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A Biomechanical and Physiological Comparison of the Double Poling and Diagonal Stride Technique in Cross-Country Skiing

- Under different combinations of inclines and intensities

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ABSTRACT

Background: High efficiency is an obvious determining factor for skiing performance. Hence, it is likely that efficiency in the double poling (DP) and diagonal stride (DIA) technique may be affected by incline since the differences in mechanical characteristics between these two techniques might have advantages at different conditions.

Purpose: The purpose of the present study was to compare the DP and DIA technique at moderate (5%) and steep uphill terrain (12%), and to identify how gross efficiency (GE) and physiological responses are related to underlying biomechanical characteristics in these two techniques.

Methods: 15 male elite skiers (age 24.0 ± 2.7 yrs, body height 182.6 ± 4.6 cm, body mass 76.34 ± 6.4 kg) performed four test sequences (DP and DIA at 5%, DP and DIA at 12%) including 3 submaximal intensities performed on equal work rates, while roller skiing on a large treadmill. Oxygen uptake, heart rate and rate of perceived exertion were assessed. Reflective markers were placed on anatomical landmarks, and dynamics and kinematics synchronized and recorded.

Results: DIA at the 12% and DP at the 5% had significantly higher GE (P <0.01**)** and reduced physiological responses (heart rate and rating of perceived exertion values) (all P < 0.05), compared to all other conditions. Furthermore, longer cycle length and lower cycle rate were found for DP at the 5% and DIA at the 12% at all velocities (all P < 0.05). DIA demonstrated a high duty factor (DF), with correspondingly smaller fluctuations in the velocity of center of mass (V_{CoM}) (all P < 0.05). For DIA, the relative pole power was lower on 12% inclination at all velocities compared to the 5% inclination (P < 0.01).

Conclusion: At the 12% incline, DIA was the favourable technique. The higher gross efficiency and DF, together with the small V_{CoM} fluctuations demonstrated the advantages of using DIA at steep uphill. At the 5% incline, the higher velocity made the propulsion from the legs less efficient and consequently the skiers had to rely more on the poles. Hence, the DP was the preferred technique at moderate incline.

SAMMENDRAG

Bakgrunn: Høy effektivitet er en avgjørende faktor for prestasjon på ski. Det er sannsynlig at effektivitet i staking og diagonalgang er påvirket av stigning siden forskjeller i mekaniske karakteristikker mellom disse to teknikkene kan ha fordeler ved ulike betingelser.

Hensikt: Hensikten med studien var å sammenligne teknikkene staking og diagonalgang på moderat (5%) og bratt terreng (12%), og å identifisere hvordan effektivitet og fysiologiske responser er relatert til underliggende biomekaniske karakteristikker i disse to teknikkene.

Metode: 15 mannlige elite langrennsløpere (alder 24.0 ± 2.7 år, høyde 182.6 ± 4.6 cm, vekt 76.34 ± 6.4 kg) gjennomførte fire test sekvenser (staking og diagonal på 5%, staking and diagonal på 12%) inkludert tre submaksimale intensiteter utført på lik ytre belastning, mens de gikk på rulleski på en stor tredemølle. Oksygenopptak, hjerterate (HR) og rangert opplevd anstrengelse med Borgs Rate of Perceived Exertion (RPE) ble målt. Refleksmarkører ble plassert på anatomiske landemerker, og dynamikk og kinematikk synkronisert and tatt opp.

Resultater: Diagonalgang på 12% og staking på 5% hadde signifikant høyere effektivitet (P <0.01**)** og reduserte fysiologiske responser (HR og RPE verdier) (alle $P < 0.05$), sammenlignet med alle de andre betingelsene. Lengre sykluslengde og lavere syklusrate ble funnet i staking på 5% og diagonal på 12% for alle hastigheter (alle $P < 0.05$). Diagonalgang viste en høy duty faktor, med tilsvarende mindre hastighets fluktueringer av tyngdepunktet (alle $P < 0.05$). I diagonalgang var relativ stav power på 12% stigning mindre for alle hastigheter sammenlignet med stav power på 5% stigning ($P < 0.01$).

Konklusjon: På 12% stigning var diagonalgang den fordelaktige teknikken. Høyere effektivitet og duty faktor, sammen med små hastighets fluktueringer av tyngdepunktet demonstrerte fordelene ved å bruke diagonalgang i bratt terreng. På 5% stigning førte den høye hastigheten til at fremdriften fra beina ble mindre effektiv, og som en konsekvens ble langrennsløperne mer avhengig av å bruke stavene. Derfor var staking den foretrukne teknikken på moderat stigning.

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ABBREVIATIONS

ANOVA:	Analysis of Variance
CL:	Cycle length
CoM:	Center of mass
CR:	Cycle rate
DIA:	Diagonal Stride
DF:	Duty Factor
DP:	Double Poling
HR:	Heart Rate
GE:	Gross efficiency
P_p:	Pole Power
RPE:	Rate of Perceived Exertion
$V_{CoM:}$	Velocity of the Center of Mass
XC:	Cross- country
5%:	Moderate incline
12%:	Steep uphill incline
$DP_{5\%}$:	Double poling performed on moderate incline
$DP_{12\%}$:	Double poling performed on steep uphill
$DIA_{5\%}$:	Diagonal stride performed on moderate incline
$DIA_{12\%}$:	Diagonal stride performed on steep incline

1. INTRODUCTION

Competitive cross-country (XC) skiing is performed in varying terrain with widely varying speeds. In the majority of races, the distance is performed, and equally divided between uphill, flat and downhill terrain. The skiers frequently change between different sub-techniques, which are characterized by altered movement patterns and distribution of propulsive forces generated by upper body poling and lower body leg push-off.

In the classical technique, diagonal stride (DIA) has traditionally been the major sub-technique used in uphill, and double poling (DP) has traditionally been adopted for skiing at flat, slight up-or downhills terrain. During DIA arms and legs move in a reciprocal way and is similar to walking and running (Winter, 1979) and one arm and the contralateral leg generate propulsion simultaneously and vice versa (Kehler, Hajkova, Holmberg, & Kram, 2014) allowing for a relatively continuous propulsion during the cycle. This means that the legs and arms have to be accelerated and decelerated forward and backwards asynchronously relative to the center of mass (CoM), which may cost considerable amounts of metabolic energy (van Ingen Schenau, de Koning, & de Groot, 1994). A main contributory factor from arms/pole actions in DIA is to generate pole force over a relatively long time and emphasize force production in the later part of the poling cycle (Lindinger, Gopfert, Stoggl, Muller, & Holmberg, 2009).

DP is a synchronous movement, where the arms and legs move simultaneously in the sagittal plane. Compared to DIA, DP show a more dynamic poling pattern, characterized by a higher pole force applied during a relatively short poling phase. These characteristics are directly correlated to DP velocity (Holmberg, Lindinger, Stoggl, Eitzlmair, & Muller, 2005). Contrary to DIA, propulsive forces are solely generated through the poles in DP, as the skis remain gliding forward. Thus, in DP one does not have to accelerate and decelerate the legs relative to the CoM to the same extent as in DIA. Despite a pronounced upper-body work in DP, dynamic leg work contribute in the production of propulsive forces by elevating CoM and increasing mechanical energy of the body, which is transferred to work on the poles in the poling phase (Danielsen, Sandbakk, Holmberg, & Ettema, 2015; Holmberg, Lindinger, Stoggl, Bjorklund, & Muller, 2006). This transfer is accomplished by strong vertical fluctuations, more than in DIA, which has been discussed as a possible reason for DP to have a higher cost of locomotion at steeper uphills than DIA (Pellegrini et al., 2013; Zoppirolli, Pellegrini, Bortolan, & Schena, 2015). However, DP allows the use of powerfull leg muscles to contribute significantly to external power, independent of the velocity of the skis (Danielsen et al., 2015). In DIA, legs extend fast at high velocities and consequently power is reduced. In DIA relatively small velocity fluctuations of the CoM (V_{CoM}) in horizontal direction have been found (Kehler et al., 2014), while in DP the V_{CoM} fluctuations were reported to be more pronounced and likely related to short propulsion periods and long recovery time in DP (Zoppirolli et al., 2015). In general, movement forms that allows for smaller V_{CoM} fluctuations in the horizontal direction (e.g. cycling) have been found to be more efficient than movements where the V_{CoM} fluctuations is higher e.g. running; Ingen Schenau and Cavanagh (1990), counting out each other effect on motion of CoM. In XC skiing this might be particularly relevant in steep terrain; when gravity is accelerating the CoM downwards, it might be reasonable to assume that the longer the time of propulsion (acceleration that counteracts gravity) over the cycle the less V_{CoM} fluctuations, which makes DIA more beneficial than DP at steep and low speed. At lower inclines, where velocity is high, the time of ski propulsion obviously must become shorter, and the time of propulsion from the skis likely decreases. At some high speed, the time of ski propulsion likely becomes too low, and it may become advantageous to completely rely solely on propulsion through the poles. That is, the horizontal V_{CoM} can be disconnected from the propulsion time of the skis.

In general, it is reported that skiers prefer to use the DP technique at high velocities on flat and slight uphill terrain, while DIA is the preferred technique in uphills where lower velocities are used (Pellegrini et al., 2013). One of the reasons for this is probably that DIA is more economical than DP on slopes steeper than 4º whereas DP requires less energy to maintain a given velocity on flatter terrain (Andersson, Bjorklund, Holmberg, & Ortenblad, 2016; Pellegrini et al., 2013). The ability to efficiently transform metabolic energy into work (i.e., skiing efficiency/economy) is obviously a determining factor for skiing performance (Sandbakk, Holmberg, Leirdal, & Ettema, 2010), which in the case of DP and DIA efficiency may be affected by incline since the differences in generation of propulsive forces and V_{CoM} fluctuations between these techniques may have advantages at different conditions. The understanding of underlying mechanisms related to efficient DP and DIA techniques are particularly relevant today since the use of double poling in classical cross-country ski races has increased. In some classical races, skiers have even achieved excellent results without any grip wax using only double poling. During submaximal DP (16.0 km/h) and DIA (9.5 km/h), Andersson et al. (2016) reported that the gross efficiency (GE) linearly increased with incline during DIA, while for DP the relationship between GE and incline exhibited a slightly inverted u-shape. Because the velocity was unaltered work rate increased with incline in Andersson et al. (2016). Since GE is strongly dependent on work rate (Sandbakk et al., 2010) the relationships in Andersson et al. (2016) are affected by the different work rates. Thus, the results are inconclusive with regard to the relationships between incline and GE. Therefore, there is a need to study the effects of technique (DP vs DIA) at similar work rates, which has not yet been done for classical XC skiing research.

The purpose of the present study were to compare DP and DIA on moderate and steep uphill terrain, and identify how GE and physiological responses are related to underlying biomechanical characteristics in these two techniques performed at similar external work rates. More specifically, this study aims to describe possible advantages and disadvantages of using DP and DIA on different inclines and intensities, from an energetic and mechanical point of view. In the current study the moderate (5%) and steep uphill incline (12%) were chosen because they are relevant inclines where skiers at a homogenous national level prefer to apply DP and DIA. For this purpose, metabolic rate (MR), heart rate (HR), rating of perceived exertion (RPE), propulsion characteristics, CoM velocity fluctuations and power distribution between poles and skis were examined. It was hypothesized that GE would be highest for DP on moderate incline (5%) and DIA at the steep uphill (12%). It was expected that negative mechanical characteristics such as short relative propulsion periods and high CoM velocity fluctuations would be associated with low GE.

2. METHODS

2.1 PARTICIPANTS

15 elite male cross-country skiers competing at national and international level (age 24.0 ± 2.7 yrs, body height 182.6 ± 4.6 cm, body mass 76.34 ± 6.4 kg) volunteered to participate in this study. All skiers were familiar with treadmill roller skiing from previous training and testing. The study was registered at and approved by Norwegian Social Science Data Services, and approved by the Regional Ethics Comittee. Prior to obtaining written informed consent, the protocol and procedures were explained both in writing and verbally to each subject where it was explicitly stated that they could withdraw at any time.

2.2 EXPERIMENTAL DESIGN

Before the testing session, a 15-minute, test-specific low intensity warm up was performed on inclines relevant to the subsequent testing sessions, which also ensured that the roller ski wheels and bearings reached a proper temperature (Ainegren, Carlsson, & Tinnsten, 2008). To investigate DP and DIA at relevant inclines on submaximal intensities, two different inclinations and three different intensities were selected. The intensities were chosen to correspond the work rates: 150, 200 and 250 Watt. Calculated velocities for the work rates are shown in table 2.1.

Table 2.1: Calculated velocities for the intensities

Inclination	150 Watt	200 Watt	250 Watt
5%	9.4 km/h	12.5 km/h	15.7 km/h
12%	4.9 km/h	6.5 km/h	8.1 km/h

Four test sequences (two inclines and two techniques) including three intensities were performed (2.1). The intensities at both inclines were calculated by finding velocities representing a work rate of 150, 200 and 250 Watt, for a skier with an expected body weight of 78 kg and an estimated rolling friction coefficient (μ) corresponding 0.022. The estimated μ was based on previous testing conducted with comparable roller ski wheels. The participants skied both DP and DIA at 5% and 12% incline at the targeted work rates. The 5-minute submaximal test performed at 200 W was chosen based on earlier pilot testing to induce aerobic steady-state condition (blood lactate < 4mmol/L) with a competition relevant technique. Experimental conditions were divided into four testing sequences and consisted of; $DP_{5\%}$, $DIA_{5\%}$, $DP_{12\%}$ and $DIA_{12\%}$, in which each test sequence lasted 11-minutes. All skiers performed the test sequences in a randomized order. Each test sequence started with one 5-min bout of steady-state submaximal roller skiing at a work rate of 200 W, where all skiers could reach aerobic steady state conditions, where respiratory variables and heart rate were collected during the two last minutes. Thereafter, a 60 s. break was implemented to assess blood lactate concentration and rating of perceived exertion before an incremental test started, i.e. three 90-s bouts at constant intensities corresponding to 150, 200 and 250 W where kinetics were collected during the last 75 s. at every increment, allowing 15 s. adaption to the current load level. The low intensity (150 W) corresponded to low intensity training where skiers execute around 80% of their training (Sandbakk & Holmberg, 2014) and the high intensity (250 W) corresponded to a workload comparable to the one used in distance races for this group of skiers. The skiers were told to ski as normal as possible, and to utilize the double poling technique or the diagonal stride technique as advised.

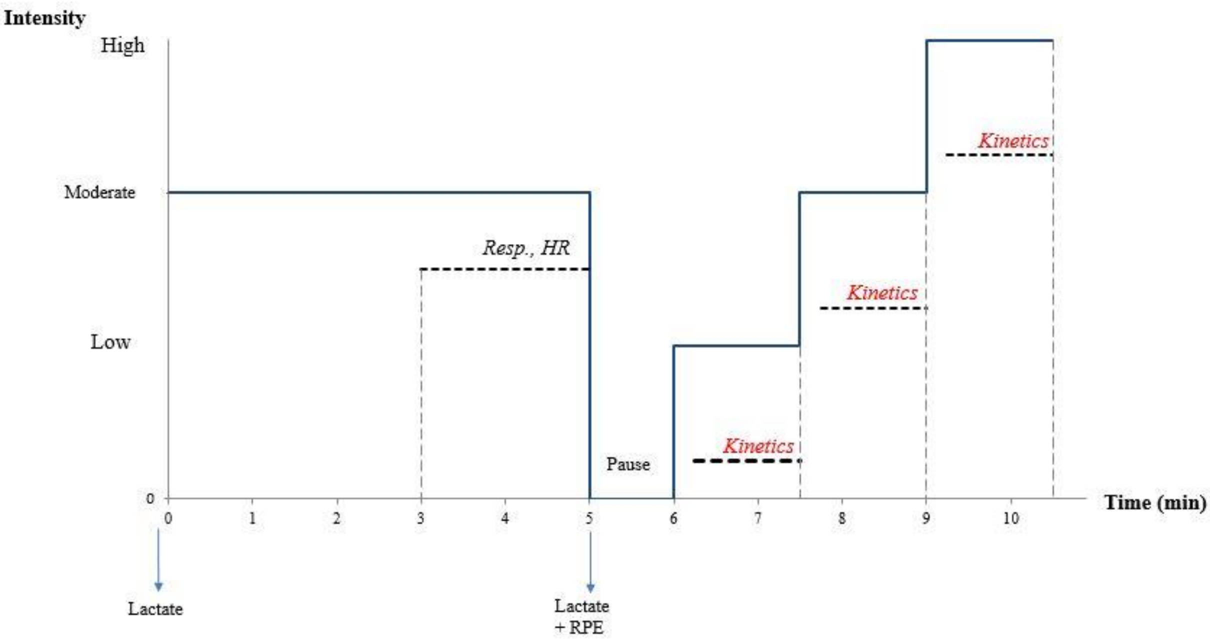

Figure 2.1 shows the test protocol with intensity (corresponding 150, 200 and 250 W) on the y-axis with the duration in minutes on the x-axis. Respiratory variables and HR were obtained during the last two minutes of the 5 min bout on moderate intensity, indicated by the dashed line. Kinetics were recorded during the incremental stages from low to high intensity, and are indicated by the dashed lines.

2.3 INSTRUMENTS AND MATERIALS

Roller skiing was performed on a 5×3-m motordriven treadmill (Forcelink Technology, Zwolle, The Netherlands). The incline and speed were calibrated using the treadmill software. All testing was done employing either DP or DIA. To minimize variations in rolling resistance, all of the skiers used the same pair of roller skis with standard wheels (IDT Sports, Lena, Norway, resistance category 2). The surface of the treadmill belt was covered with non-slip rubber and the participants used poles with special carbide tips, available at incremental lengths of 5 cm (Madshus UHM 100, Biri, Norway). The athletes were secured with a safety harness connected to an emergency brake.

The rolling friction force (F_f) of the roller skis was regularly determined by a towing test, described previously by (Sandbakk et al 2010), and the friction coefficient (μ) was calculated by dividing F_f by the normal force (N): $\mu = F_f \cdot N^{-1}$. The overall mean value of μ was included in the calculation of work rate. μ was independent on both mass, speed and incline.

2.4 PHYSIOLOGICAL MEASUREMENTS

Respiratory variables were continuously measured by an open circuit indirect calorimetry using an Oxycon Pro apparatus (Jaeger GMbH, Hoechberg, Germany). At the beginning of each test day, the system was calibrated against a known mixture of gases (16.00 ± 0.04 % O_2 and 5.00 ± 0.1 % CO_2, Riessner-Gase GmbH & Co, Lichtenfels, Germany), and the expiratory flow meter was calibrated with a 3-L volume syringe (Hans Rudolph Inc., Kansas City, MO). Heart rate was recorded using a Polar heart rate monitor (Polar M800, Polar Electro OY, Kempele, Finland). Lactate concentration in whole blood was obtained from a 20-µl blood sample collected from the middle and ring finger, and analyzed using Biosen C_line Sport lactate analyzer (EKF-diagnostic GmbH, Barleben, Germany). The same researcher collected all lactate samples during testing to minimize variation in procedure. Metabolic rate was determined from VO_2 and CO_2, and gross efficiency was calculated as the work rate divided by the metabolic rate and is presented as a percentage. In addition to physiological response, rating of perceived exertion using the Borg RPE scale was assessed for the lower, upper and whole body (Borg, 1970).

2.5 DYNAMICS

The resultant pole forces (i.e. the force directed along the poles) was measured by a 60 g load cell in both poles. The load cells were placed on top of an aluminum (50 g) tube which was mounted directly at the top of and inside the pole tube. A small (8 mm diameter) ball was located in between the load cell and the aluminum tube which minimized the cross-talk between forces directed solely along the pole and forces associated with squeezing, bending or rotation of the handle grip. A motion capture system was applied in order to measure pole motion, so that weight bearing and horizontal components of poling force could be determined. The pole force measurements were calibrated by applying a range of weights of known magnitudes, simultaneously measured using a Kistler force platform (Kistler Number, Switzerland etc). Pole forces were wirelessly sampled at 1500 Hz using a telemetric system (TeleMyo DTS, Noraxon, Scottsdale, AZ, USA).

2.6 KINEMATIC MEASUREMENTS

Nine Oqus infrared cameras (Qualisys AB, Gothenburg, Sweden) captured three-dimensional position characteristics of passive reflective markers at a sampling frequency of 250 Hz. Each recording session lasted approximately 75 s., which ensured at least 30 cycles for each recording sequence. Initially, the participants were given around 15 s. in order to allow technique adaptation. The coordinate system was calibrated according to the manufacturer's specifications at the start of each testing day and/or between every third participant to ensure precisely and correct data. The same researcher positioned passive reflective markers on anatomical landmarks bilaterally by using double sided tape (3M, USA). These landmarks were on the shoe at the distal end of the fifth metacarpal of the foot, the lateral malleolus (ankle), the lateral epicondyle (knee), the greater trochanter (hip), the lateral end of the acromion process (shoulder), the lateral epicondyle of humerus (elbow), styloid process of ulna (wrist) and C7 (upper back). A total of 8 markers were placed on the poles and roller-skis. One marker was placed on the lateral side of each pole, 5 cm below the handle, and one marker placed on the lateral side of the pole tip. Two markers were fixed on the left side of the treadmill in alignment to movement direction with a 1 m. distance, in order to continuously register incline throughout the protocol. Two markers were attached on each ski, one marker 1 cm behind the front wheel, and one marker 1 cm in front of the back wheel of each roller ski. All were fastened with double sided tape. Acquisition software (Qualisys Track Manager, Qualisys AB, Gothenburg, Sweden) was used to sample and synchronize kinetics and kinematics, and the evaluation of data was completed in a self-written Matlab (8.4.0 R2014b, Mathworks Inc., Natick, MA, USA) script designed specifically for analysis of the classic technique. Position data for each marker were digitally low-pass filtered using Chebyshev II (cut-off frequency 20 Hz).

2.7 DATA ANALYSIS

Calculation of metabolic rate and gross efficiency:

The aerobic metabolic rate was calculated in accordance to Sandbakk, Hegge, and Ettema (2013) from VO_2 and VCO_2 in aerobic steady state conditions, as the product of VO_2 and the oxygen energetic equivalent using the associated respiratory exchange ratio (RER) and standard conversion tables (Péronnet & Massicotte, 1991). Gross efficiency was calculated as the external work rate performed by the entire body divided by the metabolic rate.

Calculation of work rate:

Work rate was calculated in accordance to Sandbakk et al. (2010), as the sum of power against gravity (P_g) and friction (P_f):

$Pg = m \times g \times sin\alpha \times v$

$Pf = (1 - Fpole\ perp) \times m \times g \times cos\alpha \times \mu \times v$

Where $F_{pole\ perp}$ is the cycle average of the perpendicular component of poling force, m is the body mass of the skier, g the gravitational constant, α inclination of the treadmill (in radian), v the velocity of the treadmill. μ, the frictional coefficient (0.018), deviated from 0.022, which was used to determine velocities for the calculated work rates. The mean body mass of the athletes were predicted to 78 kg, which was used as reference weight in the calculations of velocities. However, a mean body mass of 76 kg was achieved in current study. By using this setup, small variances in targeted work rates of 150 – 200 - 250 Watt occurred because of inter-individual body mass differences. In terms of a competitive situation, all skiers compete in the same tracks, whether high or low body mass. Hence, the same velocity was selected for all participants for the various work rates, independent of the skiers' body weight.

Calculation of biomechanical parameters:

Body center of mass was determined from the position and the mass of the body segments (including the mass of the skis and poles) and calculated as a percentage of total body mass by use of regression equations and the parameters reported by de Leva (1996). The body was approximated as a system of 11 linked rigid segments connected by frictionless revolute joints, and were defined in the sagittal plane as; Two feet, two legs, two thighs, two upper arms, two forearms (including the hands) and the trunk (including head). The lengths of the segments were determined based on the kinematic data and averaged over the entire period of analysis. Joint center positions of the ankle, knee, hip, shoulder and elbow were taken from the position data.

The pole angels were defined in order to calculate the parallel and perpendicular components of pole force from the resultant pole force:

$F_{pole\ \mathrm{par}} = F_{pole\ \mathrm{res}} \times \cos \alpha$

$F_{pole\ \mathrm{perp}} = F_{pole\ \mathrm{res}} \times \sin \alpha$

where α is the angle between the poles and the treadmill.

Poling power (P_{pole}) was calculated in order to examine the total power contributions from skis and poles on 5% and 12% incline. Contribution from the skis was calculated as the difference between the total external power and the poling power. The resultant force from poles were measured, and P_{pole} calculated as:

$P_{pole} = F_{pole\ \mathrm{res}} \times V_{CoM\ \mathrm{tot}} \times \cos \alpha$

where $F_{\mathrm{poles\ res}}$ is the resultant pole force, $V_{\mathrm{CoM\ tot}}$ is the total velocity of the CoM, and α is the angle between the CoM velocity vector and the $F_{\mathrm{pole\ res}}$ vector. For $V_{CoM\ tot}$, the velocity of the CoM in the horizontal (anterio-posterio) and in the vertical directions in the global coordinate system was found by differentiation of position with respect to time, and by adding the components of the treadmill velocity in the respective directions as a constant.

Pole plant was defined as the time point where the velocity of the tip of the poles became equal to the treadmill belt speed in the horizontal directions (anterio-posterio). Pole lift off was identified as when the velocity of the pole tips exceeded zero in the perpendicular direction. Pole propulsive time was defined as the time period between pole plant and pole lift off. In DIA, propulsive forces from the skis can only occur when the skis is at full stop with respect to the ground. Ski thrust time was calculated as the time period when the velocity of the back roller ski markers were equal to the velocity of the treadmill belt in the direction along the treadmill surface.

Cycle definitons

One cycle was defined as the time period from the left pole plant through the subsequent left pole plant. One DP cycle was defined from one pole plant to the next pole plant. Cycle time (CT) was the time of one cycle movement, and cycle rate was calculated from 1/CT. The duty factor was calculated as the total propulsive time divided by cycle time, where the total propulsive time was defined as the sum of the propulsive time periods of any of the poles or skis.

2.8 STATISTICAL ANALYSIS

All data were checked for normality using the Shapiro Wilk test and is presented as means and standard deviations (±SD). A two-way repeated measures ANOVA (2×2; incline 5% and 12%; Technique: DP and DIA) were used to assess the physiological variables. A three-way repeated measures ANOVA (2×2×3; incline 5% and 12%; Technique: DP and DIA; Low, Mod, High) were used to assess the kinetics. The level of statistical significance was set at $\alpha = .05$ for all analysis. All statistical tests were performed with Office Excel 2010 (Microsoft Corporation, Redmond, WA, USA) and SPSS 23.0 Software (SPSS Inc, Chicago, IL).

3. RESULTS

Actual power used, presented as mean and SD over each intensity was: 147.1 ± 12.4, 195.5± 16.5 and 244.6 ± 20.5 at Low, Mod and High, respectively.

3.1 GROSS EFFICIENCY AND PHYSIOLOGICAL RESPONSES

Gross efficiency for all conditions are presented in figure 3.1. A significant interaction effect ($P < 0.01$) between technique and incline was found. Both incline and technique affected GE. The skiers had higher GE in $DP_{5\%}$ than $DIA_{5\%}$ ($P < 0.01$), whereas they had higher GE in $DIA_{12\%}$ compared to $DP_{12\%}$ ($P < 0.01$).

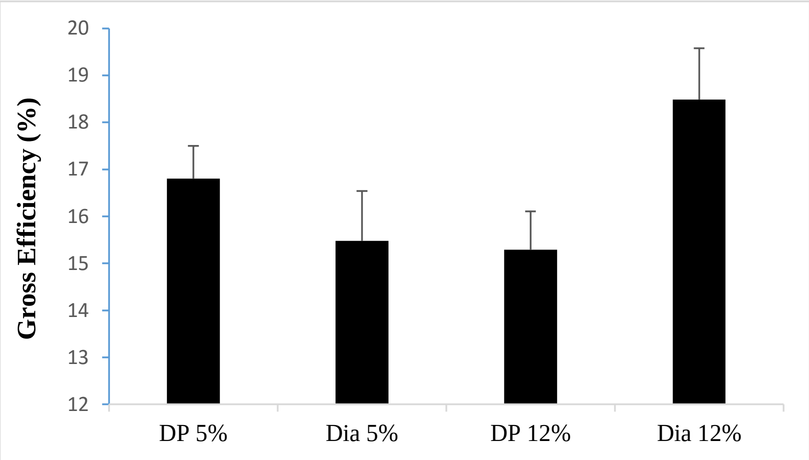

Figure 3.1 Mean and SD of Gross efficiency in 15 XC skiers during 5-min stages of roller skiing on a 5% and 12% inclined treadmill on moderate intensity using the double poling (DP) and diagonal stride (DIA) technique

Relative heart rate (HR) responses for all conditions are shown in figure 3.2. A significant interaction effect ($P < 0.01$) between technique and incline was found. Relative HR was highest for DP ($P < 0.01$), and highest on the 5% incline ($P=0.02$).

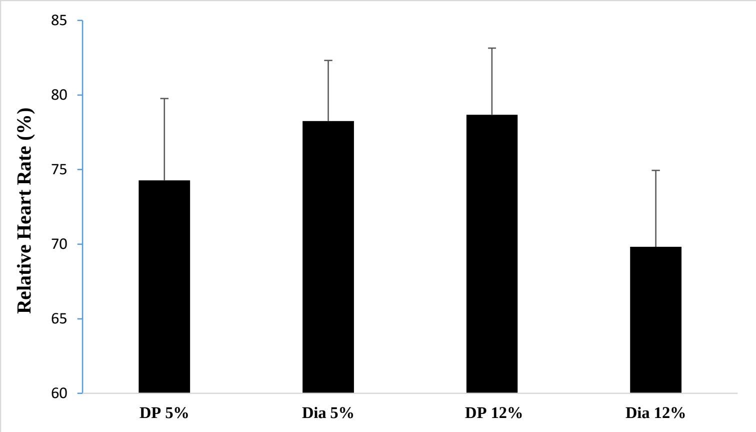

Figure 3.2 Mean and SD of Relative Heart Rate during the 5-min stages at moderate intensity, for 15 cross-country skiers while roller skiing on a 5% and 12% inclined treadmill using the double poling (DP) and diagonal stride (DIA) technique.

Figure 3.3 shows the RPE values. Significant interaction effects between technique and incline were found for all RPE values; whole body (P < 0.01), arms and legs (both P =0.02), where the skiers reported noticeably lower RPE values with $DP_{5\%}$ and $DIA_{12\%}$ than the other conditions.

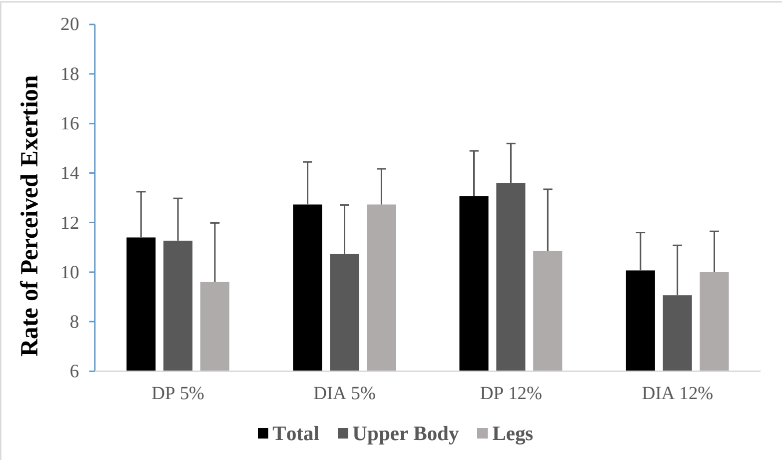

Figure 3.3. Mean and SD of 15 cross country skiers' Rate of Perceived Exertion on a 6-20 Borg scale, reported immediately after the 5-min stages, performed at moderate intensity in the double poling (DP) and diagonal stride technique (DIA) on 5% and 12% inclination.

3.2 MOVEMENT CHARACTERISTICS

Cycle length and cycle rate are presented in figure 3.4 and 3.5. There was a significant difference in CR between DP and DIA at both inclines (P < 0.01), and as intensity increased, CR increased in the case of DP, and decreased for DIA (P < 0.01). CL was shorter for both DP and DIA on the 12% compared to the 5% (P < 0.01). Significant differences in CL between DP and DIA were demonstrated (P < 0.01) with shorter CL on 12% for both techniques.

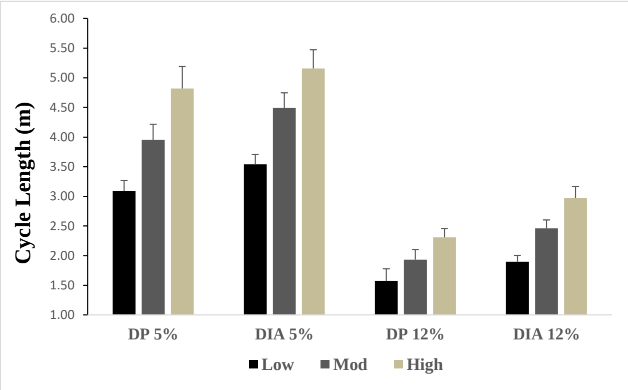

Figure 3.4 Mean and SD of the cycle length for 15 skiers during DP and DIA roller skiing on a 5% and 12% inclined treadmill, at low, moderate and high intensity.

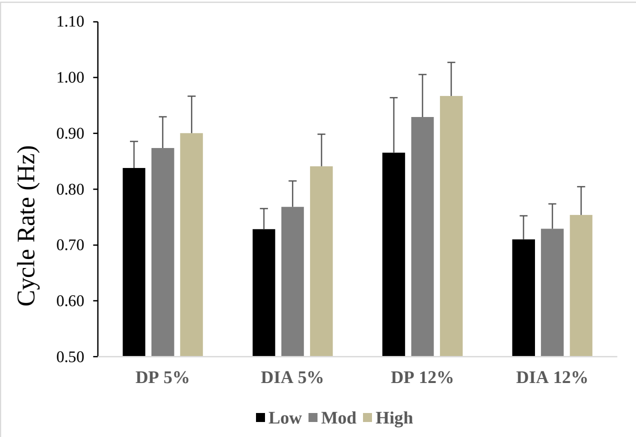

Figure 3.5 Mean and SD of the cycle rate for 15 skiers during DP and DIA roller skiing on a 5% and 12% inclined treadmill, at low, moderate and high intensity.

Figure 3.6 shows the DF. A significant difference between the techniques were observed for the DF (*P* <0.01), with values being greater for DIA compared to DP. A significant effect of incline was observed, with greater DF on the 12%. A significant interaction effect (P < 0.01) between technique and incline was found.

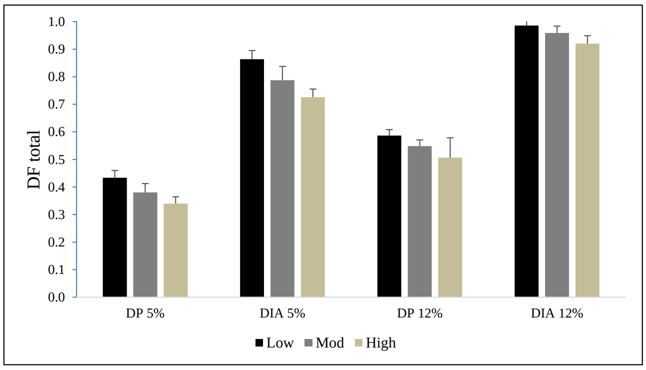

Figure 3.6 Duty Factor (total propulsive time relative to cycle time) for 15 skiers during DP and DIA roller skiing on a 5% and 12% inclined treadmill at Low, Moderate and High intensity. (Mean±SD)

Center of mass velocity fluctuations

V_{CoM} fluctuations are presented in figure 3.7. The data showed lower V_{CoM} fluctuations for DIA compared to DP at both inclines. Statistical analyses showed that V_{CoM} fluctuations were different between techniques and inclines (all $P < 0.01$), in which $DP_{12\%}$ had the greatest values. A significant technique by incline interaction at all intensities were found ($P = 0.02$).

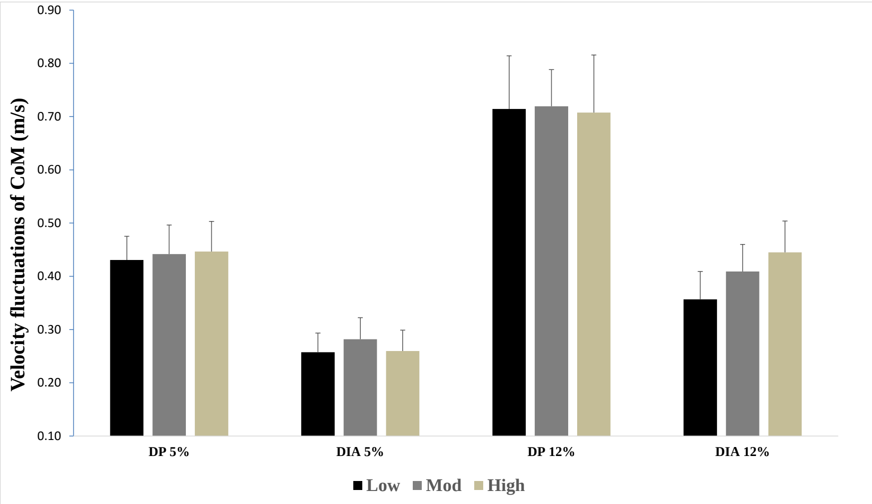

Figure 3.7 displays mean and SD of the velocity fluctuations of CoM for 15 skiers roller skiing at low, moderate and high intensity, at 5% and 12% inclination using the DP and DIA technique.

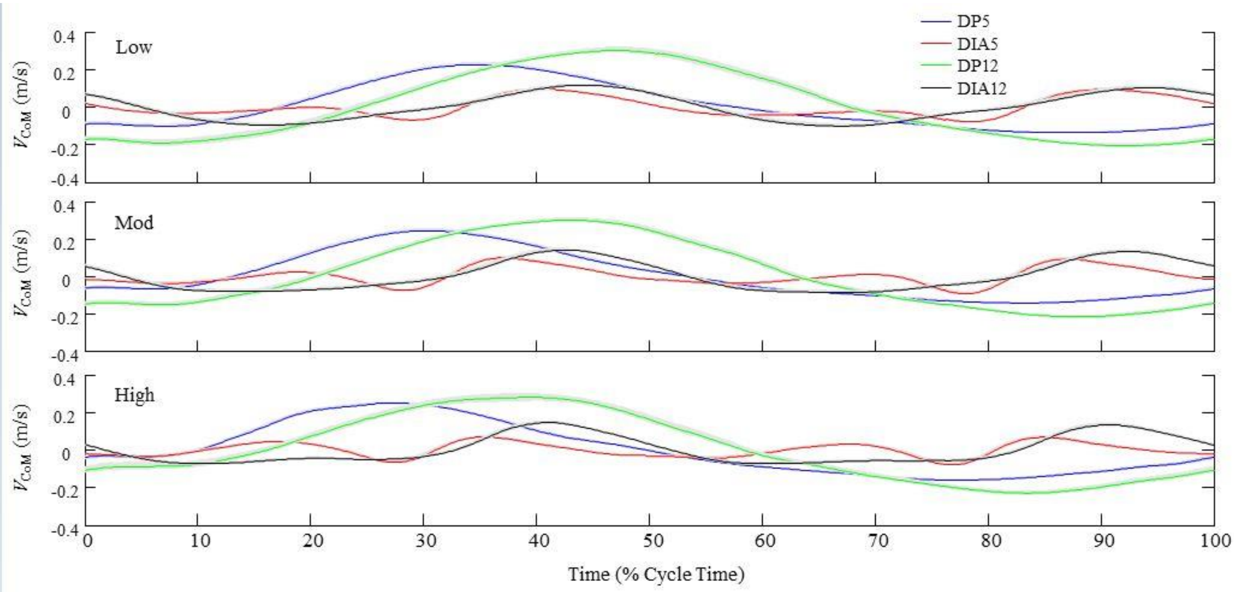

Figure 3.8 shows how the V_{CoM} fluctuates in the horizontal (anterio-posterio) direction along the treadmill belt. The mean V_{CoM} for 15 skiers is normalized to 100% of cycle time during DP and DIA on 5% and 12% inclination at low, moderate and high intensity.

Early in the DP cycle (~10%), V_{CoM} fluctuations remained relatively small followed by a rapid increase after about ~10% of the cycle. During the major part of the poling phase, V_{CoM} increased and reached the maximal value during the final part of the poling phase. The maximal value for DP steep was higher than for moderate incline. During recovery, V_{CoM} decreased, due to the absence of propulsion. A different pattern of V_{CoM} fluctuations were demonstrated in DIA, with lower fluctuations and a peak in V_{CoM} that occurred right after each ski thrust.

Poling power: Relative contributions of upper body in DIA

Pole power in DP was compared with the external power, as set by the treadmill-belt incline and velocity, and was found to be very similar, indicating high validity of pole power recordings. Thus, pole power was only analyzed for DIA. A significant decrease for relative pole power ($P < 0.001$) with incline was observed, in which $DIA_{12\%}$ demonstrated the lowest values.

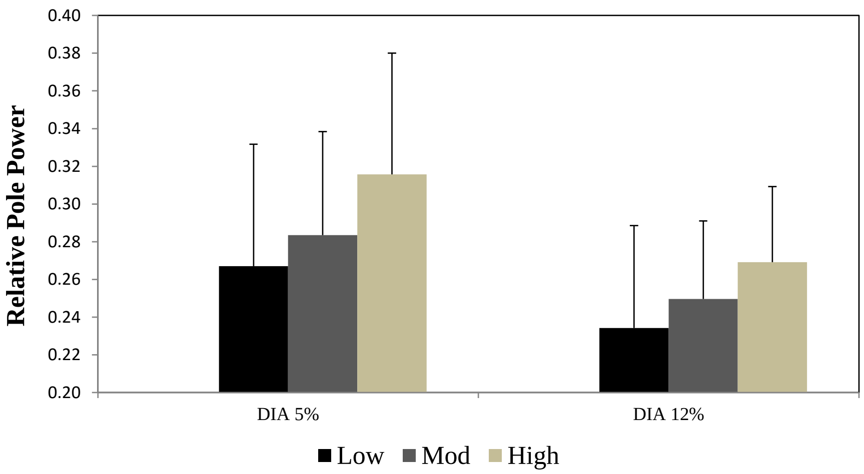

Figure 3.X displays mean and SD of relative pole power for 13 skiers performing DIA on 5% and 12% inclination at low, moderate and high intensity.

4. DISCUSSION

The current study compared the physiology and biomechanics in the DP and DIA technique employed at moderate (5%) and steep uphill (12%) incline at three different intensities that were equal for both techniques. The main findings confirmed the primary hypothesis of current study; A higher GE and reduced physiological responses were found for $DIA_{12\%,}$ compared to the other conditions, and also to a somewhat lesser extend in $DP_{5\%}$. Furthermore, significant effects in mechanical characteristics were demonstrated; longer CL and lower CR were found for $DP_{5\%}$ and $DIA_{12\%}$ at all velocities. DIA demonstrated a high duty factor, with correspondingly small V_{CoM} fluctuations. For DIA, the relative pole power were lower on the 12% inclination, at all velocities compared to the 5% inclination.

4.1 GROSS EFFICIENCY AND PHYSIOLOGICAL RESPONSES

A significant interaction effect of incline and technique was found, in which the skiers attained a higher GE on the 12% incline in DIA compared to DP, together with a higher GE on the 5% in DP. These findings are in agreement with previous studies whereby DP was more economical at inclines <3.3º and DIA was more economical at inclines > 3.3º (Andersson et al., 2016; Pellegrini et al., 2013). Given the results of current study, DP is the most efficient technique on 5%, while DIA is the most efficient on 12%, given the intensities and level of skiers used here. Furthermore, in this study the skiers consistently attained the greatest GE in $DIA_{12\%}$, which confirms previous data in roller ski skating where higher GE has been found at steeper incline (Sandbakk, Ettema, Leirdal, & Holmberg, 2012; Sandbakk et al., 2013). In DIA, the workload between upper and lower limbs provides the ability to increase total propulsion duration and thereby enable a more continuous force generation which may enhance skiing efficiency. At the same moderate work rate, HR and RPE ratings for whole body were lowest in $DP_{5\%}$ and $DIA_{12\%}$, thus in agreement with the findings for GE. DIA is a technique where propulsion from the arms and legs occur simultaneously (Kehler et al., 2014) and were the strain on the propulsive muscles are more evenly distributed throughout the movement. Current finding of a lower physiological cost in $DIA_{12\%}$ is probably explained by this. Sharing the workload over upper and lower limbs may affect the physiological cost at a given work rate. Relatively higher physiological responses during $DP_{12\%}$ can be explained by the more force demanding "condition" for the upper body muscles with all propulsive forces exerted through the poles (Holmberg et al., 2005). This is also in correspondence with the RPE values for arms and legs that favour DIA and DP, respectively.

4.2 MOVEMENT CHARACTERISTICS

In this study, differences between DP and DIA in CL and CR were found at both inclines and all three intensities. With $DP_{12\%}$, the CR was higher than DP 5%, despite the slower velocity. Conversely, compared with $DIA_{5\%,}$ CR decreased in DIA 12%. The effect of incline on CR during DP is in line with findings of (Millet, Hoffman, Candau, & Clifford, 1998). Lower skiing velocities at the same terrain are generally related with a reduced CR (Holmberg et al., 2006; Sandbakk et al., 2010). Thus, for DP, the when the work against gravity increases the skier have to employ more rapid and shorter cycles to reposition the body and poles for preparation for the next pole plant and thereby avoid excessive loss of velocity. In DIA, arms and legs provide continual distribution of propulsive force, and as a result of the longer cycle length, sharing the work load between arms and legs gave a lower cycle rate with $DIA_{12\%}$.

This coincides with the findings for the DF in current study. Compared to 5% incline, DF at 12% had greater values for both DP and DIA, meaning that more proportion of the cycle was used for generating propulsive force through the poles and skis due to a shortening of recovery phase. For $DIA_{12\%}$, a DF much higher than in DP (Fig.3.6), provide advantages because the positive accelerations from propulsive forces comes more frequently and reduces the periods of decelerations. This favours DIA when work against gravity increases. Similar results has been found by Millet et al. (1998) and Pellegrini et al. (2013), for DP and DIA, respectively.

The effect of center of mass velocity fluctuations and metabolic rate:

Also $DIA_{5\%}$ had a high DF, higher than for DP. At 12% apparently the relatively low DF in DP resulted in large V_{CoM} fluctuations. This was not the case at 5%. At least the differences with DIA were much smaller in values comparable to $DIA_{12\%}$. The mechanical work done during skiing can be minimized by limiting the amount of mechanical energy fluctuations that is associated with V_{CoM} within a gait cycle (Cavagna & Kaneko, 1977). A high DF likely resembles movements in which the V_{CoM} are low, since one can almost continuously generate external power (i.e. constant propulsion against frictional losses). Thus, the mechanical energy of CoM are kept rather constant, which means that the mechanical work (and metabolic energy demand) required to accelerate the CoM can be kept to a minimum while working against the environment. This is likely more important when working against constant gravity, impaired to the diminishing drag when decelerating. The high DF in DIA_{12} means that the CoM is almost continuously being accelerated due to the ski and pole power, thus continuously offsetting the gravitational acceleration working on the CoM in the opposite direction. In $DP_{12\%}$ the DF is much lower and the longer the period of no propulsion, the higher the V_{CoM} (in negative direction) due to the gravitational acceleration becomes. Thus, much more instantaneous power must be applied through the poles to offset gravity and to accelerate CoM more, (e.g.walking and running; Alexander (1991) and Biewener (2006)). However, this rationale does not explain why DP is preferred at 5% incline.

Poling power: relative contribution of upper body in DIA:

In DP, all power is generated through the poles by definition because the ski continuously role on the belt, not allowing any propulsive forces to be generated. However, in DIA, if we assume that pole power is mainly accomplished by the upper body work, and ski propulsion by lower extremity, the relative contribution of pole power is an indication of contribution of the upper - and lower body. At 5% incline, relative pole power was higher than at 12%, indicating less power contribution of the lower extremities. At submaximal intensities, it seems counterproductive to use large muscle groups (in the lower extremities) to a lesser extent. Apparently, the athletes still decided to rely more on smaller muscle groups in the arms at the 5% incline. A possible explanation may be that at this incline, in the current experiment, the required velocity of extension of the lower limb is unfavorably high. This velocity was directly linked to the belt speed because for propulsion the ski must not move on the surface. In the current experimental design, all velocities at 5% incline were higher than all velocities at 12% incline (see table 2.1). Fig. 4.1 shows the relationship between relative pole power and velocity. The relationship is very strong and indicates that the velocity may be a main factor determining to what degree the lower extremities are able to generate work.

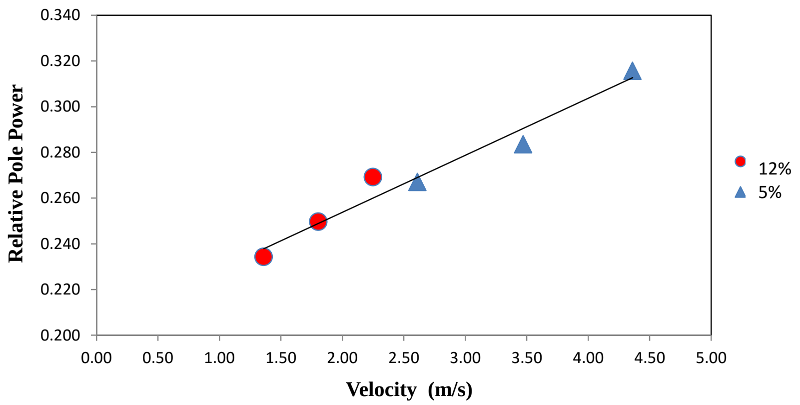

Figure 4.1 Relative pole power plotted against the velocity used on low, mod and high intensity. The red circular dots and the triangular dots shows the velocity used on 12% and 5% inclination, respectively. ($R^2 = 0.96$)

It should be noted that the current experiment was not designed to test this hypothesis (e.g., no overlap in velocity between inclines) and thus, this idea should be considered carefully. Clearly, new experiments should clarify this. However, the relatively high velocities that were attained at moderate incline seem a logical explanation for the current findings that favour DP.

4.3 METHODOLOGICAL CONSIDERATIONS

The testing was done utilizing roller skis which had some differences compared to skiing on snow. The grip was simulated using a ratchet locking mechanism on the rear wheels which enabled a perfect grip, independent of the skiers' body weight and technical skiing abilities. This is in contrast to skiing on snow where a proper technique is a key factor to gain sufficient grip. However, the movement patterns of the skiers in current study were highly automatized and they had a well-developed skiing technique. Thus, the fundamental principles of propulsion are the same, and for elite skiers this means that skiing on roller skis and snow is highly comparable. Hence, the results of the current study are expected to be of high interest also for performance on snow. However, it might be that skiers on an even higher level than ours, especially those specialized in the DP technique are able to utilize DP more efficiently also at steeper inclines, especially at high velocities. Although the conclusions should be limited to the conditions investigated and we acknowledge individual variations, our data strongly indicates that DP is favourable at moderate incline, whilst DIA is the favourable technique in steep uphill.

4.4 CONCLUSION

Altogether, the current study showed that DIA was the favourable technique on steep uphills whereas DP was the preferred technique at moderate inclines. The results revealed a higher GE and reduced physiological responses for $DIA_{12\%}$ compared to the other conditions, and to a somewhat lesser extent this also applied to $DP_{5\%}$. The high DF found in DIA, meaning that one can almost continuously generate external power, was coincided with the small V_{CoM} fluctuations leading to a reduced metabolic rate. This made DIA the most advantageous technique when gravity along the incline increased. On the 5% incline, in the current experiment, the required velocity for extension of the lower limb (i.e. DIA) was unfavorably high. As a compensation for this, allowing all power to be generated through the poles explained why DP was preferred at 5% incline. More investigations are needed for a better understanding to what degree lower extremities are able to generate work.

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