DIFFERENT TECHNICAL STRATEGIES AND BIOMECHANICAL ASPECTS OF DOUBLE POLING IN ELITE CROSS-COUNTRY SKIING

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The purpose of this study was to analyse double poling (DP) regarding biomechanical performance determinants and different strategies. Eleven elite cross-country skiers performed DP at 85% of their maximal DP velocity ($V_{85\%}$) during roller skiing (treadmill; 1° inclination) while pole forces and selected joint angles were recorded. A 2D video evaluation categorised skiers into two different DP strategy groups. Strategy A group showed higher elbow ($p < 0.01$) and hip flexion angular velocities, smaller minimum elbow, knee and hip angles, higher peak pole force, shorter time to peak pole force and a longer relative recovery time ($p < 0.05$), variables to which $V_{85\%}$ was significantly correlated ($p < 0.05$). DP strategy A provides an effective model for technique and specific strength training while its physiological economy has to be further investigated.

KEY WORDS: kinetics, kinematics, classical skiing technique

INTRODUCTION: The importance of double poling (DP) as a main classical technique has increased in modern cross-country (XC) ski racing during the last two decades due to many factors (better material, snow preparation and training methods, etc.). The introductions of the skating technique in the 80´s and the sprint discipline during the last years have put more emphasis on upper body strength and endurance training, which led to physiological adaptations. Compared to physiological studies (Van Hall et al., 2003; Hoffman et al., 1998; etc.) only a few studies have focused on the biomechanical aspects of DP. Hoffman et al. (1995) showed that increases in submaximal intensities were associated with increases in cycle rate with unchanged cycle length. Smith et al. (1996) showed among other things that faster skiers began the poling phase with the poles in a more elevated position with respect to the trunk and angled closer to vertical compared to slower skiers. Millet et al. (1998) showed that increases in speed were achieved by increasing pole force and cycle rate accompanied by a shortening of both poling and recovery time in each DP cycle. No earlier study considered current developments in DP technique, often discussed by coaches and other experts, but still not investigated. The purpose of the present study was to perform a kinetic and kinematic analysis of the DP technique in XC skiing at racing speed in order 1) to test which biomechanical aspects contribute to DP performance and 2) to investigate the hypothesis, that multiple effective technical DP strategies exist.

METHODS:

Subjects: Eleven elite cross-country skiers (members of the Swedish U-23 and Junior National Team), (21 ± 1.8 yr (20-25); 179.1 ± 4.7 cm (171-185); 70.6 ± 8.0 kg (56-83)) volunteered as subjects. All subjects were familiar with roller skiing on a treadmill both as part of their training and in testing. They had a classical pole length of 151 ± 4 cm (143-155).
Data collection and data analysis: All data were collected by a complete measurement system (Biovision, Werheim, Germany) consisting of two input boxes with 16 channels connected to A/D converter cards (DAQ 700 A/D card -12 bit, National Instruments, USA) and two portable pocket PCs (Compaq iPAQ H3800) to store the kinetic and kinematic data for further off-line analysis. The processing of all data was managed by Ike-master (Ike-Software Solutions, Salzburg, Austria).
Pole forces: All subjects used carbon-fiber racing poles. The right hand pole, specially constructed for force measurements and adjustable in length from 140 cm to 165 cm, enabled the athletes to adjust the pole to their preferred individual length (84% ± 0.5% of body height). The ground reaction force, directed along the pole was measured at 2000 Hz by a strain gauge force transducer (Hottinger–Baldwin Messtechnik GmbH, Darmstadt,

Germany) weighing 60 g and installed in a light weight (75 g) aluminium body, and both mounted directly below the pole grip. Absolute and relative peak pole force (PPF_{abs} and PPF_{rel}), time to peak pole force (TPPF) and absolute and relative impulse of pole force (IPF_{abs} and IPF_{rel}) were determined. All relative values were expressed in % of body weight (BW). Poling phase (PP) was defined as pole ground contact phase and was determined from the pole force data.

Kinematics: Joint angles of interest (elbow, hip, knee, ankle) were measured by goniometers (potentiometers: Megatron, Munich, Germany; strain gauges: Penny & Giles Controls Ltd, Cmwfelinfach, UK) at 2000 Hz. A 2D video analysis (50 Hz) was performed to document the DP movement patterns (serial pictures) and to categorize the skiers into different DP strategy groups. For each skier, three trained researchers and three international FIS World Cup XC skiing coaches independently and randomly visually evaluated the videos with special focus on shoulder and elbow movement patterns. Statistics were used to calculate group differences concerning measured biomechanical variables (see statistics). Cycle time (CT), absolute poling time and poling time relative to CT (PT_{abs} and PT_{rel}) and absolute and relative recovery time (RT_{abs} and RT_{rel}) (RT = CT - PT) were determined for each DP cycle.

Statistics: To check for statistical differences between the two groups of different DP strategies (video evaluation) regarding biomechanical variables a Mann-Whitney-U-Test was applied. Pair-wise comparisons using Pearson's product-moment correlation coefficient tests were performed for all variables. Statistical significance was set at $p < 0.05$ for all analyses.

Overall design and protocols: All measurements were performed on a motor-driven treadmill (Rodby, Sodertalje, Sweden) specially designed for roller-ski tests at 85% of the individually measured maximum DP velocity ($V_{85\%}$) (6.8 ± 0.4 $m \cdot s^{-1}$). The inclination of the treadmill was 1° and the speed was. To exclude variations in rolling resistance, all subjects used the same pair of roller skis (Pro-Ski C2, Sterners, Nyhammar, Sweden). Prior to all treadmill tests the subjects were secured with a safety harness suspended from the ceiling. The treadmill was chosen in order to achieve standardized measurement conditions over the time of the experiment, compared to measurements in the field (summer or winter).

RESULTS: The $V_{85\%}$ was correlated to absolute peak pole force (PPF_{abs}) (r = 0.70), relative peak pole force PPF_{rel} (r = 0.66), elbow flexion angular velocity during PP ($AV_{E\ flex\ PP}$) (r=0.80), minimum knee angle during PP ($KA_{min\ PP}$) (r = -0.72) (all $p < 0.05$) and minimum elbow angle during PP ($EA_{min\ PP}$) (r = -0.88, $p < 0.01$). PPF_{rel} correlated to $EA_{min\ PP}$ (r = -0.71), relative poling time (PT_{rel}) (r = -0.72), relative recovery time (RT_{rel}) (r = 0.72), extension time in the elbow joint during PP (ET_E) (r = -0.79) (all $p < 0.05$) and hip angle at the start of PP ($HA_{start\ PP}$) (r = -0.89, $p < 0.01$). The experts' 2D video evaluation showed that four of the 11 skiers made up a group where the DP pattern was clearly characterized by (1) more abducted shoulder joints, (2) smaller elbow angles at pole plant, (3) faster and (4) more distinctly flexed elbow joints and (5) faster and (6) more distinctly flexed hip joints during an (7) altogether more dynamic PP. This pattern was as DP strategy A. Four other skiers were clearly grouped with an opposite pattern relative to these seven characteristics (strategy B). An additional two skiers were judged as closer to DP strategy A (except character 2) and one skier rather performed strategy B (except character 1). The six DP strategy A skiers, including the fastest, showed different pole force characteristics with higher PPF_{rel}, shorter TPPF and higher IPF_{rel} (all $p < 0.05$) compared to the five DP strategy B skiers (Table 1). Furthermore, PT_{rel} was shorter and RT_{rel} was longer (both $p < 0.05$). Regarding the elbow joint, skiers using DP strategy A showed a smaller elbow angle at the start of PP ($EA_{start\ PP}$), a smaller $EA_{min\ PP}$, a higher $AV_{E\ flex\ PP}$ (all $p < 0.01$) and a higher amplitude of elbow extension during PP ($AMPL_{E\ ext\ PP}$) ($p < 0.05$) compared to the strategy B group. In addition, their knee and hip movement pattern was characterized by a smaller $KA_{min\ PP}$, smaller $HA_{start\ PP}$, smaller minimum hip angle during PP ($HA_{min\ PP}$) (all $p < 0.05$) and a higher hip flexion angular velocity during PP ($AV_{H\ flex\ PP}$) ($p < 0.01$).

Table 1 Significant differences in kinetic and kinematic variables between DP strategy A group (n = 6) and DP strategy B group (n = 5). Values are mean ± SD.

Variables	DP Strategy A (*n* = 6)	DP Strategy B (*n* = 5)	p
PPF_{rel} [% BW]	36±7	27±4	< 0.05
TPPF [s]	0.08±0.01	0.11±0.02	< 0.05
IPF_{rel} [%BW·s]	5.3±0.4	4.7±0.4	< 0.05
PT_{rel} [% cycle]	24±3	28±2	< 0.05
RT_{rel} [% cycle]	76±3	72±2	< 0.05
$EA_{start\ PP}$ [°]	89±5	112±11	< 0.01
$EA_{min\ PP}$ [°]	55±9	86±17	< 0.01
$AV_{E\ flex\ PP}$ [°·s^{-1}]	485±131	233±92	< 0.01
$AMPL_{E\ ext\ PP}$ [°]	102±8	76±9	< 0.05
$KA_{min\ PP}$ [°]	129±7	152±11	< 0.05
$HA_{start\ PP}$ [°]	127±9	148±7	< 0.05
$HA_{min\ PP}$ [°]	92±14	111±14	< 0.05
$AV_{H\ flex\ PP}$ [°·s^{-1}]	291±77	195±27	< 0.05

DISCUSSION: The importance of a short TPPF in DP has already been proposed by Hoff et al. (1999) showing a positive relationship between a shortened TPPF and an improved work economy. In the present study, we found no correlation between TPPF and $V_{85\%}$. Even though there may be variations between skiers at submaximal workloads, it is likely that TPPF is more important to DP performance at high skiing velocities where the ability to produce force may become a limiting factor due to the inverse relationship between contraction velocity and force. There was a positive correlation of PPF_{rel} to $V_{85\%}$, which shows the importance of generating a high PPF_{rel} to achieve high velocities in DP. Of note is that skiers using strategy A showed a shorter TPPF at $V_{85\%}$, a higher PPF_{rel} and higher IPF_{rel} (Table 1), characterizing their specific DP technique. Although their PT_{rel} was shorter, IPF_{rel} reached higher values, most likely explained by a more rapid force development up to higher PPF_{rel}. It can be assumed that an active joint flexion (from high starting position) functionally would add external load to the poles. This is supported by the fact that PPF_{rel} correlated to a smaller hip angle at the start of PP, reflecting an early active flexion by the trunk and hip flexors. Furthermore, PPF_{rel} correlated negatively to minimum elbow angle, elbow extension time during PP and relative poling time and correlated positively to relative recovery time. Altogether, this indicates a shorter and thus more explosive PP. The strategy A skiers showed a higher PPF_{rel} and differences to strategy B skiers in all variables that correlated to PPF_{rel}, except for the elbow extension time during PP (Table 1). The more accentuated, faster lowering of the center of gravity in these skiers is supported by their smaller minimum hip and knee angle and a higher hip and elbow flexion angular velocity during PP. We suggest that smaller minimum elbow, hip and knee angles together with a higher hip and elbow flexion angular velocity during PP provide two advantages: First, a higher resultant push-off force (longer force vector) during the first half of PP will lead to a higher horizontal force component (forward propulsion). Second, a higher pole ground reaction force can create a higher pre-load of the extensor muscles during the flexion phase of the stretch-shortening cycle. Skiers using strategy A, which included the best skiers, all showed smaller elbow angles at pole plant (89 ± 5° vs. 112 ± 11°), smaller minimum elbow angles resulting in larger flexion amplitudes (34° vs. 26°) and higher elbow flexion angular velocities (485 °·s^{-1} vs. 233 °·s^{-1}), compared to the skiers using strategy B (Table 1), that showed elbow movement patterns rather like the skiers in the study by Smith et al. (1996). The high correlation between DP velocity ($V_{85\%}$) and angular velocity during the initial elbow joint flexion also confirms the importance of a fast elbow flexion for a high DP performance. It can be assumed that the flexion of the elbow joint may be a critical factor regarding the transfer of force to the ground. This was in part, confirmed by the negative correlation between PPF_{rel} and the minimum elbow angle, both occurring around the same point of time, while PPF_{rel} itself correlated to DP velocity (DP performance).

CONCLUSION: In conclusion, the present study shows that the DP technique in competitive XC skiers is a complex movement and that it shows different DP strategies. Pole force variables are directly related to DP velocity and are influenced by a characteristic flexion-extension pattern in the elbow, hip, and knee joint. The best skiers' DP strategy A with the described specific pole force and joint movement characteristics first of all provides a useful DP model for technique training but also demands for a specification of upper and lower body strength training and testing (development and choice of devices, exercises, strength training contents [explosive and maximum strength]). Future research on DP should further investigate specific biomechanical aspects of the found different DP strategies and its relationship to physiological variables in order to further develop DP performance.

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