Double-Poling Biomechanics of Elite Cross-country Skiers: Flat versus Uphill Terrain

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ABSTRACT

STÖGGL, T. L., and H.-C. HOLMBERG. Double-Poling Biomechanics of Elite Cross-country Skiers: Flat versus Uphill Terrain. *Med. Sci. Sports Exerc.*, Vol. 48, No. 8, pp. 1580–1589, 2016. **Introduction:** In light of the recent revolutionary change in the use of the double-poling (DP) technique in cross-country skiing, our purpose was to compare the associated kinetics and kinematics on flat (DP_{flat}) and uphill terrain (DP_{up}), as well as to identify factors that determine performance. **Methods:** Thirteen elite male cross-country skiers completed two incremental speed tests (V_{peak}) involving roller skiing with the DP technique at moderate (13 and 24 km·h⁻¹) and high speed (15 and 28.5 km·h⁻¹) on a treadmill that was flat (1°) or tilted uphill (7°). Pole forces and three-dimensional whole-body kinematics were monitored simultaneously. **Results:** In comparison to DP_{flat}, during DP_{up}, swing times were much shorter (–48%) and peak pole forces greater (+13%) and generated later during the poling phase (+68%), with higher impulses for all force components (+87%–123%). Furthermore, pole forces were 18% more effectively oriented for propulsion. During DP_{up}, the skiers demonstrated more flexed elbows, as well as shoulder angles that were less flexed in the forward direction and less abducted throughout the poling phase, together with more highly flexed knee and ankle joints, a more upright thorax, less flexed hips, and a shortened backward swing after pole off. With DP_{up}, the skiers raised their center of mass 25% more, attaining maximal heel raise and maximal vertical position at a timepoint closer to pole plant compared with flat. On the uphill incline, the magnitude of V_{peak} was positively related to body mass, relative pole length (% body height), and magnitude of heel raise. **Conclusions:** The present findings provide novel insights into the coordination, kinetics and kinematics of elite skiers while DP on flat and uphill terrain. **Key Words:** 3D KINEMATICS, FORCE COMPONENTS, KINETICS, PROPULSIVE FORCE

Over the past three decades, the double-poling (DP) technique has come to be used to a greater and greater extent and is today decisive for success in cross-country ski races involving the classic style (10,16,21). During DP, aerodynamic drag, gravity, and friction must all be overcome exclusively by propulsive forces generated through the poles in contact with the ground as the skis glide forward continuously. The revolutionary increase in the use of the DP technique has many causes including better preparation/grooming of ski tracks, marked improvement of equipment (both the poles and gliding properties of the skis), greater upper-body strength and endurance, and substantial biomechanical

improvements (21). In addition, DP appears to be more economical than the other classical subtechniques, especially on flatter terrain (8,15).

Previous investigations of the DP technique on flat terrain (up to an incline of 1°) have revealed that the fastest skiers exhibit a distinct “preparation phase” before pole plant, with more vertical pole orientation, greater pole forces with a greater associated impulse (force integrated over time), later peak pole forces, and shorter relative poling time (PT) (as a % of the total cycle time) with longer swing (recovery) phase and longer cycles than slower skiers (10,21,25). Moreover, elite skiers increase their DP speed by increasing poling frequency and increasing or maintaining cycle length (11,25), enhancing their range of motion, reducing the minimal angles, and using more rapid angular velocities in their elbow, hip, and knee joints (11). Altogether, the characteristics of the generation of pole force and poling behavior during the swing phase, along with the placement/orientation of the poles when planted are important determinants of DP performance on flat terrain (21,25).

In recent years, utilization of DP has become even more common and several elite skiers have used this technique successfully throughout an entire race. Exclusive use of this technique eliminates the need for the kick wax traditionally applied in connection with the classic diagonal stride technique. This dramatic development began in connection with the popular long-distance races (e.g., Vasaloppet, Marcialonga, König

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Ludwig Lauf, and so on), which consist primarily of flat and slightly uphill terrain, as well as the short sprint and team sprint races (21). Since the 2014–2015 season, certain skiers also began, with remarkable success, to utilize this technique exclusively during longer World Cup distance races (e.g., Davos, Toblach), where the terrain is much more uphill (the International Ski Federation (4) stipulates that a race track should consist of 1/3 uphill, 1/3 downhill, and 1/3 undulating terrain, with, for example, an overall climb of 400–600 m for a 15-km race). The obvious gain in this latter context is that skiing without kick wax provides better glide and is more economical on certain sections of the course. This better glide is not only advantageous downhill, but also on flat and rolling terrain, because the friction between the skis and the snow is lower.

To our knowledge, only two earlier studies have examined DP on steeper terrain. Applying 2D video analysis and measurement of pole forces, Millet and colleagues (13) found that when the incline was increased from 2.1% (1.2°) to 5.1% (2.9°), the pole forces were greater, the swing phase shorter, and the duration of the poling phase unchanged. Later, Pellegrini and co-workers (15) analyzed biomechanical parameters and metabolic cost on inclines of 0°–4° and demonstrated that at 10 km·h⁻¹ amateur skiers prefer to use DP on flat terrain, changing to DP with a kick between 2° and 3°. These authors propose that this transition is due to a “limit of force” generated through the poles and the desire to reduce the stress applied to the musculoskeletal system. Furthermore, they found that the metabolic cost of DP is greater than that for diagonal skiing at inclines >4°. However, detailed kinetic and three-dimensional (3D) kinematic analysis of the DP performance of world-class cross-country skiers at high-to-maximal speeds on inclines steeper than 4° has not yet been conducted.

This rapid development of DP and its increasing use on uphill terrain (as steep as 15°) over an entire racing course motivated us to characterize more extensively how elite skiers use this technique on relevant inclines and at racing velocities. Therefore, our specific aims here were to compare DP on uphill (DP_{up}) and flat terrain (DP_{flat}), to identify the factors that determine performance, and to see whether the fastest skiers on flat terrain were also the fastest uphill. We tested the hypothesis that pole forces and 3D whole-body kinematics and performance differ between DP_{flat} and DP_{up}. We predicted that due to the greater gravitational component along the incline, during DP_{up}, skiers would assume a more upright stance, with more pronounced usage of the lower body and shorter pole swing times (ST) than during DP_{flat}.

METHODS

Participants. The 13 elite male cross-country skiers (age, 26.1 ± 4.7 yr; body mass, 75.3 ± 4.3 kg; body height, 180 ± 5 cm [means ± SD]) competing at the national and/or international level who participated were fully informed of the nature of this study before providing their written consent. The protocol was preapproved by the regional ethical review board in Umeå, Sweden (08-058M).

General overview. While roller-skiing on a flat (DP_{flat}, grade 1°) or inclined (DP_{up}, grade 7°) treadmill using the DP technique exclusively, pole forces, 3D whole-body kinematics (including the poles and roller skis) and peak speed (V_{peak}) were recorded (20,22,23). Biomechanical variables were analyzed both at the highest speed attained by all of the skiers (flat, 28.5 km·h⁻¹ and uphill, 15 km·h⁻¹), as well as at an approximately 15% slower speed (flat, 24 km·h⁻¹ and uphill, 13 km·h⁻¹). These two speeds on flat and uphill terrain are considered representative racing speeds during sprint and distance competitions, respectively.

The peak speed test. First, each participant performed a standardized 15-min warm-up involving 10 min of skiing at approximately 70%–85% of $\dot{V}O_{2\text{max}}$, followed by four 6-s sprints during the final 5 min. After a 3-min rest, the treadmill was set at an incline of 1° and initial speed of 22.5 km·h⁻¹ (achieved by linear acceleration for 10 s), after which the speed was increased by 1.5 km·h⁻¹ every 10 s until exhaustion (as decided by the investigator that the participant could no longer stay within 1.5 m of the front of the treadmill (23)). After this DP_{flat} sprint test, each skier actively recovered with 10 min of low-intensity diagonal stride skiing (8 km·h⁻¹, 3°) and then rested for 20 min.

Immediately thereafter, the skier warmed up again for 15 min, again performing four 6-s sprints during the final 5 min. After a 3-min rest, the treadmill was set at an incline of 7° and the initial speed at 12 km·h⁻¹ (achieved by linear acceleration for 10 s), after which the speed was increased by 1 km·h⁻¹ every 10 s until exhaustion. For both tests, V_{peak} was calculated by linear interpolation using the formula: $V_{\text{peak}} = V_f + ((t/10) \Delta V)$, where V_f was the speed during the last workload completed, t the duration of this last workload (s) and ΔV the difference in speed during the last two workloads (10). The V_{peak} values determined here were similar to the corresponding values observed previously with this same approach, confirming that all of the skiers performed maximally.

The roller skis and treadmill. The Pro-Ski C2 roller skis used (Sterners, Nyhammar, Sweden) exhibited a resistance friction coefficient $\mu_R = 0.016$, as measured on the treadmill surface with an instrument specifically designed for this purpose (1). The treadmill (Rodby, Södertälje, Sweden, belt dimension 3.3 × 2.5 m) was large enough to allow roller skiing, and all of the participants were accustomed to roller skiing at high speeds on this treadmill using the DP technique in connection both with their training and testing. During all testing, the subjects were secured with a slack safety harness connected to an emergency brake suspended above the treadmill.

Force measurements. All subjects used carbon-fiber racing poles specially constructed for force measurements. These poles were adjustable, which enabled the subjects to choose their own preferred length. The ground reaction force of the pole, directed along its length, was monitored by a 60-g strain gauge force transducer mounted in a lightweight (75 g) aluminum tube directly below the grip (Hottinger Baldwin Messtechnik GmbH, Darmstadt, Germany). With our system, the mean absolute values obtained differed by approximately 2.8% from those indicated by an AMTI force plate (AMTI, Watertown, MA).

3D kinematics. The 3D kinematics of the whole body, poles, roller skis, and treadmill were captured by a Vicon MX13 motion system (Vicon Peak Ltd., Oxford, UK) consisting of eight cameras sampling at 250 Hz. The global coordinate system was right-handed and defined as follows: the incline of the treadmill was set to 0°; the x -axis was the side-to-side direction across the treadmill; the y -axis was the longitudinal axis of the treadmill (i.e., the direction of motion); and the z -axis perpendicular to the ground (representing a treadmill incline of 0°). A kinematic model (Plug-In-Gait; Vicon Peak Ltd.) was used to attach 39 reflective markers (14 mm in diameter) over bony anatomical landmarks on the skier's skin or clothing.

Twelve additional reflective markers were placed on the poles (two each), roller skis (two each), and treadmill (four markers). The pole markers (fixed onto the lateral aspect with double-sided tape, with additional tape around the pole to avoid movement) were placed at the top (1 cm below the bottom of the grip) and 5 cm above the tip. Markers were placed on the left and right sides at the front and rear of the treadmill, parallel to the direction of skiing, to provide exact information about the incline and position of the treadmill in space. Two markers were placed along the midline of each roller ski, one in front of the binding and one behind the front wheel. The distance between the pivot point (where the cross-country skiing boot is fixed to the binding) and the marker placed in front of the binding was measured manually (100 mm) to assess the location of this pivot point relative to the two markers on the roller-ski (21). The parameters for body segments from the Plug-In-Gait model (Vicon Peak Ltd.), together with the masses of the two poles, two roller skis and measuring equipment over the chest, were used to calculate the center of mass (COM).

Collection and analysis of biomechanical data. All variables were calculated for both sides of the body and the mean (3D kinematics and cycle characteristics) or sum (force impulses) were used in further calculations. For each variable, the mean values for six successive cycles at each speed analyzed (DP_{flat} , 24 and 28.5 km·h⁻¹; DP_{up} , 13 and 15 km·h⁻¹) were used. Pole forces were recorded using a telemetric system (TeleMyo 2400TG2; Noraxon, Scottsdale, AZ), as well as being recorded simultaneously with 3D kinematic data using the Nexus 1.8 software (Vicon) at a sampling rate of 1500 Hz. The default time-shift of 50 ms for the analogue signal of pole force demonstrated by the Noraxon system was corrected before calculating the force and kinematic values using a Matlab routine. The raw 3D kinematic data were processed through a sixth-order, zero-lag Butterworth low-pass filter with a cutoff frequency of 12 Hz (7). Processing of all data was performed with the Vicon BodyBuilder (Vicon) and IKE-master software (IKE-Software Solutions; Salzburg, Austria).

Determination of cycle characteristics and whole body kinematics. Cycle characteristics (rate and length) and the phases of poling (PT and ST) were calculated from the pole force data. The distance covered during the poling phase was calculated as treadmill speed (m·s⁻¹) multiplied by PT (s). In addition, the distance between the pole tip and pivot point at the time of pole plant and pole off was

recorded (by projecting both relevant markers onto the sagittal plane). The start of the preparation phase—the preparation point—was determined as the instant during the swing phase at which the pole tip demonstrated its greatest displacement in the forward direction (along the y -axis). The preparation phase was defined as the period from this preparation point until pole plant (21). The vertical amplitude of COM displacement was calculated as the difference between its minimal and maximal positions during the cycle, with the additional rise due to the stationary treadmill being determined as (treadmill speed) $\times$ (the sine of the treadmill grade) $\times$ (the time between the minimal and maximal values for COM).

The thorax angle was calculated relative to the vertical (z) axis (0° fully upright, 90° parallel to the horizontal plane). For the ankle, 90° represented the neutral position, with angles < 90 indicating dorsiflexion and > 90 indicating plantar-flexion. In the case of the shoulder angles, 0° was when the arm was parallel to the body, with no abduction, respectively anteversion/retroversion. For all other angles (elbow, hip, and knee), maximal extension was defined as 180°.

Calculation of components of the pole forces. The pole angles were defined such that all three components of force (vertical, horizontal, and sideward), as well as the propulsive component (along the treadmill plane in the direction of skiing) could be calculated directly from the resultant pole force and the sine or cosine of the relevant pole angle. The vertical and horizontal pole forces were determined as the resultant pole force multiplied by the cosine of the angle of the pole vector (from the top to the tip marker) with respect to the vertical (z) and y -axis, respectively; although the sideward pole force (along the x -axis) was the product of the resultant pole force and the sine of the angle of the pole vector with respect to the projection of this vector onto the y - z (sagittal) plane. Finally, the propulsive force was calculated as the resultant pole force multiplied by the cosine of the angle between the pole and treadmill plane vectors in the direction of skiing (i.e., projection of the y -axis onto the plane of the treadmill). In addition, the forward pole angle was defined as the angle between the y -axis and the projection of the pole vector onto the y - z (sagittal) plane.

The resultant, vertical, horizontal, sideward, and propulsive force impulses were calculated by trapezoidal numerical integration and the values for the two poles added together. The average cycle force (ACF) and average cycle propulsive force (ACPF) were determined by dividing the resultant and propulsive force impulse, respectively, by cycle time. The external power was calculated as the sum of the power exerted against gravity (system mass $\times g \times$ sine of the grade $\times$ skiing speed) and against friction (system mass $\times g \times$ cosine of the grade $\times \mu_R \times$ skiing speed), where the system mass is equal to the mass of the skier (including equipment) and g is 9.81 m·s⁻² (17,19). Poling power was determined as ACPF multiplied by skiing speed (m·s⁻¹). The effectiveness index was the ratio between ACPF and ACF (%).

Statistical analyses. All data were normally distributed (as assessed by the Shapiro–Wilk test) and are presented

as means and standard deviations ($\pm$ SD). Two-way (two speeds and two grades) analyses of variance (ANOVA) with repeated measures were conducted. In addition, the values obtained were evaluated by calculating the effect size ($\rho\eta^2$) and statistical power. To determine the relationships between V_{peak} and kinetic and 3D kinematic variables, Pearson product-moment correlations were calculated. For all analyses, the level of statistical significance was set at $\alpha = 0.05$. In the Results section, the pooled data for the two submaximal speeds on both grades are presented, whereas the detailed data are presented in Tables 1–4. All statistical analyses were carried out using SPSS 22.0 (SPSS Inc, Chicago, IL) and Office Excel 2010 (Microsoft Corporation, Redmond, WA) softwares.

RESULTS

The peak velocities with DP_{flat} and DP_{up} were 32.0 ± 1.7 (29.5–35.5) and 16.0 ± 0.7 (15.1–17.2) $\text{km}\cdot\text{h}^{-1}$, respectively, with corresponding test durations of 73 ± 11 and 50 ± 7 s. Both peak velocity and duration of the test were closely correlated between DP_{flat} and DP_{up} (both, $r = 0.87$, $P < 0.001$).

Cycle characteristics and pole kinematics. The cycle rate was 28% higher during DP_{up} than DP_{flat} (0.96 ± 0.15 Hz vs 1.23 ± 0.8 Hz, $P < 0.001$) and increased at the more rapid speeds (1.01 ± 0.11 Hz vs 1.18 ± 0.13 Hz, $P < 0.001$) (Table 1). Cycle length was 23% shorter during DP_{up} than on flat terrain (3.18 ± 0.23 m vs 4.14 ± 0.64 m, $P < 0.001$) and unaffected by speed. PT was 56% longer (0.39 ± 0.03 s vs 0.25 ± 0.02 s), whereas ST was 48% shorter (0.43 ± 0.04 s vs

0.82 ± 0.15 s) during DP_{up} than DP_{flat}. Both of these variables were reduced at more rapid speeds ($P < 0.001$ in all cases), whereas the ratio between PT and ST remained constant (DP_{up}, $47\% \pm 3\%$; DP_{flat}, $24\% \pm 3\%$, Fig. 1A and B).

The distance from the pole tip to pivot point on the boot-ski binding (projected onto the sagittal plane) was shorter during DP_{up} than DP_{flat}, both at the time of pole plant (24 ± 11 cm vs 39 ± 13 cm, $P = 0.002$) and pole off (156 ± 12 cm vs 166 ± 13 cm, $P = 0.002$) and, consequently, the total distance covered during DP_{up} was 12% shorter (180 ± 19 cm vs 205 ± 17 cm, $P < 0.001$). All three of these variables were independent of speed ($P > 0.05$).

The forward pole angle (with respect to the horizontal direction) at the instant of pole plant was unaffected by the grade of the terrain ($80^\circ \pm 6^\circ$ vs $78^\circ \pm 3^\circ$, $P > 0.05$), but at pole off the incline of the pole was less during DP_{up} than DP_{flat} ($33^\circ \pm 2^\circ$ vs $23^\circ \pm 1^\circ$, $P < 0.001$). At more rapid speeds, the pole became more inclined toward the horizontal direction at both timepoints ($P = 0.002$ and <0.001 , respectively). At pole off, the hand was approximately 12 cm in front of the center of the pelvis in the horizontal direction and uninfluenced by grade or speed ($P > 0.05$). The maximal backward swing of the arms with DP_{flat} was 5.9 ± 7.5 cm behind the center of the pelvis 0.16 ± 0.07 s after pole off and with DP_{up}, 7.1 ± 7.6 cm in front of the pelvis at 0.04 ± 0.01 s (both, $P < 0.001$). The duration of preparation was shorter during DP_{up} (8 ± 12 ms vs 99 ± 45 ms, $P < 0.001$) and unaffected by speed.

Pole kinetics and effectiveness. The peak pole force was 13% greater during DP_{up} than DP_{flat} (417 ± 68 N vs 368 ± 62 N,

TABLE 1. Cycle characteristics and pole kinematics associated with DP on flat (1°) and uphill (7°) terrain at medium and high submaximal speeds at each grade.

Parameter	DP _{flat} (1°)		DP _{up} (7°)		F	P	Effect Size $\rho\eta^2$	Test Power
	24 $\text{km}\cdot\text{h}^{-1}$	28.5 $\text{km}\cdot\text{h}^{-1}$	13 $\text{km}\cdot\text{h}^{-1}$	15 $\text{km}\cdot\text{h}^{-1}$				
Cycle rate (Hz)	$0.88 \pm 0.13^*$	$1.05 \pm 0.18^*$	$1.16 \pm 0.10^*$	$1.31 \pm 0.08^*$	$F_{1,12} = 63^a$ $F_{1,12} = 94^b$	<0.001 <0.001	0.95 0.94	1.0 1.0
Cycle length (m)	$4.19 \pm 0.61^{**}$	$4.08 \pm 0.68^{**}$	3.15 ± 0.28	3.19 ± 0.20	$F_{1,12} = 46^a$ $F_{1,12} = 0.7^b$	<0.001 0.43	0.79	1.0
Poling time (s)	$0.27 \pm 0.02^*$	$0.24 \pm 0.02^*$	$0.41 \pm 0.04^*$	$0.36 \pm 0.03^*$	$F_{1,12} = 235^a$ $F_{1,12} = 191^b$	<0.001 <0.001	0.95 0.94	1.0 1.0
Swing time (s)	$0.89 \pm 0.16^*$	$0.74 \pm 0.15^*$	$0.46 \pm 0.05^*$	$0.40 \pm 0.03^*$	$F_{1,12} = 132^a$ $F_{1,12} = 51^b$	<0.001 <0.001	0.92 0.81	1.0 1.0
Distance from pole tip to pivot point at pole plant (cm)	$36.5 \pm 12.7^*$	$41.9 \pm 14.3^*$	23.1 ± 9.4	23.5 ± 12.5	$F_{1,12} = 15.6^a$ $F_{1,12} = 3.1^b$	0.002 0.10	0.57	0.95
Distance from pole tip to pivot point at pole off (cm)	$165 \pm 13^*$	$168 \pm 14^*$	154 ± 15	154 ± 11	$F_{1,12} = 14.8^a$ $F_{1,12} = 2.9^b$	0.002 0.12	0.55	0.94
Forward pole angle at pole plant ($^\circ$)	81 ± 6	80 ± 7	79 ± 3	$76 \pm 4^*$	$F_{1,12} = 3.3^a$ $F_{1,12} = 15.1^b$	0.10 0.002	0.56	0.95
Forward pole angle at pole off ($^\circ$)	$25 \pm 1^*$	$22 \pm 2^*$	$33 \pm 2^*$	$31 \pm 2^*$	$F_{1,12} = 480^a$ $F_{1,12} = 183^b$	<0.001 <0.001	0.98 0.94	1.0 1.0
Distance from hand to pelvis at pole off (cm)	-12.5 ± 4.4	-12.1 ± 5.0	-11.9 ± 7.6	-12.1 ± 5.2	$F_{1,12} = 0.52^a$ $F_{1,12} = 0.0^b$	0.82 0.95		
Maximal distance from hand to pelvis at end of back swing (cm)	$7.5 \pm 9.2^*$	$4.3 \pm 6.9^*$	$-8.4 \pm 6.9^{**}$	$-6.0 \pm 8.3^{**}$	$F_{1,12} = 36^a$ $F_{1,12} = 0.0^b$	<0.001 0.95	0.75	1.0
Time from pole off to instant of maximal backward swing (s)	$0.19 \pm 0.09^*$	$0.12 \pm 0.07^*$	$0.04 \pm 0.02^*$	$0.04 \pm 0.01^*$	$F_{1,12} = 32^a$ $F_{1,12} = 26^b$	<0.001 <0.001	0.73 0.68	1.0 1.0
Duration of preparation phase (ms)	$100 \pm 46^{**}$	$97 \pm 45^{**}$	8 ± 11	8 ± 13	$F_{1,12} = 66^a$ $F_{1,12} = 0.08^b$	<0.001 0.78	0.85	1.0

The values presented are means $\pm$ SD. F and P values were obtained by two-way ANOVA (two grades, two speeds).

*Significantly different from all other conditions.

**Significantly different from both speeds on the other grade.

^aMain effect of grade.

^bMain effect of speed.

NS, not statistically significant.

TABLE 2. Pole kinetics associated with DP on flat (1°) and uphill (7°) terrain at medium and high submaximal speeds.

Parameter	DP _{flat} (1°)		DP _{up} (7°)		<i>F</i>	<i>P</i>	Effect Size ρ^2	Test Power
	24 km·h ⁻¹	28.5 km·h ⁻¹	13 km·h ⁻¹	15 km·h ⁻¹				
Peak pole force (N)	349 ± 67 ^{*,**}	386 ± 58	409 ± 62 ^{**}	424 ± 75	$F_{1,11} = 7.8^a$ $F_{1,11} = 7.6^b$	0.018 0.018	0.41 0.41	0.72 0.71
Time to peak pole force (ms)	86 ± 16 [*]	68 ± 7 [*]	138 ± 36 [*]	115 ± 30 [*]	$F_{1,11} = 44^a$ $F_{1,11} = 36^b$	<0.001 < 0.001	0.80 0.76	1.0 1.0
Relative time to peak pole force (% PT)	31.7 ± 5.3 ^{*,**,*}	24.7 ± 1.8 ^{*,**,*}	33.3 ± 8.0 ^{**}	27.6 ± 7.4	$F_{1,11} = 2.1^a$ $F_{1,11} = 41^b$	0.18 < 0.001	0.79	1.0
Resultant force impulse (N)	89 ± 14 [*]	82 ± 14 [*]	172 ± 32 [*]	150 ± 26 [*]	$F_{1,11} = 143^a$ $F_{1,11} = 29^b$	<0.001 < 0.001	0.93 0.72	1.0 1.0
Vertical force impulse (N)	71 ± 11 [*]	66 ± 11 [*]	137 ± 24 [*]	119 ± 21 [*]	$F_{1,11} = 138^a$ $F_{1,11} = 20^b$	<0.001 0.001	0.93 0.65	1.0 0.98
Horizontal force impulse (N)	48 ± 10 [*]	43 ± 9 [*]	96 ± 20 [*]	83 ± 15 [*]	$F_{1,11} = 158^a$ $F_{1,11} = 58^b$	<0.001 < 0.001	0.94 0.84	1.0 1.0
Propulsive force impulse (N)	50 ± 10 [*]	44 ± 9 [*]	113 ± 22 [*]	98 ± 17 [*]	$F_{1,11} = 200^a$ $F_{1,11} = 52^b$	<0.001 < 0.001	0.95 0.83	1.0 1.0
ACF (N)	76 ± 8 [*]	83 ± 8 [*]	194 ± 26	195 ± 31	$F_{1,11} = 308^a$ $F_{1,11} = 2.7^b$	<0.001 0.13	0.97	1.0
Average cycle propulsive force (N)	42 ± 6 [*]	45 ± 7 [*]	127 ± 18	127 ± 20	$F_{1,11} = 362^a$ $F_{1,11} = 2.3^b$	<0.001 0.16	0.92	1.0
Effectiveness index (%)	56 ± 6 ^{*,**,*}	54 ± 6 ^{*,**,*}	65 ± 3	65 ± 4	$F_{1,12} = 42^a$ $F_{1,12} = 1.4^b$	<0.001 0.26	0.92	1.0
External power (W)	176 ± 10 [*]	210 ± 12 [*]	397 ± 22 [*]	458 ± 26 [*]	$F_{1,12} = 4175^a$ $F_{1,12} = 3984^b$	<0.001 < 0.001	1.0 1.0	1.0 1.0
Poling power (W)	281 ± 38 [*]	356 ± 55 [*]	458 ± 65 [*]	531 ± 85 [*]	$F_{1,12} = 131^a$ $F_{1,12} = 141^b$	<0.001 < 0.001	0.92 0.93	1.0 1.0

The values presented are means ± SD. *F* and *P* values were obtained by two-way ANOVA (two grades, two speeds).

*Significantly different from all other conditions

**Significantly different from the other speed at the same grade.

***Significantly different from 15 km·h⁻¹.

****Significantly different from 13 km·h⁻¹.

*****Significantly different from both speeds on the other grade.

^aMain effect of grade.

^bMain effect of speed.

$P = 0.018$) and was higher at more rapid speeds (405 ± 66 N vs 379 ± 64 N, $P = 0.018$) (Table 2). The time required to attain peak pole force was 68% longer during DP_{up} than DP_{flat} (129 ± 33 ms vs 77 ± 12 ms, $P < 0.001$) and decreased at more rapid speeds. The relative time to peak pole force (% PT) was similar with both techniques ($30.4\% \pm 7.0\%$ vs $28.2\% \pm 3.0\%$, $P = 0.177$) and fell at higher speed ($P < 0.001$).

The impulse of the sideward (mediolateral) force component during DP_{up} was greater than during DP_{flat} (8.5 ± 3.1 N vs 5.1 ± 2.4 N, $P < 0.001$) and unaffected by speed, but represented only 5%–6% of the resultant force impulse. All other force impulses (resultant, vertical, horizontal, and propulsive) decreased at more rapid speeds and were greater (87%–123%) with DP_{up} than DP_{flat} (all, $P < 0.001$). The ACF was 144% higher during DP_{up} than DP_{flat} (195 ± 27 N vs 80 ± 8 N, $P < 0.001$) and the ACPF was 189% higher (127 ± 19 N vs 44 ± 6 N, $P < 0.001$) in both cases, independent of speed. The effectiveness index was 18% higher during DP_{up} than DP_{flat} ($65\% \pm 3\%$ vs $55\% \pm 6\%$, $P < 0.001$) and unaffected by speed. The external power was 121% higher during DP_{up} than DP_{flat} (427 ± 23 W vs 193 ± 11 W, $P < 0.001$), whereas the poling power was 56% greater (495 ± 75 W vs 318 ± 44 W, $P < 0.001$). Both increased at more rapid speeds ($P < 0.001$).

3D kinematics of the upper body. The elbow angle was more flexed at the time of pole plant ($65^\circ \pm 8^\circ$ vs $78^\circ \pm 9^\circ$, $P < 0.001$) and pole off ($112^\circ \pm 9^\circ$ vs $129^\circ \pm 9^\circ$, $P < 0.001$) and reached a lower minimum ($51^\circ \pm 6^\circ$ vs $55^\circ \pm 6^\circ$, $P = 0.002$)

during DP_{up} than DP_{flat}, with no effect of speed (Table 3). With DP_{up} a smaller range of motion in elbow flexion ($15^\circ \pm 7^\circ$ vs $23^\circ \pm 9^\circ$, $P = 0.004$) and extension ($62^\circ \pm 10^\circ$ vs $74^\circ \pm 9^\circ$, $P < 0.001$) which both became more pronounced at higher speed ($P = 0.028$ and $P = 0.014$) were observed. The shoulder angle at the time of pole plant was flexed less forward ($38^\circ \pm 9^\circ$ vs $45^\circ \pm 7^\circ$, $P < 0.001$) and less abducted ($70^\circ \pm 6^\circ$ vs $81^\circ \pm 13^\circ$, $P = 0.007$) during DP_{up} than DP_{flat}. Moreover, the thorax was more upright at pole plant ($42^\circ \pm 5^\circ$ vs $44^\circ \pm 5^\circ$, $P = 0.001$) and pole off ($68^\circ \pm 7^\circ$ vs $74^\circ \pm 5^\circ$, $P < 0.001$), but the maximal forward angle of approximately 75° was similar, and the thorax became more inclined as the speed increased.

The amplitude of the vertical COM displacement within a single cycle (including the additional rise of the COM along the incline of the treadmill) was 25% greater during DP_{up} than DP_{flat} (503 ± 35 mm vs 404 ± 49 mm, $P < 0.001$) and higher at more rapid speeds (438 ± 41 mm vs 470 ± 43 mm, $P = 0.001$). The vertical displacement of the COM exclusively due to the inclination was 140% greater during DP_{up} than DP_{flat} (204 ± 18 mm vs 85 ± 20 mm, $P < 0.001$). The maximal vertical position of the COM occurred closer in time to the pole plant during DP_{up} than DP_{flat} (99 ± 40 ms vs 157 ± 39 ms, $P = 0.002$), with no effect of speed. The horizontal distances between the COM and the pivot point of the boot binding at pole plant were similar during DP_{up} and DP_{flat} and longer at more rapid speeds (91 ± 33 mm vs 131 ± 58 mm, $P = 0.006$). At pole off with DP_{up}, the COM was positioned further behind the pivot point in horizontal direction than with DP_{flat} (180 ± 44 mm vs 123 ± 46 mm, $P < 0.001$).

TABLE 3. 3D kinematics of upper-body joint angles and the COM associated with DP on flat (1°) and uphill (7°) terrain at medium and high submaximal speeds ($N = 13$).

Parameter	DP _{flat} (1°)		DP _{up} (7°)		<i>F</i>	<i>P</i>	Effect Size η^2	Test Power
	24 km·h ⁻¹	28.5 km·h ⁻¹	13 km·h ⁻¹	15 km·h ⁻¹				
Elbow angle at pole plant (°)	77 ± 8*	78 ± 10*	65 ± 8	66 ± 9	$F_{1,12} = 31^a$	<0.001	0.72	1.0
Elbow angle minimum (°)	57 ± 8**	53 ± 5***	51 ± 7	50 ± 5	$F_{1,12} = 0.1^b$	0.76	0.56	0.95
					$F_{1,12} = 15.1^a$	0.002		
					$F_{1,12} = 7.7^b$	0.017		
Elbow angle at pole off (°)	129 ± 9*	129 ± 9*	111 ± 11	112 ± 8	$F_{1,12} = 86^a$	<0.001	0.88	1.0
					$F_{1,12} = 0.3^b$	0.61		
Shoulder flexion angle at pole plant (°)	47 ± 7**	44 ± 8**	39 ± 9**	37 ± 10**	$F_{1,12} = 23^a$	<0.001	0.66	0.99
					$F_{1,12} = 10.3^b$	0.007		
Shoulder abduction angle at pole plant (°)	79 ± 13	84 ± 14**	65 ± 5**	76 ± 7	$F_{1,12} = 10.3^a$	0.007	0.46	0.84
					$F_{1,12} = 21^b$	0.001		
Thorax angle at pole plant (°)	42 ± 5**	45 ± 6	39 ± 5**	45 ± 5	$F_{1,12} = 18^a$	0.001	0.60	0.97
					$F_{1,12} = 48^b$	<0.001		
Thorax angle minimum (°)	73 ± 5****,*****	78 ± 5*****	72 ± 6*****	76 ± 5	$F_{1,12} = 2.1^a$	0.17	0.80	1.0
					$F_{1,12} = 46^b$	<0.001		
Thorax angle at pole off (°)	71 ± 5	78 ± 6**	66 ± 7**	70 ± 7	$F_{1,12} = 29^a$	<0.001	0.71	1.0
					$F_{1,12} = 42^b$	<0.001		
Vertical displacement of COM within a cycle (mm)	377 ± 48****	432 ± 52	500 ± 36****	507 ± 35	$F_{1,12} = 99^a$	<0.001	0.89	1.0
					$F_{1,12} = 17^b$	0.001		
Instant of COM maxima with respect to pole plant (ms)	-165 ± 34**	-150 ± 44**	-99 ± 34	-99 ± 49	$F_{1,12} = 15.9^a$	0.002	0.57	0.95
					$F_{1,12} = 2.4^b$	0.15		
Horizontal distance from COM to pivot at pole plant (mm)	91 ± 33****	143 ± 51*****	91 ± 55	118 ± 68	$F_{1,12} = 0.9^a$	0.35	0.48	0.86
					$F_{1,12} = 11.1^b$	0.006		
Horizontal distance from COM to pivot at pole off (mm)	-125 ± 44	-121 ± 50	-191 ± 41**	-170 ± 49**	$F_{1,12} = 39^a$	<0.001	0.76	1.0
					$F_{1,12} = 5.1^b$	0.044		

The values presented are means ± SD. *F* and *P* values were obtained by two-way ANOVA (two grades, two speeds).

*Significantly different from both speeds at other grade.

**Significantly different from all other conditions.

***Significantly different from 15 km·h⁻¹.

****Significantly different from the other speed at the same grade.

*****Significantly different from 13 km·h⁻¹.

^aMain effect of grade.

^bMain effect of speed.

3D kinematics of the lower body. The hip angle at pole plant ($140^\circ \pm 11^\circ$ vs $125^\circ \pm 12^\circ$, $P < 0.001$) and pole off ($101^\circ \pm 9^\circ$ vs $95^\circ \pm 7^\circ$, $P = 0.009$) was more extended during DP_{up} than DP_{flat}, but the minimal hip angles were similar and unaffected by speed (Table 4). The knee angle at pole plant was similar with both techniques, but more flexed when minimal ($121^\circ \pm 6^\circ$ vs $108^\circ \pm 8^\circ$, $P < 0.001$) and at the time of pole off ($124^\circ \pm 7^\circ$ vs $117^\circ \pm 9^\circ$, $P = 0.007$) during DP_{up}, increasing with speed at all three of these timepoints ($P = 0.027$ – 0.002). The ankle angle at pole plant was similar, whereas the minimal ankle angle ($63^\circ \pm 2^\circ$ vs $50^\circ \pm 8^\circ$, $P < 0.001$) and ankle angle at pole off ($73^\circ \pm 5^\circ$ vs $64^\circ \pm 11^\circ$, $P = 0.007$) were more dorsiflexed during DP_{up}. Maximal heel raise was similar for DP_{up} and DP_{flat}, whereas the instant of maximal heel raise was closer to the time of pole plant during DP_{up} (19 ± 57 ms vs 61 ± 23 ms, $P = 0.023$).

Correlations to V_{peak} . Body mass and relative pole length (% body height) were positively correlated with V_{peak} during both DP_{flat} and DP_{up} ($r = 0.53$ – 0.75 , $P < 0.05$). PT, cycle time, and cycle length at both moderate and high speeds with DP_{flat} were correlated to V_{peak} ($r = 0.53$ – 0.82 , $P < 0.05$), but not with DP_{up}. ST was positively related to V_{peak} only at the more rapid skiing speeds during both DP_{flat} ($r = 0.82$, $P < 0.05$) and DP_{up} ($r = 0.61$, $P < 0.05$). With the exception of the magnitude of heel raise at the more rapid speeds ($r = 0.55$, $P < 0.05$), no further correlations between V_{peak} and other parameters during DP_{up} were found.

The time to peak pole force during DP_{flat} was positively correlated to V_{peak} at both moderate ($r = 0.56$, $P < 0.05$) and

high skiing speeds ($r = 0.82$, $P < 0.05$). With the exception of a correlation between the resultant force impulse and V_{peak} during high-speed DP_{flat} ($r = 0.56$, $P < 0.05$), no further correlations between peak pole force, impulse of force, average force, and effectiveness were found. With DP_{flat}, at both speeds, the distance between the pole and the pivot point at pole plant, the entire distance covered during the poling phase, and the forward pole angle at pole plant were correlated with V_{peak} ($r = 0.61$ – 0.81 , $P < 0.05$). Skiers with less pronounced minimal knee angles during the poling phase ($r = 0.52$ and 0.61 , $P < 0.05$) achieved higher V_{peak} at both inclines with DP_{flat}.

DISCUSSION

The present study revealed that DP_{up} differs dramatically from DP_{flat} in a number of respects with the main findings being illustrated schematically in Figure 2. With DP_{up} the cycle rate was higher and increased with speed and the cycle length shorter and independent of speed, whereas the ratios between poling and ST were approximately 1:1 and 1:3 for DP_{up} and DP_{flat}, respectively, independent of speed in both cases. DP_{up} involved greater peak pole forces generated slightly later during the poling phase, higher impulses for all force components, higher power output and a more effective translation of the resultant force into propulsion. During DP_{up}, skiers demonstrated more flexed elbows, with less pronounced range of motion in elbow flexion and extension; shoulder angles less flexed in the forward direction and less

TABLE 4. 3D kinematics of lower-body joint angles and heel raise associated with DP on flat (1°) and uphill (7°) terrain at medium and high submaximal speeds ($N = 13$).

Parameter	DP _{flat} (1°)		DP _{up} (7°)		<i>F</i>	<i>P</i>	Effect Size $\rho\eta^2$	Test Power
	24 km·h ⁻¹	28.5 km·h ⁻¹	13 km·h ⁻¹	15 km·h ⁻¹				
Hip angle at pole plant (°)	126 ± 13*	124 ± 11*	142 ± 10	139 ± 13	$F_{1,12} = 95^a$ $F_{1,12} = 2.9^b$	<0.001 0.11	0.89	1.0
Hip angle minimum (°)	97 ± 8**	91 ± 6	92 ± 8	94 ± 13	$F_{1,12} = 0.4^a$ $F_{1,12} = 1.4^b$	0.53 0.26		
Hip angle at pole off (°)	98 ± 7	92 ± 7***	100 ± 7	102 ± 12	$F_{1,12} = 9.5^a$ $F_{1,12} = 1.5^b$	0.009 0.24	0.44	1.0
Knee angle at pole plant (°)	141 ± 8	137 ± 7**	142 ± 11	139 ± 10	$F_{1,12} = 0.3^a$ $F_{1,12} = 6.3^b$	0.60 0.027	0.34	0.64
Knee angle minimum (°)	125 ± 6***	117 ± 6***	109 ± 7	107 ± 10	$F_{1,12} = 38^a$ $F_{1,12} = 9.8^b$	<0.001 0.009	0.76 0.45	1.0 0.82
Knee angle at pole off (°)	128 ± 7***	119 ± 8	119 ± 9	116 ± 11	$F_{1,12} = 10.8^a$ $F_{1,12} = 16.5^b$	0.007 0.002	0.47 0.58	0.85 0.96
Ankle angle at pole plant (°)	70 ± 4****	67 ± 5	65 ± 10*	62 ± 13	$F_{1,12} = 2.6^a$ $F_{1,12} = 6.1^b$	0.12 0.029	0.34	0.63
Ankle angle minimum (°)	65 ± 3***	62 ± 2***	50 ± 7	50 ± 10	$F_{1,12} = 28^a$ $F_{1,12} = 2.0^b$	<0.001 0.18	0.70	1.0
Ankle angle at pole off (°)	76 ± 5***	71 ± 5***	66 ± 11	63 ± 12	$F_{1,12} = 10.4^a$ $F_{1,12} = 19.2^b$	0.007 0.001	0.46 0.62	0.84 0.98
Maximal heel raise (mm)	55 ± 34*****	96 ± 44	74 ± 41	77 ± 50	$F_{1,12} = 0.0^a$ $F_{1,12} = 4.0^b$	0.99 0.067		
Instant of maximal heel raise with respect to pole plant (ms)	-54 ± 29	-67 ± 18	-2 ± 47***	-4 ± 67	$F_{1,12} = 6^a$ $F_{1,12} = 12.4^b$	0.023 0.004	0.36 0.51	0.67 0.90

The values presented are means ± SD. *F* and *P* values were obtained by two-way ANOVA (two grades, two speeds).

*Significantly different from both speeds at other grade.

**Significantly different from 13 km·h⁻¹.

***Significantly different from all other situations.

****Significantly different from 15 km·h⁻¹.

*****Significantly different from the other speed at the same grade.

^aMain effect of grade.

^bMain effect of speed.

abducted throughout the poling phase; more flexed knees and dorsiflexed ankle joints; and a less flexed thorax and hip angle at the time of pole plant and pole off.

During DP_{up}, skiers raised their COM 25% more (including the steady elevation of the COM along the incline), attaining the maximal position, as well as maximal heel raise at timepoints closer to pole plant and demonstrated no distinct preparation phase, such as that seen with DP_{flat}. Body mass, relative pole length, and ST at higher speeds were positively correlated to V_{peak} both on flat and uphill terrain, but PT and cycle length were positively related to V_{peak} only during DP_{flat}. During DP_{up}, the magnitude of heel raise was positively related to V_{peak} . During DP_{flat}, the faster skiers took longer to reach peak force, exhibited less knee flexion during the poling phase, planted their poles more in the forward direction and covered a greater total distance throughout the poling phase. Finally, V_{peak} during both situations was closely related.

Cycle characteristics and interactions between forces. In comparison to DP_{flat}, during DP_{up}, the cycle rate was almost 30% higher and cycle length was 23% shorter, despite the slower speed. Slower skiing speeds on the same terrain are usually associated with a reduced cycle rate (11,14,24,25). However, the augmented effect of gravity along the incline and lack of kick wax requires a skier to use more rapid and shorter cycles to avoid excessive loss of speed. The effect of incline on cycle rate during DP observed here is in line with the findings of Millet and colleagues (13).

During contemporary DP at top speeds on flat terrain, PT can be as brief as 200 ms, which is comparable to ground

contact times during jumping tasks, such as the drop jump. Indeed, a short PT might limit performance, emphasizing the need for explosive production of high peak forces (10,11,21,25,26). However, with DP_{up}, the PT was 56% longer than with DP_{flat}, constituting approximately 50% versus 25% of the total cycle, respectively, at both speeds in agreement with previous reports on DP_{flat} (10,21,25) (Fig. 1). This longer PT during DP_{up} is also reflected in greater peak pole forces slightly later during the poling phase, distinctly greater force impulses, greater power output, and better effectiveness. These greater pole forces (i.e., peak pole force, impulse of forces, power output) might be explained by the slower skiing speeds (13 and 15 km·h⁻¹ vs 24 and 28.5 km·h⁻¹), enabling longer generation of force, as well as by the enhanced pull of gravity that must be overcome. Moreover, the better effectiveness is attributed to a pole angle that is more advantageous for generation of propulsive forces, especially during the first part of the poling phase. It is noteworthy that the relative timing of force (time to peak pole force) was similar for DP_{up} and DP_{flat}. Therefore, despite distinct differences in the cycle characteristics, the basic pole kinetics appeared to be very much alike.

In contrast to PT during DP_{flat}, the 48% shorter ST during DP_{up} appears to be the limiting factor. It is noteworthy that the ST measured at the two submaximal speeds are 10%–30% shorter than those reported previously during DP at maximal speed on flat terrain (14,24,25) and on a 5.1% (2.9°) incline (13). The more pronounced gravitational component on the incline requires the skiers to reposition their body and poles rapidly in preparation for the next pole plant to avoid excessive reduction of speed during this phase. The calculated

FIGURE 1—A, Absolute PT and ST and (B) relative (% cycle time) PT during DP on flat and uphill at two submaximal speeds (mod, high).

speed loss during the nonpropulsive swing phase, based on the effect of gravity and friction, was approximately 0.17 and 0.14 m·s⁻¹, respectively, at the two submaximal speeds during DP_{flat} and almost 3.5 times greater during DP_{up} (0.56 and 0.49 m·s⁻¹). Although not analyzed here, it can be assumed that the swing phase requires special technical skills which become more important with every increase in incline. It is

noteworthy that the reduction in ST with inclination observed here is not demonstrated during running or walking at constant speed (5,6) or when running at top speed (27), during which stride kinematics are reported to be remarkably constant.

Joint kinematics. In comparison to DP_{flat}, DP_{up} involved more highly flexed elbow joints at the time of pole plant, followed by less pronounced elbow flexion (14° vs 23°) and extension (61° vs 74°), as well as less abduction and forward flexion of the shoulder (i.e., a more compact upper-body posture, with the arms closer to the body). Furthermore, during DP_{up}, the angle of the trunk and hip were less flexed at both pole plant and pole off, whereas flexion and extension of the hip, knee, and ankle were more pronounced. At pole off, the hands holding the poles were at the same position with both techniques (approximately 12 cm in front of the center of the pelvis in the horizontal direction), thereafter moving backward so that at the end of the backward swing (which lasted 4 times longer during DP_{flat}), they were approximately 7 cm in front of the pelvis with DP_{up} and 6 cm beyond this point with DP_{flat}, respectively (Fig. 2). Thus, to cope with the reduced ST, DP_{up} is characterized by a more upright posture, an extended “pumping” motion of the lower-body joints, a shorter backward swing of the arms with less extended elbow joints at pole off, and a more synchronized trunk extension and forward movement of the arms during the swing phase. Altogether, these differences enable the skier to reposition his body and poles more rapidly for the next pole plant and assist in the vertical rise in COM required along the incline.

Analogies with sprint running can be found. The so-called front side mechanics are typically characterized by high knees during the swing phase before ground contact (comparable to the high position of the COM during both DP_{flat} and DP_{up} before pole plant), less extension at the hip and knee joints at toe-off, and less maximal hip extension during the swing phase (comparable to the less extended elbows and shorter backward arm swing during DP_{up}) (12). Thus, sprint runners produce most of the applied ground reaction forces during the first half of their stance (2,12), facilitating an early shift to the swing phase, in analogy with our current findings in DP_{up}.

With DP on both flat and uphill terrain, the skiers demonstrated a clear shift of their COM in front of the pivot point at the time of pole plant, enabling them to increase the

FIGURE 2—Schematic illustration of the major findings of the present study.

pressure on the poles through greater use of their body mass (10,11). In addition, the more pronounced lower-body motion during DP_{up} allows the body mass to be used more effectively for production of pole force (10). As described by Danielsen et al. (3), during the recovery (swing) phase, the legs perform work that raises the COM (high-heel and high-hip positions) and during the subsequent poling phase, this gravitational potential energy is transformed directly into kinetic energy (“falling on the poles”).

During DP_{flat} , the majority of our skiers demonstrated a characteristic preparation phase (21), during which they reached their highest position and exhibited the most pronounced forward swing of the poles approximately 100 ms before pole plant. However, during DP_{up} , none of the skiers demonstrated such a distinct preparation phase, mainly because of the shorter swing phase, and the time-points at which vertical COM and maximal heel raise were maximal were closer in time to the pole plant.

Comparison to previous work. To the best of our knowledge, ours is the first analysis of the 3D motion of the trunk, COM, shoulders, and poles at high skiing speeds using DP on both flat and uphill terrain, and we have observed significant differences from the manner in which this technique was performed two decades ago (18). Contemporary DP is characterized by a smaller flexion range of motion of the thorax (28° here vs the 47° reported by Smith et al. (18) with less pronounced forward lean (maximal angle of 70° – 76° vs 95°), reduced shoulder flexion (37° – 47° vs 50° – 120°) and augmented vertical rise in the COM throughout the entire poling cycle (377–507 mm vs 190 mm). Moreover, in comparison to findings from 2005 on flat terrain (10), we observed more flexed elbow (69° vs 50° – 57°), knee (138° vs 107° – 125°), hip (101° vs 91° – 97°), and ankle (86° vs 50° – 65°) joints during the poling phase. One of our most important kinetic findings is the 53%–80% greater peak pole force, from approximately 235 N to 360–423 N. In addition, the ACF observed here (195 N) was 2.7- to 3-fold greater than that reported by Millet and colleagues (13) in 1998 (64–72 N).

In short, when performing DP, today’s skiers flex their trunk less and exhibit more pronounced utilization of their lower body, more flexion of the joints during the poling phase (to enable greater application of body mass for propulsion) and more extension to a higher heel–higher hip position during the swing phase (9,10), enabling them to generate greater pole forces. Less trunk flexion might reduce loading of the cross-country skier’s lower back and, thereby, the prevalence of back problems among cross-country skiers.

Correlations with performance. Our current findings regarding associations between various parameters and performance during DP_{flat} are in agreement with those of Stöggl and Holmberg (21), whereas in the case of DP_{up} , we observed very few such correlations. One possible explanation is that the skiing technique and/or V_{peak} on the uphill incline was more homogenous, a proposal supported by the smaller coefficient of variation in V_{peak} with DP_{up} (4.2%) than DP_{flat}

(5.3%). Another possibility is that the lack of correlations DP_{up} might be related to different physiological demands.

The faster skiers had more body mass and relatively longer poles, in line with a previous report on elite sprint cross-country skiers (20). Faster skiers during DP_{flat} , but not DP_{up} , planted their poles more in the forward direction and at less of an angle and used a longer poling phase and more time before attaining peak pole force, in agreement with our previous findings (21), as well as those of Smith and colleagues (18). Exaggerated flexion of the knees correlated negatively with V_{peak} during DP_{flat} . Therefore, despite the fact that skiers today use their lower bodies to an even greater extent (10,18), it appears that a further increase in utilization of the lower body is less beneficial.

Future lines of investigation and limitations. Here, we have described several biomechanical characteristics of elite cross-country skiers while performing DP_{up} that differ from those associated with DP_{flat} , as well as the factors that influence performance. However, several questions remain to be investigated on elite skiers in the laboratory, as well as on snow: 1) How do various physiological factors influence DP performance on uphill versus flat terrain? 2) At what incline do the other classical techniques become superior to DP for elite skiers and which external factors (e.g., snow characteristics and the profile of the track) determine this shift? 3) Under what conditions might it be favorable to use DP exclusively (with only glide wax), compared with using all of the classical techniques (both glide and grip wax) during a race? 4) Exactly how is the mechanical energy of the COM converted between gravitational and kinetic forms during contemporary DP?

Furthermore, the substantial differences in the kinematics and kinetics associated with DP_{up} and DP_{flat} might not be entirely due to the incline. Because the power output under the two conditions was quite different (approximately 495 W vs 318 W), use of an additional condition with similar power output on the flat and inclined surfaces would have helped to clarify whether the incline or the difference in power was primarily responsible for the differences observed here. Furthermore, one might expect that the estimated external power (power exerted against friction and gravity) is in balance with the poling power measured. The higher poling power actually detected (especially in the case of DP_{flat}) might reflect either errors in the measurement of the pole force and 3D kinematics and/or limitations associated with estimation of the external power. This estimation did not take into account 1) accelerations and decelerations of the COM within a given cycle, 2) alterations in rolling friction within a cycle as a result of changes in the normal force acting on the roller skis, or 3) possible shear forces associated with controlling the movement of the roller skis in the forward direction.

CONCLUSIONS

This study demonstrates distinct differences between DP cross-country skiing on flat versus uphill terrain. One of the

major limitations with DP_{flat} appears to be the short ground contact, whereas during DP_{up}, the approximately 50% shorter ST appears to be a limitation. On uphill terrain, it is possible to produce distinctly higher force impulses and peak pole force during the cycle. At the same time, the reduced ST during DP_{up} appears to necessitate a more upright posture, with greater utilization of the lower body employing a characteristic “pumping” motion, more flexed elbow joints and less maximal backward swing of the arms. Together with well-synchronized trunk extension and forward swing of the arm, these features allow more rapid repositioning of the body and poles for the next pole plant and assist in the enhanced vertical rise of the COM required by the incline. With both DP_{up} and DP_{flat}, longer poles appeared to allow attainment of higher peak velocities. However, it is questionable whether merely an increase in pole length, without the greater strength and conditioning possibly required and adequate skiing technical skills to handle longer poles, would enhance DP velocity, and further examination of this question is warranted.

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Our data document the revolutionary changes in the DP technique that have occurred over the past decades and enable skiers to use this technique to a greater extent on a variety of inclines. The trend toward exclusive utilization of the DP technique during classical races challenges the traditional classical style in which diagonal skiing has been the primary subtechnique. More studies of the DP technique are warranted, including further evaluation of its advantages and disadvantages on different types of terrain, snow conditions, and with various racing formats.

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