Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Medicine and Health Sciences
Department of Neuromedicine and Movement Science

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Choice of technique in classical roller-skiing

The influence of speed, incline and work rate, and relationship between power and technique choice

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Kunnskap for en bedre verden

Abstract

Purpose: Classical cross-country (XC) skiing mainly consists of three different sub-techniques, double poling (DP), double poling with kick (DK) and diagonal stride (DIA), which are utilized based on factors such as speed and terrain. The purpose of this study was to investigate how changing speed, incline and work rate determines sub-technique choice, and additionally to investigate whether individual differences in DP and DIA use is related to upper- and lower-body power. ***Methods:*** Nine female (age 20.4 ±2.1 years, body weight 65 ±6.6kg and body height 171.6 ±4.3cm) and 12 male (age 21.2 ±4 years, body weight 72.4 ±4.7kg and body height 179.6 ±5.9cm) XC-skiers performed nine different ≈5-minute tests at the same relative work rate. The tests were divided into three subsets, with three tests at different levels for each subset. In each subset, one factor was kept constant during the 5-minute test, constant work rate (WR-c), constant speed (SPD-c) and constant incline (INC-c). Incline, speed and/or work rate changed every 15 seconds, depending on the subset. All protocols consisted of an initial order with increasing incline at WR-c and SPD-c, and increasing speed at INC-c, and a reversed order where the same factors decreased. 3D-kinematics were recorded to identify sub-technique choice. On a separate day, maximum upper- and lower-body power was estimated with a bench pull (BP) and a leg press (LP) exercise. Influence of speed, incline and work rate were analyzed separately for men and women for each subset with a one-way ANOVA. ***Results***: For both genders, speed and work rate at which a sub-technique was used was significantly affected ($p \leq 0.018$) for WR-c and SPD-c subsets, respectively. In women, incline of sub-technique use was only significantly affected at minimum incline of DK use ($p=0.022$) at SPD-c. In men, incline of sub-technique use was significantly affected in four out of 12 occasions at WR-c and SPD-c ($p \leq 0.019$). At INC-c, fewer changes in sub-technique were evident, but skiers used a higher ´gear´ as speed increased. Direction of change significantly affected maximum incline of DP (5.3% initial order and 4.8% reversed order, $p=0.001$) and DK (7.7% initial order and 7.2% reversed order, $p=0.023$) use. The combination of 10km/h and 7% incline, and 10km/h and 5% incline occurred at all three subsets. 11 and nine participants, respectively, used a different sub-technique despite speed and incline combination being identical. No significant correlations between amount of DP or DIA use and BP, LP, or BP/LP power ratio was found. ***Conclusion:*** Sub-technique choice is primarily determined by incline, speed seems to play a lesser role by resulting in use of a higher ´gear´ at higher speed. Not only speed and incline combination, but also how one attains that combination seems to influence choice of technique. Individual differences in DP and DIA use do not seem to occur due to differences in power capacity. It is possible that power capacity is a prerequisite for increased use of DP or DIA, but that any differences are dependent on the correct technical execution to be evident.

Sammendrag

Formål: Klassisk langrenn består hovedsakelig av tre ulike delteknikker, staking (ST), staking med fraspark (STF) og diagonalgang (DIA), og anvendes basert på faktorer som hastighet og terreng. Hovedformålet med denne studien var å undersøke hvordan endring i hastighet, stigning og belastning avgjør teknikkvalg, i tillegg til å undersøke om individuelle forskjeller i bruk av staking og diagonalgang er knyttet til eksplosivitet i over- og underkropp. ***Metode***: Ni kvinnelige (alder 20.4 ±2.1 år, kroppsvekt 65 ±6.6kg og kroppshøyde 171.6 ±4.3cm) og 12 mannlige (alder 21.2 ±4 år, kroppsvekt 72.4 ±4.7kg og kroppshøyde 179.6 ±5.9cm) langrennsløpere gjennomførte ni ulike ≈5-minutters tester på samme relative belastning. Testene var delt inn i tre ulike undergrupper hvor tre tester ble gjennomført for hver undergruppe. For hver undergruppene, ble en faktor holdt uendret gjennom testen, konstant hastighet, konstant stigning og konstant belastning. Stigning, hastighet og/eller belastning ble endret hvert 15. sekund under testen, avhengig av undergruppe. Alle testene bestod av en del 1 hvor stigning økte ved konstant belastning og hastighet, og hastighet økte ved konstant stigning, på del 2 reduserte de samme faktorene. 3D-kinematikk ble målt for å identifisere teknikkvalg. På en annen dag ble maksimal eksplosivitet i over- og underkropp estimert ved henholdsvis benktrekk (BT) og beinpress (BP). Påvirkning av stigning, hastighet og belastning ble analysert separat for menn og kvinner for hver undergruppe ved hjelp av en enveis ANOVA. ***Resultater***: For begge kjønn ble hastighet og belastning av teknikkbruk signifikant påvirket av testene ($p \leq 0.018$) ved henholdsvis konstant belastning og konstant hastighet. Hos kvinner ble stigning av teknikkbruk signifikant påvirket bare ved minimum stigning av STF ($p=0.022$) ved konstant hastighet. Hos menn ble stigning av teknikkbruk signifikant påvirket av testene i fire av 12 tilfeller ved konstant belastning og konstant hastighet ($p \leq 0.019$). Ved konstant stigning var det færre endringer i teknikkbruk, men deltakerne brukte et høyere 'gir' når hastigheten økte. Retning på endringene i testene påvirket signifikant maks stigning av ST (5.3% del 1 og 4.8% del 2, $p=0.001$) og STF (7.7% del 1 og 7.2% del 2, $p=0.023$). Kombinasjonen av 10km/t og 7% stigning og 10km/t og 5% stigning oppstod ved alle tre undergruppene. Henholdsvis 11 og ni deltakere brukte ulik teknikk selv om kombinasjonen av hastighet og stigning var identisk. Det ble ikke funnet noen signifikante korrelasjoner mellom ST eller DIA og eksplosivitet i BT, BP eller BT/BP-ratio. ***Konklusjon***: Valg av teknikk i klassisk langrenn blir i hovedsak bestemt av stigning, men også hastighet ser ut til å spille en rolle ved å føre til bruk av høyere 'gir' ved økt hastighet. I tillegg er det ikke bare hastighet og stigning i seg selv som er avgjørende for teknikkvalg, men også hvordan en oppnår den bestemte hastigheten og stigningen. Individuelle forskjeller i anvendelse av ST og DIA ser ikke ut til å oppstå på grunn av forskjeller i eksplosivitet. Det er mulig at eksplosivitet er en forutsetning for anvendelse av teknikkene, men at forskjellene ikke blir synlige uten korrekt teknisk utførelse.

Acknowledgement

I would like to thank my supervisor Prof. Gertjan Ettema which was of significant importance with his support, advise and knowledge in the field of study. A thank you is also in its place to the rest of the employees at Center for Elite Sport Science/The Norwegian Olympic Sport Center, Region Mid-Norway at Granåsen, and especially Jørgen Danielsen for his help and guidance in the laboratory.

Additionally, I would send a thank you to all the cross-country skiers who volunteered to participate in the study. At last I would like to show my gratitude to my fiancé for supporting me during my work on this thesis.

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Introduction

Competitive cross-country (XC) skiing is performed using different clearly identifiable techniques on distances ranging from about 1km and up to several miles at varying terrain. XC-skiing is carried out with a free choice of utilizing the different sub-techniques during races. Utilization of these sub-techniques has previously been described as a 'gear' system, where the athletes chooses technique based on factors such as terrain and speed (Nilsson et al. 2004).

Classical XC-skiing is one of the two main techniques used and primarily consists of three different sub-techniques, double poling (DP), double poling with kick (DK) and diagonal stride (DIA). In DP, the highest gear, only the poles are used directly for propulsion, in a synchronized manner. Although all propulsion is provided through the poles, the legs play an important role for DP performance, e.g. (Holmberg et al. 2006). By elevating the center of mass in the swing phase the legs provide potential energy which contributes to propulsion via the poles during the poling phase (Danielsen et al. 2015). DP is mostly employed on flat terrain at high speed, but in recent years, DP has also been used in entire races.

In contrast to DP, DIA is employed on steeper terrain at lower speed and is performed in a walking-like pattern. In DIA, propulsion is provided through both skis and poles. About 22% and 42% of the cycle time is used for ski and pole propulsion, respectively, but most propulsive power is provided via the skis (Lindinger et al. 2009; Vahasoyrinki et al. 2008). This ensures a large duty factor, i.e. relative cycle time which is used for propulsion, and results in lower power fluctuations at steep inclines compared to DP, where approximately 27% of cycle time is used for propulsion (Dahl et al. 2017; Holmberg et al. 2005).

In DK, the arms are used in a similar way as in DP, but the technique also includes an alternating leg kick. The leg kick provides propulsion via one ski in-between each poling phase and thus results in longer cycle times and a higher duty factor compared to DP (Nilsson et al. 2004; Gopfert et al. 2013). DK is mostly used on slightly uphill terrain, in-between the DP and DIA technique. Changes between these sub-techniques occurs several times during races. For example, Marsland et al. (2017) found that the national level athletes on average changed between the different sub-techniques almost 300 times during a 10km classical race.

As described, it is well known under which conditions these different sub-techniques in general are used. There is however no general consensus regarding which factor that triggers technique changes, and to what extent incline, speed and work rate determines technique choice. Both Cignetti et al. (2009) and Pellegrini et al. (2013) found changes from DP to DK and further from DK to DIA with increasing incline at constant speed. Pellegrini et al. (2013) also found that a larger part of the athletes preferred DP at higher speed on a constant incline.

Considering that the external work rate also increased in these studies one cannot separate the effect of speed or incline from work rate.

In contrast to these studies, Ettema et al. (2017) conducted testing where both incline and speed changed simultaneously at different sub-maximal constant work rates. They found that incline of shift was rather constant at the different work rates and therefore concluded that incline rather than speed is the main factor determining choice of technique. Since work rate was constant in this study, the effect of work rate was however uncertain. In all these studies the conditions changed once every 60 or 30seconds, and it is possible that rate of change influence the choice of technique. Also, no changes from DP to DIA has been apparent in these studies, which is in contrast to findings from XC-skiing on snow (Solli et al. 2018). A faster rate of change would in larger degree resemble outdoor conditions were changes in speed and incline might occur more abruptly. With a faster rate of change it is thus possible that changes from DP to DIA might occur to reduce the amount of technique changes. Technique changes can be viewed as an investment considering the increased metabolic cost and instability related to technique changes (Usherwood and Bertram 2003; Diedrich and Warren 1995).

Several mechanisms explaining the choice of technique have been proposed, and includes factors such as efficiency, instability, force limitation, power fluctuations, and subjective feelings of comfort (Cignetti et al. 2009; Pellegrini et al. 2013; Ettema et al. 2017; Dahl et al. 2017; Andersson et al. 2017). Which one of these mechanisms that explains the choice of technique is uncertain, and it is possible that several mechanisms influence the choice of technique. In a recently published study, Ettema et al. (2018) found that exhaustive exercise had no impact on choice of technique, and it is thus unlikely that physiological factors can explain these choices.

Pellegrini et al. (2013) proposed that there is a limited force an athlete would like to exert through the poles. With increasing incline technique changes from DP thus occurs in advantage of a technique where less force is provided via the poles, i.e. DK and DIA (Stoggl et al. 2011). In addition, during DP at steep incline, lower body contribution might be limited due to less movement perpendicular to the ground surface and thus reducing the use of potential energy as explained by Ettema et al. (2017). This would in turn place even higher emphasis on the upper body for propulsion at steep incline (Dahl et al. 2017).

In addition, Pellegrini et al. (2013) found that leg thrust time (LTT), the time the leg stands still during push of, was reduced to about 0.1 second at the highest speed during DIA. They hypothesized that this represented a time threshold to produce propulsion and thus would trigger a technique change, which also has been supported by others (Dahl et al. 2017). Similar

LTT has been reported in other studies on DIA at high speed, and LTT during DK has been shown to be considerably longer and can thus provide advantage at higher speed (Vahasoyrinki et al. 2008; Nilsson et al. 2004; Lindinger et al. 2009). If LTT limits the use of DIA at high speed one would however expect that changes from DIA would occur at a given speed, which is in contrast to the finding by Ettema et al. (2017).

In light of these two latter explanations, increased upper- and lower-body power might allow the use of DP at steeper incline and DIA at higher speed, respectively. General measures of upper- and lower-body power has previously been shown to be related to DP and DIA performance (Stoggl et al. 2011). In that case, this can also help explain the large individual differences in technique preferences found in previous studies (Pellegrini et al. 2013; Cignetti et al. 2009; Ettema et al. 2017).

The primary aim of this study was therefore to further investigate how changing speed, incline and work rate influence choice of technique in classical XC-skiing. By performing different tests where one of these parameters were held constant and changing the others, this allowed us to investigate in more detail what affects the choice of technique in classical XC-skiing. Additionally, we investigated if individual differences in DP and DIA use can be explained by differences in upper- and lower body power.

Based on previous findings by Ettema et al. (2017) we hypothesize that incline is the primary determining factor behind the choice of technique and that athletes with higher upper-/lower-body power capacity would show increased use of DP, due to the higher reliance on the upper-body for propulsion in DP compared to DIA (Stoggl et al. 2011).

Methods

Participants

12 male and nine female XC-skiers volunteered to participate in the study. The participants were junior and senior competitive XC-skiers and were familiar to roller-skiing on a treadmill. Written informed consent was signed by all participants, and they were informed that they could withdraw from the study at any point. The procedures were verbally explained to each athlete before testing. See table 1 for descriptive statistics.

Table 1: Descriptive statistics for the participants.

Descriptive statistics			
	Height (cm)	Weight (kg)	Age (yrs)
Male	179.6 ±5.9	72.4 ±4.7	21.2 ±4
Female	171.6 ±4.3	65 ±6.6	20.4 ±2.1

Expressed as mean with standard deviation (±SD)

Experimental Design

Testing was done over two days. All participants performed a bench pull (BP) and a leg press (LP) power test on the first day. In addition, body weight and height were recorded. On day two, nine different tests with classical roller-skis on a treadmill were completed. Treadmill roller-skiing was chosen in order to minimize environmental influences' and thus achieve standardized conditions which ensured accurate test execution. Kinematics was continuously recorded during the testing, and blood lactate concentration was assessed after each test.

Instruments and Materials

The LP exercise was performed in a Keiser leg press machine (Air300 Leg Press, Keiser Corporation, California, USA) designed for measuring power. In the BP, a cord from a linear displacement sensor (MUSCLELAB, Ergotest Innovation A.S., Porsgrunn, Norway) were attached to a Leoko weightlifting bar (Leoko, Tampere, Finland) in order to estimate power during the lift.

The classical roller-skiing was performed on a 5x3 meter motorized treadmill (Forcelink Technology, Zwolle, The Netherlands) constructed for roller-skiing. All individuals used the same pair of IDT roller-skis (IDT sports, Lena, Norway) equipped with wheels of rolling resistance category two. Participants were allowed to use their own pair of poles in self-preferred length. All participants roller-skied with a safety harness. The tests were preprogrammed with software designed for the treadmill (ForceLink B.V., Culemborg, The Netherlands).

Movements during roller-skiing was monitored by an Oqus 3D motion capture system (Qualisys AB, Gothenburg, Sweden). One marker was attached on the side of each ski, just in front of the back wheel, and one on the bottom of each pole. Additionally, two reflexive markers were attached on the treadmill, parallel to the belt. Six cameras recorded the position of the six markers at a sampling rate of 100Hz. The 3D system was calibrated with a L-frame and a wand of known length, on each test day. On days with more than two participants, the 3D system was calibrated between every second participant.

Data was collected with software designed for the 3D system (Qualisys Track Manager, Qualisys AB, Gothenburg, Sweden) and later analyzed with a Matlab (9.4.0 R2018a, Mathworks Inc., Natick, MA, USA) script developed to identifying the different sub-techniques (Ettema et al. 2017). Technique changes were also manually registered during the testing in order to validate the technique classified by the script.

For lactate analysis, 20 μ-L blood was collected from the fingertip of the ring- or middle finger 30 seconds after each test and analyzed by a Biosen C_line lactate analyzer (EKF diagnostics GmbJ, Magdebury, Germany).

Kinematical Data

The Matlab script was developed to classify the technique chosen by the participants (Ettema et al. 2017). Technique choice were identified based on the signals from the markers placed on the skis. With a continuous phase algorithm, the movements were identified as DP, DK or DIA. A relative phase value of ≥2 rad between the two markers on the skis were identified as DIA, a value between 0.6 and 2 as DK, and a value of ≤0.6 as DP. In addition, markers on the treadmill were used to check that incline was correct, and pole markers to check speed. Speed and incline from the tests showed to be in agreement with the calculated speed and incline from the markers. Data from the 3D-camera system was synchronized with the treadmill tests which made it possible to pinpoint the given speed and incline combination where the sub-technique was used. The determined sub-techniques given by the Matlab script was quality checked against the manually registered data. In cases of disagreement between the methods, the 3D-videos were manually checked to ensure correct classification.

Test protocol

Power testing

Before the power tests all participants performed ten minutes of running at low intensity, as warm up. The participants were instructed to pull or push as forcefully as possible during the concentric phase of the LP and BP exercise. Only the concentric phase of the lift was of interest. All participants performed the LP exercise before the BP.

The LP exercise was performed in a LP apparatus with a standardized ten-rep test. Based on the participants estimated 1RM, the apparatus estimated ten loads with increasing resistance. On the first load the participants performed two test attempts to get familiar with the apparatus before the ten-rep test started. On the forthcoming loads, only one repetition was performed. The rest time between attempts was also set by the apparatus and increased as the load increased, in order to avoid fatigue. The test was performed until the participant was not able to complete one repetition. Thus, if the estimated 1RM was too high, the test ended with fewer than ten attempts, and conversely continued if attempt number ten was successfully performed. The seat of the LP was adjusted so the angle between thighs and the calves were 90°, at the starting position and the concentric phase ended with extended knees in ≈180° angle (Fig. 1). Because of technical limitations right and left power (watt) was estimated separately for each leg and later summed for each repetition. Maximum lower-body power was identified as the single highest power achieved amongst all the lifted loads.

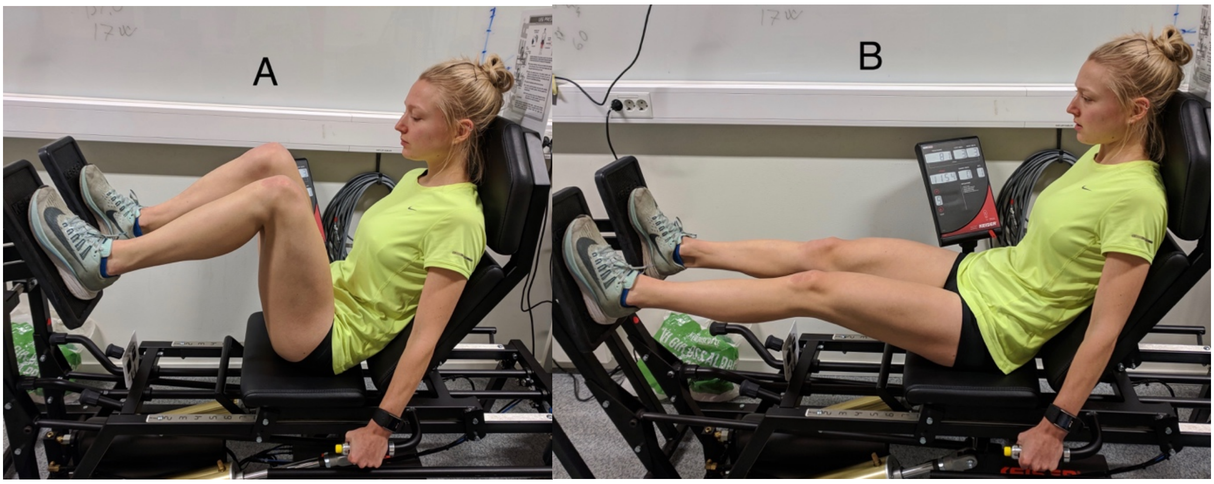


*Fig. 1: Starting (**A**) and finishing (**B**) position of the concentric phase of the LP.*

The BP was performed lying on a bench in prone position, with an olympic weight lifting bar of 20kg. Power testing was performed with at least three sets of three repetitions with increasing weight to get a valid estimate of the participants' maximum power and force-velocity relationship. If a reduction in power was not evident on the third set, higher loads were lifted.

The test started with a 20kg load, and the weights were increased in intervals of 5kg for women and 7.5kg for men. On the first load, the participants performed two sets in order to get familiar with the test. The participants were allowed to rest for 2-3 minutes between each set. The starting position was with fully extended elbows. The bar was held with a prone grip in shoulder width between right and left hand (Fig 2.). The pull ended when the bar touched the bench, flexed elbows. If the bar did not touch the bench or the elbows were not properly extended before the lift, the attempt was not approved. Power was identified based on

$$P = m * (-g + a) * v$$

where m is the mass of the lifted weight, g is the gravitational acceleration, a is the acceleration of the bar, and v the velocity of the bar. Maximum power was estimated by the software as the highest averaged power produced during the concentric phase of a repetition (MUSCLELAB, Ergotest Innovation A.S., Porsgrunn, Norway).

*Fig. 2: Starting (**A**) and finishing position (**B**) of the concentric phase of the bench pull.*

BP/LP-ratio was calculated as the ratio between maximum BP and maximum LP power.

Roller-ski testing

Before performing the nine different tests, all participants performed a ten-minute warm up on the treadmill, with low to moderate intensity at varying speed and incline to ensure that all sub-techniques were used. The participants were instructed that they could use the technique which they felt was most natural and were freely to change technique at any time during the tests.

They were also aware of the length of the tests and that speed and/or incline would change during the testing.

The different combinations of speed and incline during the tests were chosen based on where change of technique was expected to occur, in view of previous findings (Ettema et al. 2017; Pellegrini et al. 2013; Cignetti et al. 2009). They were also designed with an intensity which was expected to be sub-maximal in order to avoid fatigue during the testing (hence lactate measurements). All tests consisted of an ‘initial order’ and a ‘reversed order’ (see later for elaboration) in order to investigate the effect of direction of change. By designing several different tests this allowed us to not only investigate if the condition itself determines choice of technique, but also investigate if how one attains that particular condition affects the technique chosen. Combinations of speed and incline for the nine different tests are shown in Fig. 3.

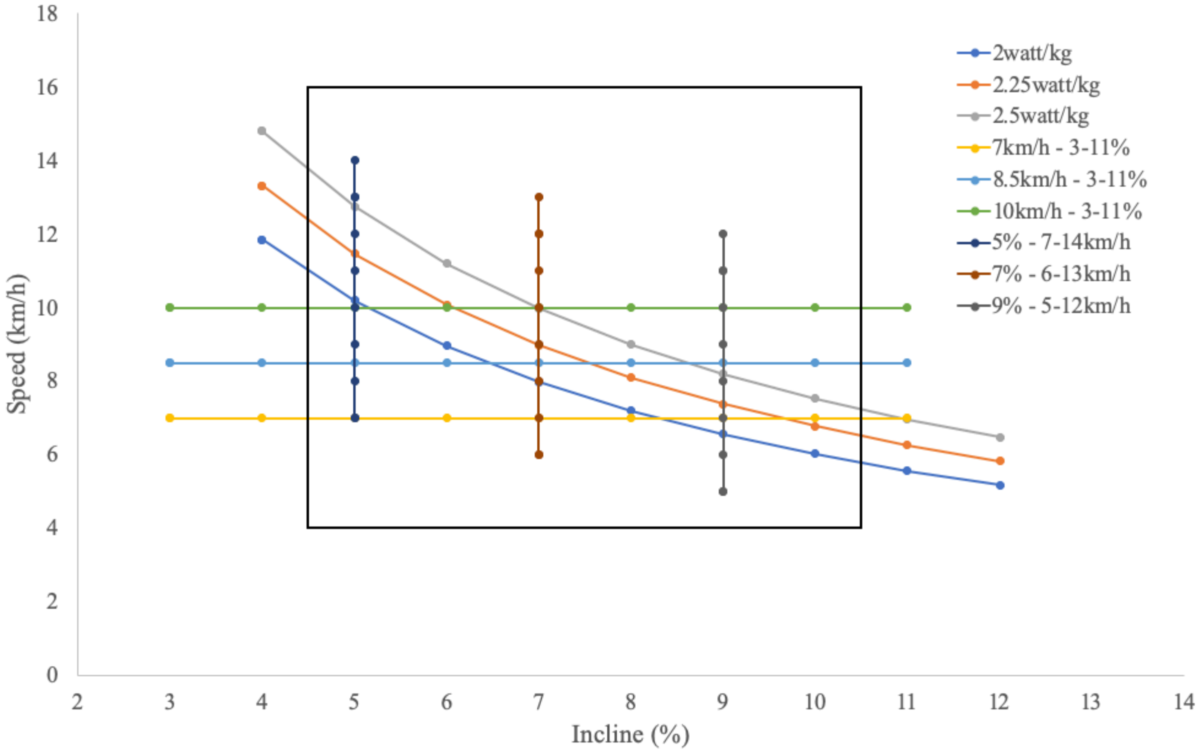


Fig. 3: Combinations of speed and incline on the different tests. Square illustrates area where change of technique was expected to occur.

The nine tests consisted of three subsets in which one of three condition parameters was held constant. In each subset, the test was repeated at three different levels. Thus, three tests were performed at three different, but constant work rates with varying speed and incline (subset WR-c), three tests at three constant inclines with varying speed and work rate (subset INC-c) and three tests at three constant speeds with varying incline and work rate (subset SPD-c). The tests were performed with identical speed and incline for all participants. Thus, the relative work rate (watt/kg) was approximately identical between participants. Same relative work rate was chosen over identical absolute work rate to get comparable incline (and speed) for all participants. This is also what would be expected during XC-skiing on snow, where the athletes compete in the same track.

At WR-c and SPD-c, the tests lasted for five minutes. The three tests at INC-c lasted for 4 minutes and 30 seconds to avoid too high intensity during these tests. All tests started with 60 seconds of constant speed and incline to ensure that the participant was familiarized with the conditions and had chosen the preferred technique. For all tests, changes in speed, incline and/or work rate occurred every 15 second after the first minute (Fig. 4-6).

The test order was quasi-randomized where all three bouts consisted of one test from each subset. In addition, the first bout started with a test with the lowest work rate from one of the subsets, see table 2 for example. This was done to ensure that the participant was properly warmed-up, and to avoid a possible influence of test order. Between each bout, the participants were allowed to rest for five minutes, otherwise the breaks were only long enough to collect blood for lactate analysis.

Table 2: Example of test order for the nine tests. Test 1.-3. refers to the order in which the tests were performed.

Test Randomization

	1. Test	2. Test	3. Test
1. Bout	2 watt/kg	8.5 km/h	9% Incline
2. Bout	10 km/h	5% Incline	2.25 watt/kg
3. Bout	7% Incline	2.5 watt/kg	7 km/h

At WR-c, the tests were performed at 2, 2.25 and 2.5watt/kg body weight. All three were performed with the same range of incline, with a starting incline of 4% which increased to 12% (initial order) with 1% increments and were reversed back to 4% (reversed order) without any break (Fig. 4). Accordingly, the corresponding speed to obtain a constant work rate changed at the same time as the incline, and combination of speed and incline were different at the three work rates.

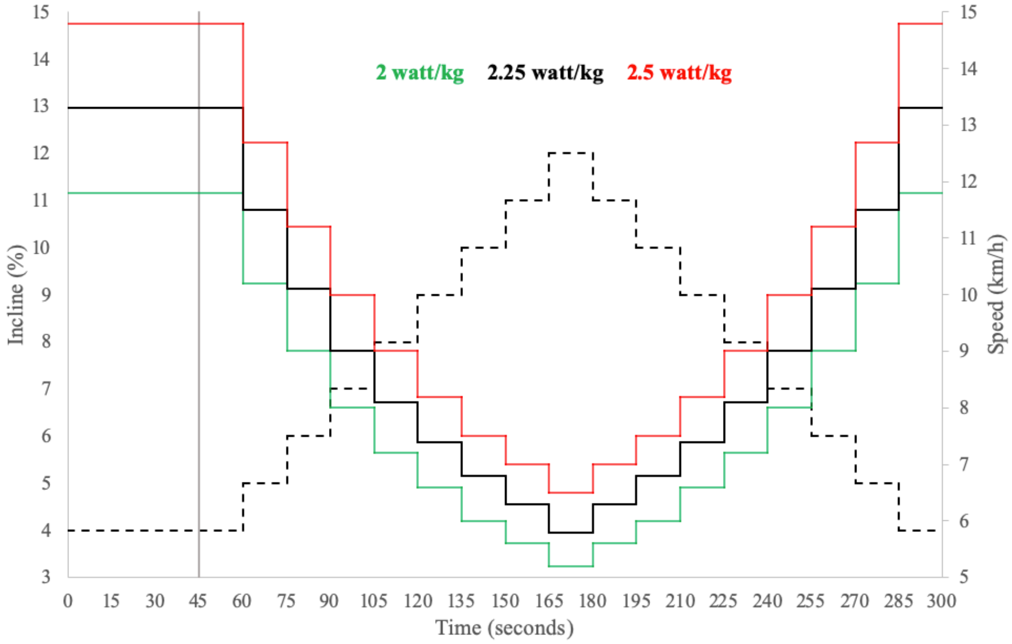


Fig. 4: Overview of combination of speed (solid line) and incline (dashed line) at WR-c. Vertical line indicates start point of the period that was considered for later analysis.

At INC-c, the tests were performed at 5%, 7% and 9% incline with corresponding speed ranging for 7-14, 6-13 and 5-12km/h, respectively (Fig. 5). The tests started with low speed and work rate, which increased (initial order) in intervals of 1km/h and were reversed back (reversed order) to low speed.

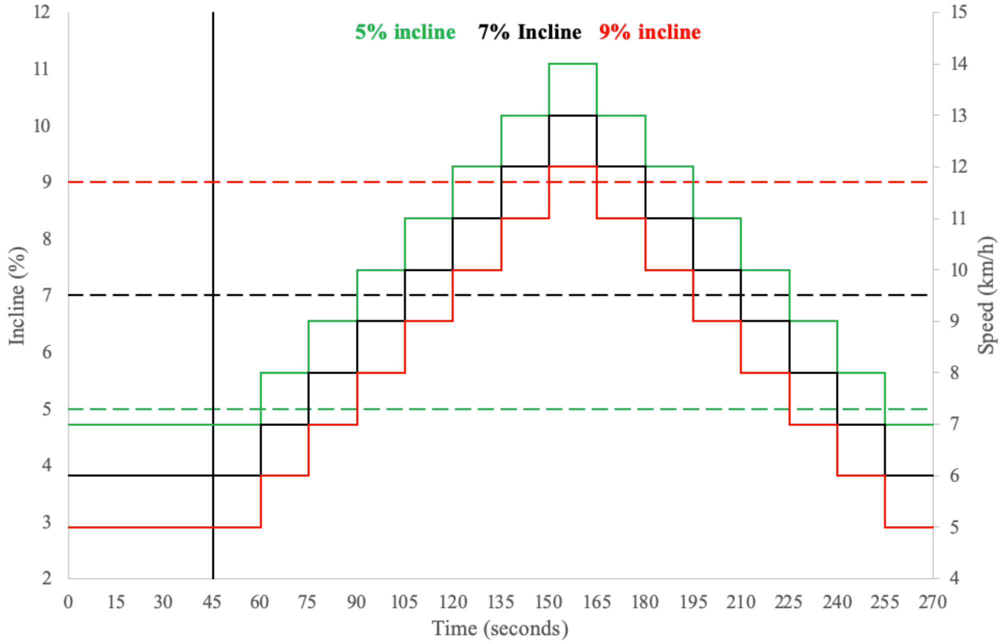


Fig. 5: Overview of combination of speed (solid line) and incline (dashed line) at INC-c. Vertical line indicates start point of the period that was considered for later analysis.

At SPD-c, the tests were performed at 7km/h, 8.5km/h and 10km/h (Fig. 6). For all tests the incline started at 3% and increased to 11% (initial order) with 1% increments. After 15 seconds at 11% incline, the incline decreased back to 3% (reversed order).

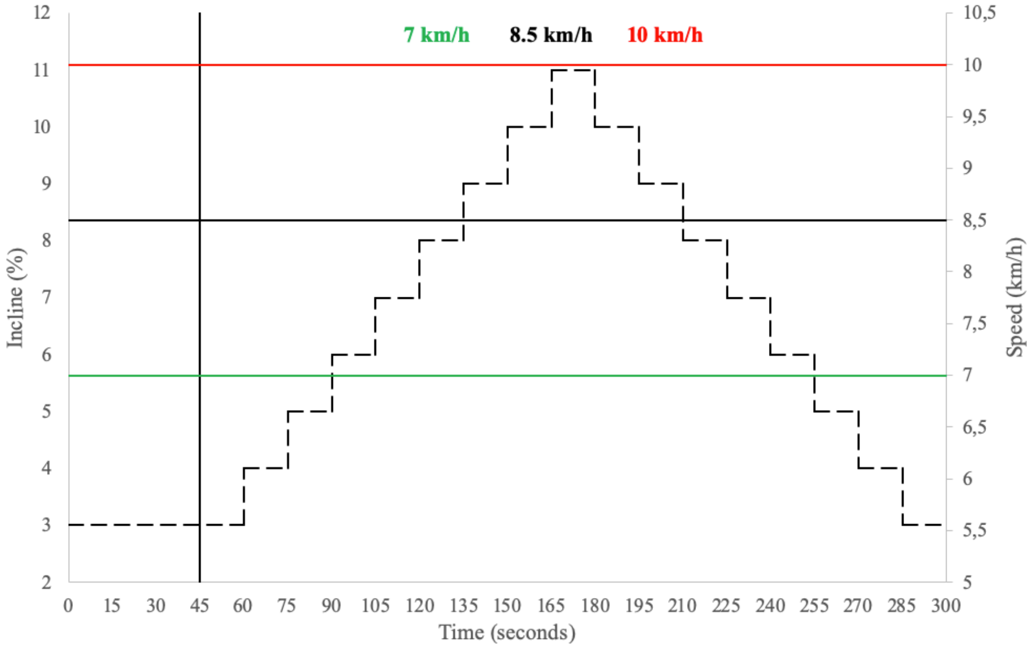


Fig. 6: Overview of combination of speed (solid line) and incline (dashed line) at SPD-c. Vertical line indicates start point of the period that was considered for later analysis.

Work Rate Calculations

Work rate was estimated based on the sum of power against gravity (P_g) and power against rolling friction (P_f)

$$P_g = m * g * \sin\theta * v$$

$$P_f = m * \mu * g * \cos\theta * v$$

Where m is the body mass of the participant, g is the gravitational acceleration, θ is the angle between the horizontal plane and the incline of the treadmill, μ is the rolling resistance friction coefficient, and v is the velocity of the treadmill in m/s. The friction coefficient was determined by a towing test as explained by Sandbakk et al. (2010) and calculated based on the following formula

$$\mu = \frac{F_f}{N}$$

Where F_f is the rolling friction force and N is the normal force. The friction coefficient was calculated to be ≈0.18 after the skis were warmed up. The ten-minute warm up preceding the testing ensured that the roller-skies were properly warmed up. Thus, further changes in the friction coefficient would be negligible in this context (Ainegren et al. 2008). In order to calculate the different speeds to keep work rate constant, the following formula were used

$$V = P_{target}/(mg * (\sin\theta + \mathrm{m}\mu * \cos\theta))$$

where P_{target} is the targeted work rate and θ is the incline between the treadmill and the horizontal plane.

Statistical Analysis

Statistical Package for the Social Sciences (SPSS 25; IBM Corp., Armonk, NY, USA) and Microsoft Excel for Mac (Excel 2016, 16.19, Microsoft Corp., Redmond, WA, USA) were used for statistical analysis. Normality was evaluated using a Shapiro-Wilk test and descriptive statistics are presented as mean with ±SD.

Only the last 15 seconds of the first minute (no changes in condition) on each test was considered in the analysis. In situations where two different sub-techniques were used for a given condition (15 seconds) the technique used for the largest part were chosen for later analysis.

A mixed ANOVA with gender as between-subject factor were conducted to investigate influence of gender. Each subset was treated separately in the analysis and the three tests at each subset was included as the within-subject factor. The outcome from the ANOVA was the minimum and maximum incline, speed and work rate (depending on subset) at which the different sub-techniques were used. Any gender effect was identified by significant within-, between-subject interaction. In such case, further analysis for all sub-techinques at the given subset was done separately for men and women. Due to significant within-, between-subject interaction (see results), a One-Way ANOVA was conducted separately for men and women to analyze the influence of the condition parameter on technique choice. The outcome variables and within-subject factor was the same as in the mixed ANOVA. If assumption of sphericity was not met, Greenhouse-Geisser correction (when epsilon <0,75) or Huynh-Feldt correction (when epsilon >0,75) were used. Because of small differences in speed between tests at WR-c (speed was based on a given incline) (Ettema et al. 2017), rounded values were used in the abovementioned ANOVA, but exact values are given in the tables.

To investigate any hysteresis effect, i.e. whether direction of protocol had an effect on technique choice, maximum incline of DP and DK on the initial (increasing incline) and reversed order (decreasing incline) were compared using a Paired-Samples t-test. Only the tests were incline changed was chosen due to the expected primary influence of incline on technique choice. An individual mean based on the six tests where used in favor of a mixed model analysis. This was done due to a lacking number of individuals employing the techniques of interest on all tests. If assumption of normality was not met a Wilcoxon Signed Rank Test was conducted and reported with median values and range. A Pearson´s correlation analysis was used to investigate the relationship between DP and DIA use and power, and men and women were compared using an Independent-Samples t-test. Statistical significance was determined based on a significance level of $P<0.05$.

Results

All tests were on average performed at sub-maximal intensities (<4mmol/l lactate) as shown in table 3. An independent samples t-test showed that in three out of the nine tests women had significantly higher lactate concentration compared to men.

Table 3: Mean (±SD) lactate values in mmol/l for men and women at each test.

	2 watt/kg	2.25 watt/kg	2.5 watt/kg	7 km/h	8.5 km/h	10 km/h	5 %	7 %	9 %
Male	1.27 ±0.92	1.74 ±1.07	1.97 ±1.09	1.46 ±0.8	1.36 ±0.76	1.85 ±0.83	2.48 ±2.29	2.2 ±1.55	1.91 ±1.57
Female	1.96 ±0.74	2.34 ±0.89	3.09 ±1.09	1.54 ±0.61	1.88 ±0.48	3.25 ±1.19	3.86 ±1.4	2.77 ±0.93	2.63 ±0.82
P-value	0.094	0.184	0.031	0.814	0.088	0.005	0.002	0.341	0.191

P-value from Independent Samples t-test on gender difference.

To illustrate how choice of technique was influenced by speed and/or incline, the mean outcome of the range of sub-technique used at the three WR-c tests are shown in Fig. 7. Face value inspection indicates that speed at which a particular sub-technique was used increased at higher constant work rate, while the incline of sub-technique use shows smaller variation over the three tests (see later for analysis).

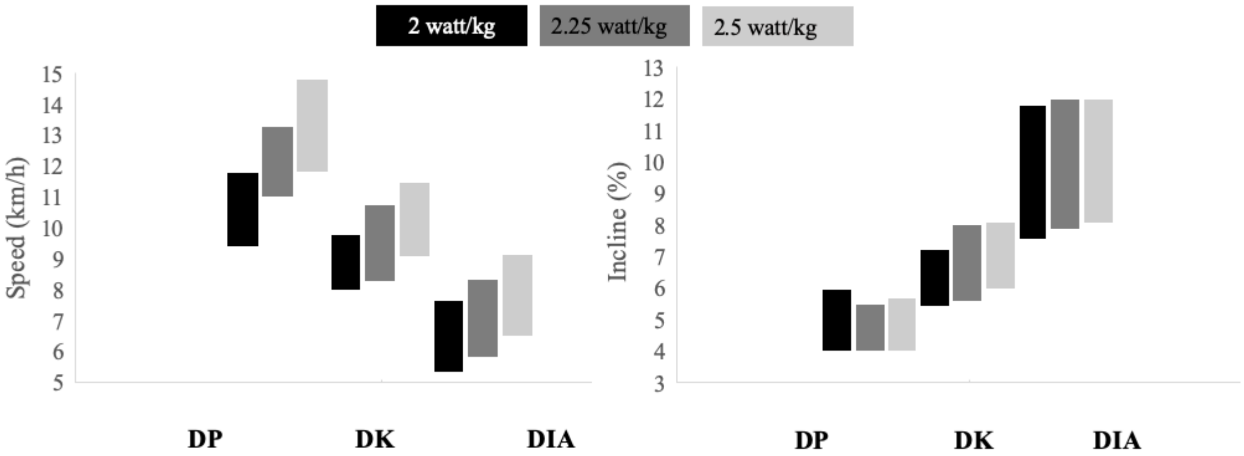


Fig. 7: Mean range of sub-technique use expressed as speed and incline at the three different WR-c tests. DP, double poling; DK, double poling with kick; DIA, diagonal stride

Influence of speed, incline and work rate.

Not all participants employed the sub-technique of interest on all three tests at a given subset. Thus, a participant who did not employ the sub-technique of interest on all three tests at a given subset, were not taken into account in the statistical analysis (See N participants in table 4-6.). Table 4-6 show the mean minimum and maximum incline, speed and work rate (depending on subset) at which a sub-technique was used by the participants. Any significant effect of the constant parameter indicates that the outcome parameter was influenced by the different levels of the subset. In other words, the minimum or maximum value of the outcome parameter at which the sub-technique was used differed at the three levels. In some instances, the minimum or maximum value of sub-technique use was influenced by protocol limitations. This resulted in a SD of 0, and p-value from the ANOVA was not given (e.g. maximum speed of DP use at WR-c, table 4).

At WR-c (2, 2.25 and 2.5watt/kg), there was a significant gender difference (as identified by work rate-gender interaction) for minimum incline and maximum speed for DIA (table 4). For women, incline for any sub-technique was not significantly affected by work rate, but speed was ($p \leq 0.002$). For men, work rate significantly affected speed for any sub-technique ($p \leq 0.018$), and the maximum incline for DK and the minimum incline for DIA (table 4).

Table 4: Average (±SD) minimum (min) and maximum (max) incline (%) and speed (km/h) of sub-technique use at the three WR-c tests for men and women separately.

Constant Work Rate						
	DP		DK		DIA	
	Min	Max	Min	Max	Min	Max
Female						
Incline						
2 watt/kg	4 ±0	6 ±1.5	5.4 ±0.9	8 ±1.6	8.3 ±1.3	11.6 ±1.3
2.25 watt/kg	4 ±0	5.6 ±1.2	5.6 ±1.1	8.5 ±1.2	8.4 ±1.3	12 ±0
2.5 watt/kg	4 ±0	5.8 ±1.2	6 ±1.6	8.4 ±1.5	8.1 ±2	12 ±0
p-value	-	0.753	0.349	0.316	0.341	0.390
Speed						
2 watt/kg	9.2 ±1.6	11.8 ±0	7.4 ±1.2	9.8 ±1.3	5.4 ±0.7	7.1 ±1
2.25 watt/kg	10.8 ± 1.6	13.3 ±0	7.8 ±0.9	10.7 ±1.2	5.8 ±0	7.9 ±0.9
2.5 watt/kg	11.8 ±1.8	14.8 ±0	8.8 ±1.2	11.6 ±2.3	6.5 ±0	9.2 ±1.6
p-value	0.002	-	<0.001	<0.001	<0.001	<0.001
N	8		8		9	
Male						
Incline						
2 watt/kg	4 ±0	5.9 ±2.3	5.5 ±0.9	6.6 ±1.0	6.9 ±1.3	12 ±0
2.25 watt/kg	4 ±0	5.4 ±1.3	5.6 ±0.9	7.6 ±1.3	7.4 ±1.3	12 ±0
2.5 watt/kg	4 ±0	5.7 ±1.0	5.9 ±0.7	7.9 ±1.5	8 ±2.0	12 ±0
p-value	-	0.459	0.347	0.001	<0.001	-
p – gender difference	-	0.933	0.926	0.147	0.018	0.302
Speed						
2 watt/kg	9.5 ±1.8	11.8 ±0	8 .4±0.9	9.7 ±1.0	5.2 ±0	8.2 ±0.8
2.25 watt/kg	11.1 ± 1.6	13.3 ±0	8.6 ±1.2	10.8 ±1.1	5.8 ±0	8.7 ±0.9
2.5 watt/kg	11.8 ±1.3	14.8 ±0	9.3 ±1.3	11.4 ±1.0	6.5 ±0	9.1 ±0.8
p-value	<0.001	-	0.018	0.002	-	0.001
p – gender difference	0.901	-	0.283	0.893	0.302	0.01
N	12		11		11	

Statistical outcome, p-values (one-way ANOVA), on the influence of work rate on minimum and maximum incline and speed of sub-technique use. P – gender difference shows p-value for work rate-gender effect. "-" Indicates that no variation occurred, i.e. SD=0. N indicates participants using the given technique at all three tests. DP, double poling; DK, double poling with kick; DIA, diagonal stride

At SPD-c (7km/h, 8.5km/h and 10km/h), there were significant speed-gender interaction at minimum incline of DK and DIA use (table 5). Speed-gender interaction was also significant for the minimum work rate at which DK and DIA were used, and maximum work rate of DK use. In SPD-c, mainly work rate, not incline, at which the sub-techniques were used was significantly affected by the set speed (table 5). For women, the minimum incline at which DK was used was significantly different between the three SPD-c tests (table 5). Incline of sub-technique use were significantly affected by speed in SPD-c for minimum incline of DIA, and maximum incline of DK, for men.

Table 5: Average (±SD) minimum (min) and maximum (max) incline (%) and work rate (watt/kg) of sub-technique use at the three SPD-c tests for men and women separately.

Constant Speed						
	DP		DK		DIA	
	Min	Max	Min	Max	Min	Max
Female						
Incline						
7 km/h	3 ±0	5.9 ±1.8	5.9 ±1.7	8 ±2.5	7.3 ±2.1	11 ±0
8.5 km/h	3 ±0	5.3 ±1.4	4.8 ±1.2	7.9 ±1	7.4±1.2	11 ±0
10 km/h	3 ±0	5.6 ±1	4.6 ±1.2	8.1 ±1	7.6 ±1.3	11 ±0
p-value	-	0.242	0.022	0.938	0.787	-
Work Rate						
7 km/h	0.90 ±0.04	1.43 ±0.34	1.4 ±0.33	1.85 ±0.48	1.73 ±0.35	2.43 ±0.05
8.5 km/h	1.09 ±0.04	1.66 ±0.33	1.51 ±0.27	2.24 ±0.24	2.11 ±0.26	2.95 ±0.04
10 km/h	1.32 ±0.06	1.98 ±0.29	1.75 ±0.33	2.72 ±0.27	2.59 ±0.35	3.49 ±0.05
p-value	<0.001	<0.001	0.014	<0.001	<0.001	<0.001
N	9		8		8	
Male						
Incline						
7 km/h	3 ±0	6.1 ±2.3	3.9 ±1.5	6.7 ±1.8	5.9 ±2.4	11 ±0
8.5 km/h	3 ±0	5.4 ±1.8	3.9 ±1.2	7.0 ±1.7	6.0±1.7	11 ±0
10 km/h	3 ±0	6.0 ±1.3	4.9 ±1.2	8.9 ±1.1	8.5 ±1.4	10.9 ±0.3
p-value	-	0.357	0.139	0.019	0.003	0.386
p – gender difference	-	0.830	0.01	0.118	0.046	0.496
Work Rate						
7 km/h	0.91 ±0.06	1.52 ±0.46	1.05 ±0.28	1.62 ±0.35	1.44 ±0.46	2.43 ±0.05
8.5 km/h	1.11 ±0.03	1.68 ±0.41	1.32 ±0.32	2.05 ±0.40	1.83 ±0.39	2.96 ±0.03
10 km/h	1.27 ±0.03	2.10 ±0.36	1.80 ±0.35	2.91 ±0.28	2.80 ±0.37	3.45 ±0.11
p-value	<0.001	<0.001	0.001	<0.001	<0.001	<0.001
p – gender difference	0.967	0.693	0.02	0.047	0.019	0.269
N	7		7		11	

Statistical outcome, p-values (one-way ANOVA), on the influence of speed on minimum and maximum incline and work rate of sub-technique use. P – gender difference shows p-value for speed-gender effect. "-" Indicate that no variation occurred, i.e. SD=0. N indicates participants using the given technique at all three tests. DP, double poling; DK, double poling with kick; DIA, diagonal stride

At INC-c (5%, 7% and 9%), only one female participant used DIA, and two female participants used DK at all three inclines. DP was not used on all three inclines by any of the female participants, and only two men used DP on all three. Therefore, analysis on the influence of INC-c on sub-technique use was only conducted for DK and DIA in men (table 6). At INC-c, work rate was significantly affected by the set incline for both DK and DIA, while speed of sub-technique use was not significantly affected (table 6).

Table 6: Average (±SD) minimum (min) and maximum (max) speed (km/h) and work rate (watt/kg) of sub-technique use at the three INC-c tests for men.

Constant Incline				
	DK		DIA	
	Min	Max	Min	Max
Male				
Speed				
5%	9.4 ±1.4	12.0 ±0.8	7 ±0	9.3 ±1.2
7%	9.4 ±1.4	12.6 ±0.5	6 ±0	9.7 ±0.5
9%	9.9 ±1.1	11.9 ±0.4	5 ±0	10.4 ±1
p-value	0,459	0,065	-	0,056
Work Rate				
5%	1.79 ±0.28	2.36 ±0.21	1.36 ±0.03	1.81 ±0.25
7%	2.38 ±0.29	3.18 ±0.13	1.50 ±0.03	2.40 ±0.17
9%	3.05 ±0.34	3.56 ±0.21	1.50 ±0.03	3.25 ±0.34
p-value	<0,001	<0,001	<0.001	<0,001
N	8		9	

Statistical outcome, p-values (one-way ANOVA), on the influence of incline on minimum and maximum speed and work rate of sub-technique use. "-" Indicate that no variation occurred i.e. SD=0. N indicates participants using the given technique at all three tests.
DK, double poling with kick; DIA, diagonal stride

Effect of protocol direction

One female participant did not employ DK on any of the tests and were not taken into account for further analysis on the effect of direction of change on DK use. The individual maximum incline on both the initial and reversed test order of the given technique is calculated based on the six tests were incline changed (SPD-c and WR-c). In cases were the sub-technique was not used on one or both orders of a given test, the data was not used for further calculations. There was no gender interaction effect on change of direction (data not shown) and further analysis was therefore conducted collectively for men and women. Average maximum incline of DK use on the initial and reversed order was 7.7% (±1.3) and 7.2% (±1.1) incline. Based on a Paired Samples t-test, direction of protocol had significant effect on DK use (p=0.023). For DP, median maximum incline was 5.3% (4-8.7) on the initial order and 4.8% (4-7.8) on the reversed order. These differences were significantly different, based on a Wilcoxon Signed Rank test (p=0.001).

History of condition

In two occasions there was an identical or almost identical speed and incline combination between one test from each subset (see Fig. 3). The combination of 10km/h and 7% incline occurred both at WR-c (2.5watt/kg), SPD-c and INC-c. The same applied for 10km/h and 5% incline, with a small deviation at WR-c (10.2km/h at 2watt/kg). This made it possible to investigate whether the preceding speed and incline combination affected choice of technique. At 10km/h and 7% incline ten out of the 21 participants used the same technique at all three tests, irrespective of the preceding condition, and thus the remaining 11 participants used a different technique at the same speed and incline combination. At ≈10km/h and 5% incline 12 participants used the same sub-technique at all three tests, and the remaining nine participants used different sub-techniques.

DP and DIA use and BP and LP power

An Independent-Samples t-test showed that men had significantly higher maximal power in both the BP and LP, and a higher BP/LP-Ratio compared to women (table 7). Based on total time from the nine tests, 26.6% (±15.92%) and 45.3% (±15.23%) was spent using the DP and DIA, respectively. Women spent 29% (±14.09) and men 24.7% (±17.53) using DP, and 41.7% (±14.53) and 48% (±15.82), respectively, in DIA. The gender difference in DP and DIA use was not significant for either DP (p=0.551) or DIA (p=0.367).

Table 7: Mean (±SD) relative maximum power in the BP and LP, and BP/LP-Ratio in men and women.

Power Measurements			
	BP (watt/kg)	LP (watt/kg)	BP/LP-Ratio
Women	4.4 ±0.7	21.7 ±2.5	0.21 ±0.03
Men	7.1 ±0.8	30.6 ±3.5	0.24 ±0.03
p-value	<0.001	<0.001	0.041

P-value from Independent-Samples t-test on the gender difference.

One outlier (>70% time in DP) was excluded from the analysis on the relationship between proportional use of DP and DIA, and relative maximum BP and LP power, and BP/LP-Ratio.

The correlation analysis was thus conducted on nine female and 11 male participants. Fig. 8 shows relative maximum BP, LP power, and BP/LP-Ratio in relation to the percentage time spent in DP and DIA. A Pearson´s correlation showed no significant correlation in any of the relationships for either men or women (table 8). There was a tendency towards a positive correlation between DP use and BP/LP-Ratio in men, and a negative correlation between maximum relative LP power and DIA use in women, but these were not significant.

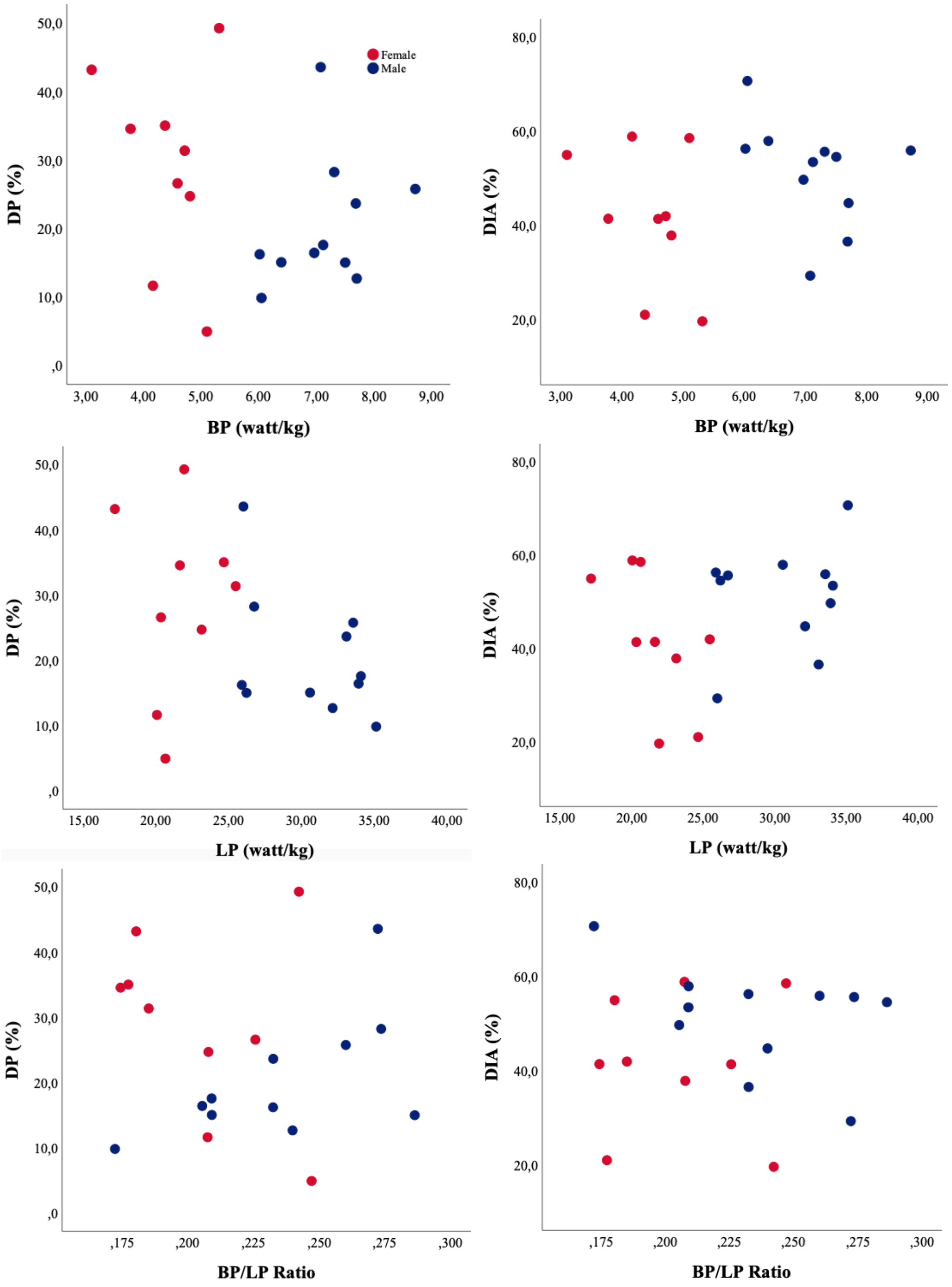


Fig. 8: Maximum relative power in BP, LP and BP/LP-Ratio in relation to percentage time in DP (left) and DIA (right) in men and women.

Table 8: R-values (p-value) on the relationship between percentage time spent in DP and DIA and relative maximum power in the BP and LP, and BP/LP-Ratio for men and women.

Correlation Analysis			
	BP	LP	BP/LP-Ratio
Male			
DP	0.33 (0.326)	-0.43 (0.187)	0.59 (0.055)
DIA	-0.37 (0.266)	0.25 (0.46)	-0.45 (0.163)
Female			
DP	-0.23 (0.551)	0.06 (0.872)	-0.35 (0.361)
DIA	-0.38 (0.308)	-0.60 (0.087)	0.05 (0.9)

Discussion

The primary aim of the current study was to investigate the influence of speed, incline, and work rate on choice of technique in classical XC-skiing, and additionally to investigate whether the amount of DP and DIA use was related to upper- and lower-body power.

Influence of speed, incline and work rate

The main findings on the influence of speed, incline and work rate on technique choice was that incline of sub-technique use was least influenced by the condition parameter. Incline does therefore seem to be the primary factor determining choice of technique as we hypothesized. These findings are in agreement with previous findings at constant work rate (Ettema et al. 2017) and have also been found at constant speed (Cignetti et al. 2009; Pellegrini et al. 2013). At SPD-c and WR-c, only at one instance (minimum incline for DK) a different incline range for a particular sub-technique was found amongst women. For men, the situation was less clear-cut; at four out of 12 instances, different incline ranges were found for a particular sub-technique. The work rate at which a sub-technique was used showed large variations and does not seem to have any influence on technique choice.

If incline was the only determining factor, one would however not expect to find changes in technique at INC-c, and changes in sub-technique would occur at the same incline at all tests, which was not always the case. At INC-c, several athletes preferred a higher gear, i.e. DP instead of DK and DK instead of DIA, when the speed increased, which is in agreement with the finding by Pellegrini et al. (2013). In other words, also speed of locomotion appears to have a role in choice of technique. The maximum incline of DK, and minimum incline of DIA increased with higher work rate (WR-c) and higher speed (SPD-c), for men. In transitions between walking and running in human locomotion, speed is the primary determining factor in gait transitions. It has however been shown that the speed at which gait transitions occurs is influenced by incline (Hreljac et al. 2007). At higher constant incline, the walk-run transition occurs at a lower speed. Based on these findings, it is possible that speed and incline combination has a somewhat similar influence on XC-skiing and human walk-run transition, but this needs further investigation.

At INC-c, none of the women used DP at all three inclines, and only two used DK and one used DIA at all three. A low number of men (n=2) also used DP at all three INC-c. This indicates that incline strongly determines sub-technique use for women, and DP use amongst men. Additionally, a lower number of men used DP and DK at all SPD-c tests compared to the WR-c tests (see N participants in table 4 and 5) where the maximum speed was higher. This might indicate that men do not use higher gears when the speed is low. In summary, even though incline seems to be the main factor determining technique choice, also speed appears to play a role where athletes prefer a higher gear when speed increases.

The seemingly different influence of test on sub-technique use in men and women is to the best of our knowledge a novel finding in controlled conditions, but gender differences in sub-technique use has previously been shown during XC-skiing on snow (Solli et al. 2018). In some conditions men and women responded differently to changes during the test (interaction at minimum incline (maximum speed) of DIA and DK use). The incline at which a particular sub-technique was used was rather constant for women at WR-c and SPD-c. While for men, more variations were seen (see above). The reason for these gender differences is unclear. The relative external work rate was identical for all participants, but women had slightly higher lactate values. The female athletes thus skied at a higher relative intensity which might have led to these differences. Ettema et al. (2018) did not find any influence of fatigue on technique choice, but there was a tendency towards earlier (lower incline) DK-DIA changes after exhaustive exercise. Based on these findings, it is possible that the slightly lower relative intensity amongst men allowed them to employ a given technique for longer due to a larger "reserve", and thus resulted in later changes to DIA at higher constant work rate. In order to further investigate this, tests with same relative intensity for men and women are needed.

As mentioned, in previous studies (Cignetti et al. 2009; Pellegrini et al. 2013; Ettema et al. 2017), changes from DP-DIA has not been apparent, which might have been due to how often speed and/or incline changed during the tests. Here, the conditions changed every 15 seconds, which in larger degree resembles some features of outdoor tracks where changes in speed and terrain may occur more abrupt. Despite this, there was only one participant that repeatedly changed directly from DP-DIA. This athlete stated that the reason for changing directly from DP to DIA was that she felt that it was not worth the investment to change via DK. Several participants who used DK, only used it for a short period (few seconds) between DP and DIA, which in a way may be a similar strategy as changes from DP-DIA, but less extreme.

Effect of protocol direction and history of condition.

Based on theory of motor control, hysteresis is expected to occur in gait transitions, which means that change in technique is affected by direction of change (Turvey 1990), in our case, increasing incline or decreasing incline, speed or work rate. This is expected to occur due to the investment which is related to technique transitions, e.g. increased metabolic cost and instability of locomotion during technique transitions (Usherwood and Bertram 2003; Diedrich and Warren 1995). This investment results in differences in point of transition. The changes from DP during the initial order of the tests occurred at a steeper incline compared to the changes to DP on the reversed order, which shows hysteresis effect. The same was apparent for changes from DK (initial order) and to DK (reversed order). The results from the overlap in speed and incline combination at the three different subsets also showed that 11 (10km/h & 7% incline) and nine (10km/h & 5% incline) out of the 21 participants used different sub-techniques despite speed and incline combination being identical. Thus, it seems that it is not only the condition itself that influenced the choice of sub-technique. Technique choice is also influenced by how one attains that speed and incline combination and the direction of change. This is novel information in the context of XC-skiing and Ettema et al. (2017) did not find any effect of direction of change. Hysteresis effect has however repeatedly been found in human walk-run and run-walk transitions (Thorstensson and Roberthson 1987; Diedrich and Warren 1995; Hreljac 1993).

DP and DIA use and BP and LP power

As in previous studies (Pellegrini et al. 2013; Cignetti et al. 2009; Ettema et al. 2017) there were large inter-individual differences in the range of sub-technique use between participants. There was however no gender difference regarding amount of DP and DIA use, which stands in contrast to what was recently published regarding gender differences in sub-technique use during XC-skiing on snow (Solli et al. 2018). More in line with previous findings was the higher maximum power and BP/LP power ratio found amongst the male athletes (Miller et al. 1993).

Solli et al. (2018) hypothesized that the increased use of DP amongst men, compared to women could be due to higher speed and larger upper-body force capacity in men. The results from our correlation analysis showed however no relationship between sub-technique use and BP, LP or BP/LP-ratio for either men or women. Thus, the hypothesis of increased use of DP with a higher BP/LP-ratio was rejected. There was a tendency towards increased use of DP with higher BP/LP-ratio for men, and less use of DIA with higher LP power in women. In addition, the BP/LP-ratio and LP power could only explain about 35% of the variation in DP use in men and 36% of DIA use in women. This shows that other factors explain a larger part of the variation in sub-technique use. It is therefore unlikely that inter-individual differences occur solely due to differences in measures of general power. It thus seems more likely that the increased use of DP amongst men found in previous studies is rather due to higher skiing speed and not upper- and lower body strength or power differences (Stoggl et al. 2018; Solli et al. 2018).

Stoggl et al. (2011) found that timing of the force application during the propulsion phase in DP and DIA was as least as important for skiing speed as power capacity. Athletes with a later peak pole force during the propulsion phase achieved a higher skiing speed, compared to those with an early peak pole force. Thus, even though increased power capacity might facilitate increased use of DP or DIA, this would not be evident in the statistical outcome if timing and other technique features are important factors. A significant proportion of the propulsion in DP is as explained provided via the lower-body (Danielsen et al. 2015). Recently, this proportion was also shown to increase at higher intensity, and at steeper incline (Danielsen et al. 2018, 2019). The lack of correlation between DP use and BP power and BP/LP-ratio might therefore also be due to the increasing importance of the legs in DP at higher intensity and incline.

Stoggl et al. (2011) used the same exercise for estimating upper-body power, and a similar exercise for the legs. In their study, maximum power in BP and performance in the squat jump exercise was positively related to maximal skiing speed in DP and DIA, respectively. It is therefore unlikely that the lack of correlation found here is due to the choice of exercise as measures for upper- and lower-body power.

Based on our findings it is therefore unlikely that inter-individual differences in technique choice is due to differences in maximum power. Additionally, one can also question whether limited leg thrust time and force limitations in the upper-body is underlying mechanisms explaining the choice of technique.

Methodological considerations

The skiing in this study was performed with roller-skis on a motorized treadmill in favor over XC-skiing on snow. This ensured controlled conditions with less variations in work rate, and identical speed and incline between participants. Additionally, differences in gear, i.e. friction of the skis, were excluded considering that all participants used the same pair of roller-skis. On the other hand, one noteworthy difference between roller-skiing and XC-skiing on snow is the static friction during the leg thrust. With roller-skis, the friction is complete, which ensures good grip and might therefore influence the amount of DIA use.

Due to technical limitations on the treadmill, changes in speed and incline could not occur continuously. With continuous changes in speed and incline it is possible that technique changes from DP-DIA would have occurred in larger degree.

Maximum power in the strength tests was based on average power during the entire concentric phase of the BP, and the highest measured power during the concentric phase in the LP exercise, due to software limitations. This introduced a systematic bias which underestimated the upper-/lower-body power ratio. The ratio can therefore not be used as a true ratio between upper- and lower-body power. Considering that the bias introduced was a systematic bias, it would however not influence the correlation analysis.

Conclusion

The current study shows that incline is the primary factor determining choice of sub-technique, and speed plays a lesser role by resulting in the use of higher gears with increasing speed. It is however not only the combination of speed and incline that determines choice of technique, but also how one attains that speed and incline combination. In some situations, men and women appear to respond differently to changes in speed and incline, which might be related to differences in performance capacity.

Inter-individual differences in DP and DIA use was not related to upper- and lower body power. It is possible that power capacity is a prerequisite for the individual differences, but the ′correct′ technical execution is necessary for this relationship to be visible. Further studies are needed in order to investigate this in detail.

References

Ainegren M, Carlsson P, Tinnsten M (2008) Rolling resistance for treadmill roller skiing. Sports Engineering 11 (1):23. doi:10.1007/s12283-008-0004-1

Andersson E, Bjorklund G, Holmberg HC, Ortenblad N (2017) Energy system contributions and determinants of performance in sprint cross-country skiing. Scand J Med Sci Sports 27 (4):385-398. doi:10.1111/sms.12666

Cignetti F, Schena F, Zanone PG, Rouard A (2009) Dynamics of coordination in cross-country skiing. Hum Mov Sci 28 (2):204-217. doi:10.1016/j.humov.2008.11.002

Dahl C, Sandbakk O, Danielsen J, Ettema G (2017) 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 8:94. doi:10.3389/fphys.2017.00094

Danielsen J, Sandbakk O, Holmberg HC, Ettema G (2015) Mechanical Energy and Propulsion in Ergometer Double Poling by Cross-country Skiers. Med Sci Sports Exerc 47 (12):2586-2594. doi:10.1249/MSS.0000000000000723

Danielsen J, Sandbakk O, McGhie D, Ettema G (2018) The effect of exercise intensity on joint power and dynamics in ergometer double-poling performed by cross-country skiers. Hum Mov Sci 57:83-93. doi:10.1016/j.humov.2017.11.010

Danielsen J, Sandbakk O, McGhie D, Ettema G (2019) Mechanical energetics and dynamics of uphill double-poling on roller-skis at different incline-speed combinations. PLoS One 14 (2):e0212500. doi:10.1371/journal.pone.0212500

Diedrich FJ, Warren WH, Jr. (1995) Why change gaits? Dynamics of the walk-run transition. J Exp Psychol Hum Percept Perform 21 (1):183-202

Ettema G, Kveli E, Oksnes M, Sandbakk O (2017) The role of speed and incline in the spontaneous choice of technique in classical roller-skiing. Hum Mov Sci 55:100-107. doi:10.1016/j.humov.2017.08.004

Ettema G, Oksnes M, Kveli E, Sandbakk O (2018) The effect of exhaustive exercise on the choice of technique and physiological response in classical roller skiing. Eur J Appl Physiol. doi:10.1007/s00421-018-3965-1

Gopfert C, Holmberg HC, Stoggl T, Muller E, Lindinger SJ (2013) Biomechanical characteristics and speed adaptation during kick double poling on roller skis in elite cross-country skiers. Sports Biomech 12 (2):154-174. doi:10.1080/14763141.2012.749939

Holmberg HC, Lindinger S, Stoggl T, Bjorklund G, Muller E (2006) Contribution of the legs to double-poling performance in elite cross-country skiers. Med Sci Sports Exerc 38 (10):1853-1860. doi:10.1249/01.mss.0000230121.83641.d1

Holmberg HC, Lindinger S, Stoggl T, Eitzlmair E, Muller E (2005) Biomechanical analysis of double poling in elite cross-country skiers. Med Sci Sports Exerc 37 (5):807-818

Hreljac A (1993) Preferred and energetically optimal gait transition speeds in human locomotion. Med Sci Sports Exerc 25 (10):1158-1162

Hreljac A, Imamura R, Escamilla RF, Edwards WB (2007) Effects of changing protocol, grade, and direction on the preferred gait transition speed during human locomotion. Gait Posture 25 (3):419-424. doi:10.1016/j.gaitpost.2006.05.005

Lindinger SJ, Gopfert C, Stoggl T, Muller E, Holmberg HC (2009) Biomechanical pole and leg characteristics during uphill diagonal roller skiing. Sports Biomech 8 (4):318-333. doi:10.1080/14763140903414417

Marsland F, Mackintosh C, Holmberg HC, Anson J, Waddington G, Lyons K, Chapman D (2017) Full course macro-kinematic analysis of a 10 km classical cross-country skiing competition. PLoS One 12 (8):e0182262. doi:10.1371/journal.pone.0182262

Miller AE, MacDougall JD, Tarnopolsky MA, Sale DG (1993) Gender differences in strength and muscle fiber characteristics. Eur J Appl Physiol Occup Physiol 66 (3):254-262

Nilsson J, Tveit P, Eikrehagen O (2004) Effects of speed on temporal patterns in classical style and freestyle cross-country skiing. Sports Biomech 3 (1):85-107. doi:10.1080/14763140408522832

Pellegrini B, Zoppirolli C, Bortolan L, Holmberg HC, Zamparo P, Schena F (2013) Biomechanical and energetic determinants of technique selection in classical cross-country skiing. Hum Mov Sci 32 (6):1415-1429. doi:10.1016/j.humov.2013.07.010

Sandbakk O, Holmberg HC, Leirdal S, Ettema G (2010) Metabolic rate and gross efficiency at high work rates in world class and national level sprint skiers. Eur J Appl Physiol 109 (3):473-481. doi:10.1007/s00421-010-1372-3

Solli GS, Kocbach J, Seeberg TM, Tjonnas J, Rindal OMH, Haugnes P, Torvik PO, Sandbakk O (2018) Sex-based differences in speed, sub-technique selection, and kinematic patterns during low- and high-intensity training for classical cross-country skiing. PLoS One 13 (11):e0207195. doi:10.1371/journal.pone.0207195

Stoggl T, Muller E, Ainegren M, Holmberg HC (2011) General strength and kinetics: fundamental to sprinting faster in cross country skiing? Scand J Med Sci Sports 21 (6):791-803. doi:10.1111/j.1600-0838.2009.01078.x

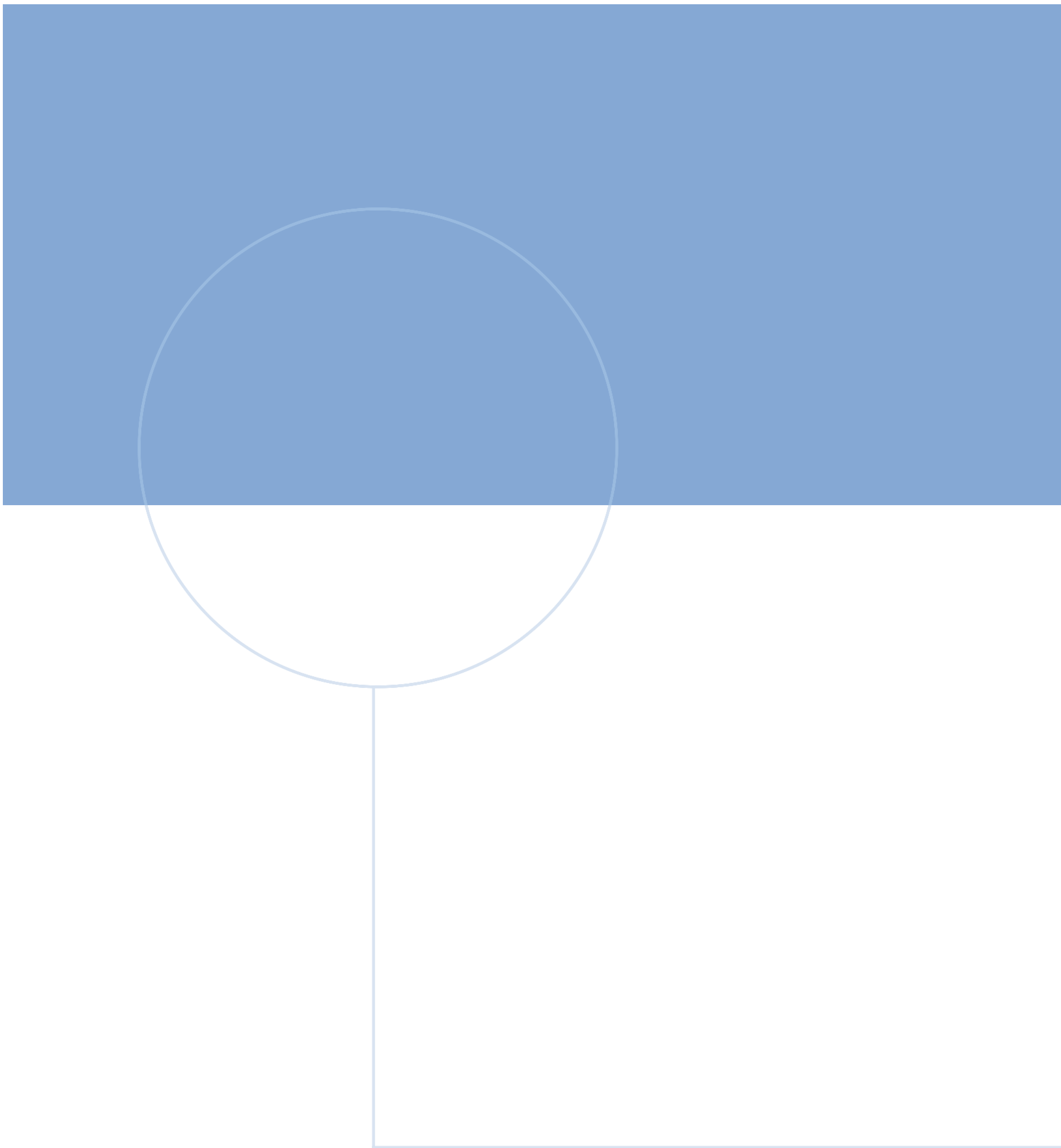
Stoggl T, Welde B, Supej M, Zoppirolli C, Rolland CG, Holmberg HC, Pellegrini B (2018) Impact of Incline, Sex and Level of Performance on Kinematics During a Distance Race in Classical Cross-Country Skiing. J Sports Sci Med 17 (1):124-133

Thorstensson A, Roberthson H (1987) Adaptations to changing speed in human locomotion: speed of transition between walking and running. Acta Physiol Scand 131 (2):211-214. doi:10.1111/j.1748-1716.1987.tb08228.x

Turvey MT (1990) Coordination. Am Psychol 45 (8):938-953

Usherwood JR, Bertram JE (2003) Gait transition cost in humans. Eur J Appl Physiol 90 (5-6):647-650. doi:10.1007/s00421-003-0980-6

Vahasoyrinki P, Komi PV, Seppala S, Ishikawa M, Kolehmainen V, Salmi JA, Linnamo V (2008) Effect of skiing speed on ski and pole forces in cross-country skiing. Med Sci Sports Exerc 40 (6):1111-1116. doi:10.1249/MSS.0b013e3181666a88



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