CHANGE OF SPEED IN SIMULATED CROSS-COUNTRY SKI RACING: A KINEMATIC ANALYSIS

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The purpose of the study was to identify the kinematic changes of the diagonal stride technique (DST) associated to a decrease of speed during a simulated cross-country ski race. Eight male cross-country skiers skied a 15 km course composed of 6 laps of 2.5 km. Full DST cycles were recorded using a digital camera for each lap. The fastest and slowest laps for each skier were selected, from which the following variables were studied: (i) cycle length and cycle frequency, (ii) propulsion length and duration, (iii) swing length and duration and (iv) trunk and knee angles. The skiing speed was significantly decreased between the first and the second part of the simulated race. The speed change was associated only with modification of the spatial components of the DST cycle (cycle and phase lengths, trunk and knee angles). The cycle durations remained constant. It was concluded that the decrease of speed resulted from a deterioration of the technique reducing the application of propulsion forces.

KEY WORDS: cross-country skiing, kinematics, speed change

INTRODUCTION: Cross-country skiing is a widely practise sporting activity involving different skiing techniques. Among them, the Diagonal Stride Technique (DST) is the original form of competitive cross-country skiing and uses parallel displacement of the limbs such as is observed in walking or running gaits. Most of the kinematic studies compared cross-country skiers of different level of performance (Marino et al., 1980; Smith, 1992; Bilodeau et al., 1996). These have shown that the best skiers are characterised by longer cycle and gliding phase lengths and similar cycle rates compared to slower skiers. In general, an overall decrease of skiing speed is observed during the race (Norman et al., 1985; Bilodeau et al., 1996). Bilodeau et al., (1996) suggested that the loss of speed was related to the appearance of fatigue and /or change in the snow conditions.
The adaptation to speed in the cycle parameters has been investigated in cross-country skiing with the analysis of skiers at selected speeds (Gagnon, 1981; Nilsson et al., 2004). Those studies reported that in cross-country skiing changes in speed have been mostly associated with changes in the temporal parameters of the cycle (i.e. cycle frequency). However the biomechanical variables responsible for the changes of speed during DST racing conditions remain to be understood.
Hence, the purpose of the study was to analyse the DST kinematic changes (i.e. temporal and spatial cycle parameters and joint angles) associated with changes in speed during a simulated race.

METHODS: A group of eight regional level males cross-country skiers (20 ± 2.6 y., 1.78 ± 0.05 m, 69.8 ± 6.9 kg, X ± SD) volunteered to take part in the study.
Each subject performed a 15 km simulated race, executing 6 laps of 2.5 km each and using the diagonal stride technique (DST) throughout. The entire test was carried out during a two hour period in order to minimise any change in the snow properties. Snow conditions consisted of large wet snow grain making the snow surface relative soft with a snow temperature of +6ºC. The subjects used their own equipment with classical skis waxed to obtain an optimum grip and glide.
The subjects were timed and filmed in the sagittal plane at each passage across the starting line. A digital camera (Panasonic NV-GX7 EG, PAL., 25 frames / s, 1/250 s of shutter speed) fixed on a tripod positioned 10 meters perpendicularly from the ski tracks, with the optical axis of the camera vertically centred on the hip of the subjects was used. A camera field of view of 8 meters width was chosen in order to record a full skiing gait cycle according

to cycle length values previously reported in the literature (Dillman *et al*., 1979; Gagnon, 1980, 1981; Bilodeau *et al*., 1996, Nilsson et al. 2004).
Video images were digitised frame by frame and point by point over a full cycle (i.e. two consecutive plants of the right ski pole). For each frame the right shoulder, the right hip, the right knee and the right ankle were manually digitized using a locally written program (University of Leeds, 1996). A digital filter (Butterworth) with a cut-off frequency of 4.5 Hz was used to smooth kinematic data (Winter, 1990).
Since one subject withdrew from the experiment, data were obtained and analysed for 7 subjects. The lap speed (LS) and the cycle speed (CS) were calculated for each subject and each lap. Regarding the overall decrease of LS and CS during the simulated race, the fastest (S1) and slowest (S2) cycles were analysed. For all skiers, S1 occurred during the first part of the race while S2 occurred during the second part of the race.
For both velocities cycle frequency, absolute duration of the swing and propulsion phases, cycle length and propulsion and swing lengths were calculated. The swing and propulsion phases were defined in accordance with Bilodeau et al., (1992) (figure 1). The changes in skier's technique between S1 and S2 were analysed by comparing the trunk angle (TA) and knee angle (KA) between the two conditions. The trunk angle was defined as the angle between the straight line (shoulder-hip) and the vertical axis. The knee angle was defined as the angle between the prolongation of the thigh segment and the shank segment. For consistency with previous methods proposed by Dillman et al. (1979), and Gagnon (1980) these angular calculations were focused on the beginning of propulsion phase (position 1, figure1) and at the end of propulsion phase (position 2, figure 1).

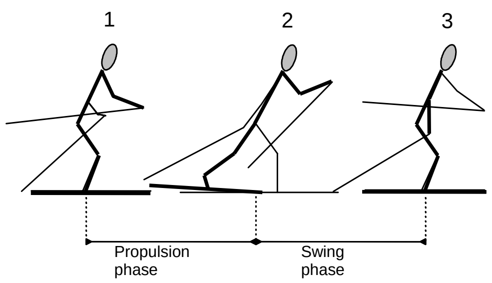

Figure 1: Determination of the propulsion phase and swing phase of the right leg
1: Feet are adjacent; 2: Central part of the right ski lifts from the snow; 3: feet are adjacent.

Mean and standard deviation were calculated for each dependent variable. To test the correspondence between LS and CS, a correlation (Spearman) was undertaken between the parameters. A non-parametric test (Wilcoxon) was chosen to compare all variables between the two cycle speeds S1 and S2. Statistical significance was accepted at the level $p<0.05$.

RESULTS: Both lap velocity (LS) and cycle velocity (CV) variables showed a similar pattern of speed throughout the simulated race irrespective to the subject (figure 2). This similar tendency was confirmed by the strong correlation between LS and CV ($r = 0.657$; $p=0.000$).

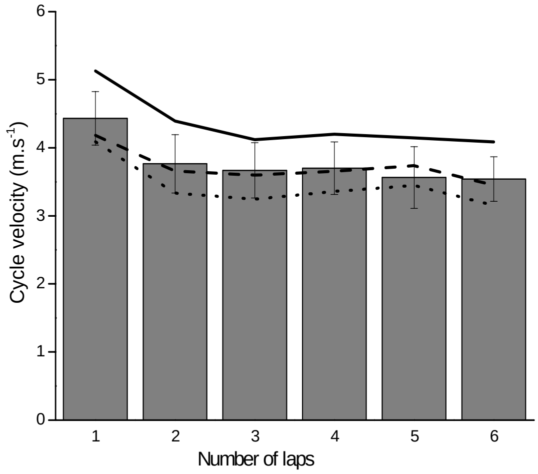

Figure 2: Cycle velocity for the 6 successive laps of the simulated 15km race. The chart bar represents the mean cycle velocity (CV) for each lap, the solid line corresponded to the fastest skier, the dash line to a median speed skier, and dot line to the slowest skier.

The mean fastest cycle speeds (S1) was 4.45 $m \cdot s^{-1} \pm 0.35\ m \cdot s^{-1}$, significantly larger than mean slowest cycle speed (S2), 3.34 $m \cdot s^{-1} \pm 0.14\ m \cdot s^{-1}$ (p=0.001).
Comparison of the temporal parameters showed no significant differences between S1 and S2 in cycle frequency (p=0.499; with data of 0.92 Hz ± 0.07 and 0.90 Hz ± 0.07 respectively), in absolute propulsion duration (p=0.388 with data of 0.16 s ± 0.03 and 0.17 s ± 0.02 respectively) and in absolute swing duration (p=0.492; with data of 0.40 s ± 0.03 and 0.40 s ± 0.03 respectively) (table 1).

Table 1: Comparison of the studied kinematic variables between the fastest (S1) and the slowest speed (S2) (NS: No significant, *p<0.05).

Variables	S1	S2	S1 vs S2
Cycle speed (m/s)	4.45 ± 0.35	3.34 ± 0.14	*
Temporal cycle variables			
Cycle frequency (Hz)	0.92 ± 0.07	0.90 ± 0.07	NS
Absolute propulsion duration (s)	0.16 ± 0.03	0.17 ± 0.02	NS
Absolute swing duration (s)	0.40 ± 0.03	0.40 ± 0.03	NS
Spatial cycle variables			
Cycle Length (m)	4.86 ± 0.36	3.75 ± 0.33	*
Propulsion Length (m)	0.70 ± 0.10	0.56 ± 0.07	*
Swing Length (m)	1.77 ± 0.16	1.30 ± 0.10	*
Angular variables			
Trunk angle at 1 (°)	37.1 ± 5.2	32.1 ± 4.22	*
Knee angle at 1 (°)	46.6 ± 3.9	53.5 ± 5.5	*
Trunk angle at 2 (°)	37.4 ± 4.3	36.5 ± 3.8	NS
Knee angle at 2 (°)	20.2 ± 4.3	18.8 ± 3.8	NS

When comparing spatial parameters, greater values were found in S1 than in S2 for cycle length (p=0.012, 4.86 m ± 0.36 and 3.75 m ± 0.33 respectively), propulsion length (p=0.012 with data of 0.70 ± 0.10 m and 0.56 ± 0.07 m respectively) and swing length (p=0.012 from 1.77 m ± 0.16 and 1.30 m ± 0.10 respectively) (table 1).
At the beginning of propulsion, trunk angle was significantly larger at S1 than at S2 (p=0.012; 37.1º ± 5.2 for S1 and 32.1º ± 4.22 for S2) while knee angle was statistically smaller for S1 (p=0.012; 46.6º ± 3.9 for S1 and 53.5º ± 5.5 for S2) (table 1). At the end of propulsion

(position 2, figure 1) no significant differences were found either in trunk angle or in knee angle between conditions S1 and S2 (table 1).

DISCUSSION: In accordance with previous observations in racing conditions (Norman et al., 1985; Bilodeau et al., 1996), skiers reduced the skiing speed during the simulated race. This indicated that the skiers were not able to sustain the same performance level during the whole simulated race, suggesting the appearance of fatigue (Bilodeau et al., 1996). The similar evolution of the skiing speed during the race for expert (Norman et al., 1985; Bilodeau et al., 1996) and regional level skiers (present study) would imply that a same racing strategy was adopted irrespective to the level of performance of the skiers. The strong correlation between lap speed and cycle speed during the whole race suggested that the slightly uphill studied portion was representative of the overall racing speed fluctuations.
The comparison between S1 and S2 showed that the decrease of skiing speed during the simulated race was associated with large deterioration of the spatial parameters while all temporal variables remained unchanged. This temporal constancy is different from previous studies where a change of speed was mostly associated with modifications in the cycle frequency, propulsion and swing durations (Gagnon, 1981; Nilsson et al., 2004). In these previous studies, skiers were tested at different speeds with long rest periods between the skiing repetitions avoiding fatigue situation. Consequently, their results were not transferable to a racing condition. The invariance in the cycle duration for different skiing speed has also been reported between athletes of different performance level during racing (Marino et al., 1980; Bilodeau et al., 1996). This suggests that the stable skiing tempo could be selected in order to minimise the energy expenditure as observed in other human gaits (Saibene and Minetti, 2003). The decrease of cycle and swing lengths suggested a decrease in force production since Norman et al. (1985) and Smith (1992) suggested that cycle and phase lengths were merely the consequence of the effectiveness of the thrust and/or the propulsive force.
In running, similar leg swing durations were observed between faster and slower runners during top speed running (Weyand et al., 2000). In addition the same authors reported that the greater running speed generated by the faster runner was obtained with larger ground reaction forces. In the present study the stable duration associated with the decrease of spatial cycle variables suggested lower forces production during the second part of the simulated race. A muscular fatigue may have occurred during the DST simulated race resulting in a limitation of the production of forces.
The diminution of the cycle spatial variables was associated with a decrease of the trunk angle (i.e. trunk extension) and an extension of the knee angle at the beginning of the leg propulsion. The technique adopted by the skiers at the beginning of the propulsion facilitate the generation of larger propulsion force by 1) tilting the trunk forward which increased the horizontal forces generated during the propulsion phase and 2) extending the knee prior propulsion to potentially place the foot head of the centre of mass and extend the time period during which force can be generated (Lees et al., 1993). The modification of trunk and knee angles during the simulated race suggested that this segmental organisation was technically and physically difficult to sustain and conducted to lower force production.

CONCLUSION: The results of the present study demonstrated that in simulated DST racing the decrease of speed was associated with a diminution of the cycle spatial variables and a modification of the trunk and knee angles at the beginning of propulsion. In contrast, the temporal variables of the cycle have not been affected. These results suggested that the skiers were not able to sustain a same level of forces produced.
Therefore, coaches should focus their attention on the skier’s ability to sustain an efficient skiing technique over the whole duration of a race, hence maintaining large cycle lengths.

REFERENCES:

Bilodeau, B., Rundell, K.W., Roy, B. and Boulay, M. (1996). Kinematics of cross-country ski racing. *Medicine and Science in Sports and Exercise,* **28**(1), 128-38.

Dillman, C. (1979). Biomechanical evaluation of cross-country skiing technique. *Journal of the United States Coaches Association,* **2**(4), 62-66.

Gagnon, M. (1980). Caracteristiques dynamiques du pas alternatif en ski de fond. *Journal Canadien des Sciences Appliquees au Sport*, **5**, 49-59.

Gagnon, M. (1981). A kinematic analysis of the alternate stride in cross-country skiing. In A. Morecki, K. Fidelus, K. Kedzior and A. Wit (eds), *Biomechanics VII-B* (pp. 483-487). Warsaw, Poland.: Polish Scientific Publishers.

Lees, A., Fowler, N., Derby, D. (1993). A biomechanical analysis of the last stride, touch-down and take-off characteristics of the women's long jump. *Journal of Sports Sciences,* **11**, 303-314.

Marino, W. G., Tetley, B., Gervais, P. (1980). A technique profile of the diagonal stride patterns of highly skilled female cross-country skiers. In C.H. Nadeau, W.R Holliwed, K.M. Newell and G.C. Roberts (eds.), *Psychology of Motor Behaviour and Sport* (pp. 615-621). Champaign, IL.: Human kinetics.

Nilsson, J., Tveit, P., Eikrehagen, O. (2004). Effects of speed on temporal patterns in classical style and freestyle cross-country skiing. *Sports Biomechanics,* **3**(1), 85-108.

Norman, R. W., Caldwell, G., Komi, P.V. (1985). Differences in body segment energy utilisation between world-class and recreational cross-country skiers. *International Journal of Sport Biomechanics*, **1**, 253-62.

Saibene, F., Minetti, A.E. (2003). Biomechanical and physiological aspects of legged locomotion in humans. *European journal of applied physiology,* **88**, 297-316.

Smith, G. A. (1992). Biomechanical analysis of cross-country skiing techniques. *Medicine and Science in Sports and Exercise,* **24**(9), 1015-22.

Weyand, P. G., Sternlight, D.B., Bellizzi, M.J., Wright, S. (2000). Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *Journal of applied Physiology*, **89**, 1991-1999.