Metabolically Optimal Gait Transitions in Cross-Country Skiing

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***Abstract*—With increasing speeds of locomotion, animals change their gait pattern to minimize metabolic cost. For example, a horse will walk at low speeds, trot at intermediate speeds and gallop at high speeds [1]. Likewise, cross-country skiers use the 2-skate technique at slow speeds, switch to the 1-skate technique at intermediate speeds, but then, in contrast to everything known about locomotion in humans and animals, they revert back to the previously rejected 2-skate technique at very high speeds of locomotion. This pattern of gait transitions suggests that the metabolic efficiency curves for 1-skate and 2-skate skiing intersect twice, rather than just once as they do for human walking and running. The purpose of this study was to test if the metabolic efficiency curves of 1-skate and 2-skate skiing intersect twice, and if so, find an explanation for this surprising result.**

Eight nationally competitive skiers were tested on a roller ski treadmill. Subjects were asked to ski at speeds of 6-33km/h at 3km/h increments, once with the 1-skate technique and once with the 2-skate technique. Oxygen consumption and 3d kinematics were recorded continuously.

We found that the metabolic efficiency curves intersected twice. We also found that pole contact time and distance was much shorter per stride when using the 1-skate technique, especially at very low and very high speeds.

I. Introduction

ALTHOUGH cross-country skiing is an ancient Nordic sport, the skate-ski technique was only recently developed. The 1988 Olympics in Calgary debuted skating as a technique in cross-country ski racing and since then its popularity has grown as an exciting winter sport. Skate skiing is a unique and largely unstudied gait, using a combination of fixed and sliding limbs to produce forward movement. It is interesting to compare the distinctive four-limbed gait of cross-country skating to four-limbed animal locomotion. Research on four-legged gaits suggests that animals select gait patterns at certain speeds to minimize metabolic cost. For instance, horses tend to walk at low speeds, trot at intermediate speeds, and gallop at high speeds. They change gait patterns when the new gait becomes less metabolically costly than the rejected gait [1]. Humans also will choose running over walking at speeds where walking has a higher metabolic cost than running [2].

Skiers tend to use two primary gait patters. These include the 2-skate technique in which the two poles are planted almost simultaneously on every second foot-fall (for example always when the left leg makes ground contact) and it resembles the galloping action of a horse, and the 1-skate technique, in which the two poles are planted almost simultaneously on every foot-fall (that is a both poles are used when the left leg makes ground contact and then again when the right leg makes ground contact). This latter gait, to our knowledge, is unknown in the four-legged animal world. It can be observed that experienced skiers use the 2-skate technique at slow speeds, switch to the 1-skate technique at intermediate speeds, and then return to the 2-skate technique at very high speeds. This last transition to a previously rejected gait is unique to skate skiing and has not been reported for any other gait transition in animal locomotion.

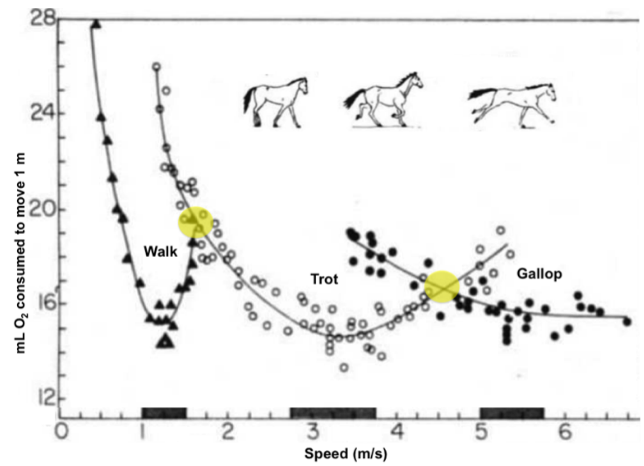

Fig. 1. The cost of transport plotted against speed for horses when walking, trotting, and galloping [1]. Intersections in the resulting curves are highlighted, indicating the speeds at which horses tend to change gait apparently in an effort to minimize the cost of transport.

Many studies estimate the economy of a technique by measuring the oxygen uptake per distance traveled [1]–[4]. When plotted against the speed of locomotion, this measurement is referred to as the cost of transport curves. Intersections of the cost of transport curves for different gait patterns indicate the speed at which one gait becomes more economical then the other. The intersections in cost of transport curves for horses walking, trotting and galloping are shown in Fig. 1 [1]. These intersections are typically thought to indicate the speeds at which an animal would tend to switch from one gait to another [1].

It would be expected that experienced skiers behave in the most efficient manner. Since skiers switch from the 2-skate to the 1-skate technique at some intermediate speed, and then return to the 2-skate technique at a high speed, we hypothesized that the oxygen cost curves for the two technique will intersect twice rather than once as observed in typical four-legged gaits exhibited by animals. The purpose of this study, therefore, was to measure the oxygen cost of each technique at a range of speeds to see if the oxygen cost curves do indeed intersect twice, and if so explain this surprising result.

II. Methods

Eight national and international skiers were recruited (1 female, 7 male). All subjects consented to the test and the University of Calgary board of ethics approved the protocol. The testing was performed on roller skis on a motor driven treadmill. The subjects were asked to ski one trial for each technique with two days rest between. The trials for each technique had identical protocols to allow for comparison of oxygen cost. The treadmill was set at a 0% grade for all of the testing and subjects were allowed to warm up and become comfortable roller skiing on the treadmill before the start of the measurements.

The trials began at a speed of 6 km/h and increased incrementally by 3 km/h. At the lower speeds, subjects skied for three minutes per stage. During each subjects first trial, anaerobic threshold was estimated using the respiratory exchange ratio. When it reached a value of 1, the following stages were shortened to 1 minute to allow subjects to reach sufficiently high speeds required for these tests. All male subjects reached at least 33 km/h and the female subject reached 24 km/h.

Gas exchange volumes were measured using a TrueOne 2400 Metabolic Measurement System, by ParvoMedics. The volumetric rate of oxygen consumed (VO2) was averaged over 30 second sample periods and normalized for body mass giving oxygen uptake in ml/kgmin. This value was then divided by the speed of travel (km/min) to give the cost of transport as the volume of oxygen per kg mass consumed per 1 kilometre of distance traveled. The cost of transport values at 6, 15, and 30 km/h were tested for significance using a non-parametric Wilcoxon signed rank test with a level of significance of 0.05.

All testing was filmed with a high-speed video camera at 200 frames per second with the optical axis perpendicular to the sagittal plane. Using the video, the duration from pole strike to pole liftoff was measured. This value was referred to as the duration of pole contact. The product of the duration of pole contact and the speed of roller skiing gave the distance of pole contact in meters. Pole recovery time was calculated as the total time of a poling cycle minus the duration of pole contact.

III. Results

The cost of transport for all subjects decreased as a function of speed (Fig. 2). The cost of transport values for the 1-skate decreased sharply to begin with, then at 15 to 18 km/h began to level off before dropping more quickly again near

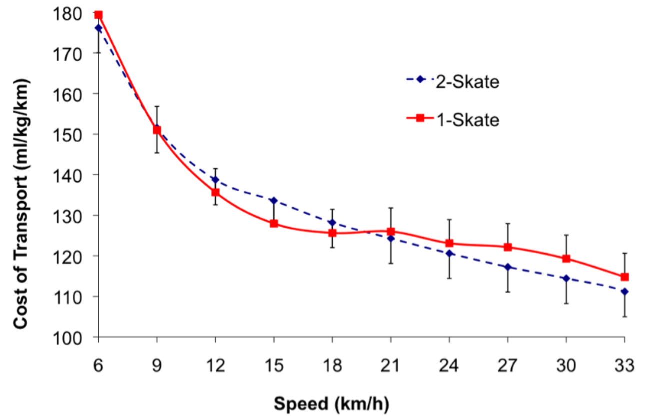

Fig. 2. Average cost of transport in milliliters of oxygen consumed to travel 1 kilometer per kilogram of body mass plotted against speed for the 1-skate and 2-skate techniques.

21 km/h. The curve for the 2-skate technique had a similar rapid decrease in cost of transport up to about 12 km/h, after which the values continued to drop at a decreased rate. When the cost of transport values were averaged at each speed for all subjects, the 2-skate technique had a higher cost at 6 km/h. The cost of transport curves for the two techniques intersect twice: just before 9 km/h and just after 18 km/h. Between the intersection points, that is for speeds of skiing of approximately 9-18km/h, the 1-skate technique had a lower cost of transport. At all speeds greater than 18 km/h or smaller than 9km/h, the 2-skate technique had a lower cost of transport. A Wilcoxen signed-rank test indicated that the differences in cost of transport were significant at speeds of 15 and 30 km/h but not at 6 km/h.

Pole contact time decreased as a function of speed for all subjects. The average duration of pole contact was shorter at all speeds for the 1-skate technique (Fig. 3). The values are similar from 15 km/h to 27 km/h; then they separate again for the two highest speeds. The 1-skate technique also has a shorter distance of pole contact (Fig. 4). The pole distances for the 2-skate technique remained much more constant than for the 1-skate technique, which increased steadily with increasing speeds of skiing, except for a slight decrease at the two highest speeds.

The pole recovery time was much shorter for the 1-skate compared to the 2-skate technique (Fig. 5). The shortest recovery times occurred in the 1-skate technique from 6 to 9 km/h and again between 27 to 33 km/h. The recovery times for the 2-skate technique varied much more than those for the 1-skate technique but were greater than for the 1-skate technique at all speeds.

IV. Discussion

The decrease in cost of transport as a function of speed is somewhat surprising since other locomotion studies tend to find a relatively constant cost of transport at high speeds of four-legged locomotion [1], [4]. Since the cost of transport was measured in terms of oxygen cost, the anaerobic contributions are neglected beyond anaerobic threshold. Perhaps this accounts for decreasing values beyond 21 km/h. Moreover, wind

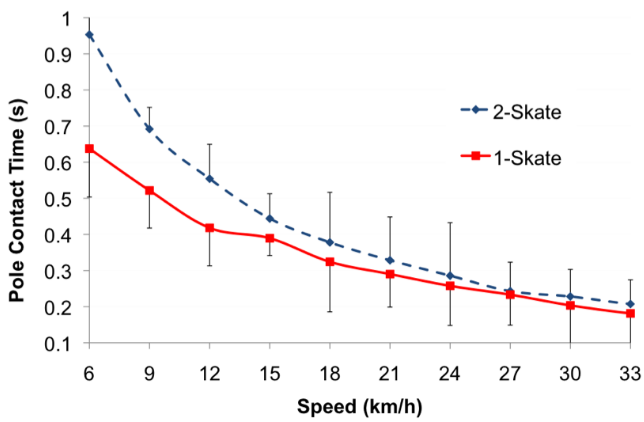

Fig. 3. The average duration of pole contact for all subjects plotted against speed for the 1-skate and 2-skate techniques.

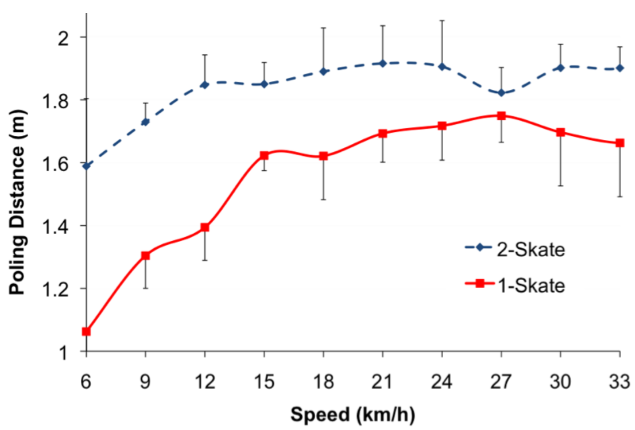

Fig. 4. The average distance of pole contact for all subjects, plotted against speed for both the 1-skate and 2-skate techniques.

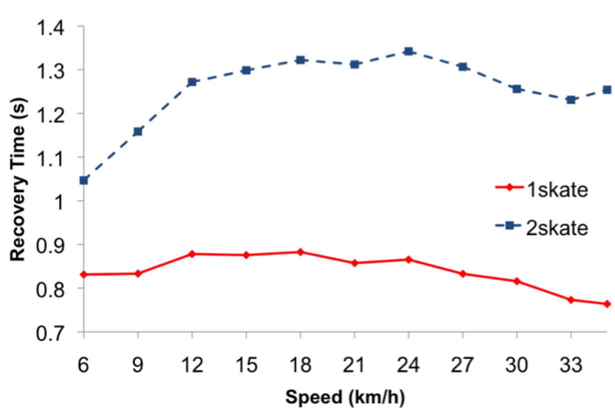

Fig. 5. The average pole recovery time for all subjects, plotted against speed for both the 1-skate and the 2-skate technique.

resistance is not a factor in the treadmill testing, and therefore may provide an under estimation of the cost of over-ground transport. Nevertheless, the measured differences in economy between the 1- and 2-skate techniques indicate that skiers do indeed ski in the least metabolically costly manner, despite being the only known gait to use a regressive gait transition.

It should be possible to explain why a gait pattern that is rejected at a low speed (2-skate technique at about 9-12km/h) is used again at a high speed of locomotion (greater than about 18-21km/h) with the mechanical differences of the two techniques at different speeds. We suspect that the difference is mainly due to the effect of the speed of locomotion on the effectiveness of propulsion with the poles. In contrast to the skis, which travel at the same speed as the skier, the poles, once planted, are fixed in the ground at zero speed while the skier travels past the pole insertion point. This implies that the leg action with the skis is essentially independent of the speed of locomotion, while the poling action is not.

Large differences in the pole contact times are seen when comparing the 1- and 2-skate techniques. At 30 and 33 km/h in the 1-skate technique, the pole contact time begins to fall sharply. Reduced contact times are especially important at high speeds. To maintain momentum, a certain amount of impulse is necessary. Since impulse is dependent on the magnitude and duration of an applied force, the reduction in the pole contact time at high speeds might reduce the impulse provided by the poling action significantly. Also, the force may be limited by the force-velocity relationship of the arm and trunk muscles when the poling action becomes very fast at the high speeds of locomotion.

In the 1-skate technique, each leg is used once for every push with both poles. This results in a reduced pole contact time in order to stride effectively with the legs, which, in turn, results in a reduced contact distance in the 1-skate compared to the 2-skate technique. In the 2-skate technique, the extended pole contact distances at low speeds of locomotion allow for a greater working distances at these low speeds. Also, since the poles are planted for a longer period of time, they may aid in balance at low speeds of locomotion, thereby reducing stabilizing muscle action required in the legs.

Another source of excessive oxygen cost in the 1-skate technique is the pole recovery. At high speeds of locomotion, the pole recovery times are much longer in the 2- compared to the 1-skate technique. At intermediate speeds, the pole recovery time is less hurried in the 1-skate technique than at the high and low speeds. This may be partially responsible for the efficiency of the 1-skate technique at intermediate speeds.

V. Conclusions

The gait transitions in cross-country skiing are highly unusual as the 2-skate technique that is used at slow speeds but rejected at intermediate speeds, is taken up again at very fast speeds. Based on the results of this study, we speculate that this occurs because the poling mechanics is affected by the speed of skiing as the poles are fixed when in contact with the ground, while the mechanics of the skis is not affected by the speed of locomotion, as the skis glide along with the skier at the same speed. The 1-skate technique is inefficient at very slow speeds because the distance traveled per poling action is much smaller than for the 2-skate technique, thereby preventing effective propulsion. The 1-skate technique is inefficient at very high speeds because the frequency of poling is much higher than in the 2-skate technique and the poling action is too quick for effective work production by the poles.

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