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	<p>Cross-country skiing is a four-legged gait, and some gait patterns, such as 2-skate skiing, are similar to those adopted by animals (galloping horse). Four-legged animals change gait patterns with increasing speeds of locomotion, at least in part, to minimize metabolic energy expenditure. For example, a horse will switch from a walk, to a trot, and finally to a gallop as speed of locomotion increases. Similarly, skate cross-country skiers will switch from a 2-skate gait to a 1-skate gait with increasing speeds of locomotion, but then unlike any other animal, will revert back to the previously rejected 2-skate gait pattern at very high speeds. We used oxygen uptake measurements, force measurements in poles and skis, 3-dimensional movement analysis and functional muscle properties to explain this result. We found that propulsion in 1-skate skiing comes primarily from the arms/poles, while propulsion comes primarily from the legs/skis in the 2-skate technique. We also found that ground contact times for the skis are virtually independent of the skiing speed while pole contact</p>		

times decrease dramatically with increasing speeds. Furthermore, propulsive forces from the arms dropped from skiing at 15 km/h to skiing at 30 km/h while simultaneously requiring much more metabolic energy. Finally, the cost of transport curves for 1-skate and 2-skate skiing intersected twice, indicating better efficiency for the 2-skate technique at slow and very fast speeds, and better efficiency for the 1-skate technique at intermediate to fast speeds. Combined, these results suggest that arm/pole action is optimized at intermediate speeds, thereby providing an advantage to the 1-skate technique which relies primarily on arm propulsion, while arm/pole action is highly inefficient at very high speeds, thus switching to the 2-skate technique which relies primarily on leg propulsion, is good strategy.

Keywords (separated by ‘-’)	Cost of transport - Efficiency - Optimal movement - Entrained breathing - Skate technique - Classic technique - Functional muscle mechanics - Force-velocity relationship - Power-velocity relationship - Force-length relationship
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Chapter 201

Energetic Considerations in Cross-Country2

Skiing3

Walter Herzog, Anthony Killick, and Kevin R. Boldt4

Abstract Cross-country skiing is a four-legged gait, and some gait patterns, such as 2-skate skiing, are similar to those adopted by animals (galloping horse). Four-legged animals change gait patterns with increasing speeds of locomotion, at least in part, to minimize metabolic energy expenditure. For example, a horse will switch from a walk, to a trot, and finally to a gallop as speed of locomotion increases. Similarly, skate cross-country skiers will switch from a 2-skate gait to a 1-skate gait with increasing speeds of locomotion, but then unlike any other animal, will revert back to the previously rejected 2-skate gait pattern at very high speeds. We used oxygen uptake measurements, force measurements in poles and skis, 3-dimensional movement analysis and functional muscle properties to explain this result. We found that propulsion in 1-skate skiing comes primarily from the arms/poles, while propulsion comes primarily from the legs/skis in the 2-skate technique. We also found that ground contact times for the skis are virtually independent of the skiing speed while pole contact times decrease dramatically with increasing speeds. Furthermore, propulsive forces from the arms dropped from skiing at 15 km/h to skiing at 30 km/h while simultaneously requiring much more metabolic energy. Finally, the cost of transport curves for 1-skate and 2-skate skiing intersected twice, indicating better efficiency for the 2-skate technique at slow and very fast speeds, and better efficiency for the 1-skate technique at intermediate to fast speeds. Combined, these results suggest that arm/pole action is optimized at intermediate speeds, thereby providing an advantage to the 1-skate technique which relies primarily on arm propulsion, while arm/pole action is highly inefficient at very high speeds, thus switching to the 2-skate technique which relies primarily on leg propulsion, is good strategy.

Keywords Cost of transport • Efficiency • Optimal movement • Entrained breathing • Skate technique • Classic technique • Functional muscle mechanics • Force-velocity relationship • Power-velocity relationship • Force-length relationship

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33 20.1 Introduction

34 Cross-country skiing is an ancient form of locomotion on skis across snow which is
 35 thought to have originated prior to formal historical records (Dresbeck 1967). In the
 36 nineteenth and early twentieth century, cross-country skiing was used as a way of
 37 transportation and hunting, particularly in the Nordic countries of Europe. In 1924,
 38 at the first winter Olympic Games, cross-country skiing was represented with a
 39 50 km and an 18 km race (for men only). In the past few decades, cross-country
 40 skiing has become a recreational sport of increasing popularity in “winter sport”
 41 countries and is recognized for its whole body involvement and its high aerobic
 42 endurance benefits.

43 Traditionally, competitions in cross-country skiing were performed using a set
 44 of snow tracks in which skis moved parallel to each other, and arms and poles were
 45 used alternately in a running type fashion. This technique of skiing is now referred
 46 to as the classic technique and is characterized by a parallel gliding of the left and
 47 right ski and the skis always pointing in the direction of the tracks. In the 1970s, the
 48 Finnish skier Pauli Siitonen introduced the skating technique of cross-country
 49 skiing into racing. In contrast to the classic technique, in the skating technique,
 50 the skis are used in a “skating” V-like fashion: that is the skis are angled to each
 51 other, and the direction of movement becomes partly sideways, rather than directly
 52 along the path of the race course. In 1987, the skating technique was used for the
 53 first time at a world championship, and then was also used for the first time at the
 54 Olympic Games 1988 in Calgary, Canada.

55 Here, we will deal exclusively with the skating technique of cross-country
 56 skiing, which in racing is also referred to as the “free technique”. In cross-country
 57 ski skating, different gait patterns are used by athletes and accomplished recrea-
 58 tional skiers. These gait patterns are classified based on the coordination of the arm
 59 and pole actions with the leg and ski actions. At very slow speeds, typically on steep
 60 uphill sections, recreational skiers use a single poling technique, similar to the
 61 herringbone technique but with a small glide phase on each ski. This technique is
 62 not used by racers, and will not be further considered here. At slow to intermediate
 63 speeds, or when skiing in a relaxed manner or on an uphill section, skiers use the
 64 so-called 2-skate technique (also referred to as “V1” or “V2 alternate” technique, or
 65 offset technique when the poling action is slightly offset to the leg action) in which
 66 skiers double pole on every other leg. Most skiers have a preferred side for double
 67 poling and so will typically double pole either on the left or on the right leg. At
 68 intermediate to fast speeds of skiing, skiers switch to the so-called 1-skate tech-
 69 nique (also referred to as V2 or Wassberg technique) in which a double pole action
 70 accompanies each step on the left and right leg. At fast to very fast (sprint) speeds,
 71 skiers revert back to the 2-skate technique that was previously rejected for the
 72 1-skate technique at intermediate to fast speeds. Finally, at very fast speeds, and
 73 mostly on slight downhill sections, skate skiers use the so-called “free skating”
 74 technique in which the poles are not used at all, and propulsion is exclusively
 75 derived from the skating actions of the legs (Cross-country skiing 2014).

Fig. 20.1 Cost of transport (ml O₂/m) for a horse walking, trotting and galloping at increasing speeds of locomotion. Note that the transition from one gait pattern to the next occurs at speeds in the vicinity of intersection between the cost of transport curves for gait patterns, indicating that gait transitions might occur to minimize the energy required for locomotion at a given speed (Adapted from Hoyt and Taylor 1981, with permission)

As mentioned above, cross-country skiing has been advocated as an excellent aerobic training exercise because of its whole body engagement. Elite cross-country ski racers therefore must be excellent endurance athletes with superior oxygen uptake capacity. The highest ever recorded oxygen uptake capacity was recorded for Bjørn Dæhlie, the most successful cross-country skier ever, with 12 Olympic medals (8 of them gold) and 17 (9 gold) world championship medals, at an astonishing 96 ml/kg/min (Bjørn 2014). Because of the high demands on oxygen uptake, it is reasonable to assume that cross-country skiers chose a gait pattern while racing that minimizes oxygen uptake, similar to a horse that switches from a walking gait, to a trot, and finally to a gallop with increasing speeds of locomotion (Hoyt and Taylor 1981) (Fig. 20.1).

If ski racers indeed choose their gait pattern in skate skiing in a manner to minimize the energy requirements for skiing at a particular speed, then it is surprising that they choose the 2-skate technique (at slow to intermediate), and then the 1-skate (at intermediate to fast) speeds, but then revert back to the 2-skate technique for fast to very fast (sprinting) speeds. This is equivalent to saying that a four legged animal, such as a horse, changes from a trot to a gallop and then back to a trot for increasing speeds of running, something that would never happen. Therefore, the question arises: why do cross-country skiers revert back to a technique (or gait pattern – 2-skate skiing) at very fast speeds, that was rejected at a slower speed in favour of another gait pattern (the 1-skate technique)?

The purpose of this study was to answer this question. We hypothesized that the reason for choosing the 2-skate over the 1-skate at slow and very fast speeds, but not at intermediate speeds, was associated with the cost of transport. In other words, we hypothesized that the 2-skate technique was more efficient at slow and very high speeds of skiing compared to the 1-skate technique, while the reverse was true for intermediate to fast speeds of skiing. A secondary question then became: is it possible to explain why the 2-skate technique is more efficient at slow and very high, but not at intermediate to fast speeds compared to the 1-skate technique? This, we felt, was an intriguing question, as it is, to our knowledge, the only form of locomotion, two-legged or four-legged, in which a gait pattern that was rejected at a slow speed is re-introduced at a high speed.

Cross-country skiing is a four-legged gait with arms and legs contributing to propulsion and the speed of locomotion. In four-legged gaits of dogs, horses and rabbits, it has been observed that breathing is coordinated with the footfall patterns (Ainsworth 1997; Attenburrow and Goss 1994; Bramble and Carrier 1983; Bramble and Jenkins 1993). Specifically, in galloping animals, inhaling is associated with an expansion of the chest cavity when the forelimbs are moved forward relative to the body, while exhaling is associated with compression of the chest cavity as occurs when the forelimbs are swung backwards relative to the body. 2-skate skiing has a footfall pattern similar to a galloping horse, and the arms swing backwards and forwards in unison in their double pole action. Therefore, it seems feasible to assume, and it has been suggested, that inhaling and exhaling in 2-skate skiing is directly tied to the arm movements (Faria 2008). It has been argued that this “respiration coupling” in animals results in a reduced metabolic requirement for locomotion, as the movement of the forelimbs in galloping animals causes natural chest expansion and compression that assists the respiratory muscles and thus reduces the metabolic cost of breathing (Ainsworth 1997; Bramble and Carrier 1983). However, whether this assertion is correct, and what magnitude this effect might have, cannot be tested in animals, as animals cannot be asked to abandon the natural respiration coupling pattern while galloping. However, in cross-country skiers performing the 2-skate technique, it is easy to measure the oxygen uptake when breathing occurs naturally with respiration coupled to the skiing motion, and when skiers are asked to abandon the natural coupled breathing patterns. Thus, the purpose of a second study described here was to test the hypothesis that respiration coupling inferred a distinct energetic advantage to cross-country skiers using the 2-skate skiing technique.

20.2 Methods

In order to accomplish the aims of this study, it was necessary to measure the kinematics and kinetics of cross-country skiing using the 1- and 2-skate techniques, and measure the oxygen uptake required for these two gait patterns. It was also necessary to make these measurements in a subset of skiers for the 2-skate

technique while using their normal respiration coupling patterns and while skiing at the same speed and effort while abandoning the normal respiration coupling pattern. All measurements were performed using roller skiing on a motor driven skiing treadmill at the facilities of the National Centre for Excellence in Sport, Calgary and Canmore.

Kinematic and Kinetic Measurements Kinematic measurements were performed using two high speed video cameras, one placed with the optical axis perpendicular to the sagittal plane of skiing, the other aligned with the optical axis in the direction of skiing, filming the skiers from behind. Forces exerted by each roller ski and each pole were obtained using instrumented skiing poles and roller skis. Force transducers inserted into the shaft of the poles measured the forces along the axis of the poles while compensating for bending forces at the pole. Forces in the roller skis were measured by replacing the normal roller ski braces that connect the ski part with the rollers with strain gauged braces that measured the forces perpendicular to the roller skis in the vertical direction, and in the medial-lateral (horizontal) plane relative to the roller skis. Anterior-posterior forces were not measured as roller skis are essentially frictionless and effective propulsion in the anterior-posterior direction is not possible in skate skiing, in contrast to classic skiing where anterior-posterior forces are essential for effective striding.

Oxygen Uptake Measurements Oxygen uptake measurements were obtained while skiers skied at steady-state, typically after 4–5 min into a specific experimental condition (i.e. speed of skiing and slope) using a ParvoMedics TrueOne 2400 Metabolic Measurement System. Oxygen uptake was collected and expired air was analyzed every thirty seconds. Expired air was converted to standard temperature, pressure and dry (STPD) conditions, and analyzed to determine the rate of oxygen consumption and metabolic energy consumed (WEIR 1949).

Protocols For comparison of the efficiency of the 1-skate and 2-skate techniques across a range of speeds, skiers ($n=8$, young, active, elite level provincial and national skiers) skied using the 1- and 2-skate techniques at speeds of 6–33 km/h at increments of 3 km/h. They were asked to ski at each speed below the anaerobic threshold for 3 min with data collection occurring once the metabolic steady-state was achieved (typically after 2–2.5 min) (Solberg et al. 2005). For speeds above the anaerobic threshold, skiers just skied for 1 min at each speed in a precisely timed manner so that conditions for the 1- and 2-skate tests were identical, and thus comparable.

In order to estimate the oxygen cost for just the upper body and poling action for skate skiing using the 1- and 2-skate techniques, skiers performed an additional series of tests with oxygen uptake measurements. In these tests, the skiers stood on fixed skis and pulled on a cross-country arm ergometer at the frequency and excursion of their own skiing at low, intermediate and high speeds (6, 15, and 30 km/h). They did this by viewing a video of their own skiing, and pretending to follow the displayed skier in a perfectly matched manner. In order to obtain the proper forces, the pole forces measured during the actual skiing test were fed back

181 to the skiers, and the resistance on the ergometer was adjusted until they satisfac-
182 torily matched the actual skiing forces. The legs were braced for this experiment so
183 that no leg propulsion was possible, ensuring that we measured exclusively the
184 oxygen cost of the arm and upper body motions at the target speeds.

185 In order to derive the functional force-velocity and power-velocity relationships
186 of the poling action for the 1- and 2-skate techniques, skiers were fixed on a roller
187 board on top of the skiing treadmill. The treadmill was then run below the fixed
188 skiers at speeds ranging from 6 to 42 km/h at increments of 6 km/h and skiers were
189 asked to perform double poling actions at maximal effort, controlled by the rhythm
190 of a metronome to give them the frequency of poling in the 1- and 2-skate
191 techniques. The forces for ten consecutive maximal effort poling actions at each
192 speed were measured, and the corresponding impulses calculated. From these force/
193 impulse-velocity relationships of the poling action, the corresponding power output
194 as a function of skiing speeds was calculated.

195 For comparison of the efficiency of skiing with and without respiration coupling
196 in the 2-skate technique, skiers ($n=9$, young, active, elite level provincial and
197 national skiers) were asked to ski at a pre-determined fast but sub-anaerobic
198 threshold (Solberg et al. 2005) speed for 5 min on the motor driven treadmill.
199 The speeds ranged from 18 to 22 km/h on a zero slope. Skiers performed the test
200 first using their normal breathing patterns and respiration coupling was confirmed
201 with the breath by breath analyzer. They then repeated this test twice more, first
202 with respiration coupling consciously abolished and breathing in a reverse coupled
203 manner: that is inhaling occurred during the push phase of the poles when the arms
204 swung backwards and compressed the chest cavity, and exhaling occurred in the
205 recovery phase, when the arms were swung forwards thereby expanding the chest
206 cavity, and second, in the control condition with breathing coupling re-established.

207 20.3 Results

208 As hypothesized, the cost of transport (or equivalently, the oxygen requirement for
209 a given speed of skiing) for the 1-skate and 2-skate techniques had two intersec-
210 tions, with the 2-skate technique being the more efficient gait pattern at the slow
211 (6, 9 km/h) and high speeds (>24 km/h), while the 1-skate technique was the more
212 efficient technique at the intermediate speeds (9–21 km/h) (Fig. 20.2). Out of the
213 eight skiers, four showed precisely this double intersection of the cost of transport
214 curves (Fig. 20.3), while the remaining four skiers, although not vastly different
215 from the first four, showed an approximation of those curves, but not the double
216 intersection.

217 Propulsion in the 1-skate technique came primarily from the arms and poles,
218 while propulsion was primarily derived from the legs and skis for the 2-skate
219 technique (Fig. 20.4). Interestingly, for both, the 1- and 2-skate techniques, the
220 propulsion contributed to skiing from the arms and poles did not increase between
221 skiing at speeds of 15 and 30 km/h, while, as one would expect, propulsion

Fig. 20.2 Mean ($n = 8$) cost of transport values as a function of skiing speed for the 1-skate (black dots) and the 2-skate (grey squares) skiing techniques. Note that the 2-skate technique was more efficient (lower values) at the slowest (6, 9 km/h) and the highest (>27 km/h) speeds, while the 1-skate technique was metabolically more efficient at intermediate speeds (12–21 km/h)

Fig. 20.3 Cost of transport values as a function of skiing speed for a single skier. Note the similarity of intersection of the 1-skate and 2-skate curves with the curves found for the mean of the group

contributed by legs and skis increased with increasing speeds of skiing throughout the tested speed range.

Oxygen uptake for the upper body and arm action increased with increasing speeds of skiing (Fig. 20.5). For all speeds measured, the 1-skate technique required more oxygen than the 2-skate technique.

The maximal impulse that can be provided by the arms and poles decreases with increasing speeds of skiing, but is slightly higher for the 2-skate technique at the

Fig. 20.4 Impulse production by arms and legs in the 1-skate and 2-skate ski skate techniques. Note that in the 1-skate technique (*left*), propulsion is derived primarily from the arms and poles, while in the 2-skate technique (*right*), propulsion comes primarily from the leg and ski action. Furthermore, note that propulsion from the skis increases with increasing speeds of skiing, while there is a slight decrease for the propulsive impulses from the arms from the 15 to the 30 km/h speeds

Fig. 20.5 Oxygen consumption for the upper arm and trunk action exclusively for cross-country skiing at increasing speeds using the 1-skate and 2-skate technique. Oxygen uptake increases with increasing speeds of locomotion and becomes significantly higher for the 1-skate compared to the 2-skate technique at a speed of skiing of 30 km/h

slow and high speeds, while it is slightly higher for the 1-skate technique at the intermediate speeds of skiing (Fig. 20.6). The corresponding power-velocity relationship for the poling action is remarkably constant across speeds for the 2-skate technique, but reaches a distinct maximum at about 18 km/h for the 1-skate technique (Fig. 20.7). Double poling power output is higher for the 1-skate technique at intermediate speeds (18 and 24 km/h) and equal or lower for the slow and very high speeds of skiing.

Respiration coupling was associated with an approximately 4 % lower oxygen cost compared to uncoupled breathing (Fig. 20.8). When accounting for the slight

Fig. 20.6 Impulse provided by maximal pole action with increasing speeds of skiing for the 1-skate and 2-skate techniques. Note that the 1-skate and 2-skate impulses differ because of the frequency of poling at a given speed which is always higher for the 1- compared to the 2-skate technique. Note furthermore, that the 2-skate technique has higher impulses than the 1-skate technique for the slowest (6 km/h) and highest speeds (>36 km/h) tested

Fig. 20.7 Power output by arms and poles as a function of skiing speed for the 1- and 2-skate techniques of skate skiing. Note, the relatively flat power curve for the 2-skate and the more curved power graph for the 1-skate technique, reaching a peak value at about 18 km/h. Note also, that the power output is greater for the 1- skate compared to the 2-skate technique for speeds of 18 and 24 km/h while for speeds <18 km/h or greater than 24 km/h the 2-skate power values are greater than the 1-skate values

shifts in the respiration exchange ratio, respiration coupling was also associated with an approximately 5 % decrease in metabolic cost compared to the uncoupled (or reverse) breathing pattern (result not shown). Careful analysis of the footfall patterns and poling patterns and associated forces did not show any differences in the kinematics or kinetics of 2-skate skiing using coupled or uncoupled breathing (results not shown).

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Fig. 20.8 Rate of oxygen consumption for skiing just below the anaerobic threshold using the 2-skate technique while breathing normally using respiration to locomotion coupling (control) and while breathing in a reverse manner to the coupled breathing (Reverse Breathing). Note that normal breathing is associated with a significantly lower oxygen demand suggesting that coupled breathing is more efficient than un-coupled or reverse breathing

20.4 Discussion

The primary aim of this investigation was to determine why cross-country skiers switched from the 2-skate to the 1-skate, and back to the 2-skate technique with increasing speeds of skiing. We hypothesized that these gait changes might be driven by the cost of transport. Specifically, we hypothesized that the 2-skate technique might be metabolically more efficient at slow and very fast speeds of skiing than the 1-skate technique, and that the 1-skate technique might be more efficient than the 2-skate technique at intermediate to fast speeds. Particularly, we were interested in why the 2-skate technique, after being rejected in favor of the 1-skate technique at intermediate to fast speeds, would be taken up again when skiers go very fast. We likened this behavior to a horse that changes its gait pattern from a trot to a gallop with increasing running speeds, and then, when running speed is further increased, changes back from the gallop to the trotting gait, a behavior that would never occur. So, why does this completely unique change in gait pattern occur in cross-country skate skiers?

The average cost of transport was found to be lower at slow and very fast speeds for 2-skate skiing and lower for intermediate to fast speeds of skiing for the 1-skate technique (Figs. 20.2 and 20.3). However, the differences in the cost of transport were relatively small, but nevertheless, were significantly different for the two techniques at 12 and 15 km/h and at 24 km/h and faster. For the lowest speeds tested (6 and 9 km/h) statistical differences between the 1- and 2-skate techniques were not reached.

So, why do cross-country skiers revert back to a gait pattern (2-skate skiing) at very high speeds when this pattern was abandoned at intermediate speeds for the

1-skate technique? A first clue to this puzzle might be revealed when realizing that propulsion is primarily coming from the legs in the 2-skate technique, and from the arms for the 1-skate technique (Fig. 20.4). A second observation is that for the 1- and 2-skate techniques, propulsion from the arms does not increase with increasing speeds of skiing beyond a speed of about 15 km/h (Fig. 20.4). Finally, despite a decrease in the impulse by the arms and poles from 15 to 30 km/h skiing, the oxygen required for performing less work at the higher speed increases substantially (Fig. 20.5), particularly for the 1-skate technique. These observations indicate that the arm and pole action becomes costly from a metabolic point of view, while not resulting in increased propulsion for the skier. Therefore, the increased propulsion must come from the leg and ski action when skiing at speeds of greater than 15 km/h, and the leg and ski action must be less costly than the arm action, thus favouring the 2-skate technique at very high speeds of skiing.

But why should the arm action become more inefficient with increasing speeds of skiing than the ski action, particularly when speeds of skiing become high (>24 km/h)? And why does the same difference in metabolic cost not exist in other four-legged locomotion, such as a running horse? The primary mechanical difference between a running horse and a cross-country skier is that in the horse, once the hooves contact the ground, the hooves are fixed at zero speed relative to the horse's body that is traveling at, let's say, 10 m/s relative to the ground and the stationary hooves. Therefore, the ground reaction time of all legs for a horse is limited by the geometry of the legs at ground contact and at take-off and the speed of the centre of mass above the legs that are fixed to the ground. Thus, contact times in a horse running decrease predictably with the speed of running (Fig. 20.9).

Fig. 20.9 Average hoof contact times for a horse walking, trotting and galloping at increasing speeds of locomotion. Note that the contact times decrease with increasing speeds of locomotion, as contact times are given by the geometry of the leg at first and last ground contact and the speed of the centre of mass of the horse. Because of the given leg length in a horse, contact times must decrease with increasing speeds of locomotion

Fig. 20.10 Mean (± 1 SD) pole and ski contact times for cross-country skate skiers skiing at increasing speeds. Note how the pole contact times decrease in a similar fashion to those observed in a horse running, while the ski contact times are virtually unaffected by skiing speed. The reason for this difference in contact time behaviour of poles and skis is that the poles are fixed to the ground during ground contact, like a horse's hooves or the feet of a runner, while the skis glide at approximately the same speed as the centre of mass of the skier. Therefore, the pole contact times of a skier are limited by geometry and speed, like the hooves of a horse, while the contact times of the skis are theoretically independent of the geometry of legs and skis and the speed of skiing. Therefore, the ski contact times can be (and are) much longer than the pole contact times, and this discrepancy increases with increasing speeds of skiing, thus favouring the muscles of the legs over those of the arms for providing propulsion at high speeds of skiing

292 The same is true for the arms and poles of a cross-country skier. Once the poles are
 293 planted in the snow, they are fixed relative to the movement of the skier's centre of
 294 mass, and the contact time is limited (Fig. 20.10). Predictably, the times of pole
 295 contact with the ground decrease with increasing speeds of skiing.

296 In contrast, the legs of a cross-country skier are not fixed to the ground once
 297 ground contact is made. The skis glide at essentially the same speed as the centre of
 298 mass of the skier, therefore, in theory, ground contact times could be infinite for any
 299 speed of skiing. Of course, practically this is not possible. However, ground contact
 300 times decrease much less with increasing speeds of skiing for the legs (skis)
 301 compared to the arms (poles) (Fig. 20.10). In fact, ground contact times for skis
 302 remain on average 850 ms for skiing at 32 km/h (~ 9 m/s), while the corresponding
 303 pole contact times for that same speed is only about 200 ms. A horse galloping at
 304 9 m/s has an average stance time of about 110–120 ms, and a human sprinter's
 305 contact time has dwindled to a mere 100 ms running at that speed. Therefore, a
 306 cross-country skier, even when skiing at extremely fast speeds, still has plenty of
 307 time to use the muscles of the legs to produce force and propulsion with the skis,
 308 while propulsion through the poles and arms becomes severely limited at high
 309 speeds of skiing because of the muscle's force-velocity relationships (Hill 1938).

310 The question then remains, why do skiers prefer the 2-skate over the 1-skate
 311 technique at slow speeds of skiing, and why is there a trend towards better

efficiency for the 2-skate technique at slow speeds. This is a difficult question to answer, but likely has to do with the balancing and the stability on the skis at slow speeds of skiing. In the 2-skate technique, balancing is typically not an issue for even moderately competent skiers at slow speeds, while it is very difficult, and often impossible to 1-skate ski at slow speeds for beginners and moderately experienced skiers, because the weight transfer from one ski to the other, and associated balancing, is much more difficult for the 1-skate than the 2-skate technique. Therefore, we tentatively suggest that the 2-skate technique is more efficient than the 1-skate technique because of the wasted energy when balancing on the skis for the 1-skate technique at slow speeds of skiing. Since we used only experienced racers for our study, we did not see significant differences in the cost of transport between the 1- and 2-skate techniques at very slow speeds of skiing. However, we believe that if we had used beginner or moderately competent skiers only, where balancing and stability of skiing plays a major component in technique, the 2-skate technique might have been significantly more efficient than the 1-skate technique for slow speeds of skiing.

A second aim of this study was to test if respiration coupling, as observed in galloping animals (Ainsworth 1997; Attenburrow and Goss 1994; Bramble and Carrier 1983; Bramble and Jenkins 1993) and cross-country skiers (Faria 2008), does indeed save metabolic energy, as has been proposed. In order to address this question, we asked experienced skiers to ski just below their anaerobic threshold speed using the 2-skate technique while inhaling and exhaling with arm recovery and arm propulsion, respectively (coupled breathing), and then reversing this breathing pattern relative to the arm movements, for the uncoupled breathing patterns. We found that coupled breathing was associated with an approximate decrease in oxygen consumption of about 4 % compared to the reversed breathing pattern (Fig. 20.8), illustrating that coupled breathing indeed offers a metabolic advantage. Of course, one might argue that by using a “reverse” breathing pattern and compare it to the coupled breathing pattern, we used the worst metabolic scenario for testing this hypothesis: that is, the skiers were asked to inhale when their chest cavity was compressed due to the arm action and to exhale when the chest cavity was expanded. Skiers not using a coupled breathing pattern likely would not fall into a reversed breathing pattern, and thus the metabolic inefficiency of “random” breathing compared to coupled breathing might not be as dramatic as what we found here. Nevertheless, our results suggest that breathing coupled with the upper body and arm movements of cross-country skiing infers a metabolic advantage, and thus should be used by racers in competitive situations.

20.5 Conclusions

We conclude from the results of this study, that in contrast to all other four-legged animal movements, cross-country skiers revert to a gait pattern at high speeds of skiing that was rejected at a slower speed of skiing in favour of another gait pattern.

353 We suggest that this is primarily caused by the increasingly inefficient action of the
 354 arms and poles with increasing speeds of skiing, and the reliance on arm propulsion
 355 when using the 1-skate technique. Furthermore, we conclude that breathing coupled
 356 with the arm action in 2-skate skiing infers a distinct metabolic advantage compared
 357 to uncoupled breathing. Therefore, we suggest that cross-country skiers
 358 carefully monitor their breathing patterns in competitive situations.

359 **References**

- 360 Ainsworth DM (1997) Pulmonary-locomotory interactions in exercising dogs and horses. *Respir*
 361 *Physiol* 110
- 362 Attenburrow DP, Goss VA (1994) The mechanical coupling of lung ventilation to locomotion in
 363 the horse. *Med Eng Phys* 16:188–192
- 364 Bjørn Dæhlie (2014) http://en.wikipedia.org/wiki/Bj%C3%B8rn_D%C3%A6hlie
- 365 Bramble DM, Carrier DR (1983) Running and breathing in mammals. *Science* 219:251–256
- 366 Bramble DM, Jenkins FA Jr (1993) Mammalian locomotor-respiratory integration: implications
 367 for diaphragmatic and pulmonary design. *Science* 262:235–240
- 368 Cross-country skiing (2014) http://en.wikipedia.org/wiki/Cross-country_skiing
- 369 Dresbeck LJ (1967) The ski: its history and historiography. *Technol Cult*
- 370 Faria IE (2008) Ventilatory response pattern of Nordic skiers during simulated poling. *J Sports Sci*
 371 12(3):255–259
- 372 Hill AV (1938) The heat of shortening and the dynamic constants of muscle. *Proc R Soc Lond*
 373 126:136–195
- 374 Hoyt DF, Taylor R (1981) Gait and the energetics of locomotion in horses. *Nature*
- 375 Solberg G, Robstad B, Skjongsberg OH, Borchsenius F (2005) Respiratory gas exchange indices for
 376 estimating the anaerobic threshold. *J Sports Sci Med* 4:29–36
- 377 WEIR JB (1949) New methods for calculating metabolic rate with special reference to protein
 378 metabolism. *J Physiol* 109:1–9

AU1
AU2

AU3

Author Queries

Chapter No.: 20320099_1_En

Query Refs.	Details Required	Author's response
AU1	Duplicate entries of Faria (2008), Bramble and Jenkins (1993), Bramble and Carrier (1983), Attenburrow and Goss (1994), Solberg et al. (2005), Ainsworth (1997) have been deleted. Please check if this okay.
AU2	Please provide volume number for "Ainsworth (1997)."
AU3	Please provide volume and page numbers for "Dresbeck (1967), Hoyt and Taylor (1981)."