

Kinematics of sprint cross-country skiing

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The purpose of our study was to characterise the diagonal stride locomotion during a new short sprint race in cross-country skiing. Thirty male cross-country skiers were sagittally filmed on an uphill portion of the 1.2-km classic race of the world cup (2004) using a digital camera. The main body joints, skis and poles were digitised frame by frame. Results indicated higher SV and SR for similar SL compared to longer distance races with a similar slope. Moreover, significant correlations were observed between SV and SR but not between SV and SL contrary to the other distance races. SL results showed that in spite of the high SR, skiers maintained an effective leg and pole thrusts. The high SR in KO sprint presented a mechanical advantage by minimising the decrease of velocity during the cycle. The importance of SR in the velocity production could be useful for practitioners to optimise the training program for this type of race. It seemed notable that the skiers had to improve temporal factors while conserving a long SL.

Key words: diagonal stride, KO sprint, kinematics, cross-country skiing

1. Introduction

The diagonal stride technique in cross-country skiing has been used for many years as a recreational pastime and competitive sport. For many years the official distance for individual races ranged from 5 to 50 km. During the last decade, new very short races (the KO sprints, <2 km) appeared in order to make cross-country skiing more entertaining. During KO sprint, each skier must run the qualification laps and the best 16 racers are qualified for the quarterfinal and so on. KO sprint presented short race duration (from 2 to 4 minutes) in comparison to classical long-distance races ranging from 20 minutes up to 3 hours.

Many studies investigated the biomechanics of the diagonal stride technique on long-distance races in regard to the race distance, the slope and the level of competitors (SOLIMAN [23], MARINO et al. [13], VIITASALO et al. [24], KOMI et al. [10], WASER [25], NORMAN et al. [18], KOMI and NORMAN [12], NORMAN et al. [20], BILODEAU et al. [3], MOGNONI [15]). Stride velocity (SV) corresponded to the product of the stride length (SL) and the stride rate (SR). Previous studies showed that as the length race increased, the stride velocity decreased being associated with an increase of SL and a decrease of SR (BERGH and FORSBERG [1]). On flat terrain, SL was greater during a 50 km race (BILODEAU et al. [3]) than during a 12 km race (KOMI and NORMAN [12]) or a 10 km race (MARINO et al. [13]) contrary to SR which was lower during a 50 km race (BILODEAU et al. [3]) than during a 12 km race (KOMI and NORMAN [12]). High significant correlation was found between SV and SL on flat or uphill portion for all distance races ranging from 10 to 50 km (SOLIMAN [23], MARINO et al. [13], NORMAN and KOMI [20], NORMAN et al. [20], BILODEAU et al. [3]). SL decreased and SR increased with the increase of the slope (BILODEAU et al. [2], [3]) when SV was significantly correlated with SR only on very important slope (12%) (NORMAN et al. [20], SOLIMAN [23], MARINO et al. [13], BILODEAU et al. [3]). Furthermore, slight uphill appeared to be the best terrain to discriminate subjects among different abilities (MARINO et al. [13], BERGH and FORSBERG [1]). All these studies have been realised between 1980 and 1996, and we could suppose that the evolution of the material and training methods during the last 10 years could be responsible for these results.

In regard to the lack of the studies on the new short race as the KO sprint, the purpose of this study was to characterise the diagonal stride locomotion during a cross-country KO sprint. In regard to previous results, where an increase of SR and a decrease of SL were observed with the decrease of the length race, we hypothesised that KO sprint locomotion was characterized by high SR and small SL .

2. Methods

2.1. Subjects

Thirty cross-country skiers were filmed during the 1.2 km classical race of the Viessmann world cup (2004). For this study, all subjects were analysed during their best laps.

2.2. Experimental procedure

Subjects were filmed, on the same track, at the end of the diagonal stride race (≈ 200 m before the end) on an uphill section (5%). The terrain was chosen in reference to previous studies showing that an uphill portion was able to discriminate subjects of different performance abilities (BERGH and FORSBERG [1]). Moreover, the last uphill portion was chosen in order to determine skier's performance just before the final sprint. Air and snow temperature at the start of the race were respectively -6.5 °C and -8 °C.

Subjects were filmed in the sagittal plane using a digital camera (Panasonic NV-GX7 EG, PAL., 25 Hz) fixed on a tripod 7.3 m perpendicularly to the ski tracks (figure 1). According to the Shannon theorem, the frequency of the camera was largely sufficient to study the stride which presented frequencies closed to 2 Hz (BILLODEAU et al. [2]). The optical axis of the camera was vertically fixed at 1 m over the ground. The shutter of the camera was set at $1/250^{\text{th}}$ s in regard to the velocity of the movement. The camera field was 6.80 meters to record more than a full stride according to stride lengths previously reported in the literature (DILLMAN et al. [5], GAGNON [7], BILODEAU et al. [2]). At the end of the test, a reference was filmed in the central portion of the track to be used in the digitising process. No markers were fixed on the different joints of the subjects because of the race condition.

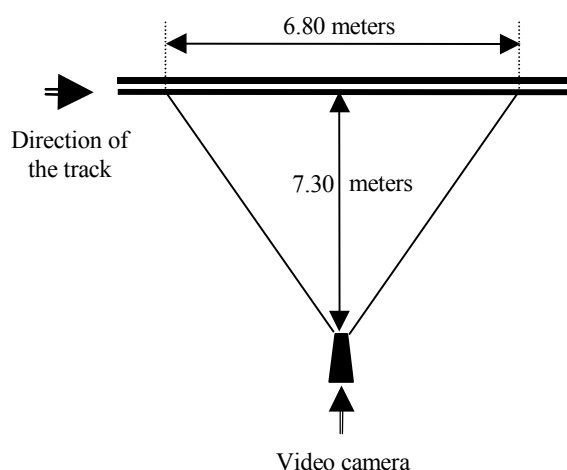


Fig. 1. Experimental set up

2.3. Data treatment

Video images were semi-manually digitised frame by frame and point by point between two consecutive plantings of poles. Twenty-five points were digitised (left

and right extremities of the skis, poles, fingers, wrists, elbows, shoulders, hips, knees, ankles, heels and toes and the top of the head (figure 2)) using Schleihau's software (kinematic analysis) validated by MONTEIL et al. [16]. In spite of this validation, the digitalisation process was tested for this study by comparing the result obtained by several digitalisations of a same subject. The average error obtained on the two axes was of $3.07 \pm 0.6\%$ indicating that the system was acceptable for in situ condition. From the 25 points, the position of the centre of gravity (CG) was calculated according to WINTER [26]. All kinematics coordinates were smoothed using a Butterworth Low-Pass filter with padded end-points and a cut of frequency of 4.5 Hz determined by a residual analysis of the difference between filtered and unfiltered signals over

a wide range of cut-off frequencies.

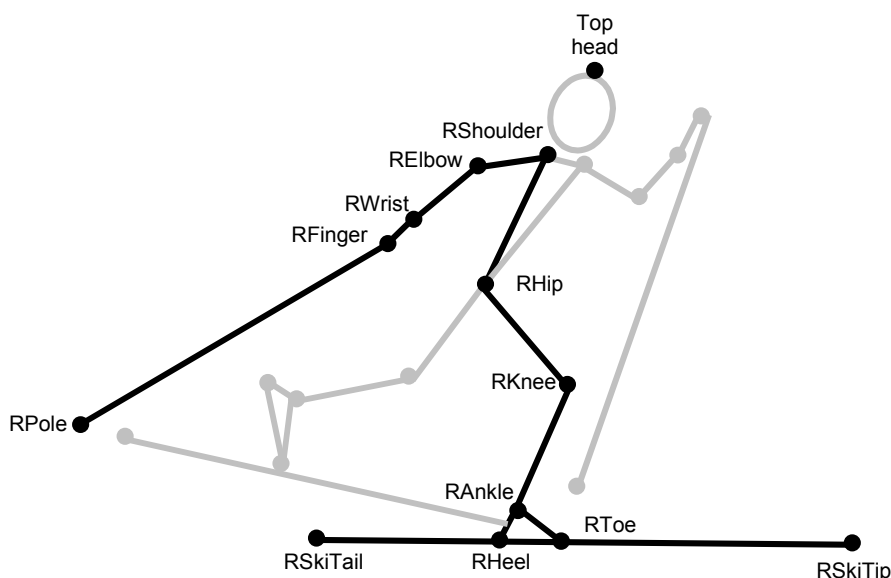


Fig. 2. Digitised points for the right and the left sides

2.4. Data analysis

Race velocity (RV) was calculated for each subject by dividing the race length (1.2 km) by the race time. According to ROY and BARBEAU [22], the beginning of the stride corresponded to the planting of right pole when the end of the stride corresponded to the planting of contralateral pole. Over the filmed portion, the stride length (SL), stride rate (SR) and stride velocity (SV) were calculated as follows:

$$SL = \sqrt{(x_{cg}e - x_{cg}b)^2 + (y_{cg}e - y_{cg}b)^2} \quad (\text{m}),$$

where: b – the beginning of the stride, e – the end of the stride, x – the horizontal co-ordinate of the CG, y – the vertical co-ordinate of the CG;

$$SR = (Te - Tb) \text{ (s)},$$

where: Te – the time of the end of the stride, Tb – the beginning of the stride; with $T = (n - 1) \times \frac{1}{25}$, where n is the number of frame between the beginning of the stride and the event;

$$SR = \frac{1}{SD} \text{ (Hz)};$$

$$SV = \frac{SL}{SD} \text{ (m}\cdot\text{s}^{-1}\text{)}.$$

2.5. Statistical analysis

Means, standard deviations and coefficient of variation ($CV = \text{standard deviation}/\text{mean}$) were calculated for each parameter. Correlation (Pearson) was calculated between SV and the different parameters in order to investigate the importance of each variable in the velocity production ($p < 0.05$).

3. Results

SV and RV were respectively $4.77 \pm 0.56 \text{ m}\cdot\text{s}^{-1}$ and $7.32 \pm 0.19 \text{ m}\cdot\text{s}^{-1}$ (table 1). The sample appeared heterogeneous at SV ($CV_{SV} = 11.7\%$) and more homogenous at RV ($CV_{RV} = 2.6\%$). SV was statistically correlated with RV ($r = 0.57$, $p = 0.001$) (table 2) showing that the fastest skiers in the portion studied were the fastest skiers in the race.

Table 1. Mean values and SD for SV , RV , SL and SR

Sprint parameters	KO sprint
$RV \text{ (m}\cdot\text{s}^{-1}\text{)}$	7.327 ± 0.191
$SV \text{ (m}\cdot\text{s}^{-1}\text{)}$	4.778 ± 0.561
$SL \text{ (m)}$	2.158 ± 0.195
$SR \text{ (Hz)}$	2.198 ± 0.278

Concerning the stride parameters, SR and SL were respectively 2.19 ± 0.27 Hz and 2.15 ± 0.19 m (table 1). For these two parameters, the sample appeared more dispersed at SR ($CV_{SR} = 12.6\%$, $CV_{SL} = 9.0\%$) than at SL .

Table 2. Correlations between SV and RV , SR and SL and their coefficients for the sample (**significant correlation $p < 0.01$; ***significant correlation $p < 0.001$)

Relationships tested	Correlation
SV / SR	0.645***
SV / RV	0.571**
SV / SL	0.199

SV was significantly correlated with SR ($r = 0.64$, $p = 0.000$, figure 3) but not with SL ($r = 0.19$, $p = 0.291$). Negative significant correlation was observed between SR and SL ($r = -0.51$, $p = 0.003$) (table 2).

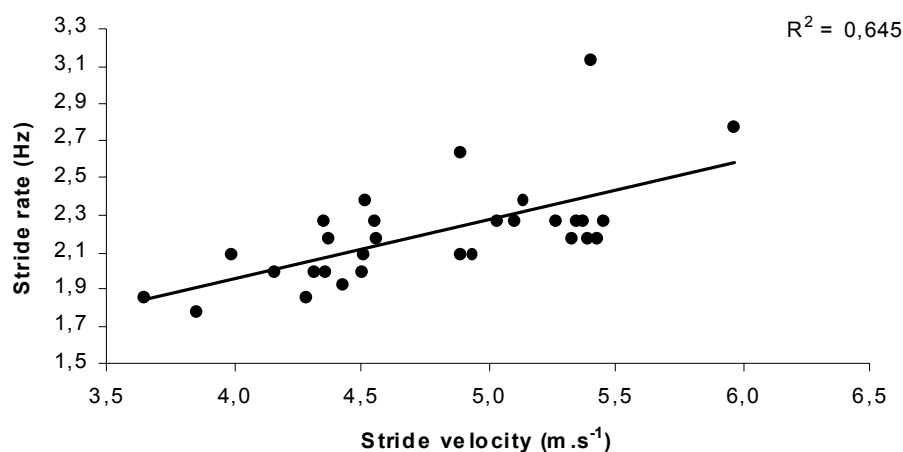


Fig. 3. Correlation between SV and SR for the population

4. Discussion

The purpose of this study was to characterise the diagonal stride locomotion during a cross-country KO sprint. In regard to previous results, where an increase of SR and a decrease of SL were observed with the decrease of the race length, we hypothesised that KO sprint locomotion was characterized by high SR and small SL . Our results showed important differences in stride parameters between KO sprint and others race distances.

RV and SV in KO sprint were higher than those reported in previous studies on longer distance races with world-class skiers (MARINO et al. [13] (10 km), KOMI et al. [10] (15 km), VIITASALO et al. [24] (85 km), NORMAN et al. [20] (15 km), NORMAN et al. [18] (30 km), BILODEAU et al. [3] (50 km)). As observed in long-distance races, SV was correlated with RV although the higher values were observed in both parameters. These results indicated that the fastest skiers in the race were the fastest skiers in the uphill portion. Results in KO sprint confirmed the results of previous studies on longer-distance races for which an uphill terrain discriminated subjects of different performance abilities (FROST et al. [6], BERGH and FORSBERG [1], BILODEAU et al. [2], [3]). The technique in cross-country skiing being partly specific to the slope, our results showed that as for the long-distance race a specific training in uphill portion had to be introduced in the technical preparation of a cross-country sprinter.

SR mean values observed in KO sprint were higher than the values obtained in longer-distance races on an equivalent slope (BILODEAU et al. [2]) and on flat terrain (KOMI et al. [10], 15 km, $SR = 1.64$ Hz; NORMAN et al. [18], 15 km, $SR = 1.66$ Hz; KOMI et al. [12], 12 km, $SR = 1.96$ Hz; BILODEAU et al. [2], 50 km, $SR = 1.62$ Hz). The higher SR measured in KO sprint confirms the increase of SR with the race length. As mentioned by HOFFMAN et al. [9], a high SR minimised the decrease of velocity during glide and recovery phases while reducing the duration of these two non-propulsive phases. A high SR presented thus a mechanical advantage while facilitating the velocity conservation. However, the mechanical advantage of the SR increase was associated with physiological disadvantage by increasing the metabolic cost as reported by MILLET et al. [14] in roller skiing and by CAVAGNA et al. [4] in walking. In KO sprint, the use of a high SR entailed a high energetic cost that did not seem to be a limiting factor in KO sprint, contrary to long-distance races because of the short duration of the race. Similar observations were mentioned in running. NOVACHEK [21] noted that in distance running, runners used a rate in relation to the energy demand of the race length except for short race like sprinting, in which runners used the higher frequency possible whatever the resultant energy cost.

In the case of SL , KO sprint mean values were similar to those observed on longer distance races on an equivalent slope (BILODEAU et al. [2]). Contrary to SR , the similar SL did not confirm the decrease of stride length with the decrease of the race length observed in previous studies. The leg and pole thrusts were mainly responsible for SL . The similar SL values observed in KO sprint suggested similar leg and poles thrusts even at the higher SR . This result was in accordance with previous results of roller skiing (MILLET et al. [14]) for which higher SR did not affect poling and leg propulsion forces.

Correlations observed in KO sprint were in opposition to those observed in long-distance races. The high SR was associated with important correlations between SV and SR , indicating that in KO sprint, SR appeared to be an important parameter in the velocity production contrary to other distance races (MARINO et al. [13], NORMAN and KOMI [19], BILODEAU et al. [2], [3]). Moreover, no correlation was observed between

SV and *SL* contrary to previous studies of longer-distance race (MARINO et al. [13], NORMAN and KOMI [19], BILODEAU et al. [2], [3]). In KO sprint, *SV* was thus related to *SR* but not to *SL* contrary to the other race distances. This confirmed that the velocity production in cross-country skiing was mainly determined by *SR* at high speeds and by *SL* at slow speed as observed in walking and running (HAY [8]). Indeed, the homogeneity of *SL* showed that at this level of competition in KO sprint, *SL* was not the determinant of the velocity production contrary to long-distance races. This phenomena could be explained by the fact that high velocity in cross-country race was developed only during short race, as the KO sprint, where the physiological disadvantage of a high *SR* was not a limiting factor of the velocity production.

Our results highlighted the importance of a high *SR* in the velocity production in KO sprint. These results showed that the KO sprint skiers to be more effective in a short-distance running had to be able to ski with an important *SR* without disturbed pole and leg thrust. Moreover, because a high *SR* increased the skier's energetic cost, the KO sprint training had to be focused on the increase of the energetic cost for a time of 3–4 minutes corresponding to the duration of a KO sprint. This was totally in opposition to the training for a long-distance race where skiers tried to reduce their energetic cost. From a mechanical viewpoint, the KO sprint training had to constrain a skier to maintain poles and leg thrust at higher and higher rate. Once again, this was in opposition to the training the long-distance race and confirmed the importance of a specific training.

5. Conclusion

The diagonal stride technique observed in KO sprint was different from the one used in the longer-distance races. The cross-country locomotion during a KO sprint was characterised by higher *SV* and *SR* associated with similar *SL* compared to the longer-distance races. This result associated with the significant correlation between *SV* and *SR* highlighted the importance of the frequency in the velocity production. These results confirmed the importance of a specific technical work. The training had to permit an improvement of the temporal factors while conserving a similar *SL*. A high *SR* is physiologically very expensive and skiers have to work out the ability to maintain a very high energetic cost for a short time.

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