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ORIGINAL ARTICLE

WILEY

Arm swing during skating at different skiing speeds affects skiing mechanics and performance

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Arm swing has been shown to lead to greater maximal speed and movement economy in cross-country skiing. The current study aimed to investigate how arm swing alters skiing mechanics and contributes to performance and acceleration of the athlete's centre of mass (COM). While skiing on snow, seven highly skilled cross-country skiers simulated V2-alternate skating without using ski poles and with double or single arm swing and without arm swing. During leg push-off the linear momentum of the body increased due to arm swing. Simultaneously, linear momentum of the arm(s) decreased in arm swing trials, indicating a transfer of momentum from arms to the rest of the body and being more prevalent with double arm swing compared to single arm swing (all $P < 0.05$). Greater maximal skiing speeds were reached with single and double arm swing, while the forward lean angle, the force leading to acceleration of COM in skiing direction, and the force effectiveness increased (all $P < 0.05$). The effects of less mass moving in single arm swing could be compensated by carrying out the arm swing faster, almost aligned in skiing direction and with a "long arm" pattern, indicating how arm swing can be conducted efficiently.

KEYWORDS
cross-country skiing, forward acceleration, momentum transfer, upper extremity contribution

1 | INTRODUCTION

Swinging the arms has been shown to cause mechanical benefits in human locomotion, such as walking and running,[1-3] and during jumping for height[4-10] or distance.[11,12] From these studies, three fundamental factors can be detected on how techniques are mechanically altered by swinging the arms. First, arm swing affects ground reaction forces (GRF) in general[4-7,13,14] and their horizontal component[11,15] in particular. Second, take-off velocity increases due to arm swing[9,11,16] and lastly, a more forward centre of mass (COM) position is found in arm swing trials,[4,5,7,15] revealing a difference in the body position. Thus, arm swing is a technique element which is appropriate to enhance the mechanics of movement and therefore increase the performance of an athlete. In cross-country (XC) skiing, arm swing has been investigated primarily in V2-alternate skating (V2A) and in leg skating without using ski poles. It has been demonstrated that with arm swing, greater maximal skiing speed is achieved.[17] At high skiing speed, greater cycle length and GRFs are produced[17,18] with a lower anaerobic energy contribution[18] and a more efficient and economic neuromuscular activation pattern.[17] This addresses two major factors influencing performance in XC-skiing[19,20]: maximal speed and skiing economy. Benefits of arm swing use have been demonstrated to be speed-dependent and of a neuromuscular and a mechanical source.[17,18] While neuromuscular effects have been shown to be predominant at high skiing speed,[17] so far investigated mechanical parameters[17,18,21] do not yet fully explain the mechanics of arm swing in XC-skiing. Rather it has been estimated that other parameters, for example, the direction of force with respect to the body position, may be more relevant.[17] To describe and understand the functionality of arm swing is important, because the skiing technique has a major impact on performance XC-skiing[19] since technical skills will allow the athletes to use their available physiological capacity efficiently and economically.[19,22] For coaches and athletes it would be important to know how earlier reported mechanical aspects combine and functionally add to performance in XC-skiing in order to improve skiing technique and performance. For this it has to be understood, if arm swing mode effects maximal skiing speed; how GRFs add to the propulsion of an athlete in V2A; if the more forward position of COM has an impact on performance and how important is the rapid deceleration of the arms at the end of the swing movement and the possibly associated transfer of momentum from the arms to the rest of the body?[7,9,16,23] This paper addresses these open questions in leg skating using 3D force and motion data of athletes skiing on snow and using recent methods to determine the acceleration of the athlete's COM. The aim is to investigate how propulsion and ski skating mechanics are affected by the use of arm swing in simulated V2A skating at submaximal and maximal skiing speeds and to show whether this leads to greater performance and effectiveness of leg push-off. It has been hypothesized that skiing with arm swing is faster than without arm swing and with double arm swing skiing is faster than with single arm swing. At submaximal and maximal speeds, arm swing leads to greater propulsion and effectiveness of GRFs by a more forward COM position. Decelerating the arm(s) toward the end of leg push-off adds to transfer of linear momentum from arm(s) to the rest of the body.

2 | METHODS

2.1 | Participants and overall design

Seven highly skilled male XC-skiers (age 31 ± 8 years, body height 181 ± 4 cm, body weight 79 ± 5 kg, VO_{2max} 73 ± 2 mL/kg/min, FIS points 115 ± 64) volunteered to participate in this investigation. This study was part of a bigger project where measurements have been conducted jointly for this and two earlier publications[17,24] so that five athletes participated in all three studies. Prior to measurements all participants gave written informed consent to the procedure and the methods of investigation and were free to withdraw from the experiments at any time. The experimental protocol and all methods used in this study were approved by the Ethics Committee of the University of Jyväskylä.

Measurements were performed during skiing on snow in the Vuokatti ski tunnel (Finland), where the air temperature and humidity were kept constant at −4°C and 85% throughout the experiments. The track had a slope of 1° and was groomed for each participant to ensure optimal conditions. The measurement area consisted of a waiting area with a heated tent, 50 m track for acceleration, and a measurement area of 18 m.

V2-alternate skating, also referred to as Gear4 is an unsymmetrical XC-skiing technique and primarily used in flat terrain and at high speeds.[25,26] While one sides' leg push-off is accompanied by a double poling action, the contralateral leg push-off is conducted simultaneously with an active forward arm swing.[21] Being fundamentally determined by this arm swing, the V2A technique and imitations of V2A have recently been subject to investigations of arm swing effects in XC-skiing.[17,18,21] To avoid an influence of poling for the current study and to isolate the arm swing movement three leg-skating techniques without poles and imitating the V2A movement were chosen to be performed by the participating athletes. First, both arms were swung forward during SWING (Figure 1A), resembling the arm swing normally carried out also in the V2A technique. Second, only one arm (on the swing assisted push-off side) was used for arm swing, while the other arm was prevented from moving by holding the hand at the hip (1SWING, Figure 1B). Since this is a common training exercise, all athletes were familiar with the implementation of this technique. Finally, both hands were held at the hips (NOSWING, Figure 1C) to preventing the arm swing completely. Participants were training all three techniques prior to the study and they were instructed and taught to remain all other movement characteristics of V2A (eg, countermovement) while skiing with SWING, 1SWING, and NOSWING. Athletes completed three trials per technique each with moderate and maximal speed, where the order of tasks was randomized. All fully recorded cycles were analysed while the setup allowed for capturing of 1-2 cycles per trial.

2.2 | Measurements

Prior to the measurements, participants performed a standardized warm-up, which included skiing in SWING, 1SWING, and NOSWING. Measurements were conducted for the three techniques at maximal sprinting speed and at a preset moderate speed of 5 ms^{-1} which was clearly submaximal for all participants. The moderate speed was paced by light cells and effective speeds were recorded with 5.21 ± 0.15 ms^{-1} for SWING, 5.23 ± 0.18 for 1SWING, and 5.19 ± 0.28 for NOSWING ($P = 0.505$).

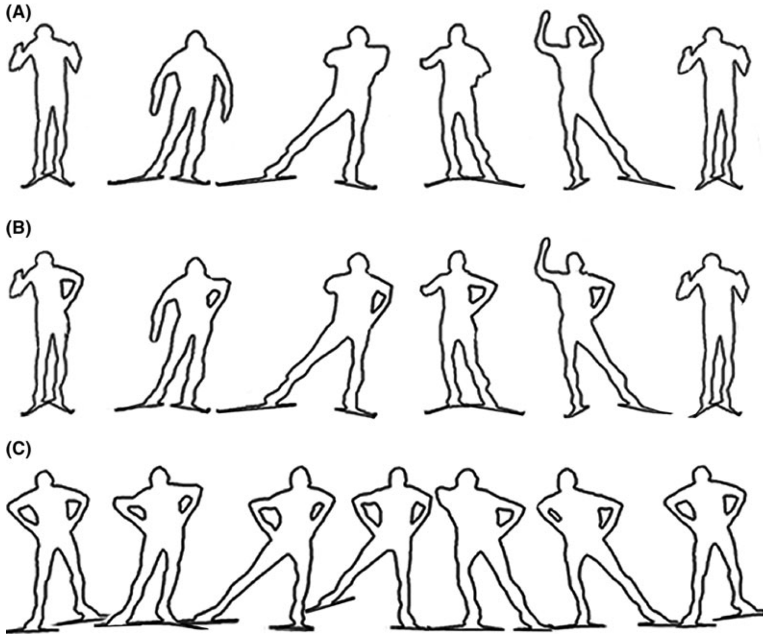


FIGURE 1 One skier performing V2-alternate skating (V2A) without poles and A, double arm swing (SWING), B, single arm swing (1SWING) and C, without arm swing (NOSWING)

Recovery time between the submaximal trials was 1.5 minutes, while athletes paused 3 minutes between, before and after maximal trials.

2.3 | Instruments and materials

One pair of racing skis (Peltonen Supra-x; Peltonen Ski Oy, Hartola, Finland, 1170 g each, 188 cm, fresh prepared with racing wax for every participant) was equipped with custom made 2D force bindings specially designed (Neuromuscular Research Centre, University of Jyväskylä, Finland) and previously used[17,24,27] for force measurements in XC-skiing. Vertical (perpendicular to the ski) and mediolateral (transverse to the ski) GRF were recorded at the side of the swing assisted push-off leg (force binding 1). On the contralateral side, vertical and anterior-posterior (along the ski) GRFs were collected (force binding 2). The force bindings and used procedures for calibration with special devices are described and pictured elsewhere.[24,27] The anterior-posterior component of GRF at the swing assisted push-off side could not be directly derived[27] and had to be estimated from data collected on the contralateral side using methods described in Göpfert et al.[24]

3D motion was recorded (100 Hz) with the Vicon Nexus motion capture system (Vicon, Oxford, UK) consisting of a 16 camera setup (T-Series T40S) installed on a wooden frame at the ceiling inside the ski tunnel.[17,24,27] The marker placement consisted of the Full Body Plug-In Gait marker setup[28] completed by markers on both trochanter major, mid sternum and mid spine as well as three markers on each ski. The latter constitute the ski segments,[24] while the others serve to increase data quality in the specific measurement condition.[24]

2.4 | Data collection

The motion capture system Vicon Nexus 1.7.1 (Vicon) was used to collect and preprocess 3D motion data. Signals from the force binding were transferred via cables to an 8-channel force amplifier (Neuromuscular Research Centre, University of Jyväskylä, Finland) which was linked to a National Instruments A/D converter card (sampling rate 1 kHz, NI 9205). Data were transmitted wireless (WLS-9163; National Instruments, Austin, TX, USA) to a receiver-card of a portable computer with a custom made data collection software (Labview 8.5; National Instruments). Participants wore a waist-bag on the middle of the back with a total weight of 2590 g containing the necessary measurement equipment.[24] An analogue trigger signal was simultaneously recorded by both data collection systems prior to each trial and used as sync peak for synchronizing data from force binding and motion capture data. The synchronization time was derived with IKE-master 1.38 (IKE Software Solutions, Salzburg, Austria) and data were merged and synchronized by means of a self-written script.

2.5 | Cycle and phase definition

The onset of ski ground contacts determined from GRF data on the arm swing assisted push-off side was defined as the start and the end of a movement cycle (Figure 2I-VI). During the ski ground contact gliding and push-off phase were separated by a characteristic minimum of GRFs (Figure 2III). Arm swing starts after weight transfer to the new gliding ski. The forward and sideward moving of the arms is accompanied by a characteristic downward and upward movement of arms' COM. Arm swing is defined from the beginning of this forward movement (Figure 2II) until the arm(s) have been slowed down to a stop (Figure 2V) coordinated in time with the end of leg push-off (Figure 2IV).

2.6 | Parameter definition

Centre of mass position was calculated from 3D motion capture data using the XC-model.[24] Further scripting (Body Language; Vicon) was used to determine the COM of the arms and the right and left arm's COM respectively. Linear momentum (p_a, p_b) was computed from the arms' or body's mass (m_a, m_b) and their COMs' velocity (v_a, v_b). The decrease and gain of linear momentum of the arms and body was calculated during leg push-off respectively. Angles between the direction of arm swing ($\boldsymbol{d_a}$, Figure 3) and the skiing direction ($\boldsymbol{y}$, θ_y), the vertical ($\boldsymbol{z}$, θ_z), the ski direction ($\boldsymbol{d_s}$, θ_s), and the trajectory of COM movement ($\boldsymbol{d_c}$, θ_c) were determined. For the comparison of arm swing techniques the COM was calculated, respectively, without the swinging arm(s) and the angle between these trajectories and the respective trajectory of the swinging arm(s) have been computed.

The position of the ski was described by the calculated ski angles; ski angulation from the y-direction (θ_o), ski edging (θ_e), and tilt (θ_t). Components of GRF ($\boldsymbol{F_{ml}}$, $\boldsymbol{F_{ap}}$, $\boldsymbol{F_v}$) measured with the force bindings were expressed in the motion capture coordinate system by means of rotational matrices using the cardan ski angles from motion capture.[24]

From the derived forces, $\boldsymbol{F_x}$ (transverse to the skiing direction), $\boldsymbol{F_y}$ (in skiing direction), and $\boldsymbol{F_z}$ (vertical to $\boldsymbol{F_x}$ and $\boldsymbol{F_y}$) the magnitude of resultant force F_r (Figure 4) could be computed by

$$F_r = \sqrt{F_x^2 + F_y^2 + F_z^2} \tag{1}$$

The displacement of the point of force application (PFA) along the binding was calculated from the ratio of the vertical GRFs measured with the front and rear part of the binding and the distance between the binding parts. Since the position of the binding in space is determined by a virtual marker (SkiOrigin), the spatial coordinates of the PFA could be calculated based on the position of SkiOrigin and the displacement along the ski.

To quantify the translational force ($\boldsymbol{F_t}$), $\boldsymbol{F_r}$ was decomposed. The share along the imagined line from PFA through the COM. $\boldsymbol{F_t}$ (Figure 4) is thereby calculated as

$$\boldsymbol{F_t} = \frac{\boldsymbol{F_r} \cdot \boldsymbol{v}}{|\boldsymbol{v}|} \tag{2}$$

where, the dot product of $\boldsymbol{F_r}$ and the spatial direction $\boldsymbol{v}$ determined by COM and PFA is divided by the distance between COM and PFA (|$\boldsymbol{v}$|). The component of $\boldsymbol{F_t}$ pointing in skiing direction is computed and labeled as $\boldsymbol{F_c}$ and representing the force on COM in skiing direction derived from force and motion capture data. Lean of the body was described by the angle between the vertical and PFA to COM direction (θ_l), and direction of resultant force is expressed by the angle (Figure 4) of $\boldsymbol{F_r}$ with respect to the vertical z (θ_r).

2.7 | Data processing and statistical analyses

IKE-master 1.38 (IKE Software Solutions) was used for the processing of the data and the calculation of mean and

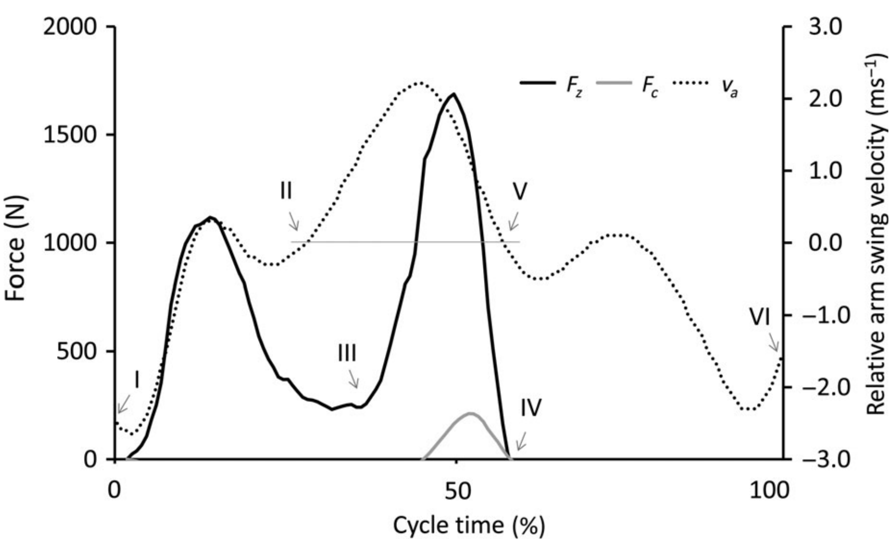


FIGURE 2 Illustration of vertical ground reaction forces (GRF) (F_z) translational force in skiing direction (F_c) and velocity of the arm in skiing direction relative to the velocity of centre of mass (COM) (v_a) during one movement cycle for one representative athlete performing SWING at maximal skiing speed. Roman numerals indicate (I) the start of the defined movement cycle, (II) the start of arm swing, (III) the separation of gliding and push-off phase, (IV) the end of pushoff, (V) the end of arm swing and (VI) the end of the movement cycle

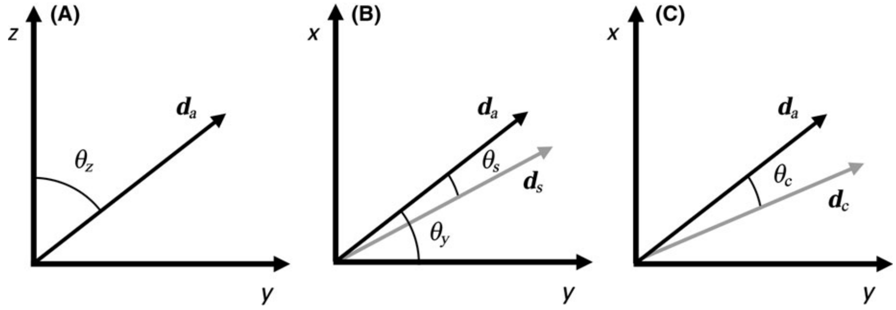


FIGURE 3 A, θ_z is defined as the anlge between direction of arm swing (d_a) and vertical axis z in the zy plane. B, θ_y is the angle between d_a and the skiing direction y and θ_s gives the angle between d_a and the direction of ski movement (d_s) both in the xy plane. C, θ_c indicates the angle between d_a and the trajectory of centre of mass (COM) (d_c) in the xy plane

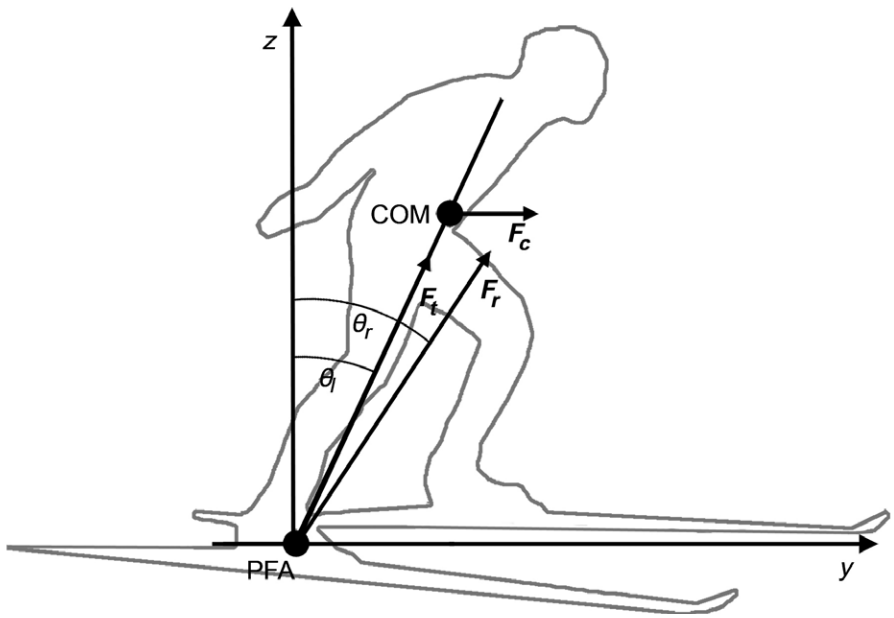


FIGURE 4 Illustration of forces acting on the cross-country skier in the skiing posture which can be described by the leaning angle (θ_l). F_r forms an angle (θ_r) with the vertical (z) axis. F_t is the component of F_r pointing from point of force application (PFA) towards centre of mass (COM) and its component in skiing direction is defined as F_c

maximal values was done with Microsoft Office Excel 2010 (Microsoft Corporation, Redmond, WA, USA). All statistical tests were conducted using the SPSS Statistics 17.0 (IBM Corporation, New York, NY, USA) software, where normal distribution of the data was examined using the Shapiro Wilk test. Since only a few of the distributions were skewed, it was decided to proceed with parametric statistics. Equivalent procedures have been shown to be highly robust to potential violations in assumptions of normality.[29] Main effects of technique and speed and interaction effect between technique and speed determined by a Two-Way repeated measures ANOVA (3×2) for technique (NOSWING, 1SWING, SWING) and speed (max, sub). Effect size (η^2) and power were calculated. If significant global differences were detected, a One-Way repeated measures ANOVA was conducted using a Bonferroni alpha correction. Differences between the two arm swing modes (1SWING, SWING) were tested using paired samples t tests if global significance was demonstrated with Two-Way-ANOVA. Techniques were thereby compared as regards maximal skiing speed and considering previously described parameters, during arm swing and leg push-off phases. Statistical level of significance was set at $P < 0.05$.

3 | RESULTS

3.1 | Maximal skiing speed

Maximal skiing speed deviated with skiing technique ($F_{2,5} = 6.6$, $\eta^2 = 0.72$, Power = 0.65, $P = 0.039$). While maximal speed was 6.41 ± 0.45 ms^{-1} with 1SWING and 6.34 ± 0.35 ms^{-1} with SWING revealing no difference ($P = 1.000$) between both arm swing techniques, in NOSWING a lower maximal skiing speed of 5.99 ± 0.22 ms^{-1} could be achieved ($P < 0.039$). Skiing with arm swing was thus 7% and 6% faster in comparison to NOSWING when skiing with 1SWING ($P = 0.032$) and SWING ($P = 0.028$) respectively.

3.2 | Cycle and phase characteristics

Cycle rate, cycle length, and the durations of push-off and gliding phases remained equal across techniques. An effect of speed and a technique × speed ($T \times S$) interaction was observed for cycle rate and the duration of push-off. All values and statistics can be found in Table 1.

3.3 | Forces, ski, lean, and force vector angles

During maximal speed, the maximum of F_c was 44% and 45% greater when skiing with 1SWING ($P = 0.007$) and with SWING ($P = 0.025$) compared to NOSWING respectively. Likewise, during 1SWING ($P = 0.006$) and SWING ($P = 0.006$) average F_c exceeded average F_c of NOSWING by 44% and 48%. In submaximal skiing speed, maximal and average F_c were maintained across techniques. Correspondingly, the effectiveness of applied force deviated across techniques at maximal ($F_{2,5} = 26.1$, $P = 0.002$) but not at submaximal skiing speed ($F_{2,5} = 3.5$, $P = 0.111$). The pairwise comparison revealed 41% greater force effectivness at maximal speed with both 1SWING ($P = 0.006$) and SWING ($P = 0.015$) compared to NOSWING (Figure 5B).

During skiing with maximal speed, the maximal forward lean angle was greater in 1SWING ($P = 0.045$) and SWING ($P = 0.023$) compared to NOSWING, but with no difference between the two arm swing modes ($P = 0.999$). At the end of leg push-off the forward lean angle was likewise greater in 1SWING ($P = 0.046$) and SWING ($P = 0.024$) compared to NOSWING, while it did not deviate between 1SWING and SWING ($P = 0.979$). At submaximal skiing speed such a difference was detected only between 1SWING and NOSWING as regarding the maximal forward lean angle ($P = 0.021$) and the forward lean angle at the end of leg push-off ($P = 0.024$). All force values, ski, lean, and force vector angles as well as detailed statistics are reported in Table 1 and Figure 5.

3.4 | Linear momentum and momentum transfer

The resultant linear momentum of the arms during NOSWING was determined by the arms mass and the movement velocity of the skier, while in the two arm swing techniques the velocity of the arm(s) could be faster or slower than the rest of the body, depending on the relative movement of the arm(s). During skiing with maximal speed the resultant linear momentum of the arm(s) was greater in 1SWING ($P = 0.002$) and SWING ($P = 0.001$) compared to NOSWING, however, was maintained between 1SWING and SWING ($P = 0.082$). At submaximal skiing speeds, the resultant linear momentum of the arms was lower compared to maximal speed. Differences were observed in the comparison of NOSWING to 1SWING and SWING (both $P = 0.003$) and between 1SWING and SWING ($P = 0.022$).

The linear momentum of the body increased during leg push-off in all techniques and speeds but deviated across skiing techniques. In maximal skiing speed the difference in linear momentum was greater for 1SWING ($P = 0.001$) and SWING ($P = 0.007$) compared to NOSWING, however no differences were detected between the two arm swing modes ($P = 1.000$). During skiing with submaximal speed the gain in linear momentum was greater during SWING ($P = 0.025$) compared to 1SWING, while in both arm swing techniques more linear momentum was gained compared to NOSWING (1SWING: $P = 0.036$ and SWING: $P = 0.020$).

During leg push-off the linear momentum in skiing direction increased for the body without the swinging arm (s), the linear momentum of the swinging arm(s) decreased during the same period while being decelerated toward the end of leg push-off. This decrease differed across skiing techniques with a considerable decrease of 5-11 Ns in arm swing techniques. The comparison between SWING and 1SWING revealed that the difference in linear momentum in skiing direction was greater in SWING during maximal ($P = 0.022$) and submaximal speed ($P = 0.009$). The decline in linear momentum of the arms was generally smaller in submaximal speed. Values and statistical details as regarding linear momentum of body and arm(s) can be found in Figure 5 and Table 2.

3.5 | Single vs double arm swing

Common to both arm swing modes, the arm(s) were firstly accelerated forward and consecutively slowed down to a stop toward the end of leg push-off (Figure 2). The swinging arm(s) were thereby moving up to 2.6 ± 0.9 ms^{-1} faster as the COM in skiing direction. In the first part of arm swing, the arm(s) were moved downwards and slightly outwards, passing the body of the skier. This was followed by swinging the arm(s) upwards and slightly inwards toward the new gliding ski. In SWING, this upward movement relative to the rest of the body was not yet stopped, when the forward swing ended. Figure 6 shows a representative example of 3D arm swing trajectory with associated swing velocity in 1SWING (Figure 6A) and SWING (Figure 6B). Distinguishing between both arm swing modes in 1SWING the mass of only one arm (4.2 ± 0.3 kg) was moved, while swinging both arms during SWING meant a doubling of the moving arm's mass (8.4 ± 0.6 kg). The absolute duration of arm swing was longer in 1SWING ($P = 0.049$) when skiing with submaximal speed (Table 2).

TABLE 1 (a) Cycle and phase characteristics, (b) forces as well as (c) ski, lean, and force vector angles during skiing with NOSWING, 1SWING, and SWING technique at maximal and submaximal speed

		Technique				Statistics			
	Speed	NOSWING	1SWING	SWING		F	P	η^2	Power
(a)									
CL [m]	Max	8.11 ± 0.83	7.88 ± 0.89	8.25 ± 0.79	T	$F_{2,5} = 2.7$	0.163	0.52	0.32
	Sub	8.41 ± 0.72	8.75 ± 1.02	9.10 ± 1.22	S	$F_{1,6} = 3.3$	0.120	0.35	0.33
					$T \times S$	$F_{2,5} = 1.6$	0.298	0.38	0.20
CR [Hz]	Max	0.75 ± 0.09	0.83 ± 0.14	0.78 ± 0.09	T	$F_{2,5} = 1.0$	0.424	0.29	0.15
	Sub	0.62 ± 0.05	0.60 ± 0.08	0.58 ± 0.09	S	$F_{1,6} = 26.3$	0.002	0.81	0.99
					$T \times S$	$F_{2,5} = 6.4$	0.042	0.72	0.64
dpo [s]	Max	0.34 ± 0.05	0.31 ± 0.05	0.33 ± 0.05	T	$F_{2,5} = 1.7$	0.267	0.41	0.22
	Sub	0.36 ± 0.07	0.36 ± 0.06	0.37 ± 0.07	S	$F_{1,6} = 6.3$	0.046	0.51	0.57
					$T \times S$	$F_{2,5} = 7.1$	0.035	0.74	0.68
dgl [s]	Max	0.45 ± 0.11	0.40 ± 0.14	0.43 ± 0.11	T	$F_{2,5} = 0.8$	0.519	0.23	0.12
	Sub	0.60 ± 0.05	0.62 ± 0.09	0.65 ± 0.17	S	$F_{1,6} = 14.8$	0.008	0.71	0.89
					$T \times S$	$F_{2,5} = 2.1$	0.220	0.45	0.26
(b)									
aF_r [%BW]	Max	119 ± 8	122 ± 7	123 ± 5	T	$F_{2,5} = 1.6$	0.298	0.38	0.20
	Sub	116 ± 5	115 ± 5	119 ± 4	S	$F_{1,6} = 2.8$	0.147	0.32	0.29
					$T \times S$	$F_{2,5} = 1.5$	0.305	0.38	0.20
maxF_r [%BW]	Max	200 ± 28	200 ± 34	204 ± 26	T	$F_{2,5} = 0.4$	0.692	0.14	0.09
	Sub	190 ± 19	191 ± 12	192 ± 13	S	$F_{1,6} = 2.5$	0.167	0.29	0.26
					$T \times S$	$F_{2,5} = 0.2$	0.829	0.07	0.07
aF_t [%BW]	Max	117 ± 8	119 ± 7	121 ± 5	T	$F_{2,5} = 1.6$	0.293	0.39	0.20
	Sub	114 ± 4	114 ± 4	118 ± 4	S	$F_{1,6} = 2.1$	0.200	0.26	0.23
					$T \times S$	$F_{2,5} = 1.0$	0.420	0.29	0.15
maxF_t [%BW]	Max	199 ± 27	198 ± 34	202 ± 27	T	$F_{2,5} = 0.5$	0.657	0.16	0.09
	Sub	188 ± 18	189 ± 11	190 ± 12	S	$F_{1,6} = 2.4$	0.175	0.28	0.26
					$T \times S$	$F_{2,5} = 0.2$	0.805	0.08	0.70
maxF_c [%BW]	Max	14 ± 4[bc]	21 ± 5[a]	21 ± 3[a]	T	$F_{2,5} = 28.6$	0.002	0.92	1.00
	Sub	13 ± 3	17 ± 6	15 ± 6	S	$F_{1,6} = 14.8$	0.008	0.71	0.89
					$T \times S$	$F_{2,5} = 1.2$	0.367	0.33	0.17
(c)									
aθ_o [°]	Max	17 ± 2	18 ± 1	17 ± 2	T	$F_{2,5} = 0.2$	0.796	0.09	0.07
	Sub	17 ± 3	17 ± 2	17 ± 1	S	$F_{1,6} = 0.2$	0.650	0.04	0.07
					$T \times S$	$F_{2,5} = 0.3$	0.738	0.11	0.08
aθ_e [°]	Max	34 ± 4	36 ± 5	32 ± 7	T	$F_{2,5} = 5.3$	0.059	0.68	0.56
	Sub	31 ± 5	30 ± 6	30 ± 6	S	$F_{1,6} = 14.8$	0.008	0.71	0.89
					$T \times S$	$F_{2,5} = 2.8$	0.155	0.53	0.33
maxθ_r [°]	Max	13 ± 2	13 ± 1	13 ± 2	T	$F_{2,5} = 0.4$	0.709	0.13	0.08
	Sub	11 ± 2	12 ± 2	12 ± 3	S	$F_{1,6} = 3.8$	0.099	0.39	0.38
					$T \times S$	$F_{2,5} = 1.3$	0.353	0.34	0.17

(Continues)

TABLE 1 (Continued)

	Speed	Technique NOSWING	1SWING	SWING		Statistics F	P	η^2	Power
endθ_r [°]	Max	12 ± 3	11 ± 2	11 ± 2	T	$F_{2,5} = 0.2$	0.840	0.07	0.07
	Sub	10 ± 2	11 ± 2	11 ± 2	S	$F_{1,6} = 0.6$	0.463	0.09	0.10
					$T \times S$	$F_{2,5} = 1.4$	0.329	0.36	0.19
maxθ_l [°]	Max	10 ± 4	15 ± 4[a]	14 ± 3[a]	T	$F_{2,5} = 15.1$	0.008	0.86	0.94
	Sub	9 ± 3[b]	13 ± 5[a]	11 ± 4	S	$F_{1,6} = 4.6$	0.076	0.43	0.44
					$T \times S$	$F_{2,5} = 0.2$	0.850	0.06	0.07
endθ_l [°]	Max	10 ± 3[bc]	15 ± 4[a]	13 ± 2[a]	T	$F_{2,5} = 13.6$	0.010	0.84	0.92
	Sub	8 ± 3[b]	13 ± 5[a]	11 ± 4	S	$F_{1,6} = 4.5$	0.079	0.43	0.43
					$T \times S$	$F_{2,5} = 0.2$	0.839	0.07	0.07

[a]Difference to NOSWING, [b]Difference to 1SWING, [c]difference to SWING ($P < 0.05$) determined with One-WAY-ANOVA.
Values are means ± standard deviation. n = 7. (a) CL, cycle length; CR, cycle rate; dpo, duration of leg push-off; dgl, duration of gliding. (b) Average (a) and maximum (max) of F_r, resultant force; F_t, translational force and F_c, component of F_t in skiing direction. (c) Average (a) and maximum (max) during leg push-off as well as the value at the end of leg push-off (end) of θ_o, ski angulation angle; θ_e, ski edging angle; θ_r, angle of resultant force vector; θ_l, forward lean angle. Main effects of technique (T) and speed (S) and interaction effect between technique and speed ($T \times S$) determined by Two-Way-ANOVA (3 × 2) for T (NOSWING, 1SWING, SWING) and S (max, sub).

During the time period where arm movement accompanies the leg push-off, effects of technique were detected in regards to the position of arms' mass, the velocity at which the arms were moved and the direction of arm swing (Table 2). The distance of the arms' mass from the shoulder, was greater in 1SWING both in maximal ($P = 0.001$) and submaximal ($P = 0.000$) speeds. Single arm swing was conducted faster compared to SWING. This was true at maximal and submaximal skiing speeds for the average resultant velocity of arm swing and the swing velocity in skiing direction. Thereby, forward arm swing velocity in 1SWING was faster already at the start of leg push-off and reached higher maximal values ($P = 0.011$). Arm swing and movement direction formed an angle of 3-6° at the start of leg push-off, where arms were swung further away from movement direction in SWING in both skiing speeds (maximal: $P = 0.007$ and submaximal: $P = 0.044$). While arm swing at the start of push-off was directed equally downwards in 1SWING and SWING, arm swing turned upward during push-off and the angle toward the vertical axis was smaller during SWING at the end of push-off compared to 1SWING in maximal ($P = 0.000$) and submaximal speed ($P = 0.000$). All values and statistics can be found from Table 2.

4 | DISCUSSION

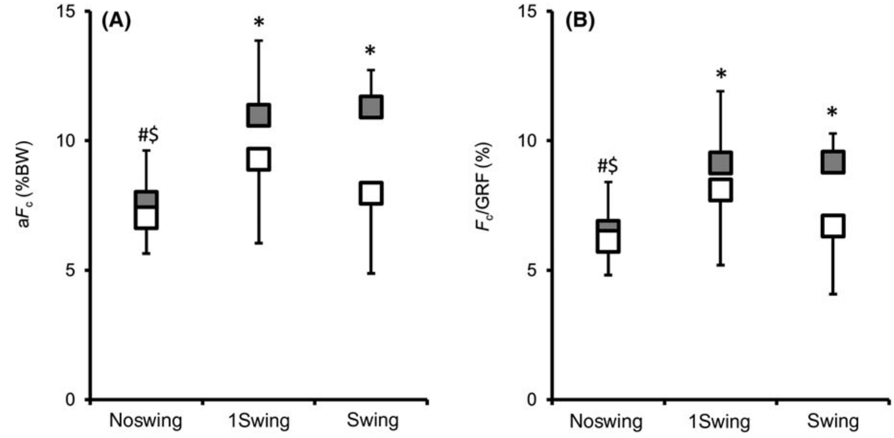
4.1 | Maximal skiing speed

Athletes performed at considerably higher maximal sprinting speed when using arm swing. This is in line with findings in XC-skiing and other sports like jumping for height or distance, where performance increased due to the use of an active arm swing.[7,9,11] Beyond that, the current study investigated and compared different arm swing techniques in XC-skiing and revealed that the arm swing mode did not influence performance when skiing on maximal speed. Our hypothesis was thus only partly confirmed, because maximal sprinting speed was increased with arm swing, but did not differ between swing techniques. Apparently, there are different possibilities on how to carry out arm swing that could be beneficial.

4.2 | Cycle and phase characteristics

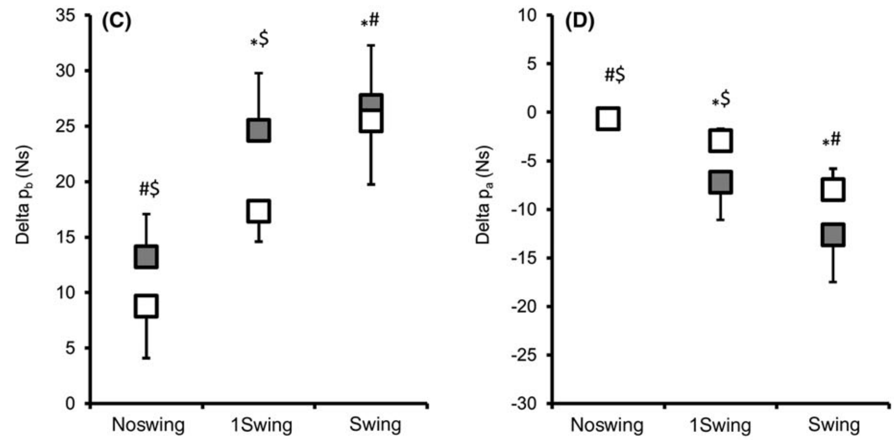
Interaction effects ($T \times S$) detected for cycle rate and duration of push-off, indicate that the constant submaximal speed and the individual maximal speed have been gained with different strategies. This is underlined by the finding of a speed effect. Greater maximal skiing speed could only be achieved by increasing cycle length and/or cycle rate, however, athletes performed their individual strategies to regulating cycle parameters rather than demonstrating a clear group difference between the investigated skiing techniques. While some participants slightly increased both cycle rate and cycle length when skiing with arm swing, others increased cycle rate with a maintained or even lower cycle length while again others increased only cycle length.

Previous investigations at moderate skiing speed showed contradictory results as regarding changes in cycle kinematics due to swinging the arms. While Göpfert et al[17] found greater cycle length, Hegge et al[18] presented data showing no differences in cycle length between NOSWING and SWING. In line with latter results, our data revealed no



	F	P	η²	Power
T	*F*(2,5) = 45.6	0.001	0.95	1.00
S	*F*(1,6) = 15.5	0.008	0.72	0.90
T x *S*	*F*(2,5) = 1.7	0.282	0.40	0.21

	F	P	η²	Power
T	*F*(2,5) = 49.8	0.000	0.95	1.00
S	*F*(1,6) = 11.2	0.015	0.65	0.80
T x *S*	*F*(2,5) = 1.2	0.367	0.33	0.17



	F	P	η²	Power
T	*F*(2,5) = 19.2	0.009	0.91	0.95
S	*F*(1,6) = 3.5	0.120	0.41	0.33
T x *S*	*F*(2,5) = 2.5	0.197	0.56	0.26

	F	P	η²	Power
T	*F*(2,5) = 34.8	0.003	0.95	1.00
S	*F*(1,6) = 16.6	0.010	0.77	0.90
T x *S*	*F*(2,5) = 5.8	0.065	0.75	0.53

FIGURE 5 A, Average F_c, B, force effectiveness F_c/ground reaction forces (GRF), C, gain in linear momentum of the body in skiing direction during leg push-off (delta p_b) and D, decrease in linear momentum of arms in skiing direction during braking of arms towards the end of leg push-off (delta p_a) during NOSWING, 1SWING and SWING at submaximal (white squares) and maximal (grey squares) skiing speed. Mean ± standard deviation of n = 7 participants. Main effects of technique (*T*) and speed (*S*) and interaction effect between technique and speed ($T \times S$) determined by Two-Way-ANOVA (3 × 2) for *T* (NOSWING, 1SWING, SWING) and *S* (max, sub). *Difference to NOSWING, #difference to 1SWING, $difference to SWING ($P < 0.05$) determined with One-WAY-ANOVA

statistical difference between skiing techniques when observing the cycle characteristic, however, six of seven athletes in the current study increased cycle length when skiing with SWING. The huge variation within the group of athletes and the statistical method applied might have prevented to finding statistical significance of differences. To elucidate the effect of swinging the arms on cycle kinematics in submaximal speeds seems to be highly important as previously conclusions have been drawn from the cycle length and applied forces on the performance of athletes[30] and the efficiency[18] or economy[31] of a skiing technique. Despite these considerations, it is not possible to draw conclusion from cycle length to propulsion gained during one single push-off. Cycle characteristics could rather be determined by a number of influencing factors; for example, the arm swing assisted push-off, the contralateral push-off accompanied by swinging the arms backwards, gliding properties and the physiological prerequisites of the athletes. Only differences between skiing techniques detected during arm swing assisted push-off can reveal the direct influence of arm swing (mode) on magnitude and effectiveness of force production. The absolute duration of push-off was retained during maximal and submaximal skiing speed, respectively, indicating that arm swing did not alter the

TABLE 2 (a) Linear momentum of arm(s), arm swing duration, arm position, arm swing velocity and (b) arm swing angles during skiing with 1SWING and SWING technique at maximal and submaximal speed

	Speed	1SWING	SWING		Statistics			
					F	*P*	η^2	Power
(a)								
p_a [Ns]	Max	57 ± 6	60 ± 5	*T*	$F_{2,5} = 31.9$	0.001	0.93	1.00
	Sub	47 ± 3	49 ± 2[a]	*S*	$F_{1,6} = 37.6$	0.001	0.86	1.00
				T × *S*	$F_{2,5} = 5.6$	0.052	0.69	5.59
das [s]	Max	0.51 ± 0.16	0.47 ± 0.11	*T*	$F_{2,5} = 9.9$	0.020	0.62	0.75
	Sub	0.76 ± 0.13	0.66 ± 0.17[a]	*S*	$F_{1,6} = 113.6$	0.000	0.95	1.00
				T × *S*	$F_{2,5} = 1.8$	0.232	0.23	0.20
la [mm]	Max	266 ± 17	222 ± 21[a]	*T*	$F_{2,5} = 118.6$	0.000	0.98	1.00
	Sub	268 ± 22	226 ± 23[a]	*S*	$F_{1,6} = 20.7$	0.004	0.78	0.96
				T × *S*	$F_{2,5} = 7.2$	0.034	0.74	0.69
av_{res}[ms^{-1}]	Max	1.9 ± 0.3	1.5 ± 0.2[a]	*T*	$F_{2,5} = 31.1$	0.001	0.84	1.00
	Sub	1.3 ± 0.2	1.2 ± 0.2[a]	*S*	$F_{1,6} = 25.8$	0.002	0.81	0.99
				T × *S*	$F_{2,5} = 16.2$	0.007	0.73	0.91
av_y [ms^{-1}]	Max	1.4 ± 0.4	1.1 ± 0.3[a]	*T*	$F_{2,5} = 17.7$	0.006	0.75	0.94
	Sub	1.0 ± 0.2	0.9 ± 0.2[a]	*S*	$F_{1,6} = 10.7$	0.017	0.64	0.78
				T × *S*	$F_{2,5} = 9.7$	0.021	0.62	0.74
startv_y [ms^{-1}]	Max	1.5 ± 0.7	0.7 ± 0.6[a]	*T*	$F_{2,5} = 11.5$	0.015	0.66	0.81
	Sub	1.0 ± 0.4	0.8 ± 0.4[a]	*S*	$F_{1,6} = 2.2$	0.190	0.27	0.24
				T × *S*	$F_{2,5} = 13.0$	0.011	0.68	0.85
maxv_y [ms^{-1}]	Max	2.6 ± 0.9	1.9 ± 0.6[a]	*T*	$F_{2,5} = 27.3$	0.002	0.82	0.99
	Sub	1.7 ± 0.3	1.4 ± 0.3[a]	*S*	$F_{1,6} = 14.9$	0.008	0.71	0.89
				T × *S*	$F_{2,5} = 13.4$	0.011	0.69	0.86
(b)								
startθ_s [°]	Max	13 ± 3	11 ± 4	*T*	$F_{2,5} = 4.8$	0.070	0.45	0.46
	Sub	12 ± 3	12 ± 2	*S*	$F_{1,6} = 0.2$	0.643	0.04	0.07
				T × *S*	$F_{2,5} = 1.1$	0.338	0.15	0.14
startθ_y [°]	Max	3 ± 2	5 ± 4[a]	*T*	$F_{2,5} = 30.1$	0.002	0.83	0.99
	Sub	3 ± 3	4 ± 2	*S*	$F_{1,6} = 3.0$	0.136	0.33	0.31
				T × *S*	$F_{2,5} = 1.0$	0.357	0.14	0.14
startθ_z [°]	Max	158 ± 16	158 ± 12	*T*	$F_{2,5} = 0.1$	0.808	0.01	0.06
	Sub	161 ± 15	160 ± 7	*S*	$F_{1,6} = 0.6$	0.447	0.10	0.11
				T × *S*	$F_{2,5} = 0.0$	0.843	0.01	0.05
startθ_c [°]	Max	6 ± 3	3 ± 2[a]	*T*	$F_{2,5} = 13.3$	0.011	0.69	0.86
	Sub	6 ± 3	4 ± 2[a]	*S*	$F_{1,6} = 0.3$	0.609	0.05	0.07
				T × *S*	$F_{2,5} = 1.5$	0.271	0.20	0.18
endθ_s [°]	Max	26 ± 3	26 ± 2	*T*	$F_{2,5} = 0.0$	0.954	0.00	0.05
	Sub	28 ± 3	28 ± 2	*S*	$F_{1,6} = 13.3$	0.011	0.69	0.86
				T × *S*	$F_{2,5} = 1.3$	0.290	0.18	0.17
endθ_y [°]	Max	8 ± 2	7 ± 2	*T*	$F_{2,5} = 0.0$	0.998	0.00	0.05
	Sub	10 ± 2	10 ± 2	*S*	$F_{1,6} = 17.9$	0.005	0.75	0.94
				T × *S*	$F_{2,5} = 0.7$	0.427	0.11	0.11

(Continues)

TABLE 2 (Continued)

	Speed	1SWING	SWING		Statistics F	P	η^2	Power
endθ_z [°]	Max	43 ± 11	24 ± 9[a]	T	$F_{2,5} = 145.3$	0.000	0.97	1.00
	Sub	48 ± 7	35 ± 6[a]	S	$F_{1,6} = 16.9$	0.009	0.77	0.90
				$T \times S$	$F_{2,5} = 20.5$	0.006	0.80	0.95
endθ_c [°]	Max	2 ± 1	1 ± 1	T	$F_{2,5} = 5.2$	0.063	0.47	0.48
	Sub	2 ± 1	1 ± 1	S	$F_{1,6} = 1.7$	0.241	0.22	0.20
				$T \times S$	$F_{2,5} = 0.3$	0.586	0.05	0.08

Values are means ± standard deviation. n = 7. (a) p_a, resultant linear momentum of the arm(s); das, duration of arm swing; la, distance of arms' mass from the shoulder; av_{res}, average resultant velocity of arm movement during leg push-off phase; av_y, average velocity of arm movement in skiing direction; startv_y, velocity of arm movement in skiing direction at the start of leg push-off; maxv_y, maximal velocity of arm movement in skiing direction. (b) θ_s, angle between arm swing direction and push-off ski; θ_y, angle between arm swing and skiing direction y, θ_z, angle between arm swing and the vertical z, θ_c, angle between arm swing and centre of mass (COM) movement direction c. Given are values at the start and at the end of push-off respectively. Main effects of technique (T) and speed (S) and interaction effect between technique and speed ($T \times S$) determined by Two-Way-ANOVA (2 × 2) for T (1SWING, SWING) and S (max, sub).
[a]Difference to 1SWING ($P < 0.05$) determined with paired samples t test.

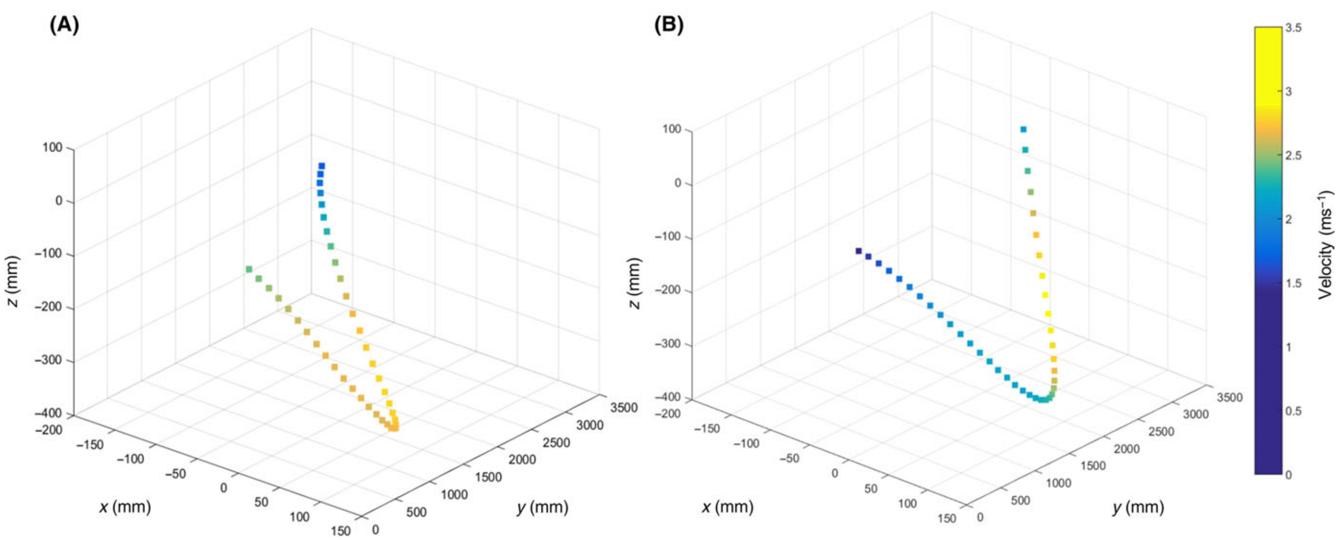


FIGURE 6 Position data (x, y, z) and respective movement velocity of the arms' centre of mass (COM) during skiing at maximal speed of A, 1SWING and B, SWING. Illustrated is the data of one participating athlete during skiing with maximal speed

timing of push-off. The comparability of push-off in terms of other parameters investigated during this phase is thus given for the current data. At greater maximal skiing speed in arm swing techniques the same duration for the gliding phase was detected meaning that athletes did not glide longer, but faster. This effect must be based on the forces produced during push-off, either by applying more GRFs or by being able to use this force more effectively.

4.3 | Forces, ski, lean, and force vector angles

Earlier findings indicate the production of greater GRF[17] due to arm swing. In high submaximal skiing speed this goes along with a more economic use of leg extensor muscles when swinging the arms as greater GRF have been produced with lower muscular activation.[17] This neuromuscular effect was, however, not evident in moderate and maximal speed.[17] In line with these findings and from a physiological point of view, metabolic costs and benefits of arm swing in XC-skiing seem to be dependent on speed.[18] Aerobic energy contribution, oxygen uptake and energy cost increased at low to moderate speeds due to swinging the arms.[18] As against in high submaximal speed anaerobic contribution was found to be lower in arm swing trials as oxygen uptake did not differ to no arm swing condition while blood lactate decreased.[18] Also in other cyclic human locomotion as running and walking, swinging the arms has been shown to reduce energy cost.[1,3,32,33] These effects have been attributed to mechanical reasons as swinging arms act as passive mass dampers[3] reducing lateral ground moments[1] and thus add to increasing lateral balance[33] and stability.[32] Mechanical effects of arm swing may play an important role also in XC-skiing in order to use applied force more effectively.[17] Indeed, a considerably greater component of translational forces in skiing direction (F_c) was detected when skiing with arm swing techniques at maximal speed. This greater acceleration gained in both arm swing techniques goes along with the greater skiing performance detected in comparison to NOSWING. Contradictory with earlier findings in leg skating,[18,21] current results indicate that the same amount of force was applied with or without arm swing in all investigated speeds. Hence, one may bring forward the argument that not the magnitude but the effectiveness of applied force caused the difference in performance. Indeed, greater force effectiveness could be demonstrated for both arm swing techniques during skiing with maximal speed. But what exactly leads to a more effective use of force? A conceivable approach would be that the athletes would be able to direct the applied force more precisely toward the COM and thus increase the share of translational force. However, our data showed that athletes direct the push-off force toward COM with a solid angle of 1-4° of deviation and thus the share of the translational force was very high in all three techniques.

The direction of applied force has been discussed to determine propulsive forces[25] and force effectiveness.[18] The direction of the resultant force vector is only dependent on the position of the ski on the track,[17,25] which the skier could alter by changing the edging and the angulation of the ski.[25] However, earlier[17] and current findings indicated that edging and angulation of the ski were not altered due to arm swing use when skiing on snow. Even specifically investigating the orientation of the resultant force in the sagittal plane, which determines the component of F_r in skiing direction, did not reveal differences between techniques. Thus, the direction of resultant force in space was not altered and eventually may not be the reason for more propulsion.

From standing long jump it is known, that a more forward position of the COM at the end of ground contact increased jumping distance.[11,16] The role of body position in XC-skiing has not yet been investigated. The current study was the first to apply the XC-model,[24] which determines the horizontal COM position validly from motion capture data. Results revealed that athletes leaned more forward during and especially at the end of push-off in both arm swing techniques at maximal speed. This means that the direction of the translational force vector in the sagittal plane was altered due to the use of arm swing and thus F_c increased. The forward lean is accordingly a main reason for skiing faster with arm swing techniques. A more forward position of the COM could originate from the position of the arms in front of the body at the end of arm swing in a dynamic situation, where balance could be regulated by compensating moments of force from gravity and GRF.[24] The angular momentum of arms may potentially help maintain the upright posture of the trunk.[34] During 1SWING at submaximal speed forward lean was likewise greater and differed to NOSWING, however the difference in average F_c between NOSWING and 1SWING was not significant even though six of seven participants increased F_c. A more targeted investigation with only two techniques should be carried out to investigate mechanisms of arm swing in submaximal speeds with basic statistics.

It is possible to investigate acceleration of and forces on COM in vertical, medio-lateral or movement direction with the approach applied during this study. This would be highly valuable to explain XC-skiing performance by, for example, performing energy or power analyses or accessing propulsion in COM movement direction. However, this study focused on the acceleration of COM in the intended skiing direction gained during a single push-off.

4.4 | Linear momentum and momentum transfer

A considerable increase of linear momentum was observed during push-off for all techniques with or without arm swing, while in arm swing trials the gain in linear momentum of the body in skiing direction was greater compared to NOSWING during skiing with maximal as well as submaximal speed. This underlines the role of leg push-off for increasing the velocity of COM,[21] however also emphasizes the role of arm swing. The movement of the arm(s) in arm swing techniques lead to a clear gain in resultant linear momentum of this segment during leg push-off and the decline in arms' linear momentum due to the braking of the forward arm movement toward the end of push-off was considerable in both arm swing techniques. Thus, linear momentum of swinging arm(s) decreased at the same time where linear momentum of the rest of the body increased. Following the concept of conservation of linear momentum[35] this indicates the transfer of momentum from the arm(s) to the rest of the body at the end of push-off.[21]

4.5 | Single vs double arm swing

Athletes took advantage of arm swing when skiing at maximal speed even though both applied arm swing techniques were distinctly different in their characteristics. The most obvious difference between both arm swing modes was certainly the difference in centrifugal mass when one arm or both arms were swinging in 1SWING and SWING respectively. The influence of mass has been investigated in jumping for distance using additional handheld weights[12,36-38] and the studies agreed that a certain amount of additional weight increased performance, namely jumping distance. For the arm swing modes used in the current study this means, that during 1SWING other mechanisms might have contributed to compensate the positive effect of swinging mass and to gain the same effect for XC-skiing performance. Arm swing was conducted faster during 1SWING compared to SWING a pattern, suitable for increasing linear momentum of the arm despite of smaller mass. Additionally, 1SWING was performed with a more extended arm. This “long arm” pattern, often claimed by coaches,[39] might lead to a greater angular momentum of arm(s). Additionally, arm swing was conducted more exactly in the forward direction at the start of push-off, while arm swing in SWING followed a sideward orientated COM trajectory. With regard to the direction of the arm swing, the most considerable difference was that the single arm swing was directed less upward at the end of push-off, which could contribute to greater linear momentum of arms in skiing direction. During skiing with submaximal speed, similar differences between arm swing modes were detected. But a slower arm swing in addition to a decreased strength of arm braking toward the end of the push-off might suggest a less distinct effect of arm swing during skiing with moderate speeds.

Overall athletes seemed to improve arm swing characteristics when only one arm was moved. It might be an easier task to swing just one arm and to pass the trunk, however, during XC-skiing races single arm swing is only relevant when skiing with legs only (Gear 5) at very high speeds in slight downhills. In this technique two consecutive single arm swings can be performed and this should be emphasized. In V2A, both arms have to be moved forward to repositioning for consecutive poling and the differences between 1SWING and SWING might reveal first requested[18] insights on how the arm swing should be conducted to be efficient. During V2A, athletes should be encouraged to carry the double arm swing out fast, with a “long arm” pattern and rather swinging in skiing direction during and less extreme upward at the end of push-off. Correlation analyses of the parameters presented in this study and within a bigger group of athletes could reveal more details accordingly.

5 | PERSPECTIVE

This explorative study investigated the mechanics of arm swing and mechanical effects of arm swing on leg push-off. Both examined arm swing techniques had positive effects on the maximal skiing speed, propulsion, and force effectiveness and thus on performance in XC-skiing. The main reason for this was the greater forward lean of the body when skiing with arm swing and the transfer of linear momentum from arms to the body. The latter effects were likewise observed in moderate submaximal skiing speed, although a clear impact on propulsion and force effectiveness could not be demonstrated in this skiing speed. While the investigated arm swing movements were distinctly different, both lead to similar effects, underlining how meaningful it was to carry out the arm swing fast, almost aligned in skiing direction and with a “long arm” pattern. This should be emphasized in technique training of XC-skiers when developing and optimizing double arm swing in V2A. Compensation mechanisms utilized during single arm swing may become important also for disabled XC-skiers. Paraskiing athletes may be able to partly compensate the negative effects of arm amputation and thus less arms' mass swinging by conducting a proper arm swing. However, future studies should reveal, how much less propulsion can theoretically be gained with different degrees of amputation, for example, by applying the relative momentum approach to XC-skiing data.[7,9,16,23] While during the current study physiological data have not been collected, the presented results highlight mechanical benefits of arm swing, which might effect on physiological parameters, too. To elucidate the costs and benefits of arm swing it is thus highly recommended that follow-up studies may simultaneously collect physiological and described mechanical data and examine their correlation during V2A-skating.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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