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Section II - Exercise Physiology & Sports Medicine

The Effects of Sub-Technique and Pole Length on Classic Roller Skiing Performance and Physiological Responses at Steep Uphill Inclination

by

Per-Øyvind Torvik[1], Johan Persson[1], Roland van den Tillaar[2]

The aims of this study were to compare performance with physiological and perceptual responses on steep uphill inclines between double poling and diagonal stride and to investigate the effects of pole length when double poling. Eight male, competitive cross-country skiers (22 ± 1.1 yrs, peak oxygen uptake (VO_{2peak}) in the diagonal stride: 69.4 ± 5.5 ml·kg^{-1}·min^{-1}) performed four identical tests, one in the diagonal stride, and three in double poling with different pole lengths (self-selected, self-selected -5 cm and self-selected +10 cm). Each test was conducted at a fixed speed (10 km/h), with inclination rising by 1%, starting with 7%, each until voluntary exhaustion. VO_{2peak}, the heart rate, blood lactate concentration, and the rating of perceived exertion were determined for each pole length in each test. The peak heart rate ($p < 0.001$) and VO_{2peak} ($p = 0.004$) were significantly higher in the diagonal stride test compared with double poling with all pole lengths. Time to exhaustion (TTE) differed significantly between all four conditions (all $p < 0.001$), with the following order from the shortest to the longest TTE: short poles, normal poles and long poles in double poling, and the diagonal stride. Consequently, a significantly higher slope inclination was reached ($p < 0.001$) using the diagonal stride (17%) than for double poling with long poles (14%), normal (13%) and short (13%) poles. The current study showed better performance and higher VO_{2peak} in the diagonal stride compared to double poling in steep uphill terrain, demonstrating the superiority of the diagonal stride for uphill skiing. However, in double poling, skiers achieved improved performance due to greater skiing efficiency when using long poles, compared to normal and short poles.

***Key words**: cross-country skiing, peak oxygen uptake, incremental test, XC skiing.*

Introduction

In recent years, double poling has become the predominant sub-technique in classic cross-country skiing. Traditionally, the advantages of using double poling have been most pronounced in flat and downhill terrains, although double poling is used even in steep uphill terrain (Welde et al., 2017) where the diagonal stride is normally regarded as more efficient (Stöggl and Holmberg, 2011). However, studies (Dahl et al., 2017; Pellegrini et al., 2011) have shown that on uphill gradients steeper than 8-9% skiers prefer diagonal stride to double poling technique.

Since all propulsion in double poling is generated through the poles, a key question is whether pole length would influence performance and physiological aspects. Recent studies examining this topic (Carlsen et al., 2018; Losnegard et al., 2017b; Onasch et al., 2017) showed that in low and moderate uphill terrains, double poling with longer poles resulted in reduced vertical displacement of the centre of mass (CoM), longer poling time when going uphill, and lower oxygen cost at a standard work load. In addition, an earlier study (Hoffman et al., 1994) showed lower oxygen cost in double poling

[1] - *Department of Sports Sciences and Physical Education, Nord University, Meråker, Norway.*
[2] - *Department of Sports Sciences and Physical Education, Nord University, Levanger, Norway.*

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with longer poles (89% vs. 83% of body length) in flat terrain, while Nilsen et al. (2003) described the advantages of long poles with longer poling time and more horizontally directed ground reaction forces. Hansen and Losnegard (2010) investigated long (>7.5 cm) and short (<7.5 cm) poles with self-preferred pole length in flat terrain and concluded that propulsion speed was higher with longer poles than with self-preferred. Further exploration of differences between pole length in steep uphill terrain showed that the effect of incline on this relationship and differences with the diagonal stride might provide important information for athletes and coaches, as well as for policy makers wishing to keep the classic diagonal stride as a competition style. The International Ski Federation (FIS) introduced new rules in 2016 concerning pole length and technique in classic competitions, where pole length was limited to 83% of the athlete's body height measured with ski boots on (FIS § ICR 348.8.1). In 2018, the FIS also included zones in the tracks where only the diagonal stride technique was permitted. Despite these restrictions, some athletes have still been able to successfully execute some races without kick wax and using mainly double poling, simulating the diagonal stride and using the herringbone technique in the technique zones.

Pole length is one of the crucial components influencing propulsion in double poling (Losnegard et al., 2017b; Stöggl and Holmberg, 2011). Beside pole length, several other key components have also contributed to the increased current use of double poling in cross-country skiing. Firstly, speed in classic cross-country skiing has increased due to athletes having stronger and better endurance-trained upper bodies (Stöggl et al., 2011), improved equipment and track preparation (Sandbakk and Holmberg, 2014; Stöggl and Holmberg, 2011) and better ski preparation along with pole quality (Stöggl and Holmberg, 2011). Secondly, a more effective double poling technique has emerged (Holmberg et al., 2005), with associated improvement in a) the sequential movement pattern in the hip, shoulder, and elbow joints (Komi and Norman, 1987; Lindinger et al., 2009), b) the forward orientation of the body, c) the orientation of the pole plant (Stöggl et al., 2011), d) the timing of pole force (Stöggl et al., 2011), e) characteristics of the repositioning of the whole body into the next stroke (Stöggl et al., 2011), and f) reduced vertical displacement range of the CoM (Carlsen et al., 2018; Losnegard et al., 2017b). All these changes in the kinematic and force components caused longer cycle lengths in the fastest skiers on flat and uphill terrain compared to slower skiers (Lindinger et al., 2009; Losnegard et al., 2017b; Stöggl and Holmberg, 2011, 2016; Stöggl et al., 2011) and they may be reinforced by longer poles.

To our knowledge, no study has investigated the effect of different pole lengths in steep uphill terrain on performance, physiological and perceptual responses to double poling, and quantified the differences in these variables compared to the diagonal stride in such terrain. Therefore, the aims of this study were to compare performance and physiological responses on steep uphill inclines between double poling and the diagonal stride and to investigate the effects of pole length when double poling.

Methods

Characteristics of the participants

Eight elite male cross-country skiers (age: 22 ± 1.1 years; body mass: 77.1 ± 5.0 kg; body height: 183 ± 3.6 cm), competing at the national level with an average of 120 ± 44 FIS points and maximal oxygen uptake (VO_{2max}) in the diagonal stride of 69.4 ± 5.1 $ml \cdot min^{-1} \cdot kg^{-1}$, participated voluntarily in the study. They were fully informed about the content of the study before giving written informed consent to participate. The study was approved by the Norwegian Centre for Research Data and conducted in accordance with current ethical standards in sports and exercise research.

Experimental design and procedures

To investigate the physiological and perceptual responses to different pole lengths and propulsion techniques in different slope inclinations, a counterbalanced crossover design with repeated measures was used. Each participant was tested under four conditions: 1) diagonal stride with normal poles (~83% of body height), 2) double poling with short poles (~80% of body height), 3) double poling with self-selected pole lengths, and 4) double poling with long poles (~88% of body height). Two tests took place on one day and two on the following day. The order of the four conditions was randomized for each participant, to avoid an order and fatigue effect. Since there were two maximal tests per day, there was at least four hours of recovery between tests.

The tests on the first and second days were at the same time of day. A standardized warm-up procedure consisted of 10 min running at 60–70% of the maximum heart rate on a motor-driven treadmill (Rodby 2500ML, Södertalje, Sweden) designed for roller ski testing. Participants then changed to skiing equipment and performed five min warm-up roller skiing with the technique and pole length specific to each test on a motor-driven treadmill (Rodby 3500ML, Södertalje, Sweden) designed for roller skiing. To exclude variations in rolling resistance, all athletes used the same pair of roller skis (SWENOR Fiberglass roller, standard resistance wheel 2, Trøsken, Norway), with Rottefella performance classic bindings (Rottefella, Klokkarstua, Norway). The poles (Swix CT1, Lillehammer, Norway) had special carbide tips to prevent them from slipping on the treadmill belt. After the warm-up, participants had a one min rest interval before the actual test started.

Participants then performed, in randomized order, one of the four progressive uphill treadmill roller skiing tests: 1) in diagonal stride and 2-4) double poling with short, self-selected, and long poles, respectively. The pole lengths were selected based on previous studies (Hansen and Losnegard, 2010; Losnegard et al., 2017b). The short poles were 5 cm shorter (~80%) than the self-selected poles, which were 83±1% of body height. The longer poles were 10 cm longer (~88% of body height) than the self-selected poles. All tests were executed at 10 km/h, an average uphill competition speed (Larsson and Henriksson-Larsén, 2008). The test started at 7% uphill, increasing 1% each minute until exhaustion. Participants were secured with a safety harness hanging from the ceiling, connected to the safety stop system of the treadmill. Testing on a treadmill was chosen to achieve standardized conditions during the measurements. The starting inclination of 7% was chosen to avoid preliminary fatigue when starting at a lower inclination.

Measurements

Mean oxygen uptake was measured using an Oxycon Pro apparatus with a mixing chamber (Jaeger GmbH, Hoechberg) every 10 s and every minute of the test, while VO_2 was calculated by the average three values closest (last 30 s) to every step change. Peak oxygen uptake (VO_{2peak}) was accepted when two of the following three criteria were achieved: a respiratory exchange ratio above 1.10, blood lactate above 8 $mmol \cdot L^{-1}$ and a plateau in VO_2 with increasing exercise intensity (Holmberg et al., 2007). Before each test, VO_2 and VCO_2 gas analysers were calibrated using high-precision gases (15.00 ± 0.04% O_2 and 5.85 ± 0.1% CO_2, (CareFusion gas GmbH Höchberg, Germany). The flow meter was calibrated with a 3 L volume syringe (Hans Rudolph Inc., Kansas City, Missouri, USA). In addition, peak inclination on the treadmill was recorded for each test together with total time to exhaustion (TTE). The heart rate was measured with a heart rate monitor (Polar RC3GPS, Polar Electro OY, Kempele. Finland), using 5 s intervals for data storage. After each test, the LT-1710 Lactate Pro analyser (Arkray Factory Inc., KDK Corporation, Shiga, Japan) was used to measure blood lactate concentration from the fingertip of each participant. The athletes' ratings of perceived exertion (RPE), measured (6–20) on the Borg scale (Borg, 1982), were also recorded after each test.

Statistical analysis

To compare the effects of pole length and propulsion on different physiological and perceptual variables, a one-way ANOVA with repeated measures on each variable was performed. To compare the heart rate and oxygen uptake under the four conditions, a four x seven (slope inclination) multivariate ANOVA was conducted. Post-hoc comparisons with Holm-Bonferroni corrections were conducted to determine differences. When sphericity assumptions were violated, Greenhouse-Geisser adjustments of the p-values were reported.

The level of significance was set at $p < 0.05$ and all data were expressed as mean ± SD. Size effect was evaluated with η^2 (partial eta squared), where $0.01<\eta^2<0.06$ constituted a small effect, $0.06<\eta^2<0.14$ a medium effect, and $\eta^2>0.14$ a large effect (Cohen, 2013). Statistical analysis was performed in SPSS, Version 23.0 (SPSS Inc., Chicago, IL).

Results

No significant differences in the RPE ($F = 1.3$, $p = 0.30$, $\eta^2 = 0.16$) or lactate concentration

(F=0.87, $p = 0.47$ $\eta^2 = 0.11$) were found between the four conditions (Table 1).

The peak heart rate (F = 22.2, $p < 0.001$, $\eta^2 = 0.76$) and peak oxygen uptake (F = 6.1, $p = 0.004$, $\eta^2 = 0.47$) were significantly higher in the diagonal stride test compared with the three double poling conditions at complete exhaustion. In addition, TTE was significantly different between all four conditions (F = 135, $p < 0.001$, $\eta^2 = 0.95$), i.e. short, self-selected and long poles double poling and diagonal stride, in order from the shortest to the longest TTE (Table 1). This also implied a significantly higher slope inclination (F = 91, $p < 0.001$, $\eta^2 = 0.93$) for the diagonal stride (17%) compared to double poling with long (14%), self-selected (13%) and short (13%) poles (Figure 1).

When analysing alterations in the heart rate and oxygen uptake under the different conditions, a significant effect of condition (F = 189.6, $p < 0.001$, $\eta^2 = 0.87$) and an interaction effect (F = 8.3, $p < 0.001$, $\eta^2 = 0.74$) were found for oxygen uptake (Figure 1). For the heart rate only, a significant interaction effect (F = 1.8, $p = 0.042$, $\eta^2 = 0.38$, Figure 2) was found.

Table 1

Physiological and perceptual variables at complete exhaustion

Variable	Diagonal stride	Double poling		
		Shorter pole	Self-selected	Longer poles
Blood lactate (mmol/l)	10.4 ± 1.5	11.2 ± 1.9	10.4 ± 1.0	11.0 ± 1.8
RPE	18.8 ± 1.0	18.0 ± 0.8	18.5 ± 1.1	18.3 ± 1.0
Peak heart rate (beats/min)	191 ± 6*	184 ± 6	185 ± 6	184 ± 4
VO_{2peak} (ml/min/kg)	69.4 ± 5.5*	66.3 ± 5.7	65.3 ± 6.7	65.6 ± 6.4
Peak slope inclination (%)	17.3 ± 1.6*	13.1 ± 1.0	13.3 ± 1.0	14.1 ± 1.4*
Time to exhaustion (s)	637 ± 86*	382 ± 53*	402 ± 56*	444 ± 78*

** indicates a significant difference with the other three conditions on a p < 0.05 level.*
RPE: rating of perceived exertion. VO_{2peak}: Peak oxygen uptake

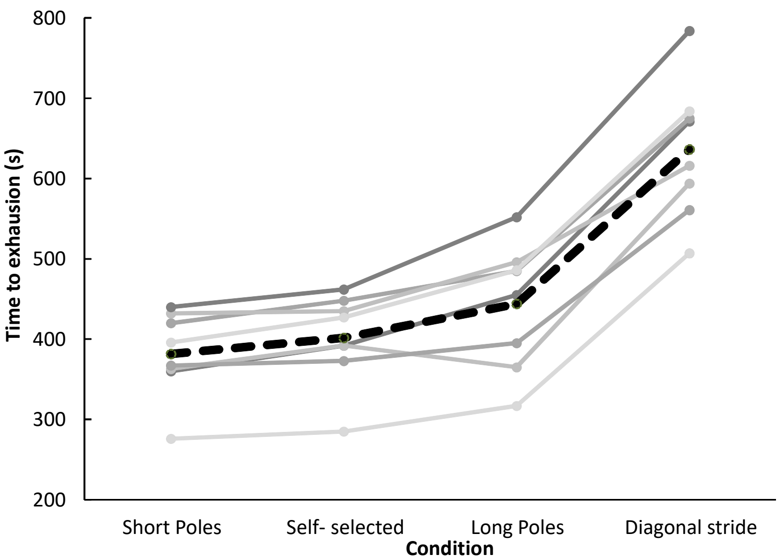

Figure 1

Individual time to exhaustion in each of the four skiing conditions and average over all participants (- - -)

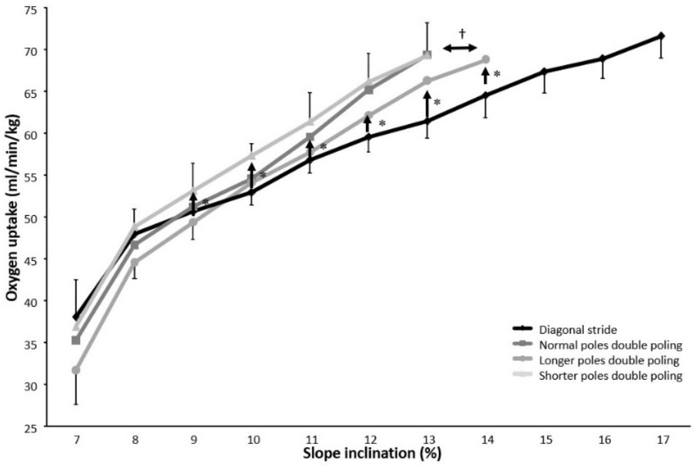

Figure 2

Mean oxygen uptake at the different slope inclinations for each of the skiing conditions
** indicates a significant difference between diagonal stride and the other conditions on the specified incline on a p < 0.05 level. † indicates a significant difference at all inclinations between double poling with long poles and short poles on a p < 0.05 level.*

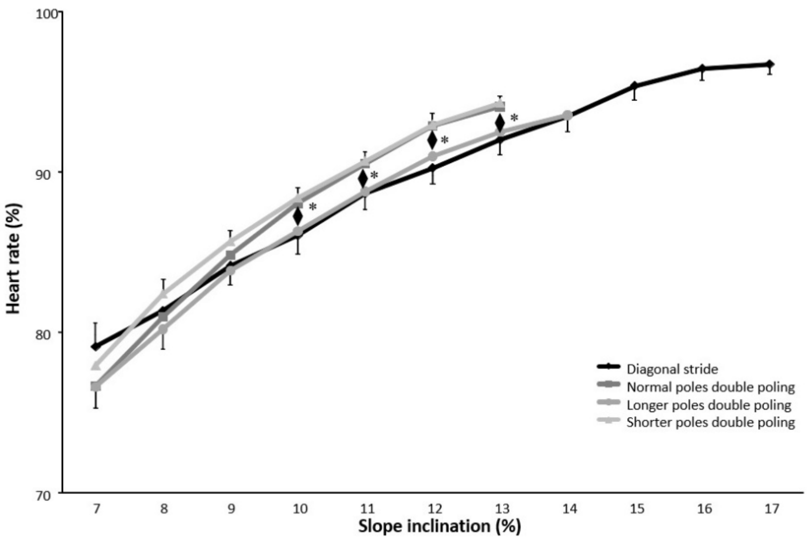

Figure 3

Mean heart rate at the different slope inclinations averaged per ***condition***
** indicates a significant difference between diagonal stride and double poling with long poles compared to double poling with normal and shorter poles on the specified inclines on a p < 0.05 level.*

Post-hoc comparison revealed lower oxygen uptake for double poling with long compared to short poles at all inclinations (range 5.0-3.25 $ml \cdot min^{-1} \cdot kg^{-1}$ from 7-13%), while oxygen uptake was lower for the diagonal stride than for double poling with short poles on inclines steeper than 9% (0.9-7.86 $ml \cdot min^{-1} \cdot kg^{-1}$ from 8-13%). From 10% inclination, oxygen uptake was also lower in the diagonal stride compared to the self-selected and short poles, while from 12%, oxygen uptake was also lower than with double poling with long poles (range 2.60-4.25 $ml \cdot min^{-1} \cdot kg^{-1}$ from 12-14%; Figure 2). Furthermore, from 10% inclination, the heart rate was significantly ($p > 0.019$-0.051) lower during the diagonal stride and double poling with long poles compared to the other two double poling conditions (Figure 3).

Discussion

This study compared performance and physiological responses on steep uphill inclines between double poling and the diagonal stride and investigated the effects of pole length when double poling. The two main findings were as follows: 1) the diagonal stride showed significantly longer TTE (i.e. improved roller ski performance) when roller skiing on steep uphill terrain than double poling independent of pole length. This difference coincided with lower submaximal oxygen cost (indicating better skiing efficiency) at all inclinations above 10%, but higher VO_{2peak} compared to the values reached in double poling; 2) increasing pole length gradually increased TTE and thereby the ability to double pole on steep inclines. This was reflected in lower submaximal oxygen cost for long versus self-selected and short poles, without any difference in the peak heart rate and peak oxygen uptake across double poling conditions.

The current study showed longer TTE in the diagonal stride XC skiing technique than double poling independent of pole length when roller skiing on steep uphill terrain. This difference coincided with lower oxygen uptake (indicating better skiing efficiency) with the diagonal stride at all inclinations above 10%, in combination with higher peak oxygen uptake compared to the values reached in double poling. These results were as expected in comparison with previous studies, where e.g. Dahl et al. (2017) showed clearly better skiing efficiency with the diagonal stride compared to double poling on inclines above 12% when roller skiing. Holmberg et al. (2007) showed gradually increasing VO_{2peak} with a higher muscle mass involved from arm cranking to the diagonal stride (i.e. whole-body work). The clear increase in VO_{2peak} in the diagonal stride compared to double poling found in our study indicates that double poling does not produce enough power to tax the cardiovascular system maximally (Undebakke et al., 2019) and thereby also limits performance in steep uphills where the diagonal stride can be used optimally. Overall our study provides novel data on the superiority of the diagonal stride technique for uphill performance and supports previous studies that have found that this is due to both greater energy delivery capacity and better efficiency.

In the diagonal stride, one or both limbs always produce propulsive force throughout the cycle, which is not the case for double poling where the short propulsion and long recovery times are less effective in steep uphills; here, considerable power is exerted against gravity. However, the roller ski brake reduces the need for vertical force to prevent the skis from slipping when executing the classic kick on roller skis, which is likely to induce more efficient forward propulsion than when skiing on snow. While this might reduce the difference between diagonal and double poling performance during on-snow skiing, it seems logical that the above-mentioned mechanisms make the diagonal stride more effective than double poling on steep uphill terrain also when skiing on snow. However, double poling on snow may outperform the diagonal stride on uphill terrain under difficult waxing and skiing conditions, and even though the diagonal stride is effective in steep parts of the track, skis without grip wax glide better and make double poling faster in downhills, flat terrain and curves in a competition track.

Although the diagonal stride seems superior in steeper uphills, double poling is a more efficient technique in other parts of the tracks and might be exclusively used in some races. In such cases, evaluation of pole length for performance in both flat and uphill double poling should be considered. This was reflected in lower submaximal oxygen cost for long versus self-selected and short poles, without any difference in peak energy delivery capacity across double poling conditions. While longer poles have been shown to be more effective in flat terrain, slight uphills and varied terrain (Hoffman et al., 1990; Onasch et al., 2017; Losnegard et al., 2017b; Carlsen et al., 2018), this is the first study to examine longer poles in steep uphills, indicating that they improve performance by enhancing skiing efficiency also in steep terrain.

The longer TTE achieved by double poling with long poles concurs with the findings of Losnegard et al. (2017b) who reported better performance (time trial) and lower oxygen costs with long poles at flat and moderate uphills. The novel findings of our study are the advantage of long poles (i.e. lower oxygen cost and heart rate) compared to the self-selected and short poles, and that this is apparent at 7-8% inclination and upward. This is of great interest in cases where this technique is exclusively used in competitions. The gap in energy cost increases between short/self-selected poles, compared to long poles with inclinations greater than 8%. The positive effect of long poles with increasing uphill inclination agrees with earlier investigations (Carlsen et al., 2018), but this has previously only been shown up to 7.9% inclination (Onasch et al., 2017).

The difference in oxygen cost with long poles versus short and self-selected poles might be explained by the longer propulsion cycle with long poles (Onasch et al., 2017), and thus more propulsion executed per cycle with the same or reduced vertical CoM displacement (Carlsen et al., 2018). In contrast, shorter poles in double poling are associated with higher poling frequency and reduced propulsive power per poling cycle (Onasch et al., 2017). Longer poles are also reported to have several kinematic advantages such as a more upright working posture, reduced vertical displacement of the CoM and more effective use of uphill (Carlsen et al., 2018). Although displacement of the CoM and range of motion (RoM) were not measured here, which must be considered a shortcoming of this study, several other studies have pointed out that less vertical displacement of the CoM in uphill skiing with longer poles has a positive influence on oxygen cost (Carlsen et al., 2018; Losnegard et al., 2017b). Consequently, these factors result in higher oxygen cost with short and self-selected poles compared to long poles.

Conclusion

The diagonal stride on roller skis showed significantly improved performance on steep uphill terrain compared to double poling independent of pole length, demonstrating the superiority of the diagonal stride technique in such terrain. This difference coincided with lower submaximal oxygen cost at all inclinations above 10%, which indicates better skiing efficiency, as well as higher peak oxygen uptake than that achieved in double poling. Hence, the diagonal stride seems to be superior to double poling on steep uphills due to both greater energy delivery capacity and better efficiency. Although VO_{2peak} was the same with all pole lengths, longer poles showed a lower heart rate and oxygen cost on comparable submaximal inclines, indicating that longer poles improve performance by enhancing skiing efficiency. This study shows that increasing pole length gradually increased performance and thereby the ability to double pole on steep inclines. Therefore, future experimental studies should analyse the effectiveness of different sub-techniques throughout entire race-tracks and include biomechanical analyses to further understand the underlying mechanisms.

References

Borg AVG. Psychophysical bases of perceived exertion. *Med Sci Sport Exer,* 1982; 14(5): 377-381. doi:10.1249/00005768-198205000-00012

Carlsen CH, Rud B, Myklebust H, Losnegard T. Pole lengths influence O2-cost during double poling in highly trained cross-country skiers. *Eur J Appl Physiol,* 2018; 118(2): 271-281. Retrieved from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5767204/pdf/421_2017_Article_3767.pdf. doi:10.1007/s00421-017-3767-x

Cohen J. *Statistical Power Analysis for the Behavioral Sciences* (2nd ed.): Routledge Ltd.; 2013

Dahl C, Sandbakk Ø, Danielsen J, Ettema G. The Role of Power Fluctuations in the Preference of Diagonal vs. Double Poling Sub-Technique at Different Incline-Speed Combinations in Elite Cross-Country Skiers. *Front Physiol,* 2017; 8(94): 1-9. doi:10.3389/fphys.2017.00094

Hansen E, Losnegard T. Pole length affects cross-country skiers' performance in an 80-m double poling trial performed on snow from standing start. *Sports Engin,* 2010; 12(4): 171-178. Retrieved from https://link.springer.com/content/pdf/10.1007%2Fs12283-010-0042-3.pdf. doi:10.1007/s12283-010-0042-3

Hoffman DM, Clifford SP. Physiological responses to different cross country skiing techniques on level terrain. *Med Sci Sport Exer,* 1990; 22(6): 841-848. doi:10.1249/00005768-199012000-00017

Hoffman DM, Clifford SP, Watts BP, Drobish MK, Gibbons PT, Newbury SV, O'Hagan PK. Physiological comparison of uphill roller skiing: diagonal stride versus double pole. *Med Sci Sport Exer,* 1994; 26(10): 1284-1289. doi:10.1249/00005768-199410000-00017

Holmberg HC, Lindinger S, Stöggl T, Eitzlmair E, Muller E. Biomechanical analysis of double poling in elite cross-country skiers. *Med Sci Sport Exer,* 2005; 37(5): 807-818. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/15870635.

Holmberg HC, Rosdahl H, Svedenhag J. Lung function, arterial saturation and oxygen uptake in elite cross country skiers: influence of exercise mode. *Scand J Med Sci Sport, 2007;* 17(4): 437-444. Retrieved from https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1600-0838.2006.00592.x. doi:10.1111/j.1600-0838.2006.00592.x

Komi PV, Norman RW. Preloading of the thrust phase in cross-country skiing. *Int J Sport Med,* 1987; 8(1): 48-54

Larsson P, Henriksson-Larsén K. Body Composition and Performance in Cross-Country Skiing. *Int J Sports Med,* 2008; 29(12): 971-975. Retrieved from https://www.thieme-connect.com/products/ejournals/abstract/10.1055/s-2008-1038735. doi:10.1055/s-2008-1038735

Lindinger S, Holmberg HC, Müller E, Rapp W. Changes in upper body muscle activity with increasing double poling velocities in elite cross-country skiing. *Eur J Appl Physiol,* 2009; 106(3): 353-363. Retrieved from https://link.springer.com/content/pdf/10.1007%2Fs00421-009-1018-5.pdf. doi:10.1007/s00421-009-1018-5

Losnegard T, Myklebust H, Skattebo O, Stadheim HK, Sandbakk J, Hallén J. The influence of pole length on performance, O2 cost, and kinematics in double poling. *Int J Sport Physiol,* 2017b; 12(2): 211-217. doi:10.1123/ijspp.2015-0754

Onasch, F, Killick A, Herzog W. Is there an optimal pole length for double poling in cross country skiing? *J Appl Biomech,* 2017; 33(3): 197-202. doi:10.1123/jab.2016-0071

Pellegrini B, Bortolan L, Schena F. Poling force analysis in diagonal stride at different grades in cross country skiers. *Scand J Med Sci Sport,* 2011; 21(4): 589. Retrieved from https://www.tandfonline.com/doi/pdf/10.1080/17461391.2016.1249031?needAccess=true. doi:10.1111/j.1600-0838.2009.01071.x

Sandbakk Ø, Holmberg HC. A Reappraisal of Success Factors for Olympic Cross-Country Skiing. *Int J Sport Physiol,* 2014; 9(1): 117-121. doi:10.1123/IJSPP.2013-0373

Stöggl LT, Holmberg HC. Force interaction and 3D pole movement in double poling. *Scand J Med Sci Sport,* 2011; 21(6): e393-e404. Retrieved from https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1600-0838.2011.01324.x. doi:10.1111/j.1600-0838.2011.01324.x

Stöggl LT, Holmberg HC. Double-Poling Biomechanics of Elite Cross-country Skiers: Flat versus Uphill Terrain. *Med Sci Sport Exerc,* 2016; 48(8): 1580-1589. doi:10.1249/MSS.0000000000000943

Stöggl LT, Müller E, Ainegren M, Holmberg HC. General strength and kinetics: fundamental to sprinting faster in cross country skiing? *Scand J Med Sci Sport,* 2011; 21(6): 791-803. Retrieved from https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1600-0838.2009.01078.x. doi:10.1111/j.1600-0838.2009.01078.x

Undebakke V, Berg J, Tjønna AE, Sandbakk Ø. Comparison of Physiological and Perceptual Responses to Upper-, Lower-, and Whole-Body Exercise in Elite Cross-Country Skiers. *J Strength Cond Res,* 2019; 33(4): 1897-1177. doi:10.1519/JSC.0000000000003078

Welde B, Stöggl TL, Mathisen GE, Supej M, Zoppirolli C, Winther AK, Holmberg HC. The pacing strategy and technique of male cross-country skiers with different levels of performance during a 15-km classical race. *PLOS One,* 2017; 12(11): Retrieved from https://journals.plos.org/plosone/article/file?id=10.1371/journal.pone.0187111&type=printable. doi:10.1371/journal.pone.0187111

Zoppirolli C, Pellegrini B, Bortolan L, Schena F. Energetics and biomechanics of double poling in regional and high-level cross-country skiers. *Eur J Appl Physiol,* 2015; 115(5): 969. Retrieved from https://link.springer.com/content/pdf/10.1007%2Fs00421-014-3078-4.pdf. doi:10.1007/s00421-014-3078-4

Corresponding author:

Per-Øyvind Torvik
Department of Sports Sciences and Physical Education,
Nord University, Levanger.
7530 Meråker Norway.
Phone: +47 74022984
Fax: +47 74112001
E-mail: per.o.torvik@nord.no