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Is there an optimal pole length for double poling in cross country skiing?

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Abstract

The aim of this study was to determine the effects of pole length on energy cost and kinematics in cross country double poling. Seven sub-elite male athletes were tested using pole sets of different lengths (ranging between 77 and 98% of participants' body height). Tests were conducted on a treadmill, set to a 2% incline and an approximate racing speed. Poling forces, contact times, and oxygen uptake were measured throughout the testing. Pole length was positively correlated with ground contact time ($r = .57, p < .001$) and negatively correlated with poling frequency ($r = -.48, p = .003$). Pole length was also positively correlated with pole recovery time and propulsive impulse produced per poling cycle ($r = .36, p = .031$; $r = .35, p = .042$, respectively). Oxygen uptake and pole length were negatively correlated ($r = -.51, p = .004$). This acute study shows that increasing pole length for double poling in sub-elite cross country skiers under the given conditions seems to change the poling mechanics in distinct ways resulting in a more efficient poling action by decreasing an athlete's metabolic cost.

Keywords: oxygen uptake, elite skiers, metabolic cost, poling kinematics, efficiency, optimal performance

Introduction

Cross country ski racing is divided into classic and skating races, which both require different skills from athletes. One thing they have in common though is the double poling action, occurring in combination with skating push-off or classic striding patterns, or in isolation, as the only propulsive force used by the skier. In double poling, skiers plant both poles simultaneously into the snow near the feet, then push them backwards to create forward propulsion. Good skiers make use of their legs and core to position their center of mass up and forward prior to planting the poles, thereby loading their poles to enhance propulsion. Pure double poling without significant propulsion from the legs and skis has become an important part of racing especially in classic ski competitions¹ which has led to an increase in the amount of research being done on this topic.^{1,2} Compared to other cross country skiing techniques, double poling enables the skier to align poling forces with the direction of skiing and therefore under certain conditions is more economical than striding or skating.^{3,4} Successful double poling performance has been shown to be positively correlated with lean trunk mass⁵, upper body strength, and a skier's maximum oxygen uptake, VO_{2max} ⁶. Furthermore, Holmberg and colleagues showed that lower body coordination, i.e. the movement of knee and ankle joints, affects double poling performance as well.^{1,7} Skiing speed in double poling is controlled by the adjustment of poling frequency, poling force, and cycle length.^{8,9} In uphill skiing with increasing slopes, recovery times decrease and cycle rates increase.⁴

While the above mentioned findings were obtained treating the athletes' equipment as a given, constant parameter, one aspect that has not been widely studied is the length of the poles chosen by an athlete. Since propulsion in double poling is determined primarily by the use of the poles, it is reasonable to assume that pole length affects a skier's performance. Athletes can either choose their pole lengths by 'what feels good' or by following guidelines published in the literature. Suggestions range from 79 to 90 % of body height, with the added

caveat that the appropriate length of a pole depends on the skiing technique, as well as to the skiers' expertise and constitution.^{10,11}

One of the first studies to focus on the effects of pole length on double poling performance was conducted by Nilsson and colleagues. They studied athletes performing single pole thrusts with three different pole lengths (78, 82 and 86 % of body height). The authors found that, compared to the other two sets, the use of the longest poles led to a longer ground contact phase, an increase in anterior-posterior impulse (in maximum poling), and a larger increase in velocity following each poling action. Based on these results they recommend a pole length of about 86 % of body height as possibly the most beneficial for maximal speed in maximum effort double poling. They further assumed that increasing pole length would lead to an increase in poling cycle duration and a decrease in poling cycle rate, and thus potentially to a decrease in propulsive impulse and speed over multiple poling cycles.¹² In order to gain insight into the trade-off between increased propulsive thrust and decreased poling frequency with increasing pole length, Hansen and Losnegard tested the effect of pole length on an 80 m all-out sprint. They observed that the shortest time for the 80 m sprint occurred with the longest poles provided, poles that were longer than the poles freely-selected by the athletes.¹³

Choosing the appropriate pole length for double poling may be quantified by the propulsive impulse that can be generated or the speed of a maximal sprint, as discussed above. However, for performance improvement in an actual race, these considerations might not be the most important. Rather, skiers might prefer to use a pole length that minimizes the metabolic cost of skiing at a given speed over a prolonged period of time, particularly with the ever increasing use of exclusive double poling in marathon racing over distances of 40km and up. Based on this consideration we propose the following hypotheses: (i) elite level cross country skiers choose pole lengths for double poling so as to minimize the energetic cost of skiing at race pace, and (ii) pole length affects the kinematics of double poling as expressed by

distinct changes in the mechanics. In accordance with previous studies (Nilsson and colleagues¹²) we expected longer poles to be associated with increased ground contact times, an increase in the propulsive impulse produced by the poles for each poling cycle, and a decrease in poling frequency.

In order to address these hypotheses, the purpose of this study was to investigate how pole length affects oxygen uptake while skiing at an approximate race pace level. A secondary aim was to determine the influence of pole length on the cycle characteristics (cycle duration, contact and recovery times, and impulse per poling cycle).

Methods

Seven sub-elite male cross country skiers were recruited to participate in this study (Table 1). All skiers used roller skiing as the primary training tool during the summer period and had ample experience roller skiing on a treadmill for training and testing purposes. All participants gave free, written informed consent to participate in the study after all procedures had been carefully explained to them, and this study was approved by the committee on human research at the University of Calgary.

All subjects used the same pair of roller skis (Marwe Classic 700 XC) and five or six sets of different length carbon fibre poles (One Way Diamond Storm), including their preferred pole length. A common cross country skiing pole consists of a handle-strap combination which is glued to a shaft. For the purpose of measuring the forces applied to the poles during the double poling trials, this construction was modified (Figure 1). Twelve strain gauges (six for each pole) were mounted to two aluminum cylinders that were then attached to left and right pole handles. The pole shafts were then bolted into each cylinder, thus enabling accurate pole force measurements and allowing for a quick switching of the force measurement system between poles. The force measuring system was calibrated by applying dynamically varying

forces to the poles on a Kistler force plate (Kistler AG, Winterthur, Switzerland) and relating the measured resultant forces with the voltage output provided by the strain gauges. Voltage signals from the poles were transmitted via a wireless 7-channel analog input sensor node (Microstrain® V-link®-LXRS®, sampling rate: 678 Hz) and processed with the corresponding software (Microstrain® Node Commander).

To guarantee comparable testing conditions for all athletes, participants were asked to ski on a treadmill set to a speed of 90 % of the individual's anaerobic threshold (determined separately, see below) and a 2 % incline. These speed and slope conditions were chosen to allow for hard but controlled and comfortable double poling for at least 25 minutes, which approximates the actual duration of double poling required during the test session. Subjects were secured by a safety harness, and were allowed to warm up individually until they indicated that they were ready for testing. In order to determine the individual anaerobic threshold for each subject, skiers performed an incremental double poling treadmill skiing test, starting at a speed of 10 km h⁻¹ at a 2 % uphill slope and increasing the speed by 1 km h⁻¹ every two minutes. The anaerobic threshold was identified according to the V-slope method¹⁴ and subsequently 90 % of the threshold speed (Table 1) was calculated to determine each athlete's individual test speed.

Following ten minutes of recovery from the anaerobic threshold test, athletes performed a five minute trial with the poles of self-selected length, then additional five minute trials with four or five poles of different lengths in random order (Table 2). Finally, the trial with the self-selected length was repeated. A five minute rest period was given between trials.

Results of the self-selected pole length represent the mean value of the first and last trials performed with the self-selected poles, while all the other results represent the value obtained for a single five minute test with longer or shorter poles than those self-selected. For each subject, data of five different pole lengths were included in the analysis.

The forces applied to the poles were measured continuously throughout all five minute trials. This information was used to calculate the ground contact time, the pole recovery time, and the total poling cycle times (and thus the cycling frequency). Furthermore, in order to obtain the force projected along the skiing direction, the skiers were filmed using a sagittal view camera (Pike F-032, 200 frames s⁻¹), that was synchronized with the pole forces. The force-time integral of this propulsive component of the poling force was calculated for each stride. Taking into account that an increasing body mass requires more mechanical work for a skier to keep a steady pace on an uphill slope, each athlete's mechanical impulse produced by the poles was normalized to body mass.

Oxygen consumption was monitored using a portable oxygen cart (COSMED 4k2b). To cancel out the effect of the different test speeds for the skiers, each participant's VO₂-data were normalized by the corresponding test speed in km h⁻¹.

Statistics

Statistical analysis was conducted with Matlab (R2013b). Each outcome variable was plotted as a function of pole length and fit to a linear regression model. Corresponding coefficients of correlation and p-values are being reported in the result's section. The level of significance was chosen as $\alpha = 0.05$.

Results

The results of this study suggest that longer poles allow for more efficient skiing than shorter poles, and indicate that energy efficiency is not the only factor athletes consider when choosing their poles. We found an inverse relationship between pole length and oxygen uptake for double poling at a given speed on a motor driven treadmill (Fig. 2; $r = - .51$, $p = .004$). Also, four out of six skiers had the highest VO₂-values skiing with the shortest poles, and three out

of six skiers had the lowest VO_2 -values skiing with the longest poles. The absolute mean and the lowest and highest oxygen uptake values are shown in Table 3.

Varying pole length proved to considerably affect poling cycle characteristics. Pole length was positively correlated with ground contact time (Fig. 3 A, $r = .57$, $p < .001$), and inversely correlated with poling frequency (Fig. 3 B, $r = -.48$, $p = .003$). There was a positive correlation between pole length and recovery time, although this relationship was not as strong as those just described above (Fig. 3 C; $r = .36$, $p = .031$). Pole length was also positively correlated with the propulsive impulse produced per poling cycle (Fig. 3 D; $r = .35$, $p = .042$). However, there was great individual variation in how athletes reacted to changes in pole lengths (Table 4).

Discussion

Pole length was found to affect the kinematics, kinetics and efficiency of double pole cross country skiing. Increasing pole lengths were associated with increased ground contact times, slower pole recovery, decreased poling frequency, increased propulsive impulse per pole cycle, and increased efficiency (i.e. equivalently decreased oxygen uptake) for skiing at a given speed on a slight uphill slope. By definition, skiing at a given speed on an uphill slope requires a defined amount of mean propulsive impulse, independent of the pole length. Since longer poles allow for longer ground contact times, and thus, greater impulses if one assumes that the average force application is about the same, then it follows that less frequent force application is required to overcome the resistance provided by the uphill slope and the roller ski friction with the ground (since the skier is essentially stationary on the treadmill, air resistance can be neglected). Therefore, increases in pole length allow for longer ground contact times, which was associated with increased propulsion per poling cycle, thus the frequency of poling could

181 be reduced, and this appears to be energetically more efficient than more frequent poling with
182 smaller propulsive impulses per poling cycle.

183 The fact that we did not measure body kinematics can be considered a limitation of this
184 study. We measured the kinematics of the poles, and the changes in poling frequency and
185 poling distance covered during ground contact and during recovery as a function of pole length.
186 These kinematic measurements showed distinct differences as a function of pole length.
187 However, since effects on poling cycle characteristics are likely to be accompanied by changes
188 of the actual poling motion, it may prove beneficial to also capture the entire body kinematics
189 with changing pole lengths in future studies.

190 Nilsson et al. argued that the thrust phase duration is the key parameter in successful
191 double poling performance. The use of short poles, they argued, requires more effort and an
192 increased force per poling cycle to maintain a certain speed, leading to less economic skiing,
193 hence an increase in oxygen demand.¹² Our findings agree with this argumentation. However,
194 in contrast to the reservation noted by Nilsson et al.¹², increasing pole lengths does not seem to
195 be associated with a corresponding penalty in oxygen uptake, and indeed that it might be
196 beneficial to go beyond their recommendation of 86 % of body height as the most optimal pole
197 length, which is a recommendation in agreement with the results of Hansen and Losnegard.¹³

198 The current findings do not allow for a definite statement regarding the optimal length
199 of a skiing pole in the double pole technique. However, our results indicate that poles of less
200 than about 80 % body height of the athlete are not efficient either in terms of applying
201 propulsive force or reducing metabolic energy requirements to produce a certain amount of
202 propulsion (Figure 2). While our findings suggest that oxygen uptake can be decreased using
203 longer poles, it is reasonable to assume that there is an upper limit in pole length: i.e., that
204 beyond a certain optimal pole length, oxygen consumption increases with increasing pole
205 length. Energetically, the optimal pole length may exceed an athlete's body height. The former

Olympic Champion and multiple world cup winning ski racer Gunde Svan once demonstrated that skiing with a single pole of approximately 2.30 m was efficient and allowed for great speed. This incident lead to an immediate change of the rules governing cross country skiing and now, according to current rules set up by the International Ski Federation (FIS), ski poles cannot be longer than an athlete's height, and two poles of equal length must be used in competitions.^{15,16}

Subjects showed different responses in terms of oxygen uptake and poling kinematics to variations in pole lengths. Such individual differences have been reported before.^{2,17} In our case, some of the differences might depend on the self-selected pole length, which determined the set of poles tested, the experience the athletes had with skiing using various pole lengths¹², or the type of skier they are.² Double poling at a given speed has been shown to be energetically more efficient than striding under a variety of conditions.^{3,18–20} However, double poling relies on a relatively small muscle mass to produce propulsion, thus local muscle fatigue is likely greater than while striding.¹² Therefore, it appears that double poling might favour strong athletes with relatively average aerobic capacity, while striding might favour relatively weak athletes with great aerobic power.

Smith and colleagues observed a distinct movement pattern in elite cross country skiers performing double poling. A considerable flexion of the trunk in combination with a fast flexion-extension sequence of the elbow during the poling phase was found to be critical for good performance. The authors suggested that the trunk flexion plays an important role in achieving beneficial pole-ground angles while trying to use the dynamics of the stretch-shortening cycle in the triceps brachii muscles thus combining effective elbow extension force and an adequate pole angle to create an optimal propulsive impulse.² This complex timing pattern might be especially complicated to maintain using short poles as short poles could cause an earlier elbow extension or greater trunk flexion than long poles, thus favouring the use of

long poles. More recent findings presented by Holmberg and colleagues¹ provide more detailed information about the poling movement that goes along well with our current results. The authors observed two different double poling strategies (A and B) with strategy A being characterized by greater elbow flexion at pole plant, faster elbow flexion, as well as greater abduction of the shoulder, and associated with the fastest skiers in the group of athletes tested in their study. Those kinematic characteristics were accompanied by higher peak pole forces (relative to the athletes' body weight), shorter times until this peak pole force was reached and bigger impulses of pole force (also relative to the skiers' body weight). Interpreting these findings, and especially the considerably smaller elbow angles at pole plant, as criteria of good double poling performance, supports our findings that choosing longer poles over shorter poles seems to be beneficial.

Furthermore, as documented in several studies,^{1,7,21} double poling is not just an upper limb activity but also involves the musculature of the trunk and legs. Following that notion, Holmberg et al.¹ extended the observations made by Smith and colleagues² analyzing not only the time courses of upper and lower limb joint angles but also the activity of selected muscles moving those limbs. They agree with the findings of previous studies, confirming that good performance in double poling not only requires strong upper limbs and trunk but also the contribution of the legs and well timed coordination of both. The authors observed a characteristic sequence of movement right before the pole plant ("high hip – high heel") in all their participants. Extension of ankle, knee and hip joints and a forward tilt of the trunk were followed by a quick flexion of said joints, with the minimum angles occurring close to the peak pole force. The authors suggested that this "active downward acceleration" of the athlete's centre of gravity considerably contributes to the force applied to the poles which eventually can be used for propulsion.¹ This particular starting position and the resulting range of motion

of the centre of gravity might be limited by shorter poles: that is, their use could lead to a less efficient poling motion.

The results of this acute study suggest that skiers do not necessarily choose a certain pole length for reasons of efficiency. But they do indicate that increasing pole length has energetic advantages during double poling in cross country skiing. However, it must be emphasized that these results were obtained with our subjects roller skiing on a treadmill, which was set to a specific speed (90 % of the speed at anaerobic threshold) and slope (2 % uphill). Different speeds or slopes may affect optimal pole length, as might the performance level of the skiers participating in the test. While we tested sub-elite athletes, the effects of changes in pole length might differ in novices or top level athletes. Furthermore, even though double poling is known to be energetically efficient, local muscle fatigue might be the limiting factor for double poling rather than oxygen uptake. Therefore, measurements of local muscle fatigue might prove beneficial when evaluating the lengths of poles for a given race situation. Nevertheless, we conclude from this study that increasing pole lengths is of energetic advantage in double pole cross country skiing at a pace that can be maintained for long distance races. Since half the subjects had the best efficiency with the longest poles, poles even longer than those tested here might show an even better efficiency.

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Table 1 Subject characteristics

Subject	Weight [kg]	Height [cm]	Shoulder height [cm]	Self-selected pole length [cm]	Self-selected pole length [% of body height]	Anaerobic threshold [km h ⁻¹]
1	73	174	150	155	89	14
2	76	180	149	155	86	17
3	76	184	158	160	87	14
4	75	180	155	155	86	13
5	80	188	159	167	89	14
6	68	175	147	155	89	13
7	75	187	158	160	86	14

Table 2 Pole lengths used by the subjects during the testing, indicated by the respective percentage of each subject's body height. The dark grey coloured boxes mark the self-selected pole lengths. For subject 5, only kinematic data are available.

Subject	1	2	3	4	5	6	7
Pole length [cm]							
139	80 %	77 %		77 %		79 %	
149	86 %	83 %		83 %		85 %	
155	89 %	86 %	84 %	86 %	82 %	89 %	83 %
160	92 %	89 %	87 %	89 %	85 %	91 %	86 %
167	96 %	93 %	91 %	93 %	89 %	95 %	89 %
175			95 %	97 %	93 %		94 %
180			98 %		96 %		96 %

Table 3 Descriptive overview: oxygen uptake over all trials for each subject. Mean (for all trials), maximum, and minimum VO₂ values are reported for each subject with pole lengths corresponding to the maximum and minimum values.

Subject	1	2	3	4	6	7
Mean VO ₂ (± SD) [mL min ⁻¹ kg ⁻¹]	37.5 (1.0)	46.9 (.6)	34.6 (.6)	42.8 (.5)	36.5 (1.2)	40.2 (1.0)
Max VO ₂ (pole length)	39.0 (80 %)	47.7 (77 %)	35.3 (87 %)	46.7 (77 %)	38.5 (79 %)	41.2 (86 %)
Min VO ₂ (pole length)	36.0 (96 %)	46.0 (93 %)	33.7 (95 %)	42.2 (86 %)	35.4 (89 %)	38.8 (96 %)

Table 4 Results of individual linear regression analyses for all examined variables.

Subject		1	2	3	4	5	6	7
Contact time	r	.76	.95*	.54	.98**	.98**	.93*	.91*
	p	.138	.014	.350	.004	.005	.023	.030
Poling frequency	r	-.02	-.79	-.60	-.97**	-.94*	-.06	-.98**
	p	.970	.109	.282	.005	.017	.929	.002

Recovery time	r	.51	.68	.28	.95*	.90*	-.49	.96*
	p	.378	.203	.645	.012	.039	.407	.010
Propulsive impulse	r	.19	.88*	-.58	.89*	.88*	.48	.96*
	p	.761	.047	.310	.041	.049	.416	.010
VO2	r	-.92*	-.98**	-.60	-.82		-.64	-.97**
	p	.026	0.004	.285	0.087		.241	.007

* = $p < .05$, ** = $p < .01$

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Figure 1 Handle, strap and part of the shaft of a pole, modified for measuring the forces applied to it, with the sensor being located between handle and shaft. The schematic shows equally spaced orthogonal pairs of strain gauges placed on the aluminum cylinder that was bolted to the handle. The wire links the sensor to the transmitter.

Figure 2 Pole length and oxygen uptake are negatively correlated. Individual test speeds are presented in the legend, the circled symbols indicate a subject's self-selected pole length and corresponding normalized VO_2 -value.

Figure 3 Kinematic characteristics: (A) Increasing pole-ground contact time (mean of left and right pole contact times) with increasing pole length. (B) Decrease of the poling frequency (mean of left and right poling frequency) with longer poles. (C) Increasing recovery time (mean of left and right pole recovery time) with increasing pole length. (D) Increase of propulsive impulse produced per poling cycle (the sum of the impulses generated with left and right pole) with increasing pole length.

Fig. 1

Fig. 2

Fig. 3