FUNCTIONAL MUSCLE MECHANICS IN SPORTS: WHY WE SHOULD CARE!

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The mechanical properties of muscles frequently determine the performance limits of athletes. Nevertheless, even the most basic properties of muscles, such as the force-length and force-velocity relationships are rarely considered in sport performance analysis. Here, we demonstrate with examples of track cycling and cross-country skiing that many technical choices in sport can be explained by an understanding of the basic properties of skeletal muscles and that performance can be enhanced as a result of this understanding. There is a gap of research between sport and muscle mechanics that is largely unexplored but offers exciting possibilities for basic science and applied athletic coaching and training.

KEY WORDS: sport, muscle, performance, muscle properties, force-length relationship, force-velocity relationship, optimization, cross-country skiing, cycling.

INTRODUCTION: Muscles move joints and produce coordinated movements. In sports, the specific properties of muscles determine to a great degree the potential of an athlete to perform well, and will often set natural upper limit boundaries to performance. These upper boundaries may be associated with obvious limits of muscles, such as strength, endurance, work capacity, but may also be caused by less obvious properties of muscles, such as the integration of muscles into the musculoskeletal system (joint moment arms, excursion), or integration into the nervous system (coordination, ability to learn complex movement tasks).

While the strength of muscles and endurance or work capacity are easy to measure, and are quantified frequently in athletes to assess their “fitness”, basic properties, such as the force-length relationship, force-velocity relationship and history-dependent properties are rarely considered within the constraints of the human musculoskeletal system, and neither are adaptations of these properties to exercise training. In the past, we demonstrated that force-length properties adapt to the everyday, chronic exercise requirements of training in elite athletes. Specifically, we showed that thigh muscles in elite cyclists had different force-length properties than the muscles of elite runners (Herzog et al., 1991). Similarly, we demonstrated that power output in sprint cycling is directly affected by athlete positioning, and that these changes in power production could be explained with changes in muscle excursion and the speed of muscle shortening (Yoshihuku and Herzog, 1990; Yoshihuku and Herzog, 1996).

Track cycling is an ideal sport for the study of muscle mechanics because seat height, crank length, and upper body lean directly affect the excursion of the lower limb muscles and the part of the force-length relationship that is utilized during a pedal revolution. Similarly, crank length and gear ratio directly determine the speed of muscle shortening (and thus the range of the force-velocity relationship) that is utilized when pedaling at a given speed.

Muscle properties, and how they affect performance, are important in other sports as well, but are harder to measure and more difficult to interpret than in track cycling. Over the past three years, we attempted to identify relevant mechanical properties of muscle functioning in cross-country skate skiers. This was motivated by the observation that cross-country skiers use a gait pattern for slow skate skiing (less than about 12km/h), a different gait pattern for medium speed skate skiing (12-21km/h), and go back to the slow gait pattern for fast skate skiing (greater than about 21km/h).

Cross-country skate skiing is a four-legged gait, resembling a galloping horse. But a horse would never go from a trot to a gallop and back to a trot with increasing speeds of locomotion, but that is precisely what cross-country skiers do: they go from a 2-skate to a 1-skate and back to a 2-skate skiing technique with increasing speeds of locomotion. The reason for this behavior is possibly associated with the observation that the cost of transport is smaller for

2-skate skiing at slow and fast speeds, and is smaller for 1-skate skiing at intermediate speeds (Figure 1).

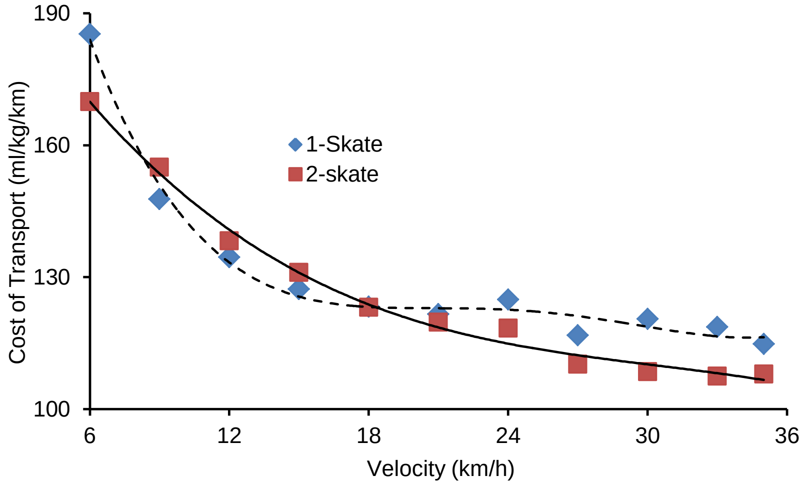

Figure 1 Oxygen cost of transport as a function of speed for an Olympic level skier using the 1-skate and 2-skate techniques. Note the double intersection of the curves, which indicates that the more efficient technique at slow speeds is also the best at very high speeds, an observation that has never been made before in any four-legged locomotion.

The difference between a running horse and a cross-country skier is that the horse's hooves are fixed when they hit the ground, thus ground contact times become smaller when the horse runs faster. For the skier, this is true for the arms and poles, which are fixed once they hit the ground, and thus ground contact times decrease with increasing speeds. But this is not true for the legs and skis, which glide when ground contact is made, and thus, leg ground contact times do not depend directly on the speed of skiing. Therefore, the arm action in skate skiing directly depends on the speed of skiing, while the leg action does not. This has important implications for the muscle mechanics of the arms while poling, and for the legs while gliding and pushing off.

The purposes of this work were (a) to identify why cross-country skate skiers return to a gait pattern at very high speeds that was rejected at medium speeds, and (b) to explain this unique gait transition with muscle mechanical considerations.

METHODS: Elite cross-country skiers (n=20 in total) were analyzed while skate skiing (using roller skis) on a motor driven skating treadmill for different purposes. In a first study, oxygen uptake was measured for 1-skating and 2-skating at speeds ranging from 6km/h to 36km/h at increments of 3km/h. Kinematics were measured with two high speed cameras set up with their optical axes perpendicular to the sagittal and frontal planes. Forces in poles and skis were measured with a system developed in house specifically for this purpose. Forces in poles were one-dimensional along the axis of the poles; forces in the skis were three-dimensional along the long axis of the skis, perpendicular to that axis in the horizontal plane (when standing still) and vertical to the skis.

In a second study, oxygen uptake was measured only for the arm action when producing the same forces as in actual skiing on a poling ergometer, and mimicking the movements and rhythm of skiing displayed for each athlete on a TV screen.

In a third study, the force-length and force-velocity properties of the arm action while poling were measured. The force-length property was measured isometrically by moving the athletes' arms and poles to the position corresponding to 0%, 10%, 20% …. 100% of the poling action, and asking the athletes to exert the maximal isometric force. For the force-velocity properties, athletes performed poling actions in the rhythm of 1-skating, 2-skating, while standing on roller skis fixed to the treadmill and the treadmill was moving at speeds ranging from 6km/h to 42km/h at increments of 6km/h. The instruction given to the athletes was to perform ten poling cycles at each speed as hard as possible, and the 6-9th poling cycle were analyzed for peak force and impulse.

RESULTS: The cost of transport is smaller for 2-skating at slow and fast speeds, and smaller for 1-skating at intermediate speeds, on average and for most individual skiers (figure 1).
1-skate skiing relies primarily on arm propulsion, while 2-skate skiing relies primarily on leg propulsion (figure 2). The oxygen cost for the 1-skate poling action is greater than for the 2-skate poling action at all speeds (figure 3). For 1- and 2-skate skiing, the force and propulsive impulse that can be generated is relatively unchanged for slow and intermediate speed skiing, but drops off quickly at speeds of about 25-30km/h.

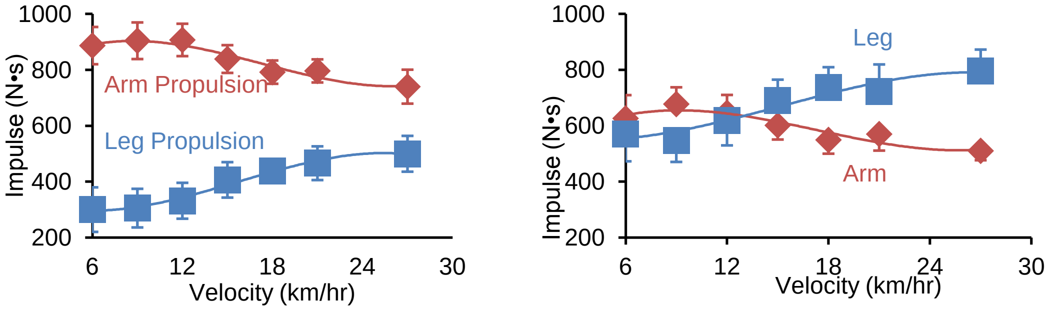

Figure 2 Contributions of arms and legs to propulsion in 1- (left) and 2-skate (right) skiing.

Finally, while ski (leg) contact times decreased from 1.27s (0.97s) at a speed of 6km/h to 0.87s (0.69s) at a speed of 36km/h for the 1-skate (2-skate) techniques, respectively, the corresponding pole contact times decreased from 0.64s (0.95s) to 0.17s (0.20s), respectively (figure 4).

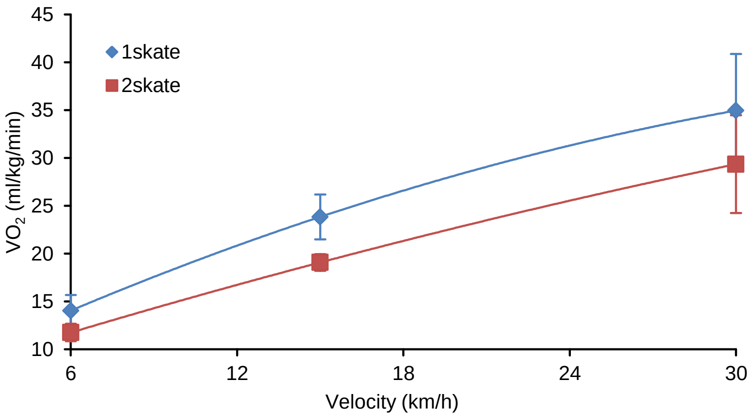

Figure 3 Metabolic cost of the arm and poling actions for 1-skate and 2-skate skiing at different speeds.

DISCUSSION: Recreational and elite skiers prefer the 2-skate technique when skiing at very slow or very fast speeds, while they prefer the 1-skate technique when skiing at intermediate speeds. This counter-intuitive choice of reverting to a gait pattern at very high speeds that was rejected in favor of another gait pattern at intermediate speeds is unique in the animal world. These changes in gait pattern appear to be driven by energy considerations: the 2-skate technique has a lower cost of transport at slow and very fast speeds than the 1-skate technique, while the reverse is true at intermediate speeds.
Why is this curious change in gait pattern not observed in other four-legged gaits? And what mechanical factors might cause this unique change in gait patterns in cross-country skate skiing? First and possibly foremost, cross-country skiing is unique in that the ground contact times (and thus the period of active propulsion) of the skis are not directly affected by the speed of skiing. The athlete's centre of mass and the skis have approximately the same

speed at all times, while this is not true for any animal gait where the feet are fixed on the ground, and thus ground contact times are directly affected by the speed of movement. Although the ground contact times become shorter when skate skiers increase speed, the ski contact times are still very long (>0.6s) even at the fastest racing speeds. However, the pole contact times, like the feet of animals, are fixed to the ground, and thus contact times decrease dramatically with increasing speed, thus reducing the amount of time available for producing propulsive forces (figure 4).

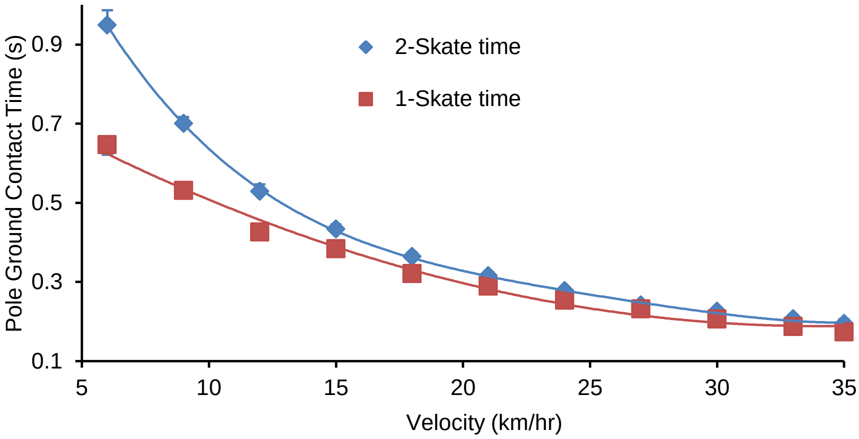

Figure 4 Pole ground contact times as a function of the speed of skiing for the 1-skate and 2-skate technique.

Since the 1-skate technique relies much more heavily on propulsion from the arms and poles than the 2-skate technique, and since propulsive forces are substantially compromised at high speeds and pole contact times are significantly shorter in 1-skate than 2-skate skiing, the mechanics of 1-skate skiing becomes inefficient at high speeds and thus skiers prefer the 2-skate technique at very high speeds of skiing.

For intermediate speeds of skiing, poling forces are maximal and the impulse generated by the poling action relative to the oxygen cost is maximal for 1-skate skiing, thereby creating optimal conditions from a muscle mechanics point of view to utilize the 1-skate technique for skiing at speeds ranging from about 12-20km/h. At slow speeds, the cost of transport is likely smaller in the 2-skate compared to the 1-skate technique because of the smaller excursion of the centre of mass from the intended direction of travel, and the associated greater stability. This interpretation needs verification with novice skiers, who usually master the 2-skate technique quickly while having difficulties with the technically more demanding 1-skate technique.

CONCLUSIONS: Gait transitions of recreational and elite cross-country skiers can be explained with the relationship between cost of transport and skiing speed. The surprising result of reverting to a gait pattern at very high speeds that was abandoned at intermediate speeds is explained with the gliding action of the skis and the fixed ground contact of the poles which creates conditions for the muscle mechanics of arms and legs that is unique to the “four-legged” gaits observed in skate skiing.

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