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Biomechanical and energetic determinants of technique selection in classical cross-country skiing

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ABSTRACT

Classical cross-country skiing can be performed using three main techniques: diagonal stride (DS), double poling (DP), and double poling with kick (DK). Similar to other forms of human and animal gait, it is currently unclear whether technique selection occurs to minimize metabolic cost or to keep some mechanical factors below a given threshold. The aim of this study was to find the determinants of technique selection. Ten male athletes roller skied on a treadmill at different slopes (from 0° to 7° at 10 km/h) and speeds (from 6 to 18 km/h at 2°). The technique preferred by skiers was gathered for every proposed condition. Biomechanical parameters and metabolic cost were then measured for each condition and technique. Skiers preferred DP for skiing on the flat and they transitioned to DK and then to DS with increasing slope steepness, when increasing speed all skiers preferred DP. Data suggested that selections mainly occur to remain below a threshold of poling force. Second, critically low values of leg thrust time may limit the use of leg-based techniques at high speeds. A small role has been identified for the metabolic cost of locomotion, which determined the selection of DP for flat skiing.

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1. Introduction

Cross-country skiing is a form of locomotion performed with the use of passive locomotory tools, skis and poles, in which propulsion is generated by both upper and lower body musculature and which allows travel on snow with a reduced cost of transport compared to walking and running (Minetti, 2004; Saibene & Minetti, 2003).

Classical cross-country skiing can be performed by using three main techniques: diagonal stride, double poling, and double poling with kick (Bilodeau, Rundell, Roy, & Boulay, 1996; Smith, 1992). Diagonal stride (DS) is performed by exerting force through the skis and poles while the arms and legs are moved in a coordinated pattern that resembles that of walking or running, since the push of one arm is performed along with the push of the contralateral leg. The leg's propulsive action entails a stop in the motion of the ski and a rapid downward and backward movement of the leg that can be described as a backward kick. Double poling (DP) is performed with symmetrical and synchronous movements of both poles, the propulsive action of which is enhanced by a considerable trunk flexion while the legs' involvement is minimal (Holmberg, Lindinger, Stoggl, Bjorklund, & Muller, 2006). Double poling with kick (DK) is performed through a poling action similar to that described for DP but, in this case, propulsion is obtained also by a left or a right leg kick. The techniques are therefore characterized by different contributions from the lower and upper limbs and by different coordinative patterns.

Cross-country skiers can switch between techniques according to changes in speed and track slope; the different techniques can thus be considered to be a gear system (Nilsson, Tveit, & Eikrehagen, 2004) and the selection of the appropriate technique could have important implications for locomotory efficiency and performance. It is generally known that DS is used mainly on moderate to steep uphill slopes, that DP is selected for skiing on flat tracks (and it is the preferred technique at high speeds), and that DK is mainly used for skiing on low to moderate slopes. However, the parameters that determine the selection of these techniques are still unknown.

A widespread assumption in human and animal locomotion is that gaits are selected to minimize metabolic energy cost (Alexander, 1989; Margaria, 1938; Mercier et al., 1994; Rubenson, Heliams, Lloyd, & Fournier, 2004). Margaria (1938), who first investigated the walk to run transition in humans, reported that walking is metabolically more expensive than running at the speed at which humans change gait, whereas below this speed the opposite is true. A similar metabolic advantage has been observed in horses as they change from walk to trot and gallop (Hoyt & Taylor, 1981). Also hopping animals, such as the kangaroo, seem to select metabolically optimal gaits in relation to different locomotion speeds, the transition in this case being from pentapedal walking to bipedal hopping (Dawson & Taylor, 1973). These findings suggest that gait selection occurs in a number of species in order to minimize the metabolic cost of locomotion. However, some more recent studies on horses (Farley & Taylor, 1991) and humans (Hreljac, 1993; Minetti, Ardigo, & Saibene, 1994; Rotstein, Inbar, Berginsky, & Meckel, 2005) have found that the actual transition occurs at a speed that is lower than the energetically optimal transition speed. It is moreover questionable that both animals and humans could have a precise perception of the metabolic cost they are paying (Farley & Taylor, 1991) and also the time needed "to make a decision" about the preferred gait mode is much less than the time needed to reach a metabolic steady state. Several researchers have thus hypothesized that gait transitions are the result of a subjective feeling and that local factors, such as muscular overexertion, could prevail over central factors (i.e., metabolic related variables). According to this hypothesis, comfort criteria would be predominant over energy savings criteria (Daniels & Newell, 2003; Prilutsky & Gregor, 2001; Thorstensson & Roberthson, 1987). Many studies have investigated the role of biomechanical parameters in determining the transition between gaits in humans and animals, some of them finding that transition occurs in horses when the critical value of musculoskeletal forces is reached (Biewener & Taylor, 1986; Biewener, Thomason, Goodship, & Lanyon, 1983; Farley & Taylor, 1991; Taylor, 1985).

Even if it is reasonable to hypothesize that, in analogy with other vertebrates, the transition between gaits in humans could be triggered by kinetic factors, no agreement has so far been reached on the existence of a critical force level or other mechanical factors at the transition from walking to

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