	PS elbow flexion ROM while poling on preferred side (°)	-.62
	PS shoulder extension at pole plant on preferred side (°)	-.64
$\%\ HR_{Max}$	VO_{2Max} (l•min^{-1})	-.66
	$VO_{2\,Max}$ (ml•kg^{-1}•min^{-1})	-.65
	Ski angle at ski plant on preferred side (°)	-.71
	Ski angle at ski plant on non-preferred side (°)	-.61
	NP shoulder extension at pole release on non-pref. side (°)	-.70
	Angular velocity of NP hip abduction (°•s^{-1})	-.70

Table 6 – Significant correlations between physiological variables and kinematic performance/fitness variables for the 2-skate technique.

Physiological Variable	Kinematic Performance/Fitness Variable	r (p<0.05)
$\%VO_{2Max}$	$VO_{2\,Max}$ (ml•kg^{-1}•min^{-1})	-.86
	%cycle spent gliding on poling side	-.62
	Total time per cycle spent gliding on poling side	-.58
	Non-poling side elbow extension ROM during poling (°)	-.63
	Poling side hip abduction at ski release (°)	-.60
	Angular velocity of poling side hip abduction (°•s^{-1})	-.63
	Non-poling side minimum hip abduction (°)	-.63
	Non-poling side knee flexion at ski plant (°)	.63
	Maximum poling side shoulder extension (°)	-.66
$\%\ HR_{Max}$	$VO_{2\,Max}$ (ml•kg^{-1}•min^{-1})	-.67
	Average angle of forward velocity vector (°)	-.62
	Poling side knee flexion at ski release (°)	-.73
	Maximum poling side elbow angle during poling (°)	.64
	Non-poling side shoulder extension at pole release (°)	-.58

Table 7 – Significant correlations between physiological variables and kinematic performance/fitness variables for the offset technique.

Physiological Variable	Kinematic Performance/Fitness Variable	r ($p<0.05$)
%VO_{2Max}	Forward flexion of trunk at pole plant (°)	-.60
	Poling side lateral pole orientation at pole plant (°)	.68
	Non-poling side min. ankle dorsiflexion during skating (°)	.68
% HR_{Max}	Net medio-lateral CM displacement per cycle (m)	-.61
	Average angle of forward velocity vector (°)	-.64
	Poling side vertical pole inclination at pole plant (°)	-.62
	Non-poling side max. ankle dorsiflexion during skating (°)	.81
	Non-poling side minimum hip abduction (°)	-.70
	Poling side hip abduction at ski release (°)	-.86

CHAPTER 5 – DISCUSSION

Between Technique Comparisons based on Physiological Responses

This study appears to be the first to compare skate-skiing techniques performed at equivalent submaximum intensities on the basis of simultaneously recorded physiological and kinematic measurements. Differences in joint angles and other kinematic variables are explained in detail only to elucidate certain differences in economy (i.e., oxygen consumption) or other physiological mechanisms between the 1-skate, 2-skate and offset techniques. Discussions of kinematic differences independent of physiological consideration were not made and would be fairly tenuous because all skiers performed at an equal velocity of $5.4 m \cdot s^{-1}$.

The purpose of this comparison was to identify physiological differences between techniques to determine which technique(s) is the most economical. Economy is defined as the submaximum oxygen consumption required to complete a given task (Cavanagh & Kram, 1985). Since the constraints of the task in this study were held constant, any observed differences in oxygen consumption would therefore indicate a difference in movement economy between techniques. Economy also influences movement efficiency (Cavanagh & Kram, 1985). Efficiency is traditionally defined as the mechanical work performed (Force x distance) divided by the energy expended. Generally speaking, if oxygen consumption were taken to represent energy expended, a more economical technique would also be more efficient. In this study, mechanical work was not measured. However, the forces each athlete needed to overcome in order to move at the same velocity (distance/time) were controlled to be as similar as possible. These forces included the force required to overcome air resistance. Air resistance is related to surface area, surface drag and velocity. Velocity was equal across skiers and low enough that surface area and surface drag would be considered negligible. The other factor that potentially could have influenced velocity was the surface drag between the snow and the ski base, which would vary according to snow conditions and the ski base preparation. To control for this factor, athletes were instructed to prepare their ski bases in the same manner. Additionally, snow and weather conditions remained relatively constant throughout the day. Since these components of mechanical work were as similar as possible any differences in oxygen consumption and efficiency could be attributed either to differences in the way athletes performed each technique (i.e., kinematic) or differences in aerobic fitness.

Oxygen Consumption

Average values for oxygen consumption were not significantly different between techniques ranging between 43.2 and 44.9 $ml \bullet kg^{-1} \bullet min^{-1}$. These values were comparable to the offset values of 39.2 and 40.0 $ml \bullet kg^{-1} \bullet min^{-1}$ observed by Hoffman and Clifford, (1990) and Saibene et al., (1989) respectively.

The actual values verified that, on average, subjects were performing all three techniques at the submaximum intensity of less than 70% VO_{2Max} that is typically prescribed for extended duration aerobic training sessions (Bergh, 1987; Eisenman, Johnson, Bainbridge, & Zupan, 1989). The absence of any significant difference in oxygen consumption between the 1-skate, 2-skate, and offset indicates that any skate-skiing technique may be employed on flat terrain, exclusively or in combination, during training when the primary objective is to elicit an appropriate submaximum-intensity cardiovascular (i.e. primarily aerobic) training effect.

Minute Ventilation

The average minute ventilation values observed in this study ranged from 84.8 to 91.4 L•min^{-1}. These values were comparable to the 96.0 and 82.0 L•min^{-1} observed by Hoffman et al., (1990) and Hoffman and Clifford, (1990) respectively, in two studies of rollerskiing performed at similar low intensities.

The 1-skate was observed to elicit a higher (p<0.05) VE than the 2-skate. This difference occurred despite no between-technique differences in VO_2 or the other physiological variables examined. The reasons for the disassociation between the typically linear VE-VO_2 relationship can be explained biomechanically. Faria (1994) observed greater minute ventilation from cross-country skiers when they performed simulated poling actions versus upright cycling at equivalent submaximum rates of oxygen consumption. Faria attributed the higher VE to a higher breathing rate that served to overcompensate for a lower tidal volume in order to meet each subject's ventilatory needs. This reduction in tidal volume was attributed to the repeated trunk flexion and associated contraction of the abdominal musculature required for synchronous (i.e., double) poling (Faria, 1994). This movement could effectively reduce and constrict the action of the diaphragm during inspiration, thereby limiting the available tidal space and reducing the volume of air per breath (i.e., tidal volume)

(Faria, 1994). Alternatively, the breathing rate could increase as it becomes entrained with the rhythms of peripheral limb movements, such as poling or skating, which occur at higher rates than the normal exercise breathing rate. This phenomenon has also been observed in the sport of rowing (Mahler, Shuhart, Brew, & Stukel, 1991).

In the present study, the absence of a meaningful Pearson-product correlation between minute ventilation and cycle rate for the 1-skate minimizes the likelihood that VE was higher for this technique due to the entrainment of breathing rate with poling. However, it seems plausible that the higher VE observed during performance of the 1-skate would be related to its greater poling demands (27.9% of cycle time) compared to the 2-skate (19.2%) and the repeated trunk flexion associated with this action. These demands could generate a ventilatory response similar to that described by Faria (1994) characterized by a reduced tidal volume due to constriction of the abdominal wall and a super-compensatory increase in breathing rate. A linear regression equation was derived to determine how much of the variance in 1-skate VE was explained by variables related to trunk flexion and abdominal muscle co-contraction during poling. A moderate relationship (adjusted $R^2 = 0.67$, $p<0.05$) was determined between VE (y) and the angles of trunk flexion at pole plant (x_1) and pole release (x_2) on the preferred side, and the angular velocity of trunk flexion during poling (x_3) on the non-preferred side. This relationship is described by the following equation:

$$y = -2.34x_1 + 1.14x_2 - 1.19x_3 + 228.91 \qquad \text{Eq. 1}$$

The prediction of minute ventilation for the 1-skate using Eq. 1 involves a standard error of the estimate of ±5.55 L•min^{-1}. A similar relationship was not observed for the 2-skate despite the similarities between the 1-skate and 2-skate on selected kinematic parameters related to poling including the trunk angle at pole plant, the angular velocity of trunk flexion during poling and the vertical inclination of the poles at pole plant (see Table 8). The absence of a relationship between minute ventilation and poling kinematics for the 2-skate may have been due to the reduced metabolic demands of this technique, resultant from requiring half as much poling as the 1-skate.

Table 8 - Selected poling kinematics for the 1-skate and 2-skate.

Poling Variable	**1-skate**		**2-skate**
	Preferred side	Non-preferred side	
Trunk angle at pole plant (°)	66.19	64.59	62.63
Angular velocity of trunk flexion (°•s^{-1})	42.43	37.53	37.09
Vertical inclination of preferred side pole at pole plant (°)	13.61	14.47	14.03
Vertical inclination of non-preferred side pole at pole plant (°)	14.34	15.16	13.36

Heart Rates

Average heart rates were observed to be virtually identical between techniques as well as to heart rate value of 151 beats•min^{-1} observed by Hoffman and Clifford (1990) in a study of offset performed at a velocity of 3.94 m•s^{-1}.

It is interesting to note that a difference in VE was observed between the 1-skate and 2-skate despite the presence of practically identical heart rates across techniques. This finding suggests that comparisons between skating techniques based only on HR reported in previous research (Bilodeau et al., 1991, 1996; Boulay et al., 1994) may not have been valid in terms of assessing the physiological component of the technique selection question.

Respiratory Quotient

Virtually identical RQ values were observed for the 1-skate (0.84), 2-skate (0.83), and offset (0.84) techniques. Hoffman et al. (1991) reported higher RQ. values for performance of double poling over offset on rollerskis. The researchers suggested that this finding might have been due to greater carbohydrate utilization and lactate production from the arm muscles because of the upper body demands of double poling. In the present study, the absence of differences between techniques for RQ, VO_2 or HR suggests that the higher VE and the greater poling demands of the 1-skate did not manifest in greater energy demands.

Conclusions and Recommendations for Between Techniques Analyses

The results of this study indicate that performance of the 1-skate, 2-skate or offset at an equivalent submaximum velocity will elicit an aerobic training benefit. However, the question of selecting the most economical technique to optimize race performance is less clear and warrants further discussion. Although not a significant difference, the 2-skate required 1.7 $ml \cdot kg^{-1} \cdot min^{-1}$ less oxygen consumption than the 1-skate. This represented a difference of 2.5% of VO_{2Max} between the two techniques. It has been reported that the offset is not slower than the 1-skate or 2-skate on flat terrain at maximum intensity (Bilodeau et al., 1991; Boulay et al., 1994). However, the researchers of both of these studies failed to examine the performance of skate-skiing techniques at the submaximum velocities generated under race-specific intensities. Race-specific intensities would require a greater and more sustained contribution from the aerobic energy system than is required for the short duration full-out efforts studied by Bilodeau and colleagues (1991) and Boulay (1994). In such an instance, the physiological variables measured in this study, especially oxygen consumption, would be most appropriate as criteria for determining technique selection. Several of the subjects in this study reported that the offset is not employed over flat terrain during races because it is perceived to be slower than either the 1-skate or 2-skate at the required race-specific intensity. This perception was confirmed by Bilodeau and colleagues (1996) who reported that 28 of 34 skiers used the 2-skate on a flat section of terrain during a 30 km skating race at the 1994 Canadian National Cross-Country Ski Championships. It stands to reason that the inclusion of the offset technique in this analysis may have been unnecessary and may have added enough between subject variation to obscure a distinction in economy between the 1-skate and 2-skate at a submaximum intensity on flat terrain. A linear relationship between velocity and VO_2 has been observed in cross-country skiing for both skate-skiing (Bedford, 1991; Saibene et al., 1989) and the classic technique (MacDougall et al., 1979;

Saibene et al., 1989). It is therefore not unlikely that the 2.5% difference between the 1-skate and 2-skate on flat terrain observed in this study would be maintained as performance intensity increased up to race specific velocities. At race intensity, a 2.5% difference in VO_2, particularly for men's races longer than 20 km (i.e. finish time > 50 minutes), would almost certainly affect energy system utilization, conservation of muscle glycogen and finishing times. Additionally, individual differences in fitness and/or technique might amplify any differences in economy between the 1-skate and 2-skate techniques. The question of technique selection between the 1-skate and 2-skate at race pace appears to be a feasible problem for future inquiry.

Within Technique Analyses

Within technique differences in economy between athletes were determined through examination of bivariate correlations between the percentage value of each athlete's maximum oxygen consumption and kinematic variables. A lower percentage of maximum oxygen consumption was indicative of more economical technique.

Within technique differences in percent of maximum heart rate (HR_{Max}) based on correlations between percent HR_{Max} and kinematic performance variables were also completed. Most cross-country skiers rely on exercise heart rate to monitor their training intensity during training and the knowledge of any relationships between kinematic variables and heart rate would be useful information for coaches and athletes.

2-skate

Significant negative correlations (p<0.05) were observed between %VO_{2Max} during 2-skate performance and %cycle time spent gliding on the poling side ski as well as the total time spent gliding on the poling side glide ski. More economical performance of 2-skate at sub-maximal aerobic intensities appeared, therefore, to be related to the ability to glide for longer periods of time as well as for a greater percentage of each cycle.

A greater percentage of gliding time would be directly related to a smaller portion of each cycle spent in generating the propulsive forces of poling and/or skating. There is some evidence that skating time was reduced for the 2-skate as indicated by the negative correlation between %VO_{2Max} and the angular velocity of hip abduction of the poling side thigh. This would suggest that athletes who performed at a lower percentage of their VO_{2Max} tended to more vigorously abduct their poling side thigh during the application of skating forces. In the present study, longer gliding times were likely related to the ability to generate stronger propulsive forces during skating and/or poling. This was because all subjects skied at an equivalent velocity of 5.4 $m \cdot s^{-1}$ and all ski bases were prepared identically to keep the force of ski-snow friction equal. Some evidence of the relationship between stronger propulsive force application and improved 2-skate economy can be deduced from the negative correlations between %VO_{2Max} and several kinematic variables. These included a greater range of motion during extension of the non-poling side elbow during poling and more abduction of the poling side hip at ski release during skating.

Similar trends were observed in the correlations between %HR_{Max} and several kinematic variables. Greater knee extension of the poling side knee at ski release and greater shoulder extension of the non-poling side shoulder at pole release are indicative of the relationship between larger propulsive forces and reduced heart rate. Also, reduced heart rate was also related to a greater average angle of the forward velocity vector. A greater deviation from the direction of travel during each 2-skate cycle could be a result of greater medio-lateral displacement of the CM resultant from longer periods of gliding during each cycle.

In their examination of the relationship between faster performance of the 2-skate and kinematic variables Smith and Heagy (1994) observed similar patterns of longer glide times and stronger application of propulsive forces. The results of this study suggest that the most economical manner to perform the 2-skate might also be the fastest way to perform it.

Economical performance of the 2-skate appears to be related, at least in part, to an increased ability to glide which, due to experimental control of velocity and frictional forces, is likely due to an athlete's ability to generate stronger poling and/or skating forces. However, a strong correlation ($r = -0.86$, $p < 0.01$) was observed between 2-skate economy (i.e., %VO_{2Max}) and aerobic fitness as represented by maximum oxygen consumption (VO_{2Max}). A similar correlation was also observed between %HR_{Max} and VO_{2Max}. Several researchers (Bilodeau et al., 1992; Smith & Heagy, 1994) questioned whether differences in 2-skate performance between skiers were related to fitness or individual technique. It appears that for the 2-skate, technical economy is related to the ability to produce stronger propulsive forces and longer glide times which, in turn, requires a higher level of aerobic fitness. In the present study, a relatively small subject pool (n = 11) prohibited the use of a factor analysis to determine which kinematic and/or fitness factors were most closely related to 2-skate economy.

1-skate

Significant negative correlations were observed between 1-skate economy (i.e., $\%VO_{2Max}$) and kinematic performance variables related to longer poling times, both on the preferred side ($r = -0.74$, $p<0.01$) and for the combined poling time ($r = -0.64$, $p<0.05$). The 1-skate technique differs from the 2-skate and offset in that there is basically twice as much poling per cycle and it could be expected that poling would be related to economy. The relationships cited suggest that a more sustained application of poling forces is more economical to 1-skate performance at a submaximum aerobic intensity. This observation is supported by the significant correlations between 1-skate economy and other kinematic variables which emphasize an enhanced poling duration including greater extension ($r = -0.68$, $p<0.05$) and ROM ($r = -0.62$, $p<0.05$) of the preferred side elbow while poling on the preferred side in addition to a more extended preferred side shoulder ($r = -0.64$, $p<0.05$) at pole plant on the preferred side. These findings differ from the apparent need for more vigorous poling and longer glide times required during performance of the 2-skate in the present study. This difference may be attributable to the relatively low performance velocity used in this study. The 1-skate is typically employed for sprinting at higher velocities and a different ratio between poling and gliding times might then be utilized.

A theme different than the emphasis on poling time emerged from the significant correlations between percentage of maximum heart rate and 1-skate kinematic variables. A lower heart rate was related to greater ski angles at ski plant on both the preferred ($r = -0.71$, $p<0.05$) and non-preferred sides ($r = -0.61$, $p<0.05$). Greater ski angles at ski plant would require increased lateral rotation of the hips and lead to a wider base of support which could, in turn, facilitate the balance necessary for applying the longer poling durations discussed above. Additionally, there was a significant correlation between faster abduction of the non-preferred side hip ($r = -0.70$, $p<0.05$) during skating and lower heart rate. Faster hip abduction may be achieved with increased lateral hip rotation as this allows the vastus lateralis to assist the gluteals with abduction.

As with the 2-skate, increased 1-skate economy (i.e., $\%VO_{2Max}$) was related to higher aerobic fitness as defined by either absolute ($r = -0.68$, $p<0.05$) or relative ($r = -0.60$, $p<0.05$) VO_{2Max}. Like the 2-skate, it appears that the kinematic parameters associated with the more economical performance of the 1-skate technique at a submaximum velocity, specifically sustained poling force application and increased hip rotation and abduction, require a higher level of aerobic fitness.

Offset

Few correlations between economy (i.e., $\%VO_{2Max}$) and kinematic variables were observed with the performance of the offset technique. A more erect trunk at pole plant (*r* = -0.60, $p<0.05$) and a more vertical lateral orientation of poling side pole at pole plant (*r* = 0.68, $p<0.05$) were observed to be related to improved economy. The nature of the relationship was that as a skier becomes more erect it could be expected that his poles would be more vertically oriented than if he had greater trunk flexion and greater body lean. However, the effect of a more erect posture on offset performance, specifically the ability to apply efficient poling or skating forces as discussed in previous research (Karvonen et al., 1987; Hoffman, 1992), is difficult to establish.

A clearer trend for the offset technique is apparent upon examination of the significant correlations between percentage of maximum heart rate and kinematic performance variables. A lower exercise heart rate was associated with a greater net medio-lateral displacement of the CM (*r* = -.61, $p<0.05$) and a larger average angle of the forward velocity vector (*r* = -.64, $p<0.05$). Additionally, a reduced heart rate during performance of the offset was correlated with greater abduction of the poling side hip at ski release (*r* = -.86, $p<0.01$) and a greater minimum hip abduction on the non-poling side (*r* = -.70, $p<0.05$). The tendency for increased side-to-side movement would be facilitated by greater abduction of the hips. These findings differ from the reduction in lateral movement associated with faster offset velocities on uphills observed in previous research (Smith et al., 1989; Aro et al., 1990). Viitasalo and colleagues (1997) suggested that energy was wasted due to increased lateral movements observed during the uphill performance of the offset in a race. The results of this study suggest that increased side-to-side movement may in fact be more economical.

Unlike the 2-skate and 1-skate, there was no relationship between economical performance of the offset and aerobic fitness. The offset technique is rarely used on flat terrain under the low velocity conditions of this study and is acknowledged to be a technique reserved for climbing moderate to steep inclines (Bilodeau et al., 1996). Although individual differences in technique were related to differences in offset economy these were apparently achieved without a need for higher aerobic fitness. Further examinations of offset technique economy over terrains on which the technique is commonly employed might elicit a similar relationship as between fitness, economy and kinematic parameters as described in this study for the 1-skate and 2-skate.

Conclusions and Recommendations for Within Techniques Analyses

Within-techniques analyses revealed certain relationships between the economical performance of the 1-skate and 2-skate techniques and specific groups of kinematic performance variables. With the 1-skate, lower oxygen consumption was associated with longer poling times and increased hip rotation and hip abduction during skating. It is likely that these hip movements effectively widened the skier's base of support thereby improving balance and facilitating the application of longer poling forces. During performance of the 2-skate, lower oxygen consumption was associated with both longer gliding times and a larger portion of the 2-skate cycle devoted to gliding. Since velocity and the magnitude of the ski-snow friction were constant across subjects the increased gliding was most likely achieved by the observed application of stronger and more vigourous poling and skating forces. A skier's ability to perform both the 1-skate and 2-skate in a more economical fashion was also related to his possessing a higher level of aerobic fitness as defined by his VO_{2Max} for treadmill running. It is plausible that the kinematic adjustments described above could only be achieved with increased aerobic fitness. Coaches and athletes should therefore consider an athlete's aerobic fitness level when attempting to alter technique to improve performance. For example, the recommendation to emphasize increasing cycle length for the 2-skate made in previous research (Smith & Nelson, 1990) should likely only be made with co-requisite improvements in aerobic fitness.

Future study of economical performance of the 1-skate and 2-skate should likely be conducted at higher velocities that approach race specific velocities to determine if the relationships observed in this initial study hold at higher velocities. Additionally, it is probable that all skiers cannot perform comfortably at the same velocity. The velocity used in this study of 5.4 $m{\bullet}s^{-1}$ may not have felt "natural" to any of the subjects and may have caused unusual performance of a certain technique and/or performance at a greater percentage of their maximum then they might otherwise at a higher velocity. This problem likely obscured numerous relationships between economical skiing and selected kinematic parameters. To overcome this dilemma, future study of 1-skate and 2-skate economy on flat terrain should employ a design where skiers perform at an equivalent submaximum intensity (e.g., 70% VO_{2Max}). Economy could then be defined as velocity such that a higher velocity was more indicative of a greater economy. Each skier would be skiing at an individual velocity that is comfortable to them and the resulting within-technique relationships between economy and kinematic parameters might be more salient.

Less clear correlations between submaximum performance of the offset and kinematic variables were observed. Improved economy appeared to be associated with increased medio-lateral CM movement and a more erect posture. Although it is unclear what effect these changes would have on economy when the offset is performed on moderate to steep uphills where it is typically employed. Also, no relationship between economical performance of the offset and fitness was observed. Future study of the economical performance of the offset should be conducted on moderate to steep uphills. Under these conditions a relationship between aerobic fitness and economical movement might be established and the kinematic adaptations that can be achieved with improved fitness could be discerned.

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Appendix 1 – Advance subject information letter

Thank you for your interest and involvement in this study. The purpose of this project is to determine the most economical technique(s) on flat terrain as well as the movement characteristics related to efficient and economical skate-skiing. During the testing process you will ski three trials, each lasting approximately 4 to 5 minutes, around the Lappe stadium. You will be instructed to employ a different skating technique for each trial. You will be following a snow machine which will be travelling at a constant velocity for each of the trials. Each trial will be videotaped by two cameras. Additionally you will be wearing a portable metabolic measurement device on your back and breathing all expired air into a facemask which will cover your mouth and nose. The entire device weighs approximately 1 kg. Please note the following conditions before your testing session:

- Wear tight black clothing for the testing. The videotape of each subject skiing will be digitized to generate a stick figure which will be used to calculate the various joint angles as well as the position of the centre of mass throughout each trial. The video image is black and white and the sharp contrast seen between black clothing and the white tape which will be applied over your joint centres promotes the quickest and most accurate digitizing. If you do not have black clothing then another dark solid colour is acceptable.

- Do not eat food or ingest caffeine 2 hours prior to your testing session. All of your metabolic measurements will be recorded during the testing process with a portable metabolic measurement device. The presence of recently ingested food will alter the way your body metabolizes available substrate and this will effect your oxygen consumption values.

- Please be on time. The earlier the entire testing process can be completed the less it will be effected by changes in temperature and weather conditions. Your help in this regard will be appreciated.

During the week of March 9 to 13 you will need to complete a treadmill-running VO_2max test. Your metabolic values need to be expressed as a percentage of your maximum. Sign-up times will be available on Wednesday.

Your participation is overwhelmingly appreciated. As a subject you will receive an individual biomechanical report of your skating performance as well as information regarding your capacity to consume oxygen at various heart rates which is essential to accurately determining your training zones. Please call me at 343-8187 (day) or 767-5735 (eve.) if you have any other questions, comments or concerns.

Thank you

Stephen McIlwaine

Appendix 2 - Subject Consent Form (On-snow Testing)

I_____________________________, hereby consent to participate in the on-snow portion of this study which seeks to determine the most economical skate-skiing technique(s) on flat terrain as well as the movement characteristics associated with efficient and economical skating.

I understand that I will be asked to perform three (3) consecutive on-snow skiing trials using each technique at a submaximum exercise intensity. I understand that I will be required to breath into a facemask that covers my nose and mouth and wear a wireless heart rate monitor transmitter around my chest throughout each test. Although unlikely, I understand that there may be some nausea, dry mouth and throat or some other minor physical discomfort while wearing a face-mask during approximately 20 total minutes of skiing.

I understand that the direct benefits to me from participating in this study include a comparative biomechanical assessment of each my skating techniques and physiological information regarding the establishment of my training zones. This information will be provided to me in a confidential manner. I understand that these results will be preserved on disc within the Department of Kinesiology at Lakehead University for the next seven (7) years should I need to review them during this time. I also understand that the final results of this study can be provided to me at my request. Finally, any publication of the final results will not reveal my identity as I will be referenced by number.

____

Signature of participant   Date

Appendix 3 - Schedule for Subject Prep. and Metabolic Equipment Cleaning

7:45-7:55	Prepare Subject #1 (P-1, HR-1)
8:15-8:25	Prepare Subject #2 (P-2, HR-2)
8:25-8:35	Clean-up Subject #1, Disinfect P-1 & HR-1
8:45-8:55	Prepare Subject #3 (P-1, HR-1)
8:55-9:05	Clean-up Subject #2, Disinfect P-2 & HR-2
9:15-9:25	Prepare Subject #4 (P-2, HR-2)
9:25-9:35	Clean-up Subject #3, Disinfect P-1 & HR-1
9:45-9:55	Prepare Subject #5 (P-1, HR-1)
9:55-10:05	Clean-up Subject #4, Disinfect P-2 & HR-2
10:15-10:25	Prepare Subject #6 (P-2, HR-2)
10:25-10:35	Clean-up Subject #5, Disinfect P-1 & HR-1
10:45-10:55	Prepare Subject #7 (P-1, HR-1)
10:55-11:05	Clean-up Subject #6, Disinfect P-2 & HR-2
11:15-11:25	Prepare Subject #8 (P-2, HR-2)
11:25-11:35	Clean-up Subject #7, Disinfect P-1 & HR-1
11:45-11:55	Prepare Subject #9 (P-1, HR-1)
11:55-12:05	Clean-up Subject #8, Disinfect P-2 & HR-2
12:15-12:25	Prepare Subject #10 (P-2, HR-2)
12:25-12:35	Clean-up Subject #9, Disinfect P-1 & HR-1
12:45-12:55	Prepare Subject #11 (P-1, HR-1)
12:55-1:05	Clean-up Subject #10, Disinfect P-2 & HR-2
1:15-1:25	Prepare Subject #12 (P-2, HR-2)
1:25-1:35	Clean-up Subject #11, Disinfect P-1 & HR-1
1:55-2:05	Clean-up Subject #12, Disinfect P-2 & HR-2

Appendix 4 – On-snow subject data record

Subject #__________

Name______________________________ Age______ Competitive

Exp._______

Height______cm Weight_______kg

Summer Address______________________________

____

____

Time start_________

Air Temp.______°C Snow Temp._______°C Bar._______mmHG

Wind__________

Technique #1:____________________

4 minutes: HR_____ VO_2_______ VCO_2_______ RQ______ FeO_2______

$FeCO_2$_______

Technique #2:____________________

4 minutes: HR_____ VO_2_______ VCO_2_______ RQ______ FeO_2______

$FeCO_2$_______

Technique #3:____________________

4 minutes: HR_____ VO_2_______ VCO_2_______ RQ______ FeO_2______

$FeCO_2$_______

Comments:

(Post VCO_2 volts_________)

Appendix 5 – instructions for Subject Preparation, Clean-up and Equipment Disinfection

SUBJECT PREPARATION (10 minutes)

☞Have subject read and sign Informed Consent.
☞Record subject information; weight and height (no shoes), age, etc.
☞Have subject put on HR monitor chest strap
☞If subject is not wearing tight dark (preferably black) clothing then supply him with necessary pieces.
☞Affix joint markers on clothing over joint centres.
☞Secure mask over face. Have subject cover adaptor hole and exhale to ensure that there is a seal.
☞Accompany subject up to stadium with data info sheet and disinfected pneumotach.
☞Accompany subject who has just finished previous test back to chalet.

SUBJECT CLEAN-UP AND EQUIPMENT DISINFECTION (10-15 minutes)

Subject

☞Ask subject if he is O.K.
☞Retrieve all equipment from subject.
☞Help him to remove tape from clothing.
☞Lend him a towel if he needs one to dry off.
☞Assist subject in selecting a VO_{2max} test time and give him pretest instructions with test time.
☞Thank him, give him some cookies and juice, sit with and talk with him for a few minutes and if he indicates that he feels fine then thank him again and send him on his way!

Pneumotach and mask

☞Remove adaptor ring from mask and place both pieces in Madicyde solution.
☞Pull lines out of locking ring.
☞Place locking ring, variable selector, pneumotach and plug cap separately (i.e., disassembled), as well as HR Monitor chest strap in Madicyde solution, soak for 5 minutes.
☞Evacuate all water from lines with pump-syringe from Luer end (3 to 4 pumps/line).
☞Rinse all pieces soaked in Madicyde thoroughly with water (15 to 20 seconds).
☞Wipe dry with paper towelling.
☞Reinsert lines into locking ring (green on the outside). Purge lines once more to remove any water remaining in pins.
☞Reassemble pneumotach with variable selector on "high".
☞Replace adaptor in mask.

Appendix 6 - KB1-C Calibration Procedures

This procedure must be completed in the described order prior to each new subject using the pneumotach that will be employed for their test (very important).

1. Enter New Subject Data

☞It is very important that the Barometric pressure is entered correctly.

2. Calibrate Gas Analyzers:

☞Ensure that you are in the testing environment (i.e., outside) before beginning this procedure. The entire calibration procedure should be performed outside. Check also that the red gas port on the KB1-C is completely free and unobstructed

☞From the HOME screen press CAL

☞Enter the calibration gas values: 16% O_2 & 4% CO_2 (If an error is made in entering calibration gas values then press ENTER/EXIT to return to HOME screen and press CAL to repeat procedure correctly)

☞Press O

☞KB1-C will zero on the ambient air *(90s.)*

☞When prompted connect the calibration gas via the gas bladder bag to the centre gas port on the KB1-C. Ensure that the bladder bag is completely empty before filling. Turn on the gas and fill the bag. Do not overfill the bag. Turn off the gas. Press START to initiate the calibration process (*120 s.*).

☞Check the calibration values when the KB1-C has finished calibrating. If the O_2 value is not between 15.91 and 16.09 and/or the CO_2 is not between 2.91 and 4.09 then press CAL to repeat the calibration procedure.

☞Disconnect the gas supply and press START. The unit will now zero once more on the outside air (*90 s.*).

3. Calibrate Flowhead:

☞Press FLOW.

☞Choose the HIGH setting: 3.

☞Enter either 21 L (7 pumps) or 24 L (8 pumps).

☞Connect the pneumotach to the KB1-C. Insert the open end of the pneumotach into the open end of the corrugated hosing from the 3 L syringe. Press START and pump the entered value during the 20 second countdown displayed on the KB1-C.

☞If the calibration values are within 10% of the entered values the KB1-C will go to the HOME screen at the end of the flow cal procedure. If not, a message indicating that the calibration was not within acceptable limits will be displayed. Check that the lines are clear and the pneumotach is set to high and repeat the calibration.

Appendix 7 – Digitizing record for 1-skate

Subject Id. #______________

Trial #1_________________

Master(#1)

Picture 1____:____:____ ____
Event #1____:____:____ ____, Pic. #_____
Event #2____:____:____ ____, Pic. #_____
Event #3____:____:____ ____, Pic. #_____
Event #4____:____:____ ____, Pic. #_____
Event #5____:____:____ ____, Pic. #_____
Event #6____:____:____ ____, Pic. #_____
Event #7____:____:____ ____, Pic. #_____
Event #8____:____:____ ____, Pic. #_____
Event #9____:____:____ ____, Pic. #_____
Final Pic____:____:____ ____, Pic. #_____

Slave(#2)

Picture 1____:____:____ ____
Event #1____:____:____ ____, Pic. #_____
Event #2____:____:____ ____, Pic. #_____
Event #3____:____:____ ____, Pic. #_____
Event #4____:____:____ ____, Pic. #_____
Event #5____:____:____ ____, Pic. #_____
Event #6____:____:____ ____, Pic. #_____
Event #7____:____:____ ____, Pic. #_____
Event #8____:____:____ ____, Pic. #_____
Event #9____:____:____ ____, Pic. #_____
Final Pic____:____:____ ____, Pic. #_____

Trial #2_________________

Master(#1)

Picture#1____:____:____ ____
Event #1____:____:____ ____, Pic. #_____
Event #2____:____:____ ____, Pic. #_____
Event #3____:____:____ ____, Pic. #_____
Event #4____:____:____ ____, Pic. #_____
Event #5____:____:____ ____, Pic. #_____
Event #6____:____:____ ____, Pic. #_____
Event #7____:____:____ ____, Pic. #_____
Event #8____:____:____ ____, Pic. #_____
Event #9____:____:____ ____, Pic. #_____
Final Pic____:____:____ ____, Pic. #_____

Slave(#2)

Picture 1____:____:____ ____
Event #1____:____:____ ____, Pic. #_____
Event #2____:____:____ ____, Pic. #_____
Event #3____:____:____ ____, Pic. #_____
Event #4____:____:____ ____, Pic. #_____
Event #5____:____:____ ____, Pic. #_____
Event #6____:____:____ ____, Pic. #_____
Event #7____:____:____ ____, Pic. #_____
Event #8____:____:____ ____, Pic. #_____
Event #9____:____:____ ____, Pic. #_____
Final Pic____:____:____ ____, Pic. #_____

Trial #3_________________

Master(#1)

Picture#1____:____:____ ____
Event #1____:____:____ ____, Pic. #_____
Event #2____:____:____ ____, Pic. #_____
Event #3____:____:____ ____, Pic. #_____
Event #4____:____:____ ____, Pic. #_____
Event #5____:____:____ ____, Pic. #_____
Event #6____:____:____ ____, Pic. #_____
Event #7____:____:____ ____, Pic. #_____
Event #8____:____:____ ____, Pic. #_____
Event #9____:____:____ ____, Pic. #_____
Final Pic____:____:____ ____, Pic. #_____

Slave(#2)

Picture 1____:____:____ ____
Event #1____:____:____ ____, Pic. #_____
Event #2____:____:____ ____, Pic. #_____
Event #3____:____:____ ____, Pic. #_____
Event #4____:____:____ ____, Pic. #_____
Event #5____:____:____ ____, Pic. #_____
Event #6____:____:____ ____, Pic. #_____
Event #7____:____:____ ____, Pic. #_____
Event #8____:____:____ ____, Pic. #_____
Event #9____:____:____ ____, Pic. #_____
Final Pic____:____:____ ____, Pic. #_____

Appendix 8 – Digitizing Record for 2-skate

Subject Id. #______________

Trial #1________________

Master(#1)

Picture 1____:____:____ ____
Event #1____:____:____ ____, Pic. #_____
Event #2____:____:____ ____, Pic. #_____
Event #3____:____:____ ____, Pic. #_____
Event #4____:____:____ ____, Pic. #_____
Event #5____:____:____ ____, Pic. #_____
Event #6____:____:____ ____, Pic. #_____
Event #7____:____:____ ____, Pic. #_____
Final Pic____:____:____ ____, Pic. #_____

Slave(#2)

Picture 1____:____:____ ____
Event #1____:____:____ ____, Pic. #_____
Event #2____:____:____ ____, Pic. #_____
Event #3____:____:____ ____, Pic. #_____
Event #4____:____:____ ____, Pic. #_____
Event #5____:____:____ ____, Pic. #_____
Event #6____:____:____ ____, Pic. #_____
Event #7____:____:____ ____, Pic. #_____
Final Pic____:____:____ ____, Pic. #_____

Trial #2________________

Master(#1)

Picture 1____:____:____ ____
Event #1____:____:____ ____, Pic. #_____
Event #2____:____:____ ____, Pic. #_____
Event #3____:____:____ ____, Pic. #_____
Event #4____:____:____ ____, Pic. #_____
Event #5____:____:____ ____, Pic. #_____
Event #6____:____:____ ____, Pic. #_____
Event #7____:____:____ ____, Pic. #_____
Final Pic____:____:____ ____, Pic. #_____

Slave(#2)

Picture 1____:____:____ ____
Event #1____:____:____ ____, Pic. #_____
Event #2____:____:____ ____, Pic. #_____
Event #3____:____:____ ____, Pic. #_____
Event #4____:____:____ ____, Pic. #_____
Event #5____:____:____ ____, Pic. #_____
Event #6____:____:____ ____, Pic. #_____
Event #7____:____:____ ____, Pic. #_____
Final Pic____:____:____ ____, Pic. #_____

Trial #3________________

Master(#1)

Picture 1____:____:____ ____
Event #1____:____:____ ____, Pic. #_____
Event #2____:____:____ ____, Pic. #_____
Event #3____:____:____ ____, Pic. #_____
Event #4____:____:____ ____, Pic. #_____
Event #5____:____:____ ____, Pic. #_____
Event #6____:____:____ ____, Pic. #_____
Event #7____:____:____ ____, Pic. #_____
Final Pic____:____:____ ____, Pic. #_____

Slave(#2)

Picture 1____:____:____ ____
Event #1____:____:____ ____, Pic. #_____
Event #2____:____:____ ____, Pic. #_____
Event #3____:____:____ ____, Pic. #_____
Event #4____:____:____ ____, Pic. #_____
Event #5____:____:____ ____, Pic. #_____
Event #6____:____:____ ____, Pic. #_____
Event #7____:____:____ ____, Pic. #_____
Final Pic____:____:____ ____, Pic. #_____

Appendix 9 – Digitizing record for offset

Subject Id. #______________

Trial #1_________________

Master(#1)	Slave(#2)
Picture 1____:____:____ ____	Picture 1____:____:____ ____
Event #1____:____:____ ____, Pic. #_____	Event #1____:____:____ ____, Pic. #_____
Event #2____:____:____ ____, Pic. #_____	Event #2____:____:____ ____, Pic. #_____
Event #3____:____:____ ____, Pic. #_____	Event #3____:____:____ ____, Pic. #_____
Event #4____:____:____ ____, Pic. #_____	Event #4____:____:____ ____, Pic. #_____
Event #5____:____:____ ____, Pic. #_____	Event #5____:____:____ ____, Pic. #_____
Event #6____:____:____ ____, Pic. #_____	Event #6____:____:____ ____, Pic. #_____
Event #7____:____:____ ____, Pic. #_____	Event #7____:____:____ ____, Pic. #_____
Final Pic____:____:____ ____, Pic. #_____	Final Pic____:____:____ ____, Pic. #_____

Trial #2_________________

Master(#1)	Slave(#2)
Picture 1____:____:____ ____	Picture 1____:____:____ ____
Event #1____:____:____ ____, Pic. #_____	Event #1____:____:____ ____, Pic. #_____
Event #2____:____:____ ____, Pic. #_____	Event #2____:____:____ ____, Pic. #_____
Event #3____:____:____ ____, Pic. #_____	Event #3____:____:____ ____, Pic. #_____
Event #4____:____:____ ____, Pic. #_____	Event #4____:____:____ ____, Pic. #_____
Event #5____:____:____ ____, Pic. #_____	Event #5____:____:____ ____, Pic. #_____
Event #6____:____:____ ____, Pic. #_____	Event #6____:____:____ ____, Pic. #_____
Event #7____:____:____ ____, Pic. #_____	Event #7____:____:____ ____, Pic. #_____
Final Pic____:____:____ ____, Pic. #_____	Final Pic____:____:____ ____, Pic. #_____

Trial #3_________________

Master(#1)	Slave(#2)
Picture 1____:____:____ ____	Picture 1____:____:____ ____
Event #1____:____:____ ____, Pic. #_____	Event #1____:____:____ ____, Pic. #_____
Event #2____:____:____ ____, Pic. #_____	Event #2____:____:____ ____, Pic. #_____
Event #3____:____:____ ____, Pic. #_____	Event #3____:____:____ ____, Pic. #_____
Event #4____:____:____ ____, Pic. #_____	Event #4____:____:____ ____, Pic. #_____
Event #5____:____:____ ____, Pic. #_____	Event #5____:____:____ ____, Pic. #_____
Event #6____:____:____ ____, Pic. #_____	Event #6____:____:____ ____, Pic. #_____
Event #7____:____:____ ____, Pic. #_____	Event #7____:____:____ ____, Pic. #_____
Final Pic____:____:____ ____, Pic. #_____	Final Pic____:____:____ ____, Pic. #_____

Appendix 10 - Treadmill VO_{2Max} Subject Consent Form

I______________________________, hereby consent to participate in the VO_{2max} portion of this study which seeks to determine the most economical skate-skiing technique(s) on flat terrain as well as the movement characteristics associated with efficient and economical skating

I understand that I will be asked to perform an exercise session to maximum intensity on a motorized treadmill. The procedures involved in completing this test have been thoroughly explained to me. The VO_{2max} test will entail running at increasing workloads on a treadmill until I am physically exhausted and unable to continue. I understand that I will be required to breath into a facemask that covers my nose and mouth and wear a wireless heart rate monitor transmitter around my chest throughout the test.

I understand that there may be some nausea and discomfort associated with running until physically unable to continue. In healthy fit individuals this type of exercise carries very little risk. I understand that a small short-term deleterious impact to my regular training performance may result from completing a VO_2MAX test.

I understand that the only direct benefit to me from participating in this portion of the study will be the information regarding my fitness and training gathered from completing the VO_2MAX test. This information will be provided to me in a confidential manner. I understand that these results will be preserved on disc within the Department of Kinesiology at Lakehead University for the next seven (7) years should I need to review them during this time. I also understand that the final results of this validity study can be provided to me at my request. Finally, any publication of the final results will not reveal my identity as I will be referenced by number.

____

Signature of participant   Date

Appendix 11 – Athlete preparation instructions for VO_{2Max}

Your treadmill VO_2MAX test is on ________________, March_____ at ___:_______.

Please try to adhere to the following conditions to ensure an accurate determination of your aerobic capacity:

- ❄Do not eat any food or consume caffeinated beverages 2 hours prior to your test time.
- ❄Do not consume alcohol 12 hours prior to your test time.
- ❄Do not perform a strenuous workout during the day prior to your test.

The test time will take approximately 45 minutes, including warm-up. Try to stay well hydrated prior to your test. Bring appropriate clothing and shoes for running.