Comparison of Exclusive Double Poling to Classic Techniques of Cross-country Skiing

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ABSTRACT

STÖGGL, T., O. OHTONEN, M. TAKEDA, N. MIYAMOTO, C. SNYDER, T. LEMMETTYLÄ, V. LINNAMO, and S. J. LINDINGER. Comparison of Exclusive Double Poling to Classic Techniques of Cross-country Skiing. *Med. Sci. Sports Exerc.*, Vol. 51, No. 4, pp. 760–772, 2019. **Introduction**: This study aimed to 1) determine basic physiological demands during a simulated on-snow cross-country skiing (XCS) race when using grip-waxed skis (all classic XCS techniques [CLASSIC]), versus glide-waxed skis for exclusive double poling (DP) and 2) analyze in which track sections DP is different from CLASSIC under controlled gliding conditions in elite junior and senior skiers. **Methods**: Nineteen male and female elite XC skiers performed 1) two randomized simulated XCS races over 5.3 km using DP or CLASSIC measuring section times, $\dot{V}O_2$, HR, blood lactate, and RPE; and 2) $\dot{V}O_{2peak}$ tests using diagonal stride and DP on treadmill. **Results**: The total group showed no differences in performance or physiological responses between DP and CLASSIC. Elite male skiers achieved improved (~23 s, $P < 0.05$), male juniors equal ($P > 0.05$) and females worse (~43 s, $P < 0.05$) performance with DP versus CLASSIC. Flat and undulating terrain favored DP in men, whereas uphill favored CLASSIC in females (~60 s). Uphill sections showed the greatest group differences. Greater RPE was found in the arms during DP, whereas RPE was greater in the legs using CLASSIC. $\dot{V}O_{2peak}$ in DP was ~95% of $\dot{V}O_{2max}$. **Conclusions**: Male skiers demonstrated superior performance with exclusively using DP on a Fédération International de Ski regulation-compliant XCS track, whereas junior males achieved similar, and females' weaker performance using DP versus CLASSIC. The greatest potential in females is in uphill sections where they distinctly lose time. Exclusive DP might only be beneficial in athletes with high upper-body capacity, and double-pole–specific training and technique. To generalize the findings of the current study, further analysis of snow conditions and course topography is required. **Key Words:** BLOOD LACTATE, GRIP-WAX, HEART RATE, OXYGEN UPTAKE, PHYSIOLOGICAL RESPONSE, RPE, SIMULATED RACE

Recently, the double poling (DP) technique has rapidly developed as one of the more used of the four main techniques (DP, DP with kick [DPK], diagonal stride [DIA], and herringbone) during classic cross-country skiing (XCS). In the last decade, a new sprint DP technique was proposed (1), which has recently been developed further (2–5). To date, several elite skiers exclusively execute the DP technique successfully throughout an entire race instead of using grip-wax, which allows utilization of all classic XCS techniques, such as DIA or DPK (1–3,6–8). In the long-distance Ski-Classics series, currently almost all races, (except the 50-km"Reistadløpet," which has two long uphill sections of more than 300 vertical meters), are won by exclusively using the DP technique. Even in World Cup distance racing, certain skiers have begun to successfully use exclusively DP (two podiums and two victories; unpublished data based on personal video analysis). By using skis without kick-wax during DP, the gliding properties of the ski may be enhanced. Combined with improvements in upper-body capacity and improved technique, certain athletes may be more economical and efficient on certain sections of the course. In an attempt to counteract this development, the Fédération International de Ski (F.I.S.) recently introduced two new rules to limit the exclusive use of DP: First, maximum pole

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length is limited to 83% of the athletes height, and second, introducing no-DP zones where exclusive DP is prohibited.

One question arises: Can this development in favor of the DP technique be explained based on scientific state of the art knowledge? Hoffman and Clifford (9) demonstrated the best economy on flat terrain and moderate speeds (14.2 $\text{km}\cdot\text{h}^{-1}$) using DP, whereas DIA elicited the greatest physiological demand and highest perceived effort among all analyzed classic and skating XCS techniques. The improved economy using the DP technique was attributed to more effective storage and recovery of elastic energy, a greater proportion of forces produced in line with the direction of travel, and a lower air resistance due to a partially tucked position. At that time, it was suggested that the greater economy of DP may be advantageous in certain race conditions if the upper body is adequately prepared (10). In this context, Stöggl and Holmberg (2) recently demonstrated that changes that have occurred in the DP technique enable this technique to be used more extensively on a variety of inclines. On flat terrain, the very short ground contact time has been suggested to be the main limitation, whereas on steep uphill terrain, the considerable reduction in swing time and high pole forces challenge the athlete. By adapting a special uphill DP technique (e.g., "pumping DP"), more rapid repositioning of the body is guaranteed and enhances uphill DP performance. However, it was also speculated that extended use of the DP technique might be limited by its greater anaerobic demands (11). More than 20 yr later, Pellegrini and co-workers (12) demonstrated that, in national level XC skiers roller skiing on a treadmill, DP is the preferred technique at low inclines (up to 2°C). At moderate inclines (2°C–3°C), their skiers switched to DPK and all used DIA on inclines greater than 6°C. In that investigation, no skier used DP on an incline steeper than 4°C. Furthermore, when focusing on the sprint start, it was demonstrated that using DIA was faster over the first 38 m when compared with exclusive DP (13). These later findings would not support the current trend for exclusive execution of DP during XCS racing.

Although research on the DP technique has been extensive during the past 13 yr, both with elite skiers in the laboratory roller skiing on a treadmill (1–3,14,15) and with regional-to-national level skiers (12), to date, no reports on elite athletes during competition on snow have appeared. Therefore, the physiological mechanisms and performance differences behind the exclusive DP versus all classic XCS techniques (adapted to track topography) are not yet established in a valid environment. Furthermore, the effects of biological sex or maturity level (e.g., elite juniors vs elite seniors) were not within the scope of laboratory or field trials with respect to this research question.

The aims of the current study were: 1) determine the basic physiological demands during a simulated on-snow XCS race when using grip-waxed skis and all classic XCS techniques (CLASSIC) versus only glide-waxed skis and exclusive DP with female and male world-class athletes and junior skiers under controlled gliding conditions; 2) analyze in which sections of a track exclusive DP might lead to gained or lost time compared with CLASSIC, considering both the aspect of performance level as well as sex. The hypotheses were that 1) based on their higher DP capacity, senior male XC skiers would demonstrate improved performance using the DP technique when compared to CLASSIC, while in female and or junior skiers it would be the opposite; 2) exclusive DP would be especially superior in flat and slightly uphill sections of a track, whereas DIA would be in favor on steeper uphills (i.e., >4°C).

METHODS

Participants. Nineteen elite female and male XCS athletes (current members of the Finnish National Team or Junior Team) volunteered to take part in this study (mean ± SD: age, 24 ± 7 yr; body mass, 71 ± 9 kg; height, 178 ± 6 cm). All participants were well-trained professional and semiprofessional athletes (mean $\dot{V}O_{2\max}$ 71.1 ± 7.6 $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ (range, 60–85 $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$)], routinely performing 7 to 10 training sessions each week (mean, 705 $\text{h}\cdot\text{yr}^{-1}$; range, 550–770 h), with approximately 110 $\text{h}\cdot\text{yr}^{-1}$ [range, 95–130 h] of DP or specific upper-body training). They had been competing in XC skiing competitions for the past 8 to 20 yr and were all healthy during the entire period of testing. Seven of these skiers had earned World Cup points, two of whom were among the top 4 results. For statistical analysis, participants were grouped according to performance level within the male skiers (senior males, international level [n = 5]; junior males, national level [n = 8]), and senior and junior females of national and international level (n = 6). Participants were fully informed about the study details and participation requirements with written and verbal information before providing written informed consent to participate. The study received approval from the local Ethical Committee (EK-GZ: 05/2017) and was conducted in accordance with the Declaration of Helsinki.

Overall design. To accommodate the skier's tight competition schedule, this study was carried out from March 20 to 29, 2017, after the end of the last World Cup and prior to the Finnish national championships. Due to illness, two senior international level elite female skiers who volunteered to take part in the study were not able to attend the measurements (not included above) and thus the females were not grouped as elite and juniors as males were. Each participant was analyzed on two separate days with 1) tests on snow (race simulation) as well as 2) tests in the laboratory on a treadmill using roller skis. On the first day, two separate simulated XCS races (randomized order) on snow over a distance of 5.3 km were performed. This distance of approximately 5 km (shortest distance applied in female skiers distance competitions) was chosen 1) to keep the overall load manageable for skiers performing repeated runs on a race track with a 1-h break in between, 2) to provide a proper study and test economy (logistics), and 3) to be able to get world-class athletes into the study (time budget). One trial was performed using grip-waxed skis, enabling leg push-offs and all appropriate classic techniques (CLASSIC) where appropriate, and one trial with only glide-waxed skis (entire ski base), allowing only for DP. In some parts (very steep inclines), the herringbone was allowed in case of lacking upper-body capacity for pure DP (e.g., in case of some of the females). The time engagement of each participant during the on-snow tests (including installation of the equipment at start and removal at the end of the tests) was approximately 2 h. On the second session, laboratory tests with anthropometrical measurements and two $\dot{V}O_{2peak}$ roller skiing ramp tests on the treadmill were performed. At least 48 h rest (2–5 d) was given between visits. On both testing days, all participants were asked to report well hydrated and to refrain from consuming alcohol and engaging in strenuous exercise at least 24 h before testing.

$\dot{V}O_{2peak}$ laboratory tests. The laboratory tests included the determination of body mass, body height, absolute, and relative pole length. Absolute pole length was measured from the tip of the pole to the strap, and relative was defined in terms of percent body height in shoes (F.I.S. international competition rule 343.8.1). Additionally, two incremental roller skiing (roller skis: Marwe 800 XC, wheel N°6, Marwe Oy, Hyvinkää, Finland) ramp protocols to volitional exhaustion with DIA and DP only (randomized order) were completed to get information about their peak performance and peak physiological output in both skiing techniques. The DP and DIA laboratory performance test protocols were selected based on tests that the athletes were familiar with in performance testing and training settings. To link upper-body capacity to natural skiing performance, the DP protocol was selected as an indicator for upper-body capacity (in contrast to an isolated upper-body exercise as, for example, arm cranking, or seated pull-down exercises) as previous studies have also reported (e.g., (16,17)). Each roller skiing protocol consisted of a 10-min warm-up phase, with 6 min low-intensity (~70% HR_{max}) and 4 min moderate-intensity (~80% HR_{max}), after which the ramp protocol in the respective technique began. In between the two ramp protocols, there was a break of 20 min consisting of a 2-min passive rest in which blood lactate was collected 1 min postexercise, followed by a 3-min active cool-down with blood sampling 5 min postexercise and a 15-min passive break before start of the warm-up for the second ramp test. The DIA warm-up protocol consisted of 6 min at 8 $km{\cdot}h^{-1}$ and 3° grade, followed by 4 min at 10 $km{\cdot}h^{-1}$ and 3° grade. The DIA ramp protocol had a fixed treadmill speed of 10 $km{\cdot}h^{-1}$ at a starting grade of 3° which was increased 1° every minute until volitional exhaustion. The cooldown consisted of 3 min at 6 $km{\cdot}h^{-1}$ and 3° grade. The DP warm-up protocol consisted of 6 min at 10 $km{\cdot}h^{-1}$ and 2° grade, followed by 4 min at 12 $km{\cdot}h^{-1}$ and 2° grade. The DP ramp protocol had a fixed grade of 2°, a starting speed of 14 $km{\cdot}h^{-1}$ which was increased 1 $km{\cdot}h^{-1}{\cdot}min^{-1}$ until volitional exhaustion. A previous study has shown a close link between flat and uphill DP performance in elite XC skiers, thus, the selection of the 2° inclination for the DP test (2). This inclination also represents a grade familiar to a majority of study participants. Cool-down was the same as that for DIA. For both protocols, peak values for $\dot{V}O_2$, HR, and blood lactate were established.

Simulated XCS races. In a counterbalanced X-over design, each of the participants performed one trial with CLASSIC and one trial with exclusive DP with 45-min rest in between. Each trial took place over 5.3 km (two laps of 2.65 km) on a competition track meeting the F.I.S. homologation (course design) regulations. The total climb was 178 m, with a maximal climb of 22 m and a height difference of 23 m. The exact track profile for one lap is illustrated in Figure 1.

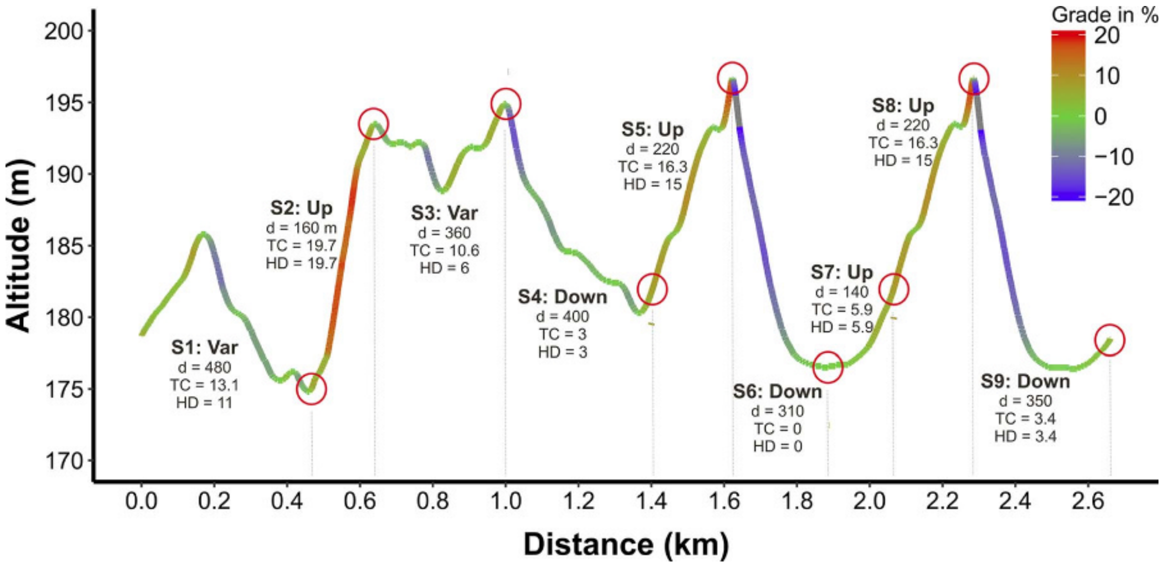

FIGURE 1—Track profile for one lap of the simulated race. S, section; d, section distance in meter; TC, total climb within section in meter; HD, height difference within section in meter; Var, variable terrain consisting of flat and undulating terrain with moderate inclines with skiers using DP or DPK; Up, uphill section; Down, downhill section.

The track was prepared each morning with one classic track all along the track. To prevent shortcutting, the skiing line within the curves was marked. The area for the section times (buried magnets—see further down) was marked with fluorescent spray. Each participant used his/her own poles (similar in the laboratory and outdoor tests and for both conditions), whereas the skis were provided by expert ski-technicians of the Finnish national team. The glide wax was similar for both conditions and across all athletes. The ski base grind and ski stiffness was similar for both conditions within each athlete (ski stiffness was selected relative to the body weight of the skier), and grip wax was selected according to snow conditions.

After an individual warm-up of approximately 30 min including the testing of the skis (grip and glide) the participants were instrumented with the measurement equipment (HR belt, $\dot{V}O_2$ portable system, and magnetometer attached on the ski). After the $\dot{V}O_2$ system was started, the athlete performed a race warm-up for approximately 8 min on the competition track. After a short break (1–2 min), where the timing system (magnetometers) was started, the skier performed the first race simulation using either the CLASSIC or DP condition. Athletes' rate of perceived exertion levels (RPE-BORG scale, 6–20) were taken at the end of the race simulation and the timing system was switched off. Blood lactate was taken from the fingertip in the second and fifth minute post time trial, and the $\dot{V}O_2$ system was removed. After a passive break of 5 min, the athlete performed an easy cool-down for 20 min on skis including a ski glide test, followed by a 10-min rest where the $\dot{V}O_2$ system was reinstalled. After another 8-min competition warm-up (similar to test trial 1), the second simulated XC skiing race, using the other condition, was performed with maximal effort. The same post time trial procedure as in the first condition was implemented.

During each trial $\dot{V}O_2$, HR, blood lactate, section times, whole-body RPE ($RPE_{WHOLE\text{-}BODY}$), legs only (RPE_{LEGS}), arms only (RPE_{ARMS}) and trunk only (RPE_{TRUNK}) were recorded. Only the mean and peak values across the entire time trial for the collected physiological parameters were entered into the statistical analysis. Furthermore, after each trial, the used skis were tested on an 80-m-long gliding track by the athlete to determine the ski gliding properties for each condition. The ski testing place was wind sheltered and consisted of a gentle downhill that provided a velocity that was comparable to race skiing speeds. Gliding tests were done using the Ski Speed ski timer (Tieto-Oskari Oy, Kajaani, Finland). Each ski was tested five times, the best and worst records were removed. The mean value of the remaining three trials was used for further analysis.

External conditions, such as snow and air temperature, humidity, as well as qualitative descriptions of the snow characteristics and atmospheric cloud cover, were measured and documented according to the methods used by the Finnish ski team. Air temperature and humidity were tested using Vaisala HM40 (Vaisala Oy, Vantaa, Finland), snow temperature with Swix digital snow thermometer T0093 (Swix, Lillehammer, Norway), snow humidity using Doser snow moisture meter type 001 (DOSER Messtechnik GmbH & Co KG, Füssen, Germany), and the atmospheric cloud cover by visual inspection of an experienced technician with numerical evaluation (0–8). In general, the weather was representative of typical spring conditions in northern Finland. The temperature was below zero during nighttime, but temperature generally rose above 0°C during the daytime. Mean air temperature across the entire testing period was +1.6°C ± 1.8°C (range, −2.7°C to +4.2°C) with snow temperatures being fairly consistent and remained under 0° (−1.1°C ± 0.9°C; range, −3.4°C to −0.6°C). Within each participant, the deviation in air and snow temperature from the start to the end of the on-snow tests was +0.6°C ± 0.3°C and +0.2°C ± 0.3°C, respectively. High air humidity (68% ± 9%) caused high snow humidity (30% ± 8% [doser]). Generally, air and snow temperatures were comparable between conditions within athletes. However, snow conditions changed from cold to wet during some trials, and in one case from wet to cold. Depending on the external conditions, the appropriate grip waxes were applied by the expert ski-technician (range in grip wax: Swix VR45 hard wax to Swix KX75 klister). In summary, we tried, as strictly as possible, to control and standardize this outdoor experiment by 1) randomization; 2) glide tests; 3) using the same ski grind, ski stiffness, and glide wax within each athlete; and 4) standardized protocol with respect to break durations, warm-up procedure, cooldown, and passive rest procedure.

Instruments. $\dot{V}O_2$ was measured using a portable metabolic cart (K5, Cosmed, Italy). Based on the expected high $\dot{V}O_2$ in a majority of the elite skiers, the mixing chamber mode with sampling taken every 10 s was applied for both the laboratory and outdoor trials. The athletes were fitted with a proper-size mask covering the mouth and nose (7450 Series V2™ Mask; Hans Rudolph Inc., Shawnee, KS). Before each test trial, the gas analyzer's oxygen (O_2) and carbon dioxide (CO_2) sensors were calibrated using a two calibration procedure with ambient air conditions (20.93% O_2 and 0.03% CO_2) and the anticipated expiratory gas percent using calibration gas containing 15% O_2 and 5% CO_2 (UN 1950 Aerosols, Cortex Biophysik GmbH, Leipzig, Germany) (rest volume: nitrogen). The flow volume was calibrated using a 3-L syringe (M9424; Medikro Oy, Kuopio, Finland). Furthermore, a Garmin HR belt was connected via ANT+ to the K5 system. Additionally, an extra HR monitor (Polar V800; Polar electro Oy, Kempele, Finland) with a sampling rate of 1 Hz and an integrated GPS was used.

For lactate analysis, a 20-μL capillary blood sample from the fingertip was collected and quantified using an amperometric–enzymatic technique (Biosen S-Line Lab+; EKF-diagnostic GmbH, Magdeburg, Germany). The lactate sensor was calirated before each test using a lactate standard sample of 12 $mmol \cdot L^{-1}$. Results within a range of ±0.1 $mmol \cdot L^{-1}$ were accepted.

To get exact intermediate times during the race for flat, uphill, downhill sections, undulating terrain, and so on, a self-developed measurement system was applied. This system included a magnetometer (Axivity IMU sensor: size, 23 × 32.5 × 8.9 mm; weight, 8 g; sampling rate, 50 Hz) that was attached to the tip of the ski. The second component was a custom-made 15-cm-long magnet unit which was a serial arrangement of three sets of double magnets (six magnets of the type: S-20-10-N; Supermagnete, Gottmandingen, Germany) connected using two 50 mm × 10 mm iron cylinders. This magnet unit was buried in the snow exactly in the middle between the two single classic tracks (between the two skis) or three in a form of an array of three magnet units crossover the whole track in sections where herringbone technique was expected (i.e., very steep uphills). The accuracy of this system was tested against that of a light-beam system, and the error was found to be within the range of its 50-Hz sampling rate. Sensor data were collected by an in-house smartphone application (SkiSense App, Salzburg Research, Salzburg, Austria) attached to the $\dot{V}O_2$ metabolic cart. All data processing was performed using R-Studio (Version 1.1.383) and the Ikemaster software (Ike Software Solutions, Salzburg, Austria).

Statistical analysis. All data exhibited a Gaussian distribution verified by the Shapiro–Wilk test and, accordingly, the values are presented as means (±SD). A 2 × 3 repeated-measures ANOVA (with the two conditions [DP vs CLASSIC] as repeated measures and the three groups [male international level, male juniors national level, females] as independent measures) was performed to test the main effects of the used skiing condition, group, and its interaction. Furthermore, a 2 × 2 ANOVA with repeated measures (two conditions, two laps) was used to check for differences in pacing between the two laps with respect to the used condition (DP vs CLASSIC). For analysis of differences between the two conditions with each single section, a 9 × 2 ANOVA with repeated measures was performed for the entire group and for each group separately (nine sections and two laps). In case of significant main effects and/or interaction effects, further *post hoc* analysis within each group as univariate ANOVA or paired sample *t* tests were performed. All tests were adjusted by Bonferroni *post hoc* corrections. Alpha level of significance was set to 0.05. In addition, the values obtained were evaluated by calculating the effect size ($_p\eta^2$) and statistical power. Individual response analysis was performed in accordance to Sylta and colleagues (18) with percent differences categorized as nonresponse, <3% difference; moderate response, 3% to 9%; or large response, >9% difference. The Statistical Package for the Social Sciences (Version 24.0; SPSS Inc., Chicago, IL) was used for statistical analysis. Graphs were done in R-Studio (Version 1.1.383) and Excel 2010.

RESULTS

Descriptive data. The absolute pole length was 147 ± 6 cm representing 82.4% ± 0.9% of body height (measured with shoes). Females used shorter poles (both absolute and relative) compared with both elite males and junior level males (81.6% ± 0.8% vs 82.7% ± 0.8% and 82.9% ± 0.7%, $P = 0.048$, $P = 0.012$). None of the skiers used a pole length greater than 83% of body height.

Laboratory tests. For the laboratory tests, HR_{peak} was 1.2% lower (range, −3.7% to 2.0%) with DP compared with DIA (190 ± 8 bpm vs 192 ± 7 bpm, $P = 0.009$) while relative and absolute $\dot{V}O_{2peak}$ was 4.9% lower (range, −14.7% to +5.4%) with DP compared with DIA (67.3 ± 7.3 $mL \cdot min^{-1} \cdot kg^{-1}$ vs 70.8 ± 7.6 $mL \cdot min^{-1} \cdot kg^{-1}$; 4.7 ± 0.8 $L \cdot min^{-1}$ vs 5.0 ± 0.8 $L \cdot min^{-1}$; both $P = 0.004$). Peak blood lactate was similar between DP and DIA (10.4 ± 1.9 $L \cdot min^{-1}$ vs 10.6 ± 2.5 $L \cdot min^{-1}$; $P = 0.664$).

Performance differences in the simulated outdoor competition. For the total group, the skiing time for the DP condition was nonsignificantly slower (14 ± 38 s) than CLASSIC ($P = 0.116$), but demonstrated a group–condition interaction ($P = 0.009$) with 2.8% (−24 s) faster skiing times in the male elite DP condition ($P = 0.018$) and 3.9% (+43 s) slower skiing times in the female skiers DP condition ($P = 0.035$). Skiing times were similar between conditions for the junior males ($P = 0.240$) (Table 1). Mean skiing speeds for DP and CLASSIC were 5.5 ± 0.8 $m \cdot s^{-1}$ versus 5.6 ± 0.7 $m \cdot s^{-1}$ for the total group. Individual response analysis revealed that across the entire group 10% demonstrated a moderately positive response with DP only, 53% no difference, and 37% moderately negative response. Within the elite males, 50% demonstrated a moderate positive response in favor of DP and 50% achieved similar results between the two conditions. In the male juniors, 75% achieved similar performance and 25% achieved moderately worse performance with DP compared with CLASSIC. In females, 33% achieved similar performance between the two conditions, and 67% had moderately worse performance with DP (Fig. 2).

Glide conditions were similar for DP and CLASSIC (13.51 ± 1.03 s vs 13.58 ± 0.81 s, $P = 0.496$). There was a low nonsignificant correlation between glide condition differences and delta changes in DP versus CLASSIC ($r_{xy} = 0.31$, $P = 0.25$). Warm-up lactate was similar between both conditions (DP: 3.0 ± 0.9 vs CLASSIC: 2.9 ± 1.2 $mmol \cdot L^{-1}$; $P = 0.660$).

Section time and lap analyses. The time differences between DP versus CLASSIC within the single sections of the track for all three groups are illustrated in Figures 3A–C. In male juniors, none of the sections showed significant difference between DP versus CLASSIC. In the male elite, especially in the variable and moderate uphill terrain, DP was faster ($P = 0.01$ to 0.05) than CLASSIC. In the females, within all uphill sections, CLASSIC was faster ($P = 0.001$ to 0.005), whereas in the two steeper downhill sections, DP was faster ($P = 0.013$–0.026).

When pooling the respective sections for the flat and moderately undulating terrain (variable terrain), the uphill sections (Up) and downhill sections (Down) and using the pooled data for DP and CLASSIC, the greatest differences between the three groups in total skiing performance were found in the uphill sections (interaction, terrain–group; $P < 0.001$).

TABLE 1. Comparison of the situations DP vs CLASSIC for the Total group, EM group, JM group, and F skiers elite and junior skiers with respect to performance (time), blood lactate, and RPE.

				ANOVA		
	Group	DP	CLASSIC	Condition	Group	Group–Condition
Skiing time (s)	EM	842 ± 63	866 ± 59[a]	$F_{1,16} = 2.2$	$F_{2,16} = 31$	$F_{2,16} = 6.6$
	JM	911 ± 39	899 ± 47	N.S.	$P < 0.001$	$P = 0.009$
	F	1158 ± 93[b]	1115 ± 87[a,b]		${}_p\eta^2 = 0.80$	${}_p\eta^2 = 0.47$
	Total	978 ± 147	964 ± 127		pow = 1.0	pow = 0.84
Lactate (mmol·L^{-1})	EM	10.7 ± 3.1	9.4 ± 4.3	$F_{1,16} = 0.4$	$F_{2,16} = 4.1$	$F_{2,16} = 2.9$
	JM	9.5 ± 1.2	10.4 ± 2.0	N.S.	$P = 0.036$	N.S.
	F	7.0 ± 2.1[c]	6.8 ± 0.7[d]		${}_p\eta^2 = 0.34$	
	Total	9.1 ± 2.5	9.0 ± 2.9		pow = 0.64	
RPE$_{\text{WHOLE-BODY}}$	EM	16.4 ± 1.3	18.0 ± 2.0	$F_{1,16} = 1.6$	$F_{2,16} = 0.9$	$F_{2,16} = 1.4$
(6–12)	JM	16.6 ± 1.2	16.6 ± 2.1	N.S.	N.S.	N.S.
	F	16.2 ± 1.0	16.2 ± 1.3			
	Total	16.4 ± 1.1	16.8 ± 1.9			
RPE$_{\text{ARMS}}$	EM	16.6 ± 2.7	16.2 ± 2.6	$F_{1,16} = 2.2$	$F_{2,16} = 0.2$	$F_{2,16} = 0.5$
(6–12)	JM	16.6 ± 1.2	16.6 ± 2.1	$P = 0.027$	N.S.	N.S.
	F	16.6 ± 2.1	15.4 ± 1.3	${}_p\eta^2 = 0.27$		
	Total	16.5 ± 2.1	15.5 ± 1.8[a]	pow = 0.63		
RPE$_{\text{TRUNK}}$	EM	15.2 ± 1.8	15.6 ± 1.3	$F_{1,16} = 0.3$	$F_{2,16} = 0.02$	$F_{2,16} = 1.5$
(6–12)	JM	15.8 ± 1.5	15.1 ± 2.4	N.S.	N.S.	N.S.
	F	14.8 ± 1.2	15.7 ± 2.2			
	Total	15.3 ± 1.5	15.4 ± 2.0			
RPE$_{\text{LEGS}}$	EM	15.2 ± 2.3	17.6 ± 1.5	$F_{1,16} = 8.8$	$F_{2,16} = 2.3$	$F_{2,16} = 0.3$
(6–12)	JM	15.5 ± 1.8	16.8 ± 2.2	$P = 0.009$	N.S.	N.S.
	F	14.0 ± 2.1	15.5 ± 1.0	${}_p\eta^2 = 0.36$		
	Total	15.0 ± 2.0	16.6 ± 1.8[a]	pow = 0.80		

[a] Significantly different to DP.
[b] Significantly different to both EM and JM.
[c] Significantly different to EM
[d] Significantly different to JM.
Mean ± SD.
F, female; JM, junior male skiers; EM, elite male; Total, total group; ${}_p\eta^2$, partial eta squared effect size; pow, statistical power; N.S., not significantly different.

More specifically, the greatest difference between DP versus CLASSIC between the three groups was found in the uphill section (interaction, condition–terrain–group: $P = 0.025$). The only difference between the three groups with respect to the comparison between DP versus CLASSIC was observed in the uphill sections ($P = 0.001$). No differences between groups were observed in the downhill and variable terrain sections. The difference between the two conditions in the uphill sections was most pronounced in females (61 ± 32 s slower with DP, $P = 0.005$) compared with nonsignificantly different values for DP and CLASSIC in both male elite ($P = 0.162$) and male juniors ($P = 0.116$).

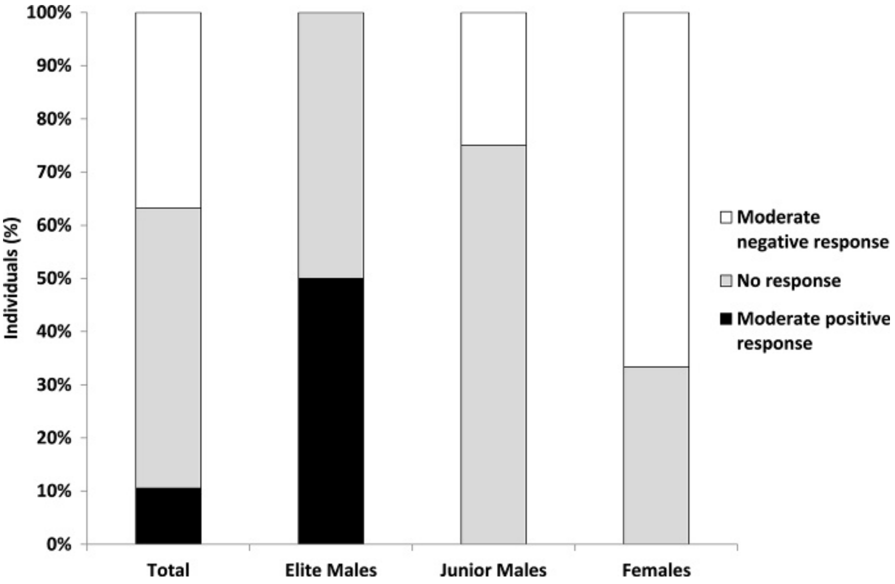

FIGURE 2—Individual response analysis with respect to DP vs CLASSIC in the total group and the three subgroups. Percent differences are categorized as nonresponse, <3% or >−3% difference; moderate positive response in favor of DP, 3% to 9%; moderate negative response in favor of CLASSIC, −3% to −9%.

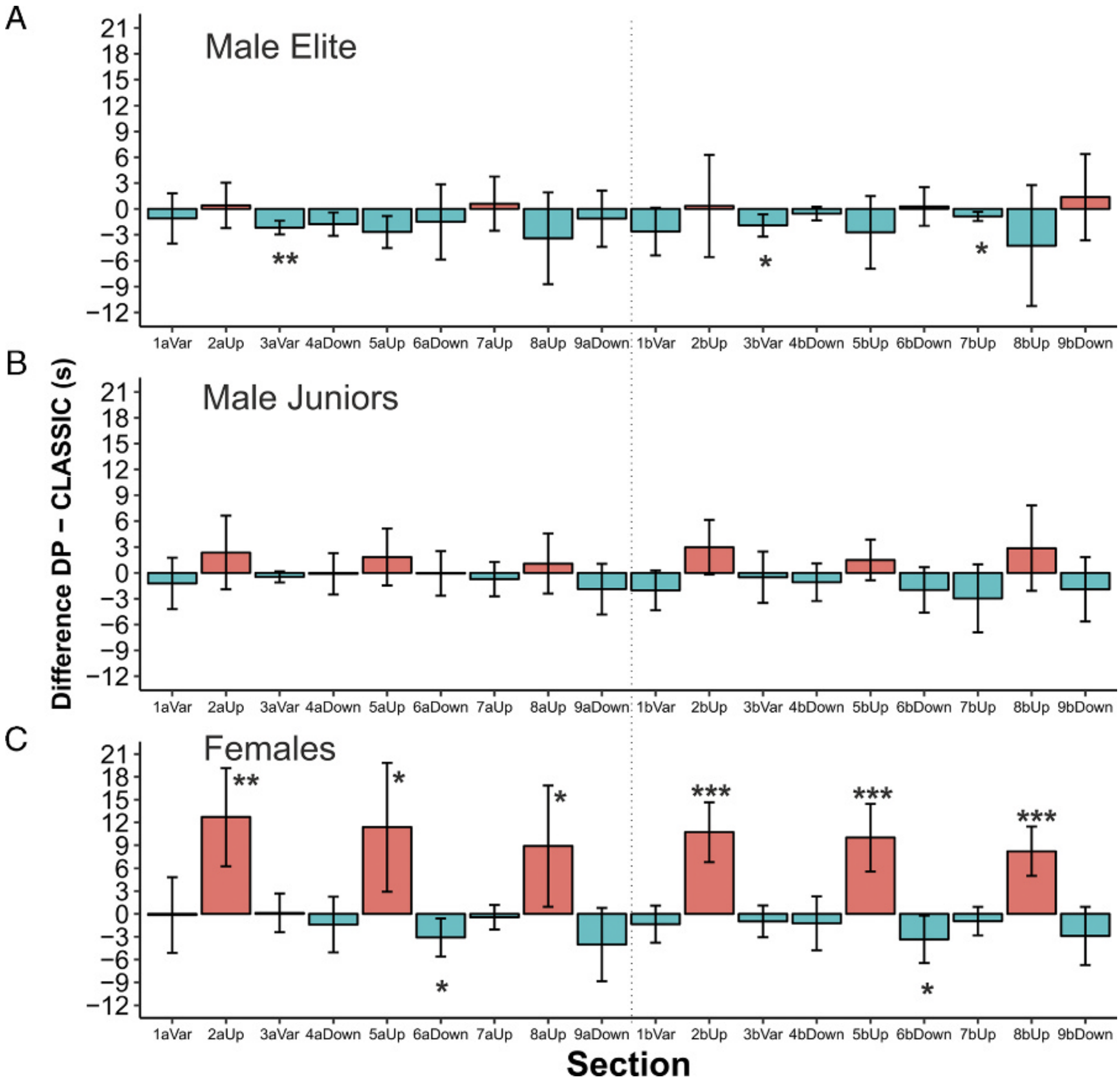

FIGURE 3—Differences DP to CLASSIC in all three groupstfgap (A, male elite; B, male juniors; C, female elite). ***Red*****, CLASSIC faster;** ***green*****, DP faster. a, first lap; b, second lap; *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$ significant difference between DP and CLASSIC within the respective section.**

Physiological and RPE differences between DP versus CLASSIC. There was no difference in HR_{mean}, $\dot{V}O_{2mean}$, $\dot{V}O_{2peak}$, tidal volume (V_T), RER, and blood lactate between the two conditions. HR_{peak} was slightly lower with DP compared with CLASSIC (180 bpm vs 181 bpm, $P = 0.032$). In contrast, mean and peak breathing frequency was higher ($P = 0.015$, $P = 0.029$) with DP compared with CLASSIC. Although there was no difference in $RPE_{WHOLE\text{-}BODY}$ and RPE_{TRUNK} (both $P > 0.05$), higher values were found for RPE_{LEGS} with CLASSIC ($P = 0.009$) and for RPE_{ARMS} with DP ($P = 0.027$). It should be noted that in the majority of significant results, the statistical power was <0.8. No group differences were found with respect to RPE values (all $P > 0.05$) (Tables 1 and 2.).

The peak HR achieved during the two simulated races relative to the maximal HR achieved during the laboratory tests were 96% ± 6% versus 97% ± 5% for DP and CLASSIC, respectively, and 92% ± 17% versus 92% ± 14% for $\dot{V}O_2$, and 85% ± 29% versus 83% ± 30% for blood lactate.

Pacing strategies (lap 1 versus lap 2 comparison). With the exception of three skiers, a positive pacing strategy with faster skiing times in lap 1 compared with lap 2 (pooled DP and CLASSIC: 478 ± 16 s vs 493 ± 16 s, $P < 0.001$), with no interaction between conditions (DP vs CLASSIC) with respect to the decrement in performance across the laps was found (DP: 482 ± 77 vs 496 ± 71; CLASSIC: 475 ± 64 vs 489 ± 64 s, both $P > 0.05$). Both peak and mean HR increased from lap 1 to lap 2 (peak HR: 178 ± 7 bpm vs 183 ± 7 bpm; mean HR, 173 ± 7 vs 178 ± 6 bpm, both $P < 0.001$). Only the mean $\dot{V}O_2$ and mean V_T increased across the laps (mean $\dot{V}O_2$, 56.7 ± 7.6 $mL \cdot min^{-1} \cdot kg^{-1}$ vs 60.5 ± 8.3 $mL \cdot min^{-1} \cdot kg^{-1}$; mean V_T, 2.4 ± 0.4 $mL \cdot min^{-1} \cdot kg^{-1}$ vs 2.6 ± 0.5 $mL \cdot min^{-1} \cdot kg^{-1}$, both $P < 0.01$), while $\dot{V}O_{2peak}$ and V_{Tpeak} remained constant. Breathing frequency and RER increased for both the mean

TABLE 2. Comparison of the situations DP vs CLASSIC for the Total group, the EM group, JM skiers, and F elite and junior skiers with respect to mean and peak values of physiological parameters.

	Group	DP	CLASSIC	ANOVA		
				Condition	Group	Group x Condition
HR_{mean} (bpm)	EM	175 ± 3	175 ± 4	$F_{1,16} = 1.6$	$F_{2,16} = 0.6$	$F_{2,16} = 2.2$
	JM	178 ± 5	177 ± 7	N.S.	N.S.	N.S.
	F	172 ± 8	176 ± 10			
	Total	175 ± 6	176 ± 7			
HR_{peak} (bpm)	EM	179 ± 4	179 ± 5	$F_{1,16} = 5.5$	$F_{2,16} = 1.6$	$F_{2,16} = 2.3$
	JM	183 ± 6	184 ± 7	$P = 0.032$	N.S.	N.S.
	F	176 ± 8	180 ± 9	${}_{p}\eta^2 = 0.26$		
	Total	180 ± 7	181 ± 7	pow = 0.60		
$\dot{V}O_{2mean}$ ($mL \cdot min^{-1} \cdot kg^{-1}$)	EM	62.4 ± 3.8	62.4 ± 3.4	$F_{1,16} = 0.2$	$F_{2,16} = 1.2$	$F_{2,16} = 5.3$
	JM	56.9 ± 7.9	58.4 ± 8.9	N.S.	N.S.	$P = 0.027$
	F	56.5 ± 3.2	54.2 ± 1.2			${}_{p}\eta^2 = 0.52$
	Total	56.9 ± 7.9	58.4 ± 8.9			pow = 0.71
$\dot{V}O_{2peak}$ ($mL \cdot min^{-1} \cdot kg^{-1}$)	EM	66.9 ± 3.7	67.2 ± 3.8	$F_{1,16} = 0.02$	$F_{2,16} = 2.1$	$F_{2,16} = 1.5$
	JM	66.5 ± 7.7	68.0 ± 6.9	N.S.	N.S.	N.S.
	F	60.8 ± 3.4	58.8 ± 1.5			
	Total	65.3 ± 6.0	65.7 ± 6.2			
V_{Tmean} (L)	EM	2.5 ± 0.2	2.6 ± 0.3[a]	$F_{1,16} = 0.1$	$F_{2,16} = 3.4$	$F_{2,16} = 3.3$
	JM	2.6 ± 0.3	2.7 ± 0.4	N.S.	N.S.	N.S.
	F	2.3 ± 0.3	2.0 ± 0.3			
	Total	2.5 ± 0.3	2.5 ± 0.5			
V_{Tpeak} (L)	EM	2.7 ± 0.2	2.8 ± 0.2	$F_{1,16} = 1.3$	$F_{2,16} = 7.9$	$F_{2,16} = 3.0$
	JM	3.0 ± 0.3	3.1 ± 0.4	N.S.	$P = 0.007$	N.S.
	F	2.5 ± 0.3	2.1 ± 0.4		${}_{p}\eta^2 = 0.59$	
	Total	2.8 ± 0.4	2.8 ± 0.5		pow = 0.88	
RF_{mean} (bpm)	EM	58.1 ± 4.1	55.6 ± 5.3[a]	$F_{1,16} = 8.2$	$F_{2,16} = 0.0$	$F_{1,16} = 0.6$
	JM	58.2 ± 4.6	54.8 ± 5.5[a]	$P = 0.015$	N.S.	N.S.
	F	57.2 ± 2.9	56.1 ± 6.1	${}_{p}\eta^2 = 0.43$		
	Total	58.0 ± 3.8	55.4 ± 5.1	pow = 0.74		
RF_{peak} (bpm)	EM	64.1 ± 4.7	61.3 ± 7.5	$F_{1,16} = 6.5$	$F_{2,16} = 0.2$	$F_{2,16} = 0.6$
	JM	67.2 ± 8.2	62.9 ± 10.2	$P = 0.029$	N.S.	N.S.
	F	63.1 ± 4.7	60.3 ± 6.2	${}_{p}\eta^2 = 0.40$		
	Total	65.1 ± 6.1	61.7 ± 7.8	pow = 0.64		
RQ_{mean}	EM	0.92 ± 0.04	0.90 ± 0.04	$F_{1,16} = 3.4$	$F_{2,16} = 0.5$	$F_{2,16} = 0.5$
	JM	0.93 ± 0.11	0.95 ± 0.14	N.S.	N.S.	N.S.
	F	0.88 ± 0.05	0.90 ± 0.03			
	Total	0.91 ± 0.08	0.92 ± 0.10			
RQ_{peak}	EM	0.95 ± 0.05	0.93 ± 0.04	$F_{1,16} = 2.3$	$F_{2,16} = 0.9$	$F_{2,16} = 0.7$
	JM	0.97 ± 0.12	1.04 ± 0.15	N.S.	N.S.	N.S.
	F	0.93 ± 0.06	0.93 ± 0.04			
	Total	0.95 ± 0.08	1.00 ± 0.11			

[a] Significantly different to DP.
Mean ± SD.
RF, respiratory frequency.

and the peak values (mean, 54.4 ± 4.8 bpm vs 59.1 ± 5.6 bpm; $P < 0.001$; peak, 62.3 ± 8.3 bpm vs 64.7 ± 8.8 bpm; $P = 0.040$). No significant interaction effects between condition and lap with sufficient statistical power were found for all measured parameters.

DISCUSSION

The main findings of the current study were sixfold: 1) total group differences between DP and CLASSIC were not observed with respect to performance, pacing strategies, or the majority of physiological parameters.; 2) within the three groups, the elite male skiers achieved higher, junior males similar and females worse performance with exclusive DP when compared with CLASSIC; 3) flat and undulating terrain favored DP in the male elite and male juniors, while the uphill sections were more advantageous with CLASSIC in females; 4) greatest discrepancies between performance groups were found in the uphill terrain for both overall performance (DP and CLASSIC pooled) and between DP and CLASSIC, with females demonstrating lower performance compared with the male skiers; 5) ski glide was not different between DP and CLASSIC and the difference in glide times was not related to the performance differences between the two conditions; and 6) analyzed skiers achieved DP $\dot{V}O_{2peak}$ values of 95% (up to 105%) when compared with DIA $\dot{V}O_{2peak}$.

Performance differences and section analysis DP versus CLASSIC. Within the total group, the application of exclusive DP with only glide-waxed skis resulted in nonsignificantly different race performance on a demanding XCS track fulfilling F.I.S. regulations when compared with CLASSIC. When analyzing the single groups separately, the male elite skiers were significantly faster (~23 s faster) with DP (demonstrating a moderate response), with no difference in junior male skiers and worse performance (~43 s) in female skiers. This result demonstrates that for DP to be beneficial over all classic techniques using grip-waxed skis, there needs to be an emphasis on the DP technique across several years of training, well-developed upper-body strength and a fine-tuned DP technique. These factors can be assumed in the male elite skiers of the current study, but not in the junior and female skiers. In the last two decades, the influence of applied research on the DP technique has increased the implementation of DP-specific training, and has thus improved the DP technique to a significant degree (1–3,14,15,19,20). In 1990, Hoffman and Clifford (9) demonstrated that on flat terrain and moderate speeds (~3.9 $\mathrm{m \cdot s^{-1}}$—not comparable with to date race speeds), the DP technique demonstrated the greatest economy among all analyzed classic and skating XCS techniques. The improved economy of DP may be only advantageous in certain race conditions if the upper body is adequately prepared (10).

When focusing on individual sections along the track, unexpectedly, elite male skiers did not benefit from exclusive DP application in the downhill sections, but only in the flat and variable terrain sections. Even in the uphill sections, no marked difference in favor of the grip-waxed condition was found. This is supported by the nonsignificant difference in gliding performance between the two conditions. Therefore, in male elite skiers the grip-wax seemed not to negatively affect the glide properties of the skis during the downhill passages (mainly crouched "tucked" position with no DP motion) but also did not contribute to enhanced uphill performance by allowing using both DIA and DPK. However, when using the highly dynamic DP motion on flat and undulating terrain at high speeds, the grip-wax seems to slow down the skis. Therefore, it might be speculated that the dynamic modern DP motion with distinct use of lower body to transfer body weight on the poles (2,3) results in deformations of the classic skis within a cycle that most likely slows down the skis during DP when the grip-wax is in contact with the snow. Grip-wax is selected according to snow, and skis are selected according to the skier, terrain type, and snow conditions. Skis with higher camber under the foot contribute to higher speed in DP, but require more effort to flex the ski to generate snow contact during leg push-offs during uphill DIA situations. Higher cambered skis are also needed when applying klister (high grip kick-wax) instead of hard-wax or in situations where the snow is contaminated with dirt. The skis in the current study were chosen such that they have full gliding properties with half skier weight and slowdown (grip wax contacts the snow) with full skier weight. It is possible that, in other external conditions, the effects of kick-wax might not be optimal (e.g., resulting in slower glide performance than glide waxed skis only), which might result in distinct advantages of exclusive DP. In contrast, during situations with very high ski frictional forces (e.g., soft, dirty, wet snow) and soft track surface leading to greater snow penetration of the pole tips during poling phase, the application of kick-wax and consequently, the use of leg push-offs, might positively outweigh the small advantages in ski glide with purely glide-waxed skis and DP only. Future studies are needed to analyze the effects of the DP motion on glide properties of classic skis in pure glide-waxed versus grip-waxed condition. Most likely, a rethinking of classic ski properties needs to take place to enhance the DP performance even in grip-waxed conditions while still allowing optimal grip during techniques with leg kicks (e.g., DIA, DPK, and herringbone). Possibly, in the near future, a smart ski might be developed that automatically changes stiffness properties according to the skiing style applied (e.g., stiffer during DP and softer during DIA). From the perspective of skiing technique, the development of new strategies like the "Klaebo" or "running diagonal stride" technique (5,21) might reduce the amount of grip-wax required to achieve adequate grip on uphill sections and thereby improved glide on other portions of the course (e.g., DP sections, downhill sections, and curves).

The lower race performance in female skiers with the exclusive DP condition was mainly associated with lower performance in the uphill sections (losing approximately 60 s within the uphills). The uphill sections in general (irrespective of DP or CLASSIC), discriminated greatest between the three groups, but also with respect to the delta differences between DP and CLASSIC. Therefore, in our females, the largest potential lies in the improvement of uphill performance, in general, and especially uphill DP. In this context, during treadmill roller skiing Sandbakk and colleagues (22) demonstrated that sex differences were more pronounced while using the DP technique. Moreover, Hegge and colleagues (23) underlined the observation that larger differences in power output (modifications of a DP ski ergometer) between men and women emerge when a greater contribution from the upper body is required. In line with these findings, uphill DP performance was shown to be associated with high power output and high peak pole forces and impulse of forces (2). Recently, Stöggl and colleagues (8) demonstrated that during a classic XCS race (10/15 km NOR championship), the greatest potential improvement in females lies in uphill terrain which fits well with the current findings. On that note, only one of the females in the current study had the capacity to DP all the uphill sections. All other female skiers needed to switch into the herringbone technique very early within the uphill sections. Using the herringbone technique without grip-wax is a difficult balance. Skiers are required to produce sufficient static friction along the V-positioned skis during push-off while avoiding gliding phases during ski placement that might lead to a disqualification during classic XCS races. Based on the lack of friction with non–grip-waxed skis, the herringbone technique is an inferior technique when compared with herringbone or DIA with grip-waxed skis, or with well-developed uphill DP technique. That the success of exclusive DP is not restricted to males can be seen in the impressive performance of some of the female elite long-distance skiers (e.g., within the Ski-Classics series) that are able to successfully DP along very challenging race tracks. However, this is not presently the case for elite female XC skiers who compete in the World Cup (5–30 km) on F.I.S. homologized hilly terrain.

The finding within the group of females in the current study is in accordance with Pellegrini and co-workers (12), demonstrating that DP is the preferred technique up to inclines of 2°, whereas at moderate inclines (2°–3°), their skiers switched to DPK and all used DIA on inclines greater than 6°. None of their skiers preferred to use the DP technique at inclines greater than 4°. This result can no longer be seen as valid based on the results within the elite male skiers of the current study. Hence, the finding of Pellegrini and colleagues (12) might be attributed toward the lower performance level in their group (national class or amateur level skiers) but also drastic improvements in DP capacity within the past years, especially in elite male XC skiers.

It is of interest that the DP situation resulted in better downhill performance when compared with the CLASSIC technique, especially in females. This might be based on the fact that females can more easily handle nongrip waxed skis in downhills and curves (no contact of grip-wax with snow and easier application of skating strokes), whereas in the elite males, this potential for improvements in downhill section no longer exists. Another aspect might be that female XC skiers prefer more or thicker grip wax than men, probably due to differences in muscle strength, especially in the upper body, which may influence their performance downhill, especially with certain snow and waxing conditions.

In summary, the section analysis of the current study can be used as a basis for modeling the track topographies where DP or CLASSIC is favored. For instance, in male skiers, besides the fact that the elite males were as fast or faster irrespective of terrain, the application of exclusive DP with only glide-waxed skis would be advised if the track consists of a greater proportions of sections with flat or undulating terrain (e.g., like in the most of the long-distance popular races). In females, pure DP might be preferred if there are demanding downhills, turny courses, and the uphills are moderately steep and not too long.

Physiological differences and pacing strategies with DP versus CLASSIC. Interestingly, no marked differences in the measured physiological parameters between exclusive DP versus CLASSIC were found. Only RPE revealed slight differences with respect to the subjective exertion of arms in DP and for the legs in CLASSIC obviously related to the pronounced upper-body and arm work with DP and the leg strides during DIA and DPK in CLASSIC. Comparisons toward other studies are problematic because this kind of experiment was, to the best of our knowledge, the first of its kind. For instance, Hoffman and Clifford (9) demonstrated that the DP technique has the greatest economy while DIA elicited the greatest physiological demand and highest perceived effort among all analyzed classic and skating XCS techniques. A direct comparison to the current study is not possible because on flat terrain, the DP technique would have been applied by the skiers irrespective of condition. In the study of Björklund et al. (24), treadmill roller skiing at an exercise intensity of 90% $\dot{V}O_{2max}$ (race intensity simulation) the $\dot{V}O_2$ and O_2 extraction decreased when switching from DIA to DP. However, the treadmill settings were different in these two conditions. Furthermore, it was speculated that extended use of the DP technique might be limited by its greater anaerobic demands (11). The comparable cardiorespiratory and metabolic responses between DP and DIA in the laboratory and DP and CLASSIC during the outdoor race simulation within the current study do not support the statements above. Finally, the two conditions did not lead to different strategies, so the change in performance between the laps was, in general, positive (decrease in performance from lap 1 to lap 2) for both conditions. This is nicely coupled to the almost identical physiological response between the conditions. The cardiorespiratory system (Cosmed K5, mixing chamber mode) applied in the current study functioned without issue during the outdoor trials.

Development of DP and/or upper-body aerobic capacity. Various studies have compared the arms and legs, upper and whole body, or DP and DIA with respect to performance or physiological response (e.g., (15,16,24–32)). When analyzing the ratio between $\dot{V}O_{2peak}$ during upper-body exercise (e.g., arm cranking, upper-body ergometer or DP) and $\dot{V}O_{2max}$ during whole-body exercises as treadmill running, arm and leg cycling, or DIA, a clear increase from approximately 70% in the 1960s up to 95% in the current study can be observed (Fig. 4). This demonstrates the enormous development in upper-body capacity, and particularly with DP, both in performance and in $\dot{V}O_{2peak}$ across the years. It is possible that this improvement can be attributed to a distinct increase in DP and upper-body training, leading to more well-trained upper-body musculature (strength and endurance). In addition to improved track preparation (e.g., less slipping of pole tips, more compact surface) and equipment (e.g., stiffer poles), the DP technique itself has dramatically improved across the years. Athletes apply more forces along the poles by using more muscle groups and more body mass coupled with more dynamic motion of the lower body (e.g., "kangaroo DP," "pumping DP" in uphills) (1–3,15).

Pole length and F.I.S. efforts to conserve all classic techniques. Several studies have demonstrated that longer poles were related to DP performance (35–38), oxygen cost (36), and poling mechanics. This results in a more efficient poling action by decreasing the athlete's metabolic cost (39). Based on these findings, it could have been observed that skiers started to use longer poles and were able to even further enhance their DP performance. The trend toward exclusive use of DP in long-distance races and also during World Cup races was largely debated within the past years. In an attempt to condemn this development and conserve all classic techniques, F.I.S. has introduced new rules to limit the usage of exclusive DP as the 83% pole length rule (introduced in season 2016/2017), "no-DP-zones" and changes in the track set-up and preparation (e.g., only one classic track in ideal line, V-boards in curves to prevent extended usage of skating kicks while changing track or in curves). Furthermore, more strict video analysis within the uphill sections is used to execute disqualifications

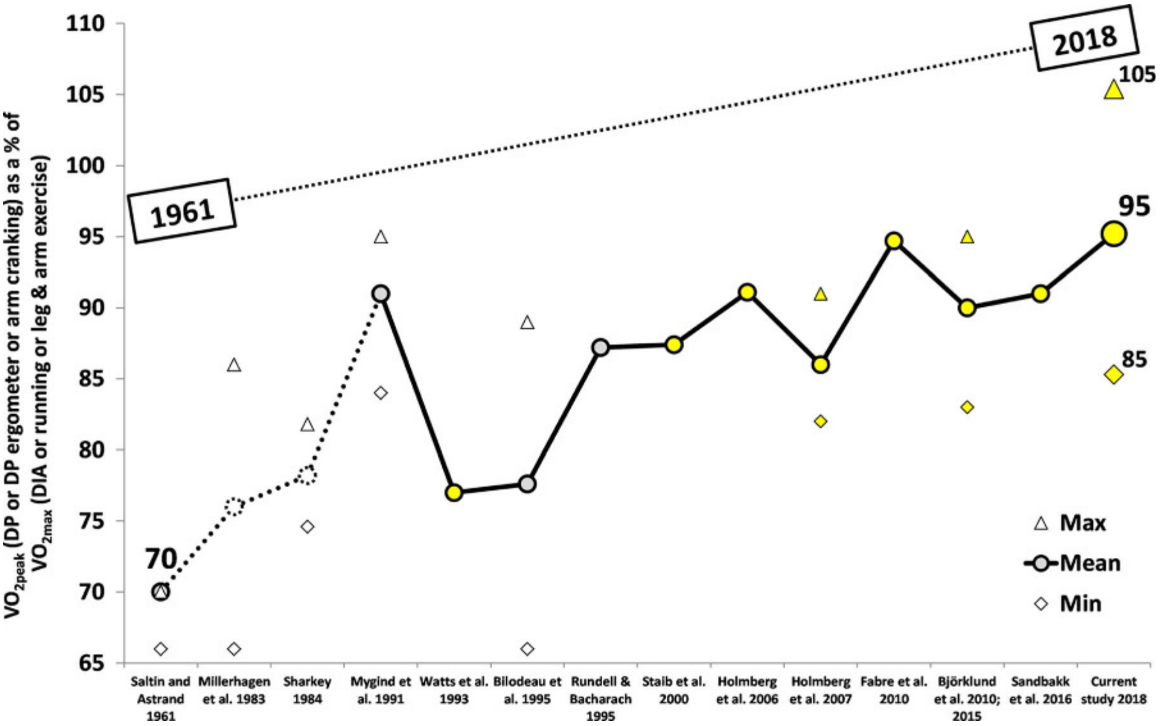

FIGURE 4—Development of the $\dot{V}O_{2peak}$ with DP or upper-body exercise (e.g., arm cranking, pulley exercises or on DP ergometers) in comparison to the $\dot{V}O_{2max}$ during whole-body exercise (e.g., treadmill running, or arm and leg cycling, or treadmill roller skiing with DIA). The *bold line* represents the group mean and the scattered line the range of the values reported. The *yellow circles* represent studies where DP $\dot{V}O_{2peak}$ was compared directly to DIA $\dot{V}O_{2max}$, and the *white circles* represent the calculated mean of the minimal and maximal values in this study. The values were either taken directly from the original publications or recalculated from the individual data reported (15–17,24,26–34).

in case of irregularly applied skating strokes (e.g., during herringbone skiing).

With respect to the applied pole lengths in our study, none of the skiers used pole lengths greater than 83%, with juniors and females using even shorter poles than allowed by F.I.S. regulation. Hence, various skiers in this group of national to international level elite skiers would have the potential to increase their pole length, or do not yet have the capacities to benefit from longer poles.

Based on the fact that in the World Cup season 2017/2018, no skier was able to win a podium with exclusive DP, it seems that these new F.I.S. regulations were successful in preventing the development of exclusive DP use and the preservation of the classic XCS techniques. Within the long-distance races, the pure DP trend continues to rise, not only in the elite skiers but also down to the subelite and recreational skiers. In this context, it is worth noting that in the most popular long-distance race—the Vasaloppet—the first victory with exclusive DP was recently achieved in 2014, starting a new era in both males and females. However, the track record in both males and females is far faster with grip-wax as compared with the records with exclusive DP (males, 3:38:41 in 2012 with grip-wax vs 3:57:18 with DP in 2017; females, 4:08:24 in 2012 vs 4:17:56 in 2016). The effects of the "no-DP-zones" need further evaluation on how long and steep these sections need to be to produce sufficient negative impact of an imitated DIA motion with no-grip wax to compensate the benefits of exclusive DP along with the remaining parts of the track.

Limitations. A limitation can be seen in the low amount of female elite skiers, being mainly attributed to the short and strict timeframe available for recruitment of these world-class athletes. Further, though the specific competition track of the current study relates to F.I.S. homologation, on other World Cup tracks, the maximal climb is much higher (e.g., Lillehammer, Holmenkollen, Falun, and Val die Fiemme have maximal climbs of 52 to 59 m versus 22 m in the current study). Furthermore, even though outdoor trials guarantee high ecological validity, acute changes in external conditions (e.g., temperature rise/fall, snow fall, sun, etc.) can lead to dilution of the results. However, based on the stable external conditions within each participant (with the exception of two athletes), the counterbalanced design, the compact time frame for both outdoor trials within 1 h, and the accompanying glide tests most of this variation were controlled. Furthermore, potential differences in the ability to recover rapidly among skiers (e.g., when comparing senior and junior athletes) can confound the findings. In general, the detection of short-time recovery status is very challenging. In the current study, the postcool-down and pretime trial blood lactate values were not significantly different. We aimed on using a best possible standardized protocol with very strict control on warm-up, cooldown, and recovery time across all skiers. For the laboratory tests, time to exhaustion was approximately 1 min longer for the DP $\dot{V}O_{2peak}$ test compared with the DIA $\dot{V}O_{2max}$ test, which might have raised the ratio of DP $\dot{V}O_{2peak}$ to DIA $\dot{V}O_{2max}$ for some of the participants. However, the duration of the DIA ramp protocol was 7 ± 1 min with comparable RPE values between protocols.

CONCLUSIONS

When pooling all the athletes together and considering the weather and race track conditions of the current study, there were no differences in race performance and physiological response on a challenging race track when exclusively using the DP technique with pure glide-waxed skis in comparison with grip-waxed skis. However, when comparing specific groups of our participants, differences can be found. In elite males, it can be demonstrated that with well-developed DP capacity (DP $\dot{V}O_{2peak}$ being approximately 95% of DIA $\dot{V}O_{2max}$) and DP technique, the exclusive DP condition was superior over the CLASSIC condition. This advantage was demonstrated primarily on flat and undulating terrain, most likely based on negative effects of the grip-wax on glide properties of the skis when using the DP technique. With respect to the females, the greatest capacity for competition performance improvement could be seen in the uphill sections where the greatest difference toward the male skiers was found in general as well as the greatest time loss when using the DP technique exclusively in comparison with the CLASSIC technique. Consequently, the exclusive application of DP might only be successful if the DP technique and the upper-body capacity (aerobic capacity, strength levels, core stability, etc.) are well developed. This potential is seen in junior skiers, and especially in females who should focus training on uphill DP technique, to be able to DP up steep and longer uphills instead of switching to the herringbone technique. The current study can serve as a basis for modeling approaches as to which tracks are best suited for the exclusive DP technique. This question needs to be evaluated in connection with the new F.I.S. regulations on classic skiing as well as in different weather and race track conditions. Our present findings indicate that with a high proportion of flat or slightly undulating terrain and only moderate uphill sections, exclusive use of DP appears to be superior, at least for the men. The DP technique may also very well be superior for females in race tracks including difficult downhill sections, curvy terrain, and only moderate and shorter uphill sections. The results of this study may also be applicable to other F.I.S. homologized tracks fulfilling similar profile characteristics (e.g., TC, HD, percent distribution of flat, uphill and downhill sections). However, to achieve detailed information and final answers on which overall track topographies and in which snow-conditions DP is beneficial versus CLASSIC, further research has to be conducted.

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