# Biomechanical Analysis of Double Poling in Elite Cross-Country Skiers

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*[1]Department of Physiology & Pharmacology, Karolinska Institute, Stockholm, SWEDEN; [2]Åstrand Laboratory, Stockholm University College of Physical Education and Sports, Stockholm, SWEDEN; [3]Department of Sport Science and Kinesiology, University of Salzburg, AUSTRIA; and [4]Christian Doppler Laboratory "Biomechanics in Skiing," Salzburg, AUSTRIA*

**ABSTRACT**

HOLMBERG, H.-C., S. LINDINGER, T. STÖGGL, E. EITZLMAIR, and E. MÜLLER. Biomechanical Analysis of Double Poling in Elite Cross-Country Skiers. *Med. Sci. Sports Exerc.*, Vol. 37, No. 5, pp. 807–818, 2005. **Purpose:** To further the understanding of double poling (DP) through biomechanical analysis of upper and lower body movements during DP in cross-country (XC) skiing at racing speed. **Methods:** Eleven elite XC skiers performed DP at 85% of their maximal DP velocity ($V_{85\%}$) during roller skiing at 1° inclination on a treadmill. Pole and plantar ground reaction forces, joint angles (elbow, hip, knee, and ankle), cycle characteristics, and electromyography (EMG) of upper and lower body muscles were analyzed. **Results:** 1) Pole force pattern with initial impact force peak and the following active force peak (PPF) correlated to $V_{85\%,}$ (r = 0.66, $P < 0.05$); 2) active flexion–extension pattern in elbow, hip, knee, and ankle joints with angle minima occurring around PPF, correlated to hip angle at pole plant (r = −0.89, $P < 0.01$), minimum elbow angle (r = −0.71), and relative poling time (r = −0.72, $P < 0.05$); 3) two different DP strategies (A and B), where strategy A (best skiers) was characterized by higher angular elbow- and hip-flexion velocities, smaller minimum elbow ($P < 0.01$) and hip angles ($P < 0.05$), and higher PPF ($P < 0.05$); 4) EMG activity in trunk and hip flexors, shoulder, and elbow extensors, and several lower body muscles followed a specific sequential pattern with changing activation levels; and 5) EMG activity in lower body muscles showed DP requires more than upper body work. **Conclusions:** DP was found to be a complex movement involving both the upper and lower body showing different strategies concerning several biomechanical aspects. Future research should further investigate the relationship between biomechanical and physiological variables and elaborate training models to improve DP performance. **Key Words:** EMG, FORCE, KINEMATICS, SKIING, TECHNIQUE

The importance of double poling (DP) as a main classical technique has increased in modern cross-country ski racing during the last two decades (23). Several factors have contributed to this development. Better track preparation and markedly improved functional characteristics of the skies and poles has increased the fractional use of DP during a race, and it has also been shown to be more economical, especially in the flatter part of the course (7). Moreover, the introductions of the skating technique in the 1980s and the sprint discipline during the last years have put more emphasis on upper body strength and endurance training. The consequence of this training has lead to physiological adaptations, which are also of importance in DP. Several studies have been performed to investigate physiological aspects of the DP technique (2,5,6,8,10–14,17–20,22,26,27,29,30).

In comparison, few studies have described and explained the DP technique in detail from a biomechanical perspective (9,15,16,25). Hoffman et al. (9) showed that increases in submaximal intensities were associated with increases in cycle rate with unchanged cycle length. Smith et al. (25) demonstrated that faster skiers showed a greater range of elbow motion with initial flexion immediately followed by extension, with higher angular velocities. They also showed 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. (15,16) extended this by investigating the effects of speed and inclination on kinetic and kinematic aspects of DP, and provided important information of the magnitude of pole force. They 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. Furthermore, they found inclination to have a significant effect on poling forces and time-related variables, that is, an unchanged poling phase duration and shortened recovery phase duration on steeper inclinations. No earlier study has used EMG to study DP.

Recently, it was found in a study on energy expenditure in cross-country skiing that the blood flow to the legs and

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corresponding oxygen uptake was larger in the lower compared with the upper body during DP (27). Although it has been shown earlier that the upper body plays a major role in DP, an optimal force transfer to the ground via the poles might not only be attained by the arm, shoulder, and the trunk muscles, but also by the active movement of the legs. There is a possibility that coactivation during flexion and extension of the hip, knee, and ankle joints, besides acting as a stabilization function, positions and repositions the body during each DP cycle. This may enable the skier to use body mass and gravity to increase PF. Therefore, to attain a deeper understanding of the biomechanics in DP, there is a need to analyze both the upper and lower body with a special focus on the interaction between these segments of the body during DP.

The specific aim of the present study was to perform a complex biomechanical analysis of the DP technique in cross-country skiing at racing speed in order to basically analyze complex mechanisms of DP and to advance hypotheses, which aspects contribute, to DP performance. This study expands upon previous work by including both upper and lower body, by using a combination of kinetic, kinematic, and electromyography measurement methods, and is performed on elite male cross-country skiers.

## 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), and 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). Their mean $\dot{V}O_{2max}$ was 72.3 ± 3.8 $mL \cdot kg^{-1} \cdot min^{-1}$ (65–80), measured during diagonal skiing on a treadmill using an ergospirometry system (AMIS 2001, Innovision A/S, Odense, Denmark) to characterize the subjects. All the skiers were fully acquainted with the nature of the study before they gave their written informed consent to participate. The research techniques and experimental protocol were approved by the ethics committee of Umeå University, Umeå, Sweden (no. 03-080).

### Measurements

**DP cycle definitions.** One DP cycle was defined as the period from the start of the pole ground contact to the start of the subsequent pole ground contact. Each DP cycle (C) was divided into a poling phase (PP) and a recovery phase (RP). All data were averaged over five cycles for each subject.

**Kinetics: pole and plantar forces.** All subjects used carbon-fiber racing poles. The right-hand pole, specially constructed for force measurements and adjustable in length from 140 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 lightweight (75 g) aluminum body, and both mounted directly below the pole grip. The pole force transducer was calibrated using a specific calibration apparatus with 10 different standard weights (5–50 kg). A validation of pole force was then performed by 30 DP imitations on an AMTI force plate (2000 Hz) (AMTI, Watertown, MA). The mean absolute error over the entire PP was 3.8%. This is equivalent to maximum mean PF deviations of −8% (−20 N) occurring around the force maxima, and 10% (26 N) in the last third of PP. 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 percentage of body weight (BW).

Vertical plantar ground reaction forces were recorded by the Pedar mobile system (Novel GmbH, Munich, Germany) (100 Hz), consisting of two pressure distribution insoles (99 capacitive sensors each), a data logger with a flash card (8 MB), and cable sets. The total foot area was divided into forefoot (FF) and rearfoot (RF) at 50% of foot length. The calibration of the insoles was performed using the Pedar calibration device. This allowed all sensors of the insoles to be calibrated with homogenous air pressure in a simple, computer-aided procedure. Validation of the insole plantar forces was performed by 30 DP imitations on an AMTI force plate, and the mean absolute error over the time course was 2.6%, whereby the insole plantar forces were below the AMTI forces throughout all DP cycles with a maximum of 6% (25 N). Relative impulses of plantar force (IF) were determined for FF and RF during the total cycle of DP ($IF_{FF\_C\ rel}$, $IF_{RF\_C\ rel}$), during PP ($IF_{FF\_PP\ rel}$, $IF_{RF\_PP\ rel}$), and during RP ($IF_{FF\_RP\ rel}$, $IF_{RF\_RP\ rel}$).

**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. Calibration measurements were performed five times at 90°, 180° (elbow, hip, and knee joint), and 110° (ankle joint), and angle values were calculated from the corresponding mean voltage data. 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. One camera was placed to film in the sagittal plane, and one was placed in the frontal plane. For each skier, three trained researchers (author group) and three international (FIS World Cup) experienced cross-country skiing coaches (external group) independently, and randomly visually evaluated the videos with special focus on shoulder and elbow movement patterns. The task of the evaluators was to create written descriptors of identifiable characteristics that differed between some skiers because of different DP strategy. The concordant descriptors of the six experts were used as criteria for classification into different DP strategy groups. Statistics were then 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. Poling frequency (Pf) was calculated from the pole force data.

**EMG measurements.** EMG activity was measured at a sampling frequency of 2000 Hz. The raw analog signals were converted to digital (DAQ 700 A/D card–12 bit, National Instruments, U.S.) and stored on two pocket PCs (measurement voltage range ± 5 V). The EMG signal was hardware band-passed (10–500 Hz at 3 dB) to remove noise at low and high frequencies. The input impedance was 10 GOhm and the common mode rejection ratio was 120 dB. The electrodes, pregelled bipolar Ag/AgCl surface electrodes (circle shaped, 18-mm-diameter gel area, 10-mm-diameter iron contact area) with an interelectrode spacing of 30 mm (Skintact, Leonhard Lang GmbH, Innsbruck, Austria), were connected to single differential amplifiers (amplification up to 5000). The electrodes were positioned parallel to the fiber direction on the surface of the muscle belly according to international standards (4), and were placed on the pectoralis major (PMa), latissimus dorsi (LD), teres major (TMa), rectus abdominis (RA), obliquus externus abdominis (OBLe), erector spinae (ES-L4), triceps brachii (caput longum) (TRI), biceps brachii (BIC), flexor carpi ulnaris (FCU), gluteus maximus (GMa), tensor fasciae latae (TFL), rectus femoris (RF), vastus medialis (VM), vastus lateralis (VL), biceps femoris (caput longum) (BF), gastrocnemius (caput laterale) (GAS), soleus (SOL), tibialis anterior (TA), and peroneus longus (PL). Reference electrodes were attached to the patella and sternum. Before electrode fixation, the skin surface was shaved, lightly abraded, degreased, and disinfected by alcohol.

**EMG preprocessing and MVC amplitude normalization.** Before all calculations of EMG variables, the raw EMG signals were preprocessed and MVC normalized as follows: the trial EMG raw data were first digitally band-pass filtered (10–300 Hz; Butterworth second order) to more fully remove low- and high-frequency noise that was not completely suppressed by the analog band-pass filter (28). The cutoff frequency of the filter was based on visual inspection using fast Fourier transformation. The data were then full-wave rectified before any further processing. For amplitude normalization of the EMG signals, maximum voluntary isometric contraction (MVC) exercises were performed for each muscle, which were trained properly with all subjects in advance (1). Preceding the training process and the actual MVC measurements, several MVC exercises using different positions were tried for each muscle in order to select exercises creating the highest EMG activity. Each MVC lasted between 2 and 3 s and was performed three times, with a 30-s rest between each trial, by each subject. MVC raw data from the best of three trials were then preprocessed in the same way as the trial data (band-pass filter, full-wave rectification). Afterward, the mean values of stepwise (value for value) moving windows (250 ms) were calculated over the entire period of each MVC. The highest determined mean of all moving windows of 250 ms, applied to the MVC data for each muscle, was taken as the reference value (100%) for amplitude normalization of the corresponding trial EMG data.

**EMG amplitude quantification.** EMG amplitude quantification for each muscle was performed by the calculation of the integrated EMG (IEMG) to characterize the tension development of the muscle and the $EMG_{peak}$ in order to highlight and compare the different intensities of activation of different muscles. IEMG was calculated from the preprocessed and MVC-normalized trial EMG data over the periods of PP, RP, and C, and expressed in units ($\%MVC \cdot s^{-1}$). For an estimation and comparison of the maximal relative intensity of activation of different muscles in DP, an $EMG_{peak}$ value, normalized to MVC (%MVC), was determined. Therefore, the preprocessed and MVC-normalized trial EMG data were 50-Hz low-pass filtered to create a linear envelope, allowing a clearer determination of peak values according to real peak EMG activation and excluding short-term EMG spikes. The maximum value of the filtered curve in PP, RP, and C was defined as $EMG_{peak}$ for each muscle and for the corresponding phase. IEMG and $EMG_{peak}$ values of each muscle were categorized into low, medium, and high using z-standardization (Table 1). For both variables, the low category was set for z-values less than −0.5, medium category for z-values between −0.5 and +0.5, and high category for z-values greater than +0.5.

**Muscle sequencing and activation levels.** To analyze the coordination patterns (muscle sequencing) in DP, the onset and offset of muscle activity were determined. Threshold for onset and offset was defined as the level +2SD above the mean base signal at rest (3), which was measured in a relaxed supine position for 30 s. To identify when a muscle switched on, a minimal switch-on time of 20 ms above the defined threshold had to be exceeded (3). During switch-on of each muscle, sections of characteristic activation development such as massive activation increases, decreases, or plateaus could be observed in the preprocessed, MVC-normalized EMG curves. To mark off those sections, the following method was developed: 1) low-pass filtering of the preprocessed and MVC-normalized

TABLE 1. $EMG_{peak}$, $EMG_{rms}$, and IEMG categories calculated by z-standardization. Mean ($\bar{x}$) and standard deviation (SD) for $EMG_{peak}$ and IEMG, respectively, were calculated over the values of all muscles of all subjects for the double poling cycle. $\bar{x}$ and SD for $EMG_{rms}$ were calculated over the defined sections.

| Variables | EMG Level Categorization Level | | |
|---|---|---|---|
| | Low | Medium | High |
| z-values | $z<\bar{x}-0.5SD$ | $\bar{x}-0.5SD \leq z \leq \bar{x}+0.5SD$ | $\bar{x}+0.5SD<z$ |
| $EMG_{peak}$ | <70%MVC | 70–150%MVC | >150%MVC |
| $EMG_{rms}$ | <18%MVC | 18–57%MVC | >57%MVC |
| IEMG | <13 units ($\%MVC \cdot s^{-1}$) | 13–24 units ($\%MVC \cdot s^{-1}$) | >24 units ($\%MVC \cdot s^{-1}$) |

EMG signals to create a smooth linear envelope (28) with still identifiable local minima and inflection points, respectively (12-Hz low-pass filter); and 2) local minima and inflection points were calculated by IKE-master software (IKE-Software Solutions, Salzburg, Austria) on the basis of mathematical standards, and were used as markers for start and end points of periods of distinctly different EMG activation intensity occurring during the switch-on phase of each muscle. In another step, $EMG_{rms}$ was calculated over the periods of the defined sections, and each $EMG_{rms}$ value was categorized into low, medium, and high using z-standardization (Table 1) with the same category settings as used for IEMG and $EMG_{peak}$ (low = z-values less than $-0.5$; medium = z-values between $-0.5$ and $+0.5$; high = z-values greater than $+0.5$). This method allowed an estimation of the change in the intensity of EMG activity during switch-on of each muscle illustrated in the muscle sequencing charts (Fig. 3, A and B).

**Data collection and data analysis.** All data except plantar forces 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) and two portable pocket PCs (Compaq iPAQ H3800) to store the EMG, kinetic, and kinematic data for further offline analysis. The synchronization between the two data loggers, the cameras, and the separate Pedar mobile system (plantar forces) was managed by a flashlight and a synchronization signal sent to one channel of each data logger, produced by the start of the Pedar mobile system. The processing of all data was managed by IKE-master (IKE-Software Solutions).

**Overall design and protocols.** All tests were performed during a 10-d period on a motor-driven treadmill (Rodby, Sodertalje, Sweden) specially designed for roller-ski tests. To exclude variations in rolling resistance, all subjects used the same pair of roller skis (Pro-Ski C2, Sterners, Nyhammar, Sweden). Before 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 with measurements in the field. An inclination of 1° was chosen for two reasons: 1) DP technique at racing speed is predominantly used on flat terrain, and 2) to compensate for the lack of air resistance while performing on the treadmill in the lab. The inclination is similar to earlier physiological studies investigating the DP technique indoors (12,17). First, a DP incremental test was performed to determine maximal DP velocity ($V_{max}$) during roller skiing on the treadmill with a constant inclination of 1°. The incremental test started at 9 $km \cdot h^{-1}$, increasing 3 $km \cdot h^{-1}$ every 4-min work period, with 1 min of rest between, until voluntary exhaustion. $V_{max}$ was calculated using the formula $V_{max} = V_f + ((t/240) \cdot 3\ km \cdot h^{-1})$, where $V_f$ was the velocity of the last completed workload ($km \cdot h^{-1}$), t the duration of the last workload (s), and 3 $km \cdot h^{-1}$ the velocity difference ($\Delta V$) between the last two workloads. Second, kinetic, kinematic, and EMG analysis of DP were performed at 85% of the individually calculated $V_{max}$ ($V_{85\%}$), which was 6.8 ± 0.4 $m \cdot s^{-1}$ (6.2–7.3) comparable to the velocity in a fast 10-km classic race. Relative velocity was chosen for the sake of similar relative exercise intensity for interindividual comparison, equalizing the situation for all skiers.

TABLE 2. Cycle, pole force, and plantar force characteristics of double poling at 85% of $V_{max}$ ($N = 11$); values are mean ± SD.

| | Variables[a] | Mean ± SD |
|---|---|---|
| Cycle | CT (s) | 1.13 ± 0.09 |
| | $PT_{abs}$ (s) | 0.30 ± 0.03 |
| | $PT_{rel}$ (% cycle) | 26.9 ± 2.9 |
| | $RT_{abs}$ (s) | 0.83 ± 0.09 |
| | $RT_{rel}$ (% C) | 73.1 ± 2.9 |
| | Pf (Hz) | 0.89 ± 0.07 |
| Pole force | $PPF_{abs}$ (N) | 235.1 ± 62.6 |
| | $PPF_{rel}$ (% BW) | 32.1 ± 7.5 |
| | TPPF (s) | 0.10 ± 0.02 |
| | $IPF_{abs}$ ($N \cdot s^{-1}$) | 36.4 ± 5.9 |
| | $IPF_{rel}$ ($\%BW \cdot s^{-1}$) | 4.9 ± 0.5 |
| Plantar force | $IF_{FF\_C\ rel}$ ($\%BW \cdot s^{-1}$) | 16.6 ± 6.9 |
| | $IF_{RF\_C\ rel}$ ($\%BW \cdot s^{-1}$) | 26.7 ± 7.3 |
| | $IF_{FF\_PP\ rel}$ ($\%BW \cdot s^{-1}$) | 5.8 ± 2.7 |
| | $IF_{RF\_PP\ rel}$ ($\%BW \cdot s^{-1}$) | 9.5 ± 1.9 |
| | $IF_{FF\_RP\ rel}$ ($\%BW \cdot s^{-1}$) | 10.9 ± 5.9 |
| | $IF_{RF\_RP\ rel}$ ($\%BW \cdot s^{-1}$) | 17.2 ± 5.9 |

[a] CT (s), cycle time; $PT_{abs}$ (s), absolute poling time; $PT_{rel}$ (% cycle), relative poling time; $RT_{abs}$ (s), absolute recovery time; $RT_{rel}$ (% cycle), relative recovery time; $P_f$ (Hz), poling frequency; $PPF_{abs}$ (N), absolute peak pole force; $PPF_{rel}$ (% BW), relative peak pole force; TPPF (s), time to peak pole force; $IPF_{abs}$ (Ns), absolute impulse of pole force; $IPF_{rel}$ (% $BW \cdot s^{-1}$), relative impulse of pole force; $IF_{FF\_C\ rel}$ (% $BW \cdot s^{-1}$), relative impulse of forefoot force during cycle; $IF_{RF\_C\ rel}$ (% $BW \cdot s^{-1}$), relative impulse of rearfoot force during cycle; $IF_{FF\_PP\ rel}$ (% $BW \cdot s^{-1}$), relative impulse of forefoot force during poling phase; $IF_{RF\_PP\ rel}$ (% $BW \cdot s^{-1}$), relative impulse of rearfoot force during poling phase; $IF_{FF\_RP\ rel}$ (% $BW \cdot s^{-1}$), relative impulse of forefoot force during recovery phase; $IF_{RF\_RP\ rel}$ (% $BW \cdot s^{-1}$), relative impulse of rearfoot force during recovery phase.

**Statistics.** All data were checked for normality and presented as means ($\bar{x}$), ranges ($x_{min} - x_{max}$), and standard deviations (±SD), calculated with conventional procedures. 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. Pairwise comparisons using Pearson's product–moment correlation coefficient tests were performed for all EMG, kinematic, and kinetic variables. Statistical significance was set at $P < 0.05$ for all analyses. All statistical tests were processed using SPSS 11.0 Software (SPSS Inc., Chicago, IL) and Office Excel 2003 (Microsoft Corporation, U.S.).

## RESULTS

**DP cycle characteristics.** Kinetic and kinematic variables are shown in Table 2 and Figure 1, A–F. CT was 1.13 ± 0.09 s (1.01–1.30). PT was 0.30 ± 0.03 s (0.25–0.34), corresponding to 26.9 ± 2.9% (22.1–30.1) of CT. RT was 0.83 ± 0.09 s (0.72–1.01), 2.8 times longer than PT. Pf was 0.89 ± 0.07 Hz (0.77–0.99), corresponding to 53 cycles per minute (46–59).

**Pole force.** The basic characteristic of the pole force curve for the entire group (Fig. 1A and Table 2) showed a distinct impact force at the beginning of pole ground contact, followed by a high rate of force development up to PPF, occurring after 0.10 ± 0.02 s (0.07–0.13). This corresponded to 31.9% (24–40) of PP, around the point of time when the minimum elbow angle occurred. The last two

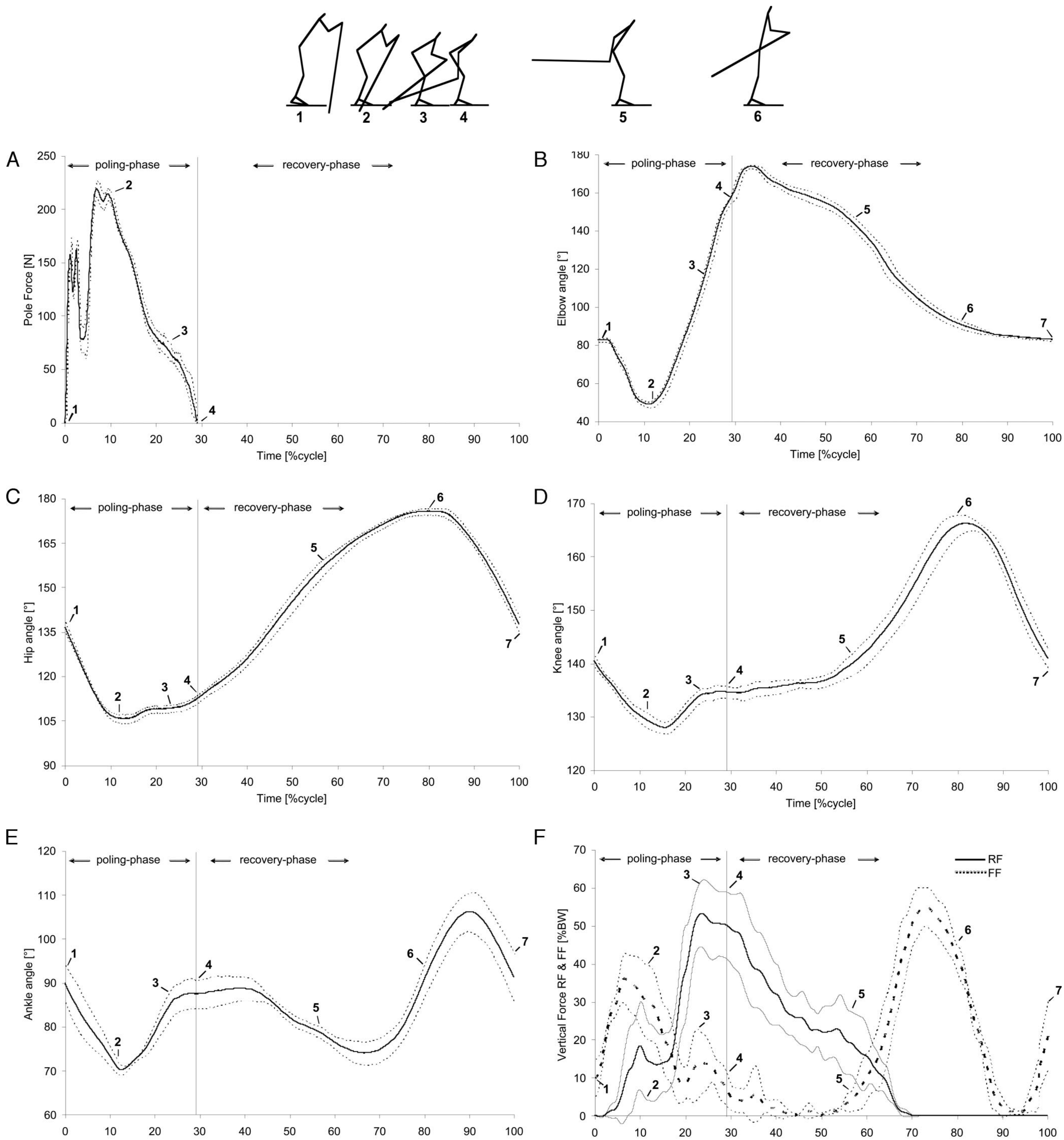


**FIGURE 1—Kinetic and kinematic cycle characteristics of one subject's DP at 85% of $V_{max}$. Time courses are mean ± SD. Time course of resultant pole force (A), elbow angle (B), hip angle (C), knee angle (D), ankle angle (E), and vertical plantar ground reaction force in forefoot and rearfoot area (F). Group data are presented in Tables 2 and 3.**

thirds of PP were characterized by a decrease of the resultant PF toward zero, which slowed down in the last third of PP. $PPF_{abs}$ was 235 ± 63 N (162–346) and $PPF_{rel}$ 32.1 ± 7.5%BW (22–44). $IPF_{abs}$ was 36.4 ± 5.9 N·s (27.2–47.5), corresponding to an $IPF_{rel}$ of 4.9 ± 0.5%BW·s (4.1–5.8).

**Joint angles.** The basic characteristics of joint-angle time courses for the entire group are described by the following variables (Fig. 1, B–E and Table 3). At the beginning of the pole ground contact the angles in the elbow, hip, and knee joints were 104 ± 19° (83–144), 136 ± 14° (111–146), and 150 ± 14° (118–177), respectively. The angle minima during PP at the end of an incipient flexion phase were 69 ± 21° (39–105), 101 ± 16° (73–121), 138 ± 14° (116–165), and 86 ± 11° (73–106) in the elbow, hip,

TABLE 3. Kinematic cycle characteristics of DP at 85% of $V_{max}$ ($N$ = 11), values are mean ± SD.

| | Variables[a] | Mean ± SD |
|---|---|---|
| Elbow | $EA_{start\ PP}$ (°) | 104 ± 19 |
| | $EA_{min\ PP}$ (°) | 69 ± 21 |
| | $EA_{end\ PP}$ (°) | 160 ± 10 |
| | $FT_E$ (s) | 0.09 ± 0.02 |
| | $ET_E$ (s) | 0.19 ± 0.02 |
| | $AV_{E\ flex\ PP}$ (°·s$^{-1}$) | 370 ± 171 |
| Hip | $HA_{start\ PP}$ (°) | 136 ± 14 |
| | $HA_{min\ PP}$ (°) | 101 ± 16 |
| | $HA_{end\ PP}$ (°) | 102 ± 17 |
| | $HA_{max\ RP}$ (°) | 170 ± 8 |
| | $FT_H$ (s) | 0.13 ± 0.03 |
| | $ET_H$ (s) | 0.69 ± 0.09 |
| | $AV_{H\ flex\ PP}$ (°·s$^{-1}$) | 248 ± 76 |
| Knee | $KA_{start\ PP}$ (°) | 150 ± 14 |
| | $KA_{min\ PP}$ (°) | 138 ± 14 |
| | $KA_{end\ PP}$ (°) | 141 ± 16 |
| | $KA_{max\ RP}$ (°) | 167 ± 6 |
| | $FT_K$ (s) | 0.15 ± 0.06 |
| | $ET_K$ (s) | 0.82 ± 0.16 |
| Ankle | $AA_{min\ PP}$ (°) | 86 ± 11 |
| | $AA_{end\ PP}$ (°) | 96 ± 5 |
| | $ET_A$ (s) | 0.19 ± 0.07 |
| | $AA_{min\ RP}$ (°) | 95 ± 14 |
| | $AA_{max\ RP}$ (°) | 105 ± 8 |

[a] $EA_{start\ PP}$ (°), elbow angle at the start of poling phase; $EA_{min\ PP}$ (°), elbow-angle minimum in poling phase; $EA_{end\ PP}$ (°), elbow angle at the end of poling phase; $FT_E$ (s), flexion time elbow in poling phase; $ET_E$ (s), extension time elbow in poling phase; $AV_{E\ flex\ PP}$ (°·s$^{-1}$), angular velocity of elbow flexion in poling phase; $HA_{start\ PP}$ (°), hip angle at the start of poling phase; $HA_{min\ PP}$ (°), hip-angle minimum in poling phase; $HA_{end\ PP}$ (°), hip angle at the end of poling phase; $HA_{max\ RP}$ (°), hip-angle maximum in recovery phase; $FT_H$ (s), flexion time hip in poling phase; $ET_H$ (s), extension time hip from $HA_{min\ PP}$ to $HA_{max\ RP}$; $AV_{H\ flex\ PP}$ (°·s$^{-1}$), angular velocity of hip flexion in poling phase; $KA_{start\ PP}$ (°), knee angle at the start of pole phase; $KA_{min\ PP}$ (°), knee-angle minimum in poling phase; $KA_{end\ PP}$ (°), knee angle at the end of poling phase; $KA_{max\ RP}$ (°), knee-angle maximum in recovery phase; $FT_K$ (s), flexion time knee during poling phase; $ET_K$ (s), extension time knee from $KA_{min\ PP}$ to $KA_{max\ RP}$; $AA_{min\ PP}$ (°), ankle-angle minimum in poling phase; $AA_{end\ PP}$ (°), ankle angle at the end of poling phase; $ET_A$ (s), extension time ankle in poling phase; $AA_{min\ RP}$ (°), ankle-angle minimum in recovery phase; $AA_{max\ RP}$ (°), ankle-angle maximum in recovery phase.

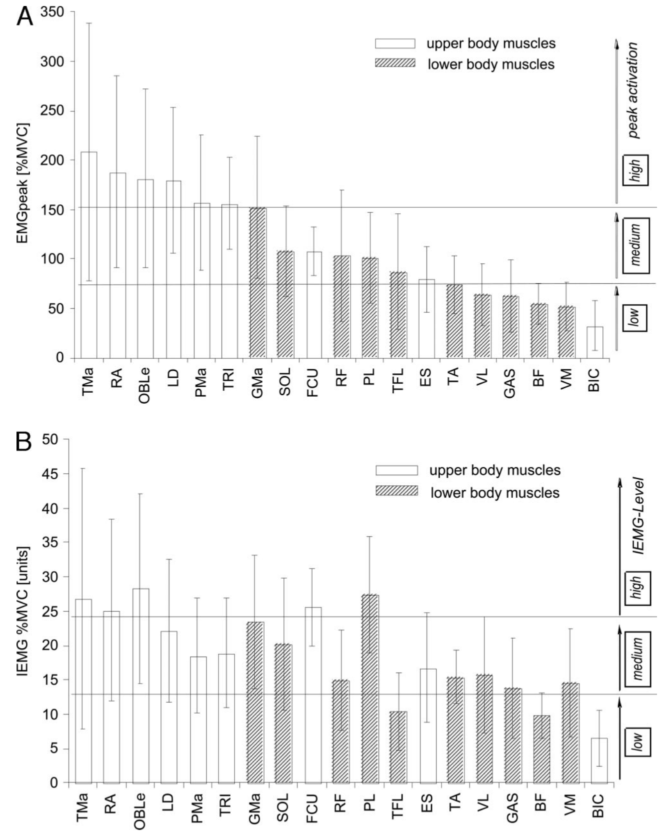


**FIGURE 2—$EMG_{peak}$ (A) and IEMG (B) values of analyzed upper and lower body muscles during DP at 85% of $V_{max}$. The data are mean ± SD. $EMG_{peak}$ and IEMG levels were categorized into HH (high_high), HM (high_medium), MH (medium_high), MM (medium_medium), ML (medium_low), LM (low_medium), and LL (low_low). Categorization levels and abbreviations for muscles are defined in the Methods section.**

knee, and ankle joints, respectively. The absolute flexion times for elbow, hip, and knee joints during PP down to the angle minima were 0.09 ± 0.02 s (0.07–0.12), 0.13 ± 0.03 s (0.09–0.19), and 0.15 ± 0.06 s (0.10–0.32), respectively. The angular velocities of elbow and hip flexion during poling phase were 370 ± 171°·s$^{-1}$ (105–689) and 248 ± 76°·s$^{-1}$ (155–408), respectively. The angle at the end of elbow extension during PP was 160 ± 10° (141–172), and the absolute elbow extension time was 0.19 ± 0.02 s (0.15–0.22). The hip and knee angles at the end of PP were 102 ± 17° (77–130) and 141 ± 16° (121–175), respectively. The ankle joint showed a slight plantar flexion in the second half of PP, starting with a minimum ankle angle of 86 ± 11° (73–106), and ending with an angle of 96 ± 5° (91–101) at the end of PP. The absolute extension time of the ankle joint caused by plantar flexion was 0.19 ± 0.07 s (0.10–0.27). Hip, knee, and ankle angles reached absolute maximum values at 170 ± 8° (158–178), 167 ± 6° (160–171), and 105 ± 8° (100–117), respectively, during the last third of RP. The absolute extension times of the hip and knee joints from the minima in PP up to the maxima in RP were 0.69 ± 0.09 s (0.51–0.83) and 0.82 ± 0.16 s (0.50–1.09), respectively.

**Plantar force.** The analysis of the plantar force distribution between FF and RF during the entire DP cycle showed that the skiers mainly loaded the RF, expressed by an $IF_{RF\_C\ rel}$ of 26.7 ± 7.3%BW·s, which was 60.8% higher than $IF_{FF\_C\ rel}$ (16.6 ± 6.9%BW·s), and also by higher relative force impulse values for RF compared with FF, separately calculated for PP and RP (Fig. 1F and Table 2). However, there was a characteristic alternate loading pattern between the RF and FF during the entire DP cycle (Fig. 1F). During PP, the load on RF increased quite rapidly, synchronous with plantar flexion (Fig. 1E), reaching the highest value toward the end. Thereafter, skiers showed a continuously decreasing load on RF during RP, with some skiers even dropping down to zero, followed by a distinct force peak in the FF during the second half of RP.

**EMG levels.** $EMG_{peak}$ and IEMG levels of the measured muscles (Fig. 2, A and B) were calculated for all skiers as a group, and categorized using z-score values (Table 1) into HH (high_high), HM (high_medium), MH (medium_high), MM (medium_medium), ML (medium_low), LM (low_medium), and LL (low_low). The abdominal muscles (RA and OBLe) and the shoulder extensor muscle TMa were the only ones that showed a HH pattern. For LD and PMa, a HM pattern was observed. Among the arm muscles, FCU showed a MH, TRI a HM, and BIC a LL pattern, whereas EMG levels for ES-L4 were MM. Among the measured

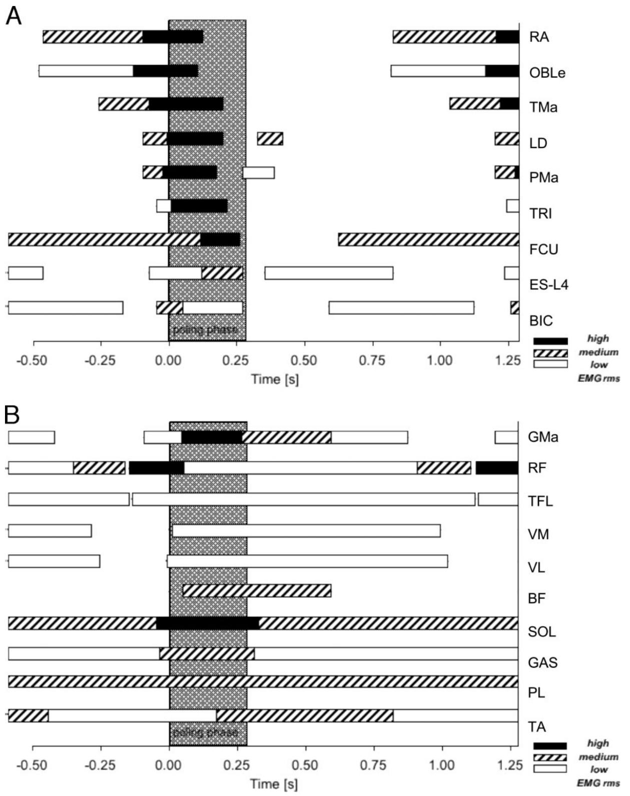


**FIGURE 3—DP coordination pattern including $EMG_{rms}$ of upper body muscles (A) and lower body muscles (B) at 85% of $V_{max}$ for the fastest skier in the group using DP strategy A. The data are mean values. The figure starts (from the left) at about halfway through the recovery phase, followed by the poling phase (start at t = 0) and finishing with the end of the recovery phase. $EMG_{rms}$ levels are categorized into high, medium and low. Categorization levels and abbreviations for muscles are defined in methods and presented in Table 1.**

lower body muscles, GMa and PL had the highest activation, but showed opposite patterns (HM and MH). The hip flexor and knee extensor RF showed a MM and TFL a ML pattern. The EMG levels for BF were LL, whereas VL and VM showed a LM pattern. In the lower leg, SOL and TA showed a MM pattern, with a LM pattern for GAS.

**Muscle sequencing (EMG).** DP coordination (switch on–switch off) patterns including $EMG_{rms}$ levels are presented for the fastest skier in the group (Fig. 3, A and B). Beginning with the second half of RP the analyzed muscles switched on in sequential order: 1) trunk flexors (RA, OBLe) with medium and high $EMG_{rms}$, at the start and then simultaneously with RF changing to high levels shortly before pole plant; 2) TMa starting with medium and thereafter increasing to high $EMG_{rms}$ directly before pole plant; 3) hip flexors (RF, TFL) starting after a short activation break with high and low $EMG_{rms}$, respectively; 4) shoulder extensors (LD, PMa) and GMa switching on with medium and low $EMG_{rms}$, respectively, directly before pole plant; 5) TRI with low $EMG_{rms}$ changing to high coinciding with pole plant, ES-L4 (low $EMG_{rms}$), and BIC (medium $EMG_{rms}$); 6) VL and VM with low $EMG_{rms}$ at the time of pole plant; 7) BF with medium $EMG_{rms}$ shortly after pole plant; and 8) FCU as the last muscle with medium $EMG_{rms}$ level. During PP all analyzed muscles showed full- or part-time activity with changing $EMG_{rms}$ levels. All upper body muscles switched off during PP in sequential order, in contrast to lower leg muscles, which were active during the entire PP. The abdominal muscles RA and OBLe, both showing high $EMG_{rms}$, were the first to switch off around the midpoint of PP. The shoulder extensors TMa, LD, and PMa with high $EMG_{rms}$ followed during the last third of PP. TRI was the next muscle to switch off right before the end of PP, followed by FCU changing from medium to high $EMG_{rms}$ around the midpoint of PP. The last muscles to switch off at the very end of PP were ES-L4 and BIC. They showed medium and low $EMG_{rms}$, respectively, during the second part of PP. All analyzed lower leg muscles (SOL, GAS, PL, TA) were active during the entire DP cycle showing variable $EMG_{rms}$ levels. SOL was the only lower leg muscle to show high $EMG_{rms}$ during PP. Two of the hip and thigh muscles demonstrated a somewhat special pattern. GMa demonstrated high $EMG_{rms}$ during almost the entire PP, changing to medium $EMG_{rms}$ directly before the end of PP, and switching off for a short period in the second half of RP. RF changed from high to low $EMG_{rms}$ during the first part of PP, and switched off (activation break) shortly before the end of RP at medium $EMG_{rms}$ level.

**Two different DP strategies.** The 2D video evaluation showed that 4 of the 11 skiers made up a group where the DP pattern was clearly characterized by more abducted shoulder joints (character 1), smaller elbow angles at pole plant (character 2), faster (character 3), and more distinctly flexed elbow (character 4) and hip joints (characters 5 and 6) during an altogether more dynamic poling phase (character 7) (Fig. 4, A–C and Table 4). This pattern was named "wide elbow" (WE) and specified as DP strategy A. Four other skiers were clearly grouped with an opposite pattern relative to these seven characteristics. This opposite pattern was named "narrow elbow" (NE) and specified as DP strategy B. An additional two skiers were judged as closer to DP strategy A, meeting six of the seven distinguishing characteristics (all except characteristic 2, smaller elbow angles at pole plant), and one skier rather performed the pattern of strategy B, meeting six of seven characteristics (all except number 1, abducted shoulder joint). Results from the statistical comparison of these two groups are shown in Table 4. The skiers using DP strategy A ($N = 6$), including the fastest skiers, showed different pole force characteristics with higher $PPF_{rel}$ ($P < 0.05$), shorter TPPF ($P < 0.05$), and higher $IPF_{rel}$ ($P < 0.05$) compared with the skiers using DP strategy B ($N = 5$) (Fig. 4A and Table 4). Furthermore, $PT_{rel}$ was shorter ($P < 0.05$) and $RT_{rel}$ was longer ($P < 0.05$). Regarding the elbow joint, skiers using DP strategy A showed a smaller $EA_{start\ PP}$ ($P < 0.01$), a smaller $EA_{min\ PP}$ ($P < 0.01$), a higher $AVE_{flex\ PP}$ ($P < 0.01$), and a higher $AMPL_{E\ ext\ PP}$ ($P < 0.05$) compared with the strategy B group (Fig. 4B and Table 4). In addition, their knee and hip movement pattern was characterized by a smaller $KA_{min\ PP}$, $HA_{start\ PP}$, $HA_{min\ PP}$ (all $P < 0.05$), and a higher $AV_{H\ flex\ PP}$ ($P < 0.01$) (Table 4, Fig. 4C). The six skiers using strategy A (WE pattern) showed high $EMG_{peak}$ and IEMG for TMa

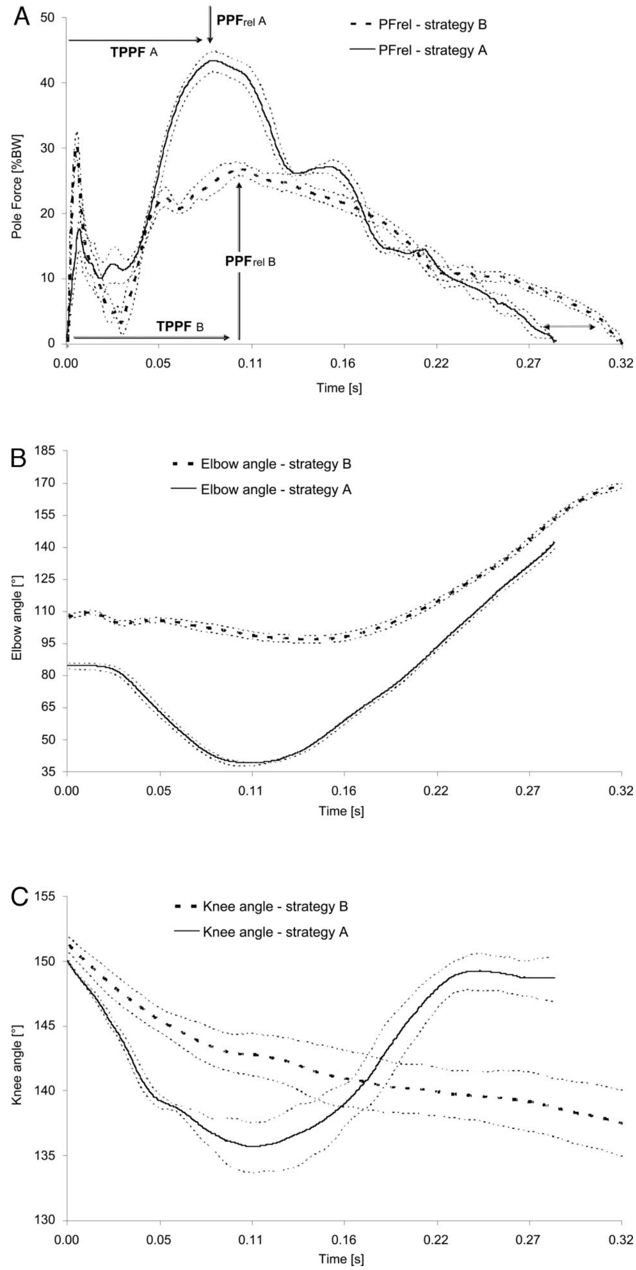


**FIGURE 4—Comparison of the pole force (A), elbow angle (B), and knee angle (C) curves between two subjects representing two different DP strategies (A and B). Time courses are mean ± SD. Strategy A = impact pole force, higher PPFrel, shorter TPPF, higher IPFrel, and shorter PTrel; strategy B = impact pole force, lower PPFrel, longer TPPF, and longer PTrel. PPFrel, relative peak pole force; TPPF, time to peak pole force; PTrel, relative poling time.**

compared with medium or low EMG levels for LD. The five skiers using strategy B (NE pattern) showed an opposite behavior with high $EMG_{peak}$ and IEMG for LD compared with medium or low EMG levels for TMa.

**Correlation analysis.** The absolute velocity at 85% of $V_{max}$ ($V_{85\%}$) was correlated to absolute peak pole force ($PPF_{abs}$) (r = 0.70), relative peak pole force $PPF_{rel}$ (r = 0.66), angular velocity in elbow flexion during PP ($AV_{E\ flex\ PP}$) (r = 0.80), knee-angle minimum during PP ($KA_{min\ PP}$) (r = −0.72) (all $P < 0.05$), and elbow-angle minimum 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, $P < 0.01$). Ankle-angle maximum during RP ($AA_{max\ RP}$) correlated to $PPF_{abs}$ (r = 0.82) and the absolute impulse of pole force ($IPF_{abs}$) (r = 0.76) (both $P < 0.05$). Poling frequency (Pf) correlated to absolute recovery time ($RT_{abs}$) (r = −0.94, $P < 0.01$), hip extension time up to the angle maximum during RP ($ET_H$) (r = −0.89, $P < 0.01$), and knee extension time up to the angle maximum during RP ($ET_K$) (r = −0.81, $P < 0.05$). $EMG_{peak}$ and IEMG values for the muscles LD and TMa were correlated to each other (r = −0.62 and r = −0.70, both $P < 0.05$).

TABLE 4. Significant differences in kinetic and kinematic variables between the groups using DP strategy A ($N$ = 6) and DP strategy B ($N$ = 5) at 85% of $V_{max}$; values are mean ± SD.

| Variables[a] | 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$^{-1}$) | 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 |

[a] $PPF_{rel}$ (% BW), relative peak pole force; TPPF (s), time to peak pole force; $IPF_{rel}$ (%BW·s$^{-1}$), relative impulse of pole force; $PT_{rel}$ (% cycle), relative poling time; $RT_{rel}$ (% cycle), relative recovery time; $EA_{start\ PP}$ (°), elbow angle at the start of poling phase; $AV_{E\ flex\ PP}$ (°·s$^{-1}$), angular velocity of elbow flexion in poling phase; $EA_{min\ min\ PP}$ (°), elbow-angle minimum in poling phase; $AMPL_{E\ ext\ PP}$ (°), amplitude of elbow extension in poling phase; $KA_{min\ PP}$ (°), knee-angle minimum in poling phase; $HA_{start\ PP}$ (°), hip angle at the start of poling phase; $HA_{min\ PP}$ (°), hip-angle minimum in poling phase; $AV_{H\ flex\ PP}$ (°·s$^{-1}$), angular velocity of hip flexion in poling phase.

## DISCUSSION

The main findings of the present study were as follows: 1) characteristic pole force pattern with an initial impact force peak at pole plant followed by a second, active force peak (PPF) positively correlated to the velocity at 85% of the skiers' $V_{max}$ during DP; 2) an active flexion–extension pattern in the elbow, hip, knee, and ankle joints with the angle minima, occurring around PPF, negatively correlated to the hip angle at pole plant, the minimum elbow angle during poling phase, and the relative poling time; 3) two different double poling (DP) strategies (A and B) were found, where strategy A was used by the better skiers and characterized by a higher angular elbow- and hip-flexion velocity, a smaller minimum elbow, hip, and knee angle, a higher pole force, and a shorter poling phase; 4) EMG activity in trunk (RA and OBLe) and hip flexors (RF), shoulder extensors (PMa, LD, and TMa), and the elbow extensor triceps brachii followed a specific sequential pattern, most noticeably during the first half of the poling phase; and 5) EMG activity in lower body muscles together with the above-mentioned joint movement in knee and ankle joints, demonstrated DP for competitive cross-country skiers is more than only upper body work.

**Pole plant and impact force.** As a preparation for the poling phase (PP), all skiers showed a clear pattern getting into a high starting position with distinctly extended hip, knee, and ankle joints ("high hip–high heel" pattern) and a clear forward shift of body weight (forward lean), shown by the increase of the forefoot force during the last part of the recovery phase (RP) (Fig. 1, C–E; Table 3). This can be seen by large amplitudes of extension in these joints up to the highest values of the entire DP cycle occurring during the last third of the RP (Table 3). A functional role of a high starting position was supported by: 1) positive correlations between a "high-heel" pattern (higher $AA_{max\ RP}$) before pole plant and both peak and impulse of pole force ($PPF_{abs}$ and $IPF_{abs}$), and 2) peak pole force ($PPF_{abs}$) correlated positively to DP velocity (performance). Previously, pole force curve characteristics in the DP technique have only been described briefly, not discussed in detail (15,16,21). We found that the resultant pole ground reaction force initiated at pole plant showed two peaks. The first peak occurred at the impact force peak associated with the collision of the pole tip with the ground, followed by a second, higher peak, being the active force peak (PPF) inducing high impulses of pole force for propulsion. It can be assumed that the impact forces at pole plant provokes a preactivation of several muscles with a high or medium activation level for the trunk flexors (RA and OBLe), the hip flexor (RF), and the shoulder extensors (TMa, LD, and PMa) occurring shortly before pole plant (Fig. 3, A and B). We suggest that this preactivation functionally leads to a higher muscle stiffness, preparing the body for pole tip impact and stabilizing the involved joints during this short phase at the beginning of PP.

**Time to peak pole force and peak pole force.** The impact force peak was followed by a high rate of force development up to PPF occurring after approximately 0.10 s. The importance of a short time to peak pole force (TPPF) in DP has already been proposed by Hoff et al. (6), 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 because of the inverse relationship between contraction velocity and force. There was a positive correlation for both relative and absolute PPF to $V_{85\%}$, which shows the importance of generating a high PPF to achieve high velocities in DP. Of note would be that skiers using strategy A showed a shorter TPPF at $V_{85\%}$, a higher $PPF_{rel}$, and higher impulse of pole force ($IPF_{rel}$) (Fig. 4A; Table 4), characterizing the specific DP technique used by these skiers. Although their $PT_{rel}$ was shorter, $IPF_{rel}$ reached higher values, most likely explained by a more rapid force development up to higher relative peak pole forces.

All skiers flexed the elbow, hip, knee, and ankle joints, with angle minima occurring around the point of PPF after one third of PP (Fig. 1, B–E; Fig. 4, B and C). The already discussed "high hip–high heel" pattern before pole plant can be interpreted as important for the following flexion in the above-mentioned joints for generating pole force. It can be assumed that the observed lowering of the center of gravity (CoG) from a high starting position by an active joint flexion functionally would add external load to the poles by 1) the body mass itself (gravity), and 2) the active downward acceleration of CoG. 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 demonstrates a shorter and thus more explosive PP. The skiers using strategy A showed a higher $PPF_{rel}$, and this was different for the skiers using strategy B in four of the five variables correlated to $PPF_{rel}$, except for the extension time in the elbow joint during PP (Table 4). The more distinct use of body mass by a more accentuated, faster lowering of CoG in these skiers is supported by their smaller hip and knee-angle minimum and by a higher angular flexion velocity in the hip and elbow joints during PP (Table 4; Fig. 4, A–C). We suggest that smaller minimum elbow, hip, and knee angles, together with a higher angular flexion velocity at the elbow and hip joints during PP, provide two advantages. First, a higher resultant pushoff 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 preload of the extensor muscles during the flexion phase of the stretch-shortening cycle.

Of special interest was the elbow-joint movement and triceps activation during PP. The mean elbow angle at pole plant in the present study was similar to what has been reported by Smith et al. (25) (104 vs 106°), but we found large interindividual differences (83–144°). Smith and coworkers suggested that more extended arms at pole plant may allow for greater elbow flexion, and thus a stronger preloading of the extensor muscles of the shoulder and the elbow joint, leading to a more effective stretch-shortening cycle (SSC), supporting the following elbow extension. It is of note that the skiers in our group 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 angular elbow-flexion velocities (485 vs $233°\cdot s^{-1}$), compared with the skiers using strategy B (Table 4), who showed elbow movement patterns rather like the skiers in the study by Smith et al. (25). Because of larger elbow angles at pole plant, they did not flex their elbows as much, and the flexion velocity during the eccentric phase was smaller; both of these factors could lead to less stretch and preload in the triceps brachii. Therefore, we suggest that if the elbow joint is extended too much at the beginning of the ground contact, and a small minimum elbow angle is desirable, a negative influence on the ratio between flexion amplitude and flexion time in the elbow joint could occur. This idea is based on findings that a fast joint flexion is of high importance to induce high elastic energy during a SSC (24). Our data showed a rapid mean elbow flexion of 35° in an absolute time of 0.09 s ($370 \pm 171°\cdot s^{-1}$) during the first part of PP, but there were large interindividual differences in angular velocity of elbow flexion ($105–689°\cdot s^{-1}$). The higher mean elbow-flexion velocity of the strategy A skiers, together with their smaller minimum elbow angles, and simultaneous with higher $PPF_{rel}$, produced a more effective stretch (eccentric phase), and thus a higher preload of the triceps brachii, which might then support the following concentric phase with more elastic energy. The lack of differences in the elbow extension time during PP between the two strategies may be explained by the fact that the skiers using strategy A showed smaller minimum elbow angles, but no differences in the elbow angles at the end of PP. They had to perform the concentric phase of elbow movement through a greater range of angles over a similar time course compared with skiers using strategy B. This fact might also lead to an advantage creating higher impulses of force during the concentric phase by the fact of a larger range of elbow-joint extension for a constant time. 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 to DP performance. It can be assumed that the flexion at 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 elbow-angle minimum, both occurring around the same point of time, whereas $PPF_{rel}$ itself correlated to DP velocity (DP performance). In addition, with a small elbow angle at pole plant, the leaver arm of the PF will be shorter, thereby allowing a higher pole force for a given shoulder extensor strength. Finally, of special note was that, independent of starting angle of the elbow joint and the following joint movement, all skiers showed a short plateau in the elbow-angle curve during the first part of PP simultaneously with impact force (Fig. 1, A and B; Fig. 4, A and B). This plateau may indicate a strategy of the skiers to stabilize the elbow joint against the impact force by creating high muscle stiffness in the triceps muscle during this short phase (Fig. 3A). Altogether, the activation pattern of triceps brachii is characterized by: 1) a sudden change from low to high activation at pole plant, presumably to stabilize the elbow joint during the impact; and 2) a further high activation up to the last third of PP, reflecting the preload by a fast elbow flexion down to the minimum elbow angle (eccentric phase), occurring simultaneous with PPF on the one hand, and the powerful concentric phase on the other hand.

**EMG levels and muscle sequencing.** The muscle sequencing during PP, based on the used EMG processing method and demonstrated in Figure 3A (best skier in the group), points to the existence of a "muscle activation chain" consisting of three important links of muscles. These were, in sequential order: 1) trunk flexors rectus abdominis and obliquus externus and the hip flexor rectus femoris; 2) shoulder extensors latissimus dorsi, teres major, and pectoralis major; and 3) the shoulder and elbow extensor triceps brachii. All these muscles showed high EMG activation levels during the first part of PP, contributing to the development of pole force. Thereafter, they switched off according to a "first in–first out" pattern, starting with the abdominal muscles around the occurrence of the minimum hip angle, simultaneously with PPF, followed by the shoulder muscles and triceps brachii during the very last part of PP.

Previous biomechanical studies (9,15,16,25) have focused on muscles affecting the shoulder and the elbow joint without analyzing a possible important role of the abdominal muscles and other trunk and hip flexors. The high $EMG_{peak}$ and IEMG of rectus abdominis and obliquus externus and the medium $EMG_{peak}$ and IEMG of rectus femoris (Fig. 2, A and B), observed in the present study before and during PP, indicate their distinct role in DP (Fig. 3, A and B). We suggest that this muscle activity pattern has a functional role to create a small hip angle at pole plant and to add power to the trunk-flexion characteristics of DP technique. Skiers using strategy A in particular demonstrated a more distinct pattern using their trunk and hip flexors, resulting in the hip-angle characteristics described above. Based on the results in this study, it can be assumed that both these factors will have an important function to positively influence the development of pole force (see correlations and Table 4).

Among the shoulder extensors, TMa, LD, and PMa showed HH, HM, and again HM activation levels (Fig. 2, A and B), respectively, and all three showed high $EMG_{rms}$ levels in the muscle sequencing chart of the best skier in the group (Fig. 3A). PMa has a double function with extension of the shoulder joint in the first part of PP, and a stabilizing function as antagonist to LD. TMa appears to act as an important shoulder extensor (HH pattern) together with LD (HM pattern). Interestingly, there were large interindividual differences in the activation levels of LD and TMa. The skiers either predominantly used LD or TMa, shown by the negative correlations of $r = -0.62$ for $EMG_{peak}$ and $r = -0.70$ for IEMG. Skiers using strategy A showed a high $EMG_{peak}$ in TMa and medium $EMG_{peak}$ in LD, whereas the skiers using strategy B showed the opposite pattern. This might be explained by the "wide elbow" pattern versus the "narrow elbow" (NE) pattern in DP, provoking muscle activation as described above. Many trainers in elite cross-country ski racing consider the WE technique to be the more modern sprintlike technique developed during the last decade, used by an increasing number of skiers, whereas the NE technique represents the older DP technique.

The forearm muscle flexor carpi ulnaris (FCU) demonstrated a very characteristic activation pattern with a short and high activation during the final pushoff. This causes an accentuated ulna abduction of the wrist, an action that coincides with an increasingly smaller pole angle (large horizontal force component) during the second half of PP having a positive effect on propulsion in the forward direction. FCU also showed medium activation during the final

RP, most likely to stop the forward swing of the poles and to come to an optimal starting position.

**Does DP only involve upper body work?.** Interestingly, we observed a clear EMG activity in the measured lower body muscles during DP as well as a distinct flexion–extension pattern in the hip, knee, and ankle joints during the DP cycle (Fig. 2, A and B; Fig. 1, C–E). What, then, is the functional role of this activity? First, it will always be a basic function to stabilize the lower body and maintain the upper body in an upright position during the normal stance. Second, trunk flexion will increase the activation level of the lower body extensor muscles, to counteract the forward flexion of the upper body and to keep one's balance. These muscles also will have an active role in extension back up to upright position. It is of note that the relative mass of the head, neck, arms, and trunk together has been calculated to represent 67.8% of body mass (28), suggesting it is a substantial amount of mass on which these muscles act. During DP there is considerable forward-downward momentum during PP, which is partly absorbed by the poles but also has to be controlled by the hip and back extensors. Already during the second half of PP an increase of activity in ES-L4 was observed, and the high and medium activation of GMa and BF most likely assist the repositioning of the upper body back up to the initial starting "high hip" position at the end of RP. Third, our data demonstrate that our skiers showed a marked active flexion–extension pattern in the hip and knee joints during the DP cycle, represented by the large amplitudes from the "high heel–high hip" starting position down to the angle minima in these joints. The active role of the lower body during trunk flexion was supported by the high activation of RF before and during pole plant (Fig. 3B), and by the fact that the skiers with a reinforced use of RF showed higher angular hip-flexion velocities (strategy A) compared with the skiers using strategy B (291 vs $195° \cdot s^{-1}$).

In addition to the above-mentioned activity of the lower body muscles during flexion and extension, a special movement pattern by the lower leg was apparent during the last two thirds of PP. This was characterized by a distinct plantar flexion occurring simultaneously with a slight knee extension. At the same time that the ankle angle increased, the vertical rear foot force increased up to its maximum. This occurred toward the end of PP, and was coupled with a low to medium activation of the dorsal flexor muscle tibialis anterior (TA) during the last third of PP. This lower leg motion, also observed with 2D video analysis, may have an "action–reaction" function, both to the flexion of the upper body and against the horizontal backward propulsion of the poles. Moreover, this action may be functional in order to generate a forward impulse and, together with the muscle action of TA, lift the frontal wax zone of the skis from the snow, which may reduce the friction between ski and snow. Regarding the muscles in the lower leg, our interpretation is that they are mainly stabilizers, but there were interindividual differences in the activity of triceps surae muscles (GAS and SOL), influenced by how active the skier was using the "high heel" pattern before pole plant. Altogether, movement patterns of the lower leg muscles point to an active role to create higher peak pole forces for higher propulsion, beyond their stabilizing function, in contrast to several groups that have described DP as only upper body work (6,17,26).

## CONCLUSION

In conclusion, the present study shows that the DP technique in competitive cross-country skiers is a complex movement involving both the upper and lower body. Pole force, in contrast to poling frequency, is directly related to DP velocity and influenced by specific muscle activation patterns and a specific characteristic flexion–extension pattern in the elbow, hip, and knee joints, with the angle minima occurring around the peak pole force. The muscles are engaged in sequential order starting with trunk and hip flexors, followed by shoulder extensors and the elbow extensor triceps brachii. In addition, some specific complementary movements are added during the last phase of the poling cycle. The best skiers use a DP strategy with specific characteristics directly correlated to DP velocity. This strategy is characterized by smaller joint angles, higher flexion velocities, and higher pole force applied during a shorter poling phase. The findings of the present study have a direct practical implication for a better understanding of the DP technique in competitive cross-country skiing. Given the increased utilization of the DP technique during competition, this information is especially relevant for those interested in function and biomechanics of this technique and for more specific information regarding technique and strength training. Future research on DP should further investigate specific biomechanical aspects of the different strategies, the relationship between these and physiological variables, and elaborate specific strength and technical models to increase pole force and DP performance.

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