# IMPULSE CONTRIBUTION FROM EACH LIMB IN SKATE CROSS-COUNTRY SKIING

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## SUMMARY
Skate cross-country skiing allows humans to use all four limbs for locomotion. Using skis and poles a skier is a quadruped with very different 'hind-limb' and 'fore-limb' configurations. The skis are used in a similar fashion to ice skates while the poles, when planted, are fixed and operate similarly to a normal leg. Skiers use a symmetrical technique (1-skate) at intermediate speeds and an asymmetrical technique (2-skate) at both low and high speeds. This work is aimed at finding the individual contributions of each limb to propulsion in skate cross-country skiing. We hypothesized that the relative contributions from skis and poles change as a function of speed, and that, in the 2-skate technique, contributions to propulsion are asymmetrical between the left and right sides of the body. The impulse from poles decreased and the impulse from the skis increased with increasing speeds of skiing for both techniques. Skiers produced greater propulsive impulses with the arms in the 1-skate compared to the 2-skate technique, primarily because of a higher poling frequency in 1- compared to 2-skate skiing. In the 2-skate technique, propulsive impulses were smaller from the ski that was loaded simultaneously with the poles. These results may have implications for how skiers select techniques at different speeds. Furthermore, the asymmetry in the 2-skate could cause localized fatigue and muscle imbalance.

## INTRODUCTION
In the late 1900s, as machine grooming became more common, cross-country skiers began to stray from the traditional style of skiing in parallel tracks, taking advantage of the hard packed surface [1]. The new skating technique made use of the skis in a skating motion while intermittently pushing with the poles. This unique movement pattern is perhaps the only form of locomotion to make use of both sliding limbs (the skis) and fixed limbs (the poles).

Cross-country skiers use the 2-skate technique when moving slowly, 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. In the 1-skate technique, a skier plants both poles simultaneously with each leg's skating push (two pole pushes per gait cycle). In the 2-skate, a skier plants both poles with every second skate-push (one pole push per skate cycle). As such, the 1-skate is symmetrical while the 2-skate is asymmetrical [2].

We found previously that the cost of transport curves (oxygen requirement per distance traveled) as a function of speed, associated with the 1- and 2-skate techniques intersect twice with a lower cost of transport for the 2-skate at low and high speeds, and a lower cost of transport for the 1-skate technique at intermediate speeds [3]. This coincides with skiers' behavior. Force production in the skis and poles may explain the cost of transport observations, and therefore gait selection in skiing. Furthermore, the asymmetrical 2-skate technique may produce localized fatigue and muscle imbalance causing injury.

The purpose of this work was to measure the impulse contributions from each limb in the 1-and 2-skate techniques at a range of speeds to help explain gait selection and localized fatigue in skate skiing. Given that the upper and lower limbs differ in how they produce propulsive impulse, and that skiing has both symmetrical and asymmetrical gait patterns, we expected the impulse contributions from each limb to vary with technique and skiing speed. Since the skating limbs are sliding, leg propulsion and cadence does not depend directly on skiing speed [4], while the poles, once planted for propulsion, have a ground contact time intimately associated with the skiers speed. The force a muscle can produce decreases as speed of shortening increases [5], therefore it is expected that the impulse the poles produce will decrease as skiing speed increases while the skis, nearly unconstrained by speed, will compensate by increasing their impulse contribution. Furthermore, we expect that the asymmetrical 2-skate movement will produce imbalances in the forces and impulses between the left and right skis.

## METHODS
Nine nationally and internationally ranked skiers were recruited to ski on a roller ski treadmill. Each subject was given a 10 min warm up to become familiar with the treadmill and equipment. Skiers were asked to ski at speeds from 6 to 27km/h with both the 1-skate and 2-skate techniques at zero slope. Skiers were allowed to become familiar with each speed and technique prior to collection of force data (1000Hz) for a 20s period. Forces in the poles were measured in the axial direction using a cylindrical transducer with six evenly spaced strain gauges. Forces were measured in the roller skis with strain gauges mounted between the shaft of the ski and each wheel. These measured forces in the vertical and medial/lateral direction relative to the upright ski. Resultant force vectors were calculated from each ski as the vector sum of the medial/lateral ski force and the vertical ski force.

Impulse per stride, contact time, and cycle time were calculated from each force trace. Using the cycle time and the impulse per stride, the impulse per minute was calculated. Impulse due to body weight was subtracted from the impulse of the skis.

## RESULTS AND DISCUSSION
As expected, impulse measured in the poles decreased with increasing speeds in both techniques, while the corresponding impulse produced by the skis increased (figures 1 and 2). In the 1-skate technique (figure 1), the absolute and relative impulse produced by the poles was much larger than in the 2-skate technique (figure 2). This is due to the higher frequency of poling in the 1-skate compared to the 2-skate technique. The 2-skate technique

relies heavily on the skis to generate the required propulsion. Therefore, it would be advantageous to use this technique at speeds where the poling motion is less efficient than the skating motion.

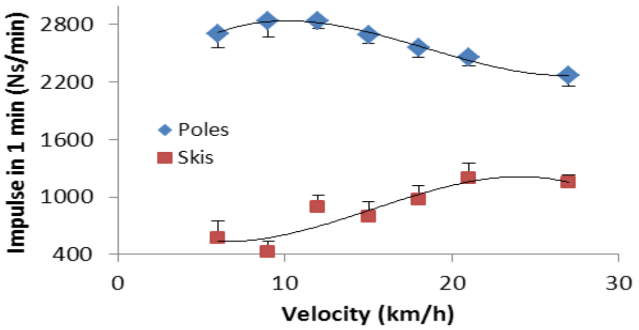


**Figure 1**: Impulse generated per minute by the skis and the poles in the 1-skate technique at velocities from 6 to 27km/h. In all figures, error bars are standard errors and the regression curves are best-fitting third order polynomials.

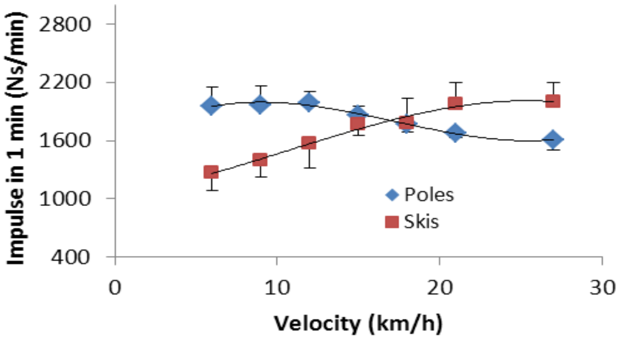


**Figure 2**: Impulse generated per minute by the skis and the poles in the 2-skate technique at velocities from 6 to 27km/h.

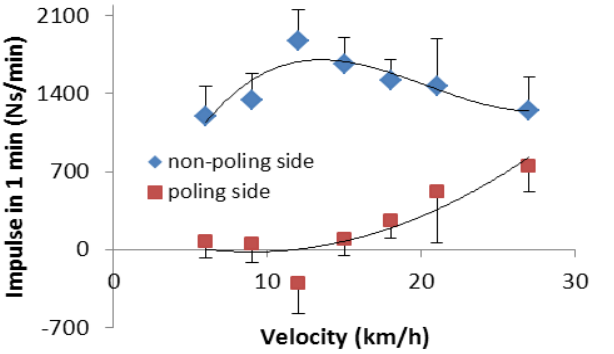


**Figure 3**: Impulse generated per minute by each ski in the 2-skate technique at velocities from 6 to 27km/h. The poling side ski has a ground contact phase which coincides with that of the poles

Asymmetries between the left and right ski impulses are not evident when looking at the 1-skate technique. However, there is a clear separation in the impulse curves for each ski in the 2-skate technique (figure 3). The poling side ski (ground contact times for this ski and the poles coincide) does not produce as much impulse as the non-poling side ski. These asymmetries were greatest at intermediate speeds and decreased at higher speeds. Perhaps a further increase in speed would require that the weaker side (poling side ski) increase its impulse further to match the impulse of the non-poling side as effort approaches a maximal level.

## CONCLUSIONS

The four limbs used in skate skiing differ greatly in their contribution to impulse production. It seems that the poles are limited in force production at high velocities because of the increasingly shorter ground contact time and increasingly quicker arm action required with increasing speed. The skis have an advantage at high speeds since the skating motion allows for an adjustable angle between the skis. By adjusting this angle the skier is able to optimize the skating motion to the speed [3]. As such, they are able to compensate for the reduced pole impulse at high speeds. To reach higher speeds, skiers must shift the burden of impulse production to the lower limbs.

In the 2-skate technique, the poles are used to a lesser degree than the 1-skate technique at all speeds. This, in part, may explain a skier's preference to use the 2-skate at high speeds since the propulsive impulse that can be produced by the arms and poles decreases dramatically at high speeds [6]. Although the impulse produced by the poles in the 1-skate technique is higher than the 2-skate technique, even at very high skiing speeds, the much more rushed poling motion may consume an excessive amount of metabolic energy for the mechanical work that can be performed by the arms. If energy spent in the skis at this speed produces more impulse than energy spent in the poling motion, the 2-skate would prove to be the more efficient technique. This would agree with our previous oxygen cost results which show that the 2-skate is more economical at high speeds [3].

The asymmetrical motion in the 2-skate technique causes the left and right skis to contribute a different amount of impulse. When the poles are planted with a single ski rather than both, the ski with which the poles are planted has a reduced impulse, while the ski on the non-poling side generates the majority of the impulse. In a long distance event, unilateral impulse production could cause localized muscle fatigue, reducing performance. Moreover, it is possible that a muscular imbalance could be created through chronic unilateral use of the 2-skate. Assuming that a symmetrical use of arms and legs is crucial for optimal performance in skiing, this data suggests that skiers who can change the poling side when using the 2-skate technique are at a distinct advantage to those who always pole on the same ski.


## ACKNOWLEDGEMENTS

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