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Norwegian University of Science and Technology
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# Abstract

**Background:** Cross-country (XC) skiing competitions are performed in hilly terrain and include terrain-inflicted fluctuation in energy cost. Several studies have researched the energy system contribution of sprint skiing. However, we have limited knowledge about the energy system contributions associated with these terrain fluctuations in distance skiing competitions, and no previous studies have examined mass start XC skiing competitions. **Purpose:** The primary aim of the study was to investigate the aerobic and anaerobic energy system contributions of a simulated XC skiing mass-start competition, on varying terrain. The secondary aim was to compare two types of anaerobic calculations and understand how the result was affected by the calculation method, using the skate technique. **Method:** 12 elite XC skiers performed two days of testing: Day 1 contained a $\dot{V}O_{2peak}$-test and submaximal measurements, used to calculate gross efficiency (GE-method) and power output-$\dot{V}O_2$ relationship (MAOD-method) for various inclines. Both methods were then employed to calculate the aerobic and anaerobic energy contributions of day 2. Day 2 contained a 21-min simulated mass start competition, finalised by an all-out sprint to exhaustion (which was used to rank skier performance). **Results:** The results were not significantly affected by calculation method (difference in anaerobic contribution between methods; p = 0.72, ES = 0.13). Whole-race aerobic energy contributions of dynamic skiing sections were reported to be ~93-94%, with supramaximal intensities performed on the steep inclines (12%), and submaximal intensities (allowing recovery) utilized on flat (2%) and downhill segments. Differences in skier performance were strongly correlated to the individual $\dot{V}O_{2peak}$ measured on day 1 (r = 0.823, p = 0.01). **Conclusion:** The current study reported a whole-race aerobic energy contribution of ~93-94% (downhill excluded) in our simulated mass start distance competition. Energy system fluctuations were highly affected by the terrain, with long periods of submaximal recovery on the flat (2%) and downhill segments, enabling supramaximal intensities to be utilized uphill and storing of energy to perform well in the finishing sprint.

# Sammendrag:

**Bakgrunn:** Langrenns-konkurranser er gjennomført i kupert terreng som aktivt fremprovoserer endringer i energikostnaden. Flere studier har tidligere forsket på energisystembidraget i langrenn sprintkonkurranser. Derimot har vi mindre kunnskap tilknyttet de terrengpåvirkede svingningene i energikostnad for distanse-konkurranser, og ingen tidligere studier har undersøkt energisystembidragene i fellesstart. **Formål:** Det primære målet med studien var å undersøke de totale og terrengpåvirkede aerobe og anaerobe energisystembidragene under en simulert fellesstart i distanselangrenn. Det sekundære målet var å sammenligne to typer anaerobe kalkuleringer og se om resultatet ble påvirket av kalkeringsmetoden i skøyteteknikk. **Metode:** 12 skiløpere på elitenivå gjennomførte to dager med testing: Dag 1 besto av en $\dot{V}O_{2peak}$-test og submaksimale målinger ble gjort for å kalkulere teknikk-spesifikk effektivitet (GE-metoden) og forholdet mellom ytre arbeid og $\dot{V}O_2$ (MAOD-metoden) for ulike stigninger. Begge metodene ble senere brukt for å beregne de aerobe og anaerobe energibidragene for dag 2. Dag 2 inneholdt en 21-minutters simulert fellesstart, som ble avsluttet med en sprint til utmattelse (sprinten ble brukt for å rangere prestasjon). **Resultater:** Resultatene ble ikke signifikant påvirket av den anaerobe kalkuleringsmetoden (forskjell i anaerobt bidrag mellom metodene; p = 0,72, ES = 0,13). Det aerobe energibidrag summert over de dynamiske løypesegmentene ble rapportert som ~93-94%, med supramaksimale intensiteter i de bratte stigningene (12%) og submaksimale intensiteter som tillot restitusjon på flatene (2%) og i nedoverbakkene. Forskjeller i skiløperprestasjoner var sterkt korrelert med individuell $\dot{V}O_{2peak}$ målt på dag 1 (r = 0,823, p = 0,01). **Konklusjon:** Dette studiet rapporterte et stort aerobt energibidrag på ~93-94% (nedoverbakker ekskludert) i distanse-langrenn fellesstart. Svingningene i energisystembidrag var sterkt påvirket av terrenget, med lange submaksimale perioder med restitusjon på flate segmenter (2%) og nedoverbakker, som tillot supramaksimale intensiteter i oppoverbakkene og ga et energioverskudd som hjalp utøverne med å prestere bra i den avsluttende sprinten.

# Acknowledgements

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# 1. Introduction

Cross-country (XC) skiing is a whole-body endurance winter-sport with competition distances ranging between ~3 minutes and ~2 hours (1), performed in different formats in either the freestyle/skating or classical technique. The racing formats include sprints, relays, skiathlons, individual- and mas start competitions across hilly courses consisting of approximately 1/3 downhill, 1/3 flat and 1/3 uphill terrain, in which different sub-techniques are employed (2). The constantly changing hilly terrain demands a high metabolic cost with a fluctuating work rate, preferably with supramaximal intensities uphill and lower intensity allowing for recovery downhill, provided by the aerobic and anaerobic energy systems (1, 3-8). Four sub-techniques are commonly utilized in freestyle competitions; the dynamic- paddling (G2), double dance (G3), single dance (G4) and the static tuck-position (G7), which are mainly chosen dependent on skiing speed and inclines (9-11). Accordingly, the change in incline, choice of intensity and use of sub-techniques in XC skiing demand high levels of combined aerobic-($P_{aer}$) and anaerobic- ($P_{an}$) power in addition to technical and tactical capabilities (1, 5, 9, 12, 13).

The high energy demand of XC skiing is reflected by the great aerobic capacity of XC skiers, representing some of the highest measured $\dot{V}O_{2max}$ values exceeding ~70 and ~80 ($mL \cdot kg^{-1} \cdot min^{-1}$) in female and male athletes (14-17). The maximal aerobic capacity and utilization have further shown to be a strong predictor of both sprint and distance skiing performance, in different level skiers (9, 10, 16, 18-23). However, some studies suggest a homogeneity in absolute aerobic capacity ($mL \cdot min^{-1}$) at the world class level, as many elite skiers approach their highest attainable absolute values (12, 14, 20). This aerobic homogeneity seems to emphasize the supplementary fast-responsive energy-production of the anaerobic systems as an essential separator between the best skiers, providing them with additional power in the fluctuating work rates and the whole-race energy demand of XC skiing competitions (4, 13, 23-26). Unfortunately, there is a lack of knowledge regarding this whole-race energy demand and energy system contribution in distance skiing competitions. Sandbakk and Holmberg (27) have suggested a distribution of ~85-95% aerobic system and ~15-5% anaerobic systems, which is a higher anaerobic energy contribution than the ~92-96% aerobic and 8-4% anaerobic energy systems contribution summarized by Gastin (26), on track running with similar racing time. Sprint prologues are on the contrary well documented, with the metabolic cost being supplied for ~75% by the aerobic system and for ~25% by the anaerobic energy systems (6, 28-31). The energy system contribution of individual course segments is additionally well documented, with several recent studies on both sprint and distance competitions (1, 3, 4, 6). These studies presented a utilization of ~110-160% of skiers $\dot{V}O_{2max}$ during the uphill segment (dependent on uphill duration and total race distance), establishing a considerable anaerobic contribution (1, 3, 4, 6). The high metabolic demand of uphill is quite unique for the sport and enabled by the reduced metabolic cost of downhill or flat skiing (1, 4, 7, 8), which allows recovery of the anaerobic systems through aerobic compensation (3). Gløersen et al. (3) found the anaerobic recovery to be substantial in a simulated 15-km race, as skiers utilized ~380% (or 299 ± 49 $mL \cdot kg^{-1}$) of their individual maximum accumulated oxygen deficit (MAOD) throughout the whole race, implying a high anaerobic recovery between the uphill sections. Interestingly, skiers paced themselves between ~0-50% MAOD in all race segments, possibly to avoid high loads on the lactic-anaerobic system, permitting greater recovery in the downhill segments due to the faster recovery-rate of the alactic-anaerobic systems (3, 32, 33). Nevertheless, these findings and other studies on energy expenditure in simulated competition courses (4, 7, 24, 34) have all examined individual time-trials. Accordingly, there is no research on the energy system distribution of mass start skiing, which to date represents 5 out of 6 Olympic events (5).

Mass start events are unique through several surrounding skiers. All skiers start at the same time and tries to keep up with the leading group throughout the course, before hopefully being the first to cross the finish line. This type of group skiing influences the air-drag, ski-friction, pacing and work rates throughout the competition, plausibly forcing some athletes above their preferred pacing intensity. The differences in segment energy distribution might vary more between skiers in comparison to individual starts, as some skiers empty their anaerobic stores earlier and at a higher rate than preferred. Whereas the accumulated energy-system contribution of the whole race might relate better to individual starts. With the weaker skiers adjusting their work rates to recover from the high intensities they were not able to endure while following the leading group.

While the calculation-method of aerobic energy contribution in exercise is somewhat agreed upon (26, 35), the calculation of the anaerobic contribution is still a subject to debate (36-38). Two methods have been applied in XC skiing; the MAOD- and gross efficiency- (GE) method (3, 6, 29, 30, 38, 39). Both methods are measured sub-maximally, with the MAOD method being dependent on a linear power output-$\dot{V}O_2$ relationship which is extrapolated to estimate the $\dot{V}O_2$ demand of supramaximal intensities. Whereas the GE method is dependent on the sub-maximal skiing efficiency of each sub-technique to be unaffected by intensity when we calculate the $P_{aer}$ (37, 40). Based om the latest research of Andersson et al. (39), were the GE- and the MAOD- method without a fixed y-intercept (based on the work rate – power input relationship) the preferred methods for calculating the anaerobic capacity of classical skiing. To date, there is no study comparing how the choice of calculation method effects the energy system contribution results for the skate technique, and therefore both methods are used in the current study.

The primary aim of the study was to investigate the aerobic and anaerobic energy system contributions of a simulated XC skiing mass-start competition on varying terrain. The secondary aim was to compare two types of anaerobic calculations and understand how the result was affected by the calculation method for aerobic vs anaerobic energy distribution in the skate technique. Due to the fluctuating terrain of supramaximal intensities uphill and ability to recover in the downhills, the author hypothesized the average whole competition energy-system contribution to be distributed with a slightly higher anaerobic contribution, in reference to other endurance-sports of the same race time. The author further expected individual variations in performance to be based on aerobic power. With the better skiers utilizing a lower anaerobic energy contribution in the uphill segments, ultimately providing them with a more anaerobic energy storage for the finishing sprint.

# 2. Methods

## Participants

Thirteen Norwegian male cross-country skiers and biathletes participated in the study, including world cup and national level medallists. The data of twelve athletes were included in the data analysis, and one participant was excluded because of inconclusive data. Biathletes have shown similar performance levels as XC skiers using the skating technique (41), and were therefore included in the study. Anthropometrical and physiological characteristics of the athletes are displayed in Table 1. The study was pre-approved by the Norwegian Centre for Research Data and was conducted in accordance with the Declaration of Helsinki. All participants were healthy at the time of testing and pre-informed about the protocol and measurements, before they signed a consent form.

**Table 1** Anthropometric and physiological characteristics of the 12 athletes included in the study.

| Variables | Mean ± SD |
|---|---|
| Age (years) | 24.8 ± 2.9 |
| Body height (cm) | 183.3 ± 5.7 |
| Body mass (kg) | 78.9 ± 5.4 |
| Body mass index ($kg{\cdot}m^{-2}$) | 23.5 ± 1.1 |
| $\dot{V}O_{2peak}$ ($l{\cdot}min^{-1}$) | 5389 ± 298 |
| $\dot{V}O_{2peak}$ ($ml{\cdot}min^{-1}{\cdot}kg^{-1}$) | 68.4 ± 3.4 |
| Heart $rate_{max}$ | 193.8 ± 7.9 |
| Peak blood lactate ($mmol{\cdot}l^{-1}$) | 12.8 ± 3.1 |

## Overall Design

This study was part of a bigger research project, with a two-day protocol performed within the same week. Day 1 included twelve submaximal exercise bouts for the determination of the PO-$\dot{V}O_2$ relationships of three sub-techniques (G2, G3 and G4), followed by a $\dot{V}O_{2peak}$-test (Figure 1). Day 2 consisted of a 21-min simulated XC mass start competition-course divided into 7 identical 3-min laps, each lap containing 4 different segments (Figure 2).

**Equipment and measurements**

The body height and body mass of the athletes were measured without equipment before each test (Secamodel nr:877; SecaGmbH&Co., Hamburg Germany). All equipment was weighed (~2.6-kg) and later added when calculating external PO. The skiers used poles of individually chosen length (~90% ± 2 body height) available in 5 cm increments, with mounted carbide tips. IDT skate elite roller skies were provided with standard category 2 wheels (IDT Sports, Lena, Norway) and NNN binding system (Rottefella, Klokkarstua, Norway). Skiing boots were self-provided by the athletes. Rolling friction was measured before and after the study, with the towing test described in Sandbakk et al. (42). The rolling friction coefficient (μ) of the skies were measured to be 0.016 ± 0.001.

Tests were performed on a 3-by-5-m motor-driven rollerski treadmill (Forcelink S-mill, Motekforce Link, Amsterdam, The Netherlands), and the treadmill belt was covered with non-slip rubber. During high-intensity exercises bouts, all athletes whore a safety harness attached to the ceiling with an emergency treadmill brake system. GoPro Hero6 camera (GoPro, Inc, San Mateo, CA) was placed behind the treadmill and used to verify sub-techniques and register unforeseen events.

Respiratory variables of the exercise bouts were measured continuously through open-circuit indirect calorimetry (Oxycon Pro, Erich Jaeger GmbH, Hoechberg, Germany). Expired gas was analysed through a mixing chamber at 10-s average values and interpolated to get second by second values, while $\dot{V}O_{2peak}$ was established through the highest moving average of three consecutive 10-s values. Ambient lab conditions were 19.8 ± 1.3˚ Celsius and 37.4 ± 9% humidity. The gas analysers were calibrated with ambient air and a gas cylinder with known concentration content of 5% $CO_2$ and 15% $O_2$. The flow turbine (TripleV, Erich Jaeger GmbH, Hoechberg, Germany) was calibrated manually with a 3-L calibration syringe (5530series, HansRudolphInc., KansasCity, Missouri, USA). All Oxycon Pro calibration procedures were repeated before each test. Blood lactic levels was measured with Biosen C-line Sport lactate measurement system (EKF Industrial Electronics, Magdeburg, Germany). Fingertip blood samples of 5 μL was extracted from the athlete’s and analysed prior of the tests (baseline value) and after each exercise. The device was calibrated every 60 min with a 12-mmol μL standard concentration. HR was measured continuously with a Garmin Forerunner 920XT (Garmin Ltd., Olathe, USA). Lower body-, upper body- and entire body rate of perceived exertion (RPE, 6-20 scale) (43) were verbally communicated after each exercise bout.

## Protocols

Day 1

The treadmill testing (Figure 1) started with a 5-min standardised low intensity warm-up on roller skies; executed on the treadmill at 10km/h and 5% incline, without respiratory measurement. After the warmup each athlete performed twelve submaximal 4-min bouts, divided into four intensity levels. Each level had three mandatory sub-techniques (G2, G3 and G4) in randomized order, were set inclines (12%, 5% and 2%) and intensity levels of each sub-technique were regulated by speeds based on extensive pilot testing and earlier research summarized in the review of Losnegard (5). Between the submaximal bouts was a 90-s rest period for recovery and necessary measurements, which increased to 120 s between the level 4 intensities. Following the last submaximal exercise bout was a recovery and preparation period of 5-10-min rest and 5-min self-paced warmup before the $\dot{V}O_{2peak}$-test. The $\dot{V}O_{2peak}$-test started at 11km/h and 10.5% incline, with an intensity increase every minute. The first 3 stages had a constant speed of 11 km/h and incline increased every minute (12% and 14%). Incline was then kept constant from 14%, while speed increased with 1 km/h per minute until exhaustion.

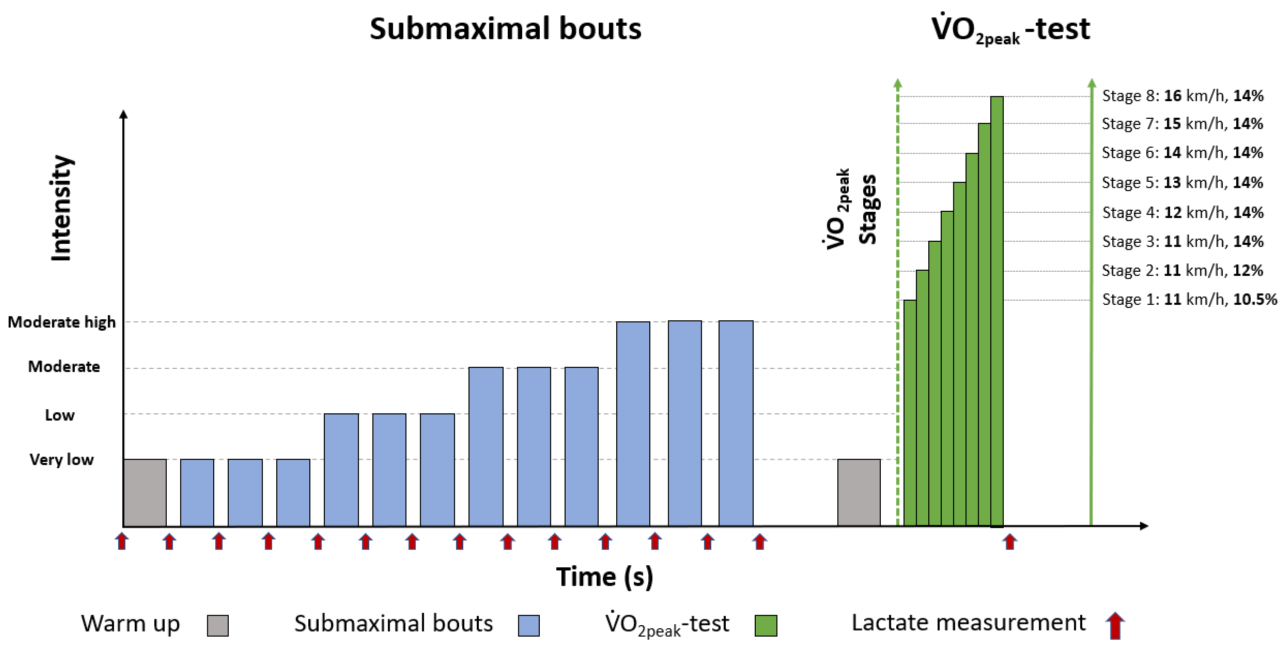



**Figure 1** Protocol for test day 1. Four submaximal intensities for the three different sub-techniques, performed in randomized order for estimation of individual Gross efficiency (GE-method) and PO-$\dot{V}O_2$ relationship (for the MAOD-method). The test day was finalised with a $\dot{V}O_{2peak}$-test to estimate individual peak aerobic power.

Day 2

Treadmill testing started with the 5-min standardized warm up (10km/h at 5% incline). To get familiar with the track profile and the G7 sub-technique, all athletes performed the simulated course on low intensity before the competition speeds. The athletes were told to sit in a standardized tuck position, with a knee angle which felt competition realistic for each skier and elbows resting on the knees during G7. Verbal information about the course profile and transitions was provided before and during each simulation, and furthermore visualized on the wall in front of the treadmill. The simulated mass start competition (Figure 2) contained a 21-min course, finalized by an all-out sprint till exhaustion. The course was divided into 7 identical laps, with 4 segments of different competition realistic inclines and speeds based on extensive pilot testing, earlier research and course profiles (2, 5). Each lap lasted 3 min and consisted of 60-, 45-, 45- and 30-s intervals. Although, course segments were somewhat tailored for commonly used sub-techniques (G2, G3, G4 and G7), athletes were free to choose sub-technique, as the course represented a real mass start competition. The fourth segment (20 km/h at 5%) was a simulation of G7, were the athletes skied to the front of the treadmill and grabbed a harness, allowing them to sit in the standardized tuck position until a new lap started. Athletes could additionally take 30-s rests during the simulation, holding on to the front of the treadmill if they were unable to continue. This was interpreted as a falling back to the chasing group, thus putting them in the secondary performance group. The competition was completed by an instant all-out sprint until exhaustion, performed on a constant incline of 5% with 20 km/h speed, increasing 1 km/h every 15-s (Figure 2).

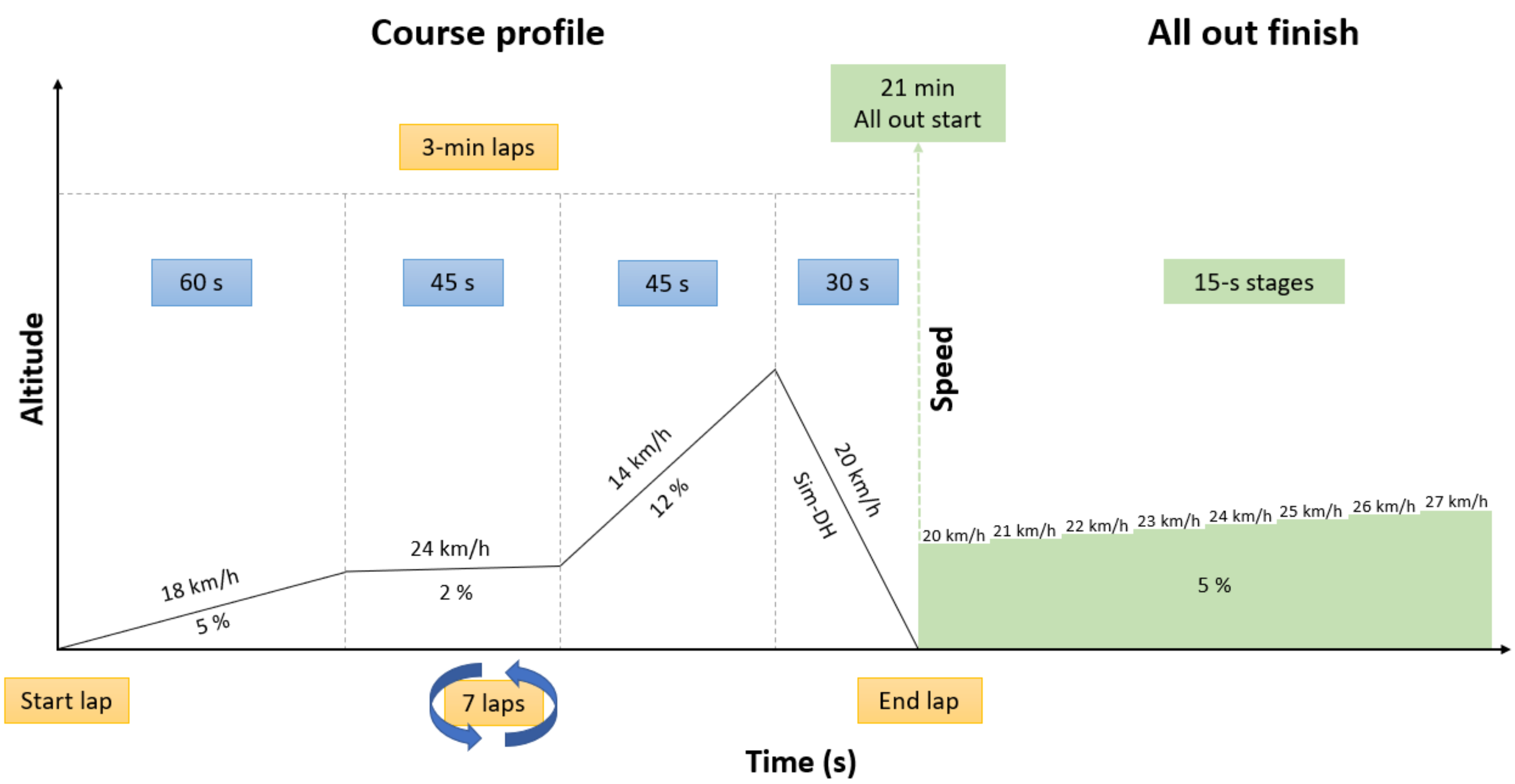



**Figure 2** Protocol for test day 2. The competition course lasted 21 min and were split into 7 identical laps of 3 min, each lap contained 4 segments in respectively moderate incline (5%), flat section (2%), steep incline (12%) and simulated downhill (Sim-DH). The competition course was finalised with an all-out sprint with a pre-set increasing intensity until exhaustion.

## Data analysis

Competition performance was established by the time till exhaustion (TTE) of the all-out sprint finish. Skiers were grouped by number of rests and therefore encouraged to complete the entire course without non-protocoled breaks.

## Calculations

The external power output (PO) is the total work done against the gravitational power ($P_g$) and frictional power ($P_f$) (eq1), when roller skiing on a treadmill without drag. The values used to calculate $P_g$ and $P_f$ were the athletes equipped body mass (m), earth gravitation (g), rolling resistance coefficient of the roller skis (μ), and the incline (∝) and velocity (v, in m/s) of the treadmill (eq2).

$$\boldsymbol{PO}\ [W] = P_g + P_f \quad \text{(eq1)}$$

$$\boldsymbol{PO}\ [W] = m \cdot g(\sin(\propto) + \cos(\propto) + \mu) \cdot v \quad \text{(eq2)}$$

GE-method

Power input (PI) was established for the calculation of gross efficiency (GE). PI was calculated with the average $\dot{V}O_2$ values and the oxygen equivalent of the final minute of each sub-technique (eq3). Oxygen equivalent was established through the RER values and the nonprotein respiratory quotient table of Peronnet and Massicotte (44), and the PI ($Kcal \cdot min^{-1}$) was converted to PI ($J \cdot s^{-1}$) in equation 4. GE was calculated from the last submaximal exercise bout of each sub-technique (eq5) and assumed to be constant in the simulated competition calculations.

$$\boldsymbol{PI}\ [Kcal \cdot min^{-1}] = (VO_2 \cdot Oxygen\ equivalent) \quad \text{(eq3)}$$

$$\boldsymbol{PI}\ [J \cdot s^{-1}] = (\boldsymbol{PI}\ [Kcal \cdot min^{-1}] \cdot 4184) \div 60 \quad \text{(eq4)}$$

$$\boldsymbol{GE}\ [\%] = (PO \div PI) \cdot 100 \quad \text{(eq5)}$$

The total PO energy is the sum of the aerobic- ($P_{aer}$) and anaerobic power ($P_{an}$) (eq6). $P_{aer}$ was calculated by multiplying PI with the athletes and sub-techniques individual GE (eq7). $P_{an}$ was calculated by subtracting each athletes $P_{aer}$ value from PO (26, 45) continually at each second of the competition course (eq8).

$$\boldsymbol{PO}\,[W] = P_{\mathrm{aer}} + P_{\mathrm{an}} \quad \text{(eq6)}$$

$$\boldsymbol{P}_{\mathbf{aer}} = (VO_2 \cdot Oxygen\ Equivalent) \cdot GE \quad \text{(eq7)}$$

$$\boldsymbol{P}_{\mathbf{an}} = PO - P_{\mathrm{aer}} \quad \text{(eq8)}$$

MAOD-method

$O_2$ deficit was estimated with the MAOD method (46) as a secondary calculation of $P_{an}$. A linear PO-$\dot{V}O_2$ relationship was determined from the four submaximal intensities of each sub-technique, based on the average $\dot{V}O_2$ of the last minute (4-Y method in Andersson et al. (39)). Subsequently, the individual regression line was extrapolated to estimate the $\dot{V}O_2$ demand of supramaximal intensities. The aerobic contribution was therefore the measured $\dot{V}O_2$ during the competition, with the anaerobic contribution being the $O_2$-deficit calculated by subtracting the measured $\dot{V}O_2$ from the $\dot{V}O_2$ demand.

Comparing methods

Both methods were converted into metabolic terms for comparison. The MAOD-method was reported in PI by using eq3 and eq4 explained above, whereas the GE-method was converted into PI by extracting GE continually from the PO as mentioned above (eq6 and eq7).

Adjusting for measurement delay

Cross correlation was used to estimate the measurement-delay of the mixing chamber, and determined to be 15 s. The energy system contributions were adjusted accordingly to fit the pre-determined total demand in the contribution models. The adjustment ultimately resulted in a loss of the last 15 s of all-out sprint measurements, as skiers dropped or spit out the mouthpiece in exhaustion after finishing.

**Pilot test for G7**

A supplementary pilot test was conducted to estimate the metabolic cost of the G7, helping us fulfill the energy system contribution model of the simulated competition. Three male Norwegian former cross-country skiers (76.3 ± 8.9 kg; 183.8 ± 2.2 cm), now training recreationally, participated in the G7 pilot test. Ethical procedures and health considerations were done identical to the initial study. Measurements and equipment were identical to the main study.

Pilot protocol

The treadmill testing started with a 10-min standardised low intensity warm up (10km/h at 5%). Followed by two 4-min G7-stages (20 km/h at 5%), sitting in the standardized tuck-position holding a harness attached to the front of the treadmill. Between the tuck-stages the athletes had a recovery period of 10-min active recovery roller skiing on the treadmill (10km/h at 5%) and 5-min passive recovery. After each tuck-stage the athletes were asked to report the level of lower- and total body RPE.

Findings

The pilot testing provided an average steady state PI of 310 ± 89.9W utilizing the G7 sub-technique. This value was included in the energy system contribution model of the MAOD-method for the 12 athletes.

**Statistical analysis**

The statistical tests were performed using SPSS. All data is represented with mean ± SD if nothing else is stated. Statistical analysis was only performed on the 8 athletes which completed the simulation without breaks. MAOD and GE differences was checked for normality with the Shapiro-Wilk test, and a paired sample t-test was used to compare the MAOD (with exclusion of the G7 sub-technique) and the GE anaerobic calculation methods. Cohen’s d test was used for effect size calculations and the magnitude was interpreted based on Cohens classification (47), with the addition of trivial effect size ($ES < 0.2$). Variances in energy cost between isolated course segments were tested for normality and compared with a One-way repeated ANOVA test. TTE and $\dot{V}O_{2peak}$ was checked for normality and a person product moment correlation analysis was performed to test the strength of the association. All differences were considered significant with $P < 0.05$.

# 3. Results

Eight skiers completed the 21-min competition course without any additional breaks caused by exhaustion. Four skiers completed the course with additional breaks, see Table 3.

Accumulated whole race energy contributions

Average absolute values of competition course energy demand, with aerobic and anaerobic energy system contributions, are summarized in Table 2A, for all 12 skiers and the 8 skiers who finished without breaks. The energy system distributions are further portrayed as percentages in Table 2B for the same groups. The average $\sum O_2$-deficit off all dynamic course sections was $149 \pm 19$ mL·kg$^{-1}$, calculated with the MAOD-method. Whereas the average $\sum O_2$-deficit of all subjects with recovery periods excluded (negative anaerobic energy contribution), were $180 \pm 15$ mL·kg$^{-1}$ for the MAOD-method and $40 \pm 8$ kJ for the GE-method.

**Table 2** Average accumulated absolute values of aerobic and anaerobic energy contribution for all 12 participants and the 8 skiers who completed the competition course without breaks, with exclusion and inclusion of the downhill segment (G7). Values are presented accordingly as **A)** kilojoule (kJ) respectively in mechanical- (GE method) and metabolic values (MAOD method), and **B)** contribution percentages (%)

**A)**

| Method | Aerobic (kJ) | Anaerobic (kJ) | Total (kJ) | Subjects (n) |
|---|---|---|---|---|
| GE | 291.6 ± 32.7 | 22.3 ± 15.0 | 313.9 ± 27.4 | 12 |
| $MAOD_{G7excluded}$ | 1793.5 ± 107.2 | 110.1 ± 97.0 | 1903.6 ± 127.6 | 12 |
| $MAOD_{G7included}$ | 2118.6 ± 102.5 | -144.3 ± 92.7 | 1974.3 ± 125.8 | 12 |
| GE | 308.0 ± 26.7 | 19.4 ± 16.9 | 327.4 ± 23.3 | 8 |
| $MAOD_{G7excluded}$ | 1846.3 ± 85.4 | 84.3 ± 101.4 | 1940.6 ± 141.5 | 8 |
| $MAOD_{G7included}$ | 2148.0 ± 103.4 | -152.6 ± 103.6 | 1995.4 ± 141.4 | 8 |
| *GE | 285.7 ± 20.0 | 18.22 ± 18.2 | 303.9 ± 22.2 | 8 |
| *$MAOD_{G7excluded}$ | 1717.5 ± 77.6 | 77.6 ± 92.3 | 1795.1 ± 166.5 | 8 |
| *$MAOD_{G7included}$ | 2020.8 ± 107.3 | -160.5 ± 92.5 | 1860.3 ± 166.5 | 8 |

**B)**

| Method | Aerobic (%) | Anaerobic (%) | Subjects (n) |
|---|---|---|---|
| GE | 92.8 ± 4.7 | 7.2 ± 4.7 | 12 |
| $MAOD_{G7excluded}$ | 94.4 ± 5.1 | 5.6 ± 5.1 | 12 |
| $MAOD_{G7included}$ | 107.5 ± 5.7 | -7.5 ± 5.7 | 12 |
| GE | 94.1 ± 5.0 | 5.9 ± 5.0 | 8 |
| $MAOD_{G7excluded}$ | 95.9 ± 5.2 | 4.1 ± 5.2 | 8 |
| $MAOD_{G7included}$ | 108.0 ± 5.3 | -8.0 ± 5.3 | 8 |
| *GE | 94.1 ± 4.8 | 5.9 ± 4.8 | 8 |
| *$MAOD_{G7excluded}$ | 96.0 ± 5.1 | 4.0 ± 5.1 | 8 |
| *$MAOD_{G7included}$ | 109.0 ± 5.9 | -9.0 ± 5.9 | 8 |

*= exclusion of the all-out sprint values

Difference between methods

There was no statistically significant difference in anaerobic capacity between GE- and MAOD- method and a trivial effect size was reported ($t(7) = 0.38$, $p = 0.72$, $ES = 0.13$). Individual differences between methods are reported in Table 3.

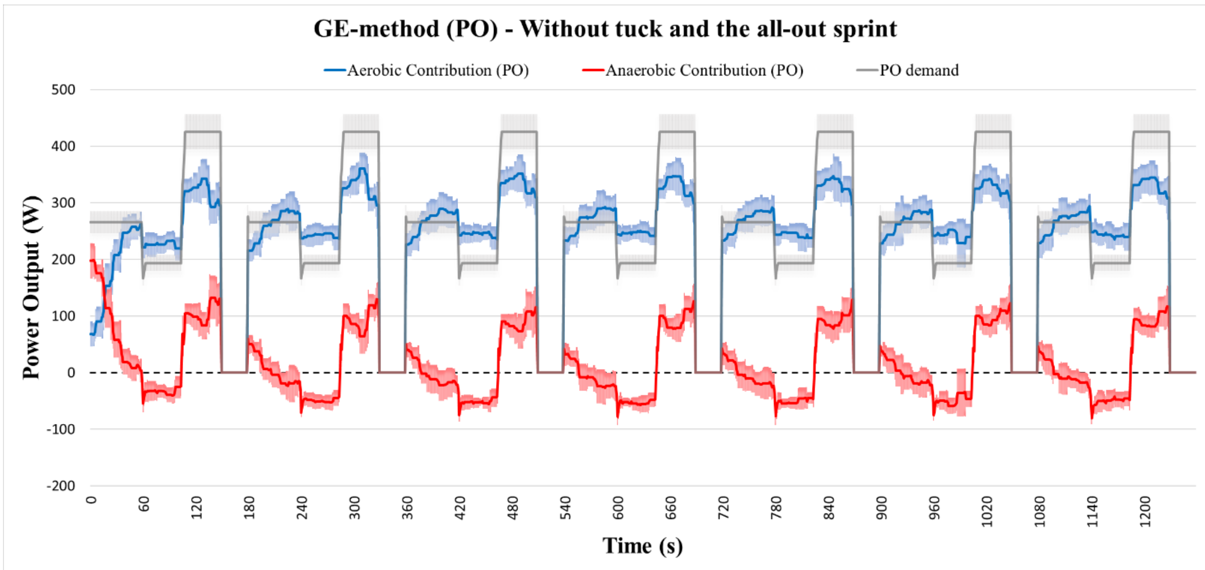
**Table 3** Individual anaerobic capacity in metabolic values, determined with the GE- method and the MAOD- method excluding G7. The difference between methods, number of breaks during the 21-min course and TTE in the all-out finish are also reported. Result order is ranked from best to worst TTE and numbers of breaks (subjects with breaks highlighted).

| Subject | GE (kJ) | MAOD (kJ) | Diff (kJ) | Breaks (n) | TTE (s) |
|---|---|---|---|---|---|
| 5 | -100.4 | -96.0 | -4.4 | 0 | 130 |
| 4 | 82.0 | 56.3 | 26.5 | 0 | 119 |
| 6 | 130.9 | 127.1 | 3.8 | 0 | 101 |
| 11 | -14.0 | -34.8 | 20.9 | 0 | 91 |
| 12 | 93.2 | 119.3 | -26.1 | 0 | 74 |
| 8 | 185.9 | 184.7 | 1.2 | 0 | 65 |
| 13 | 176.7 | 168.4 | 8.3 | 0 | 60 |
| 1 | 137 | 149.6 | -11.9 | 0 | 47 |
| 2 | 93.7 | 86.6 | 6.6 | 1 | 50 |
| 10 | 208.4 | 229.5 | -21.1 | 2 | 62 |
| 9 | 94.3 | 113.1 | -18.8 | 2 | 47 |
| 7 | 211.7 | 217.5 | -5.8 | 3 | 66 |
| Average | 108.4 ± 91.8 | 110.1 ± 97.1 | -1.6 ± 14.9 | | |

Fluctuation in energy system contribution

The fluctuation in average energy system contributions throughout the seven laps (calculated from the 8 finishing athletes) are illustrated in mechanical values (using the GE-method) and metabolic values (using the MAOD-method) in Figure 3. Average energy costs of isolated course segments are summarized in aerobic, anaerobic and total energy contributions in Table 4. A significant main effect of incline was observed in the segment energy cost for aerobic energy system contribution ($F(2,14) = 266$, $p > 0.001$, $ES = 0.97$), anaerobic energy system contribution ($F(2,14) = 459$, $p > 0.001$, $ES = 0.99$) and total energy demand ($F(2,14) = 1495$, $p > 0.001$, $ES = 0.99$) using the GE-method, and with similar results reported for the MAOD method. Additionally, pairwise comparisons of energy cost showed a statistically significant difference between all course segments, for both the GE and the MAOD methods ($p>0.02$).

A)




B)

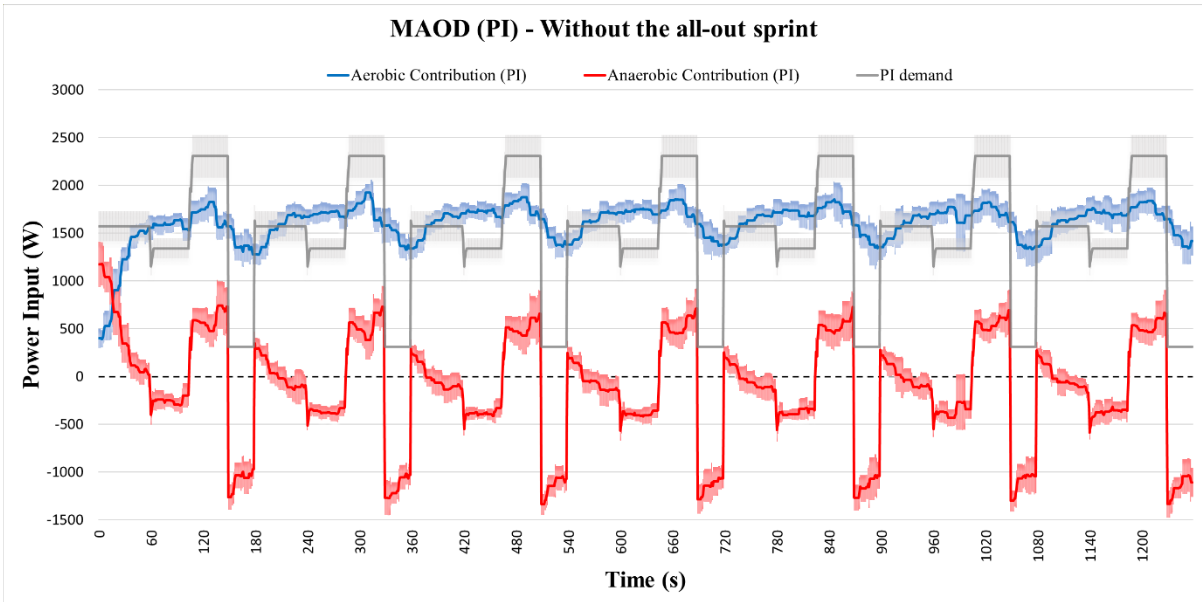



**Figure 3** Fluctuations of average (and standard deviations) of energy system contribution of the 8 skiers without breaks, in the simulated competition course (all-out sprint excluded). Graphed with (**A**) the GE- and (**B**) the MAOD- calculation method for anaerobic contribution, respectively in mechanical (power output (PO)) and metabolic (power input (PI)) values.

**Table 4**: Average aerobic (Aer), anaerobic (An) and total (Tot) energy system contributions in the flat section (2%), moderate incline (5%), steep incline (12%) and downhill (down) course segments of the 8 finishing athletes. Contributions are reported in percentages (%) and joules per second (W) for both mechanical- (GE-method) and metabolic- (MAOD-method) values.

| | **GE (PO)** | | | | **MAOD (PI)** | | | |
|---|---|---|---|---|---|---|---|---|
| | **2%** | **5%** | **12%** | **Down** | **2%** | **5%** | **12%** | **Down** |
| Aer (W) | 241 ± 15 | 255 ± 22 | 329 ± 22 | - | 1695 ± 83 | 1510 ± 91 | 1758 ± 97 | 1444 ± 85 |
| An (W) | -48 ± 10 | 11 ± 19 | 96 ± 20 | - | -355 ± 52 | 63 ± 105 | 547 ± 148 | -1134 ± 85† |
| Tot (W) | 194 ± 14 | 266 ± 19 | 425 ± 31 | - | 1340 ± 106 | 1572 ± 159 | 2305 ± 224 | 310 ± 0† |
| Aer (%) | 125 ± 4 | 96 ± 17 | 77 ± 4 | - | 127 ± 5 | 96 ± 6 | 76 ± 6 | 465 ± 31† |
| An (%) | -25 ± 4 | 4 ± 17 | 23 ± 4 | - | -267 ± 4 | 4 ± 7 | 24 ± 6 | -365 ± 31† |

†= Based on steady state energy cost of pilot-testing.

Individual skier differences

Three skiers were compared in Figure 4, in respectively mechanical- (GE-method) and metabolic values (MAOD-method), to illustrate the individual variation in energy system distribution throughout the competition course. Skier selection (for Figure 4) was based on the ranking system of Table 3, and the best performing skier (longest TTE), worst skier without additional breaks and the skier with the most breaks were graphed for comparison. Furthermore, a statistically significant correlation ($r = 0.823$, $p = 0.01$) was discovered between individual $\dot{V}O_{2peak}$ measured on day 1 and performance (TTE from the all-out sprint) in the 8 athletes who completed the course without breaks.

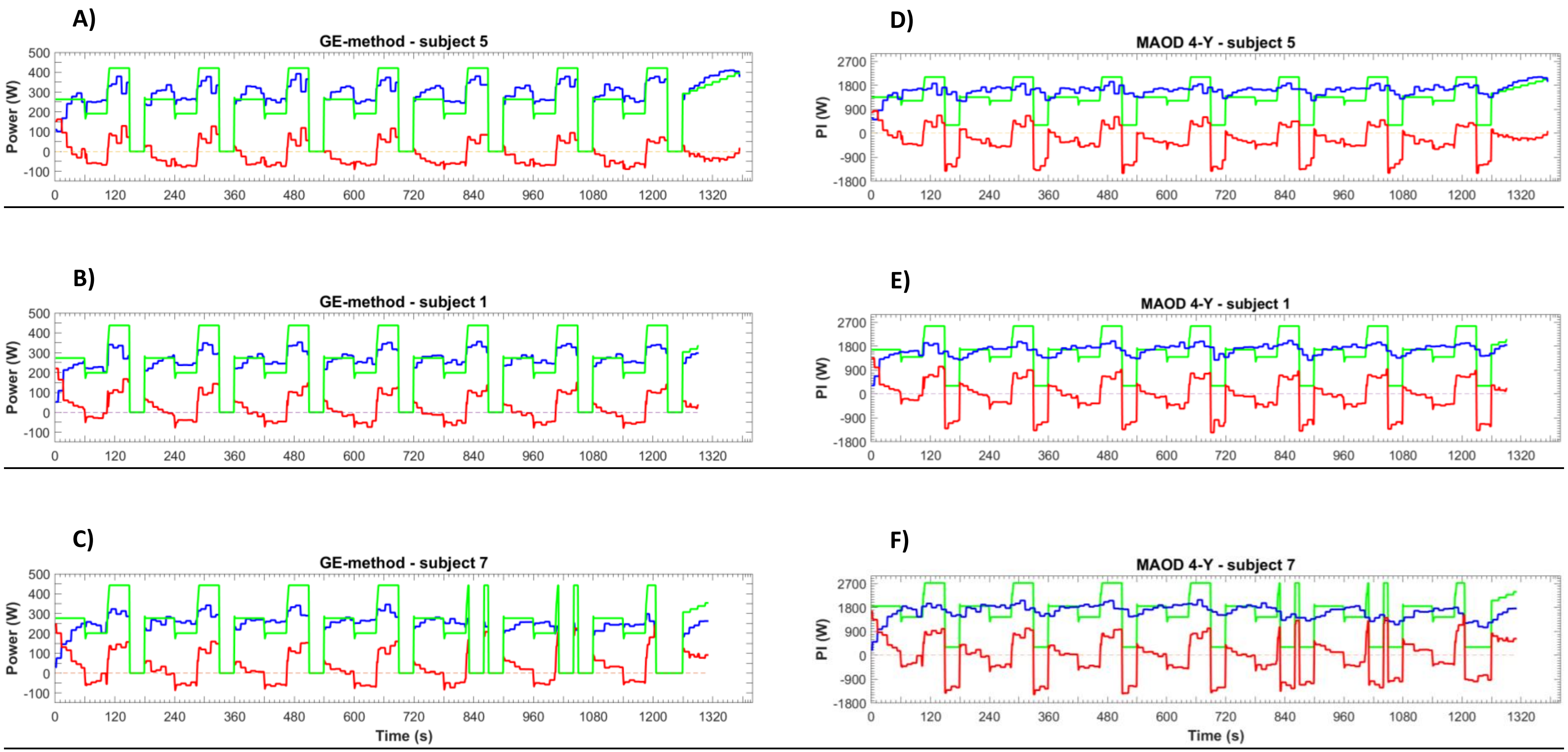



**Figure 4** Individual energy system contribution throughout the competition course and TTE, graphed with aerobic contribution (blue), anaerobic contribution (red) and total demand (green). Presented for both PO with the GE-method (A-C) and PI with the MAOD-method (D-F) in the skiers with the longest TTE (sub5), shortest TTE without breaks (sub1) and the skiers with the most breaks (sub7).

# 4. Discussion

The current study is the first to investigate the aerobic and anaerobic energy system contributions during a simulated mass start skiing competition. Average and individual energy contributions were calculated to understand the whole race and terrain-affected fluctuations in aerobic and anaerobic energy demand throughout the competition course. Due to the lack of a "gold standard", two anaerobic calculation methods (GE and MAOD) were compared to investigate how they affect the absolute energy system contributions, using the skate technique.

The main findings of the study were: **1)** The absolute mechanical- and relative values of accumulated whole race energy system contributions for the GE-method were ~292 kJ (or 93%) from the aerobic and ~22 kJ (or 7%) from the anaerobic systems. **2)** For the MAOD-method, absolute metabolic- and relative values of accumulated whole race energy system contributions were calculated to be ~1794 kJ (or 94%) from the aerobic and ~110 kJ (or 6%) from the anaerobic energy systems with exclusion of the downhill segments of the race, and ~2119 kJ (or 108%) from the aerobic and ~ -144 kJ (or -8%) from the anaerobic systems with inclusion of the downhill segments. **3)** The GE method and MAOD method resulted in non-significant differences in anaerobic capacity. **4)** Energy system contributions were affected by the fluctuating terrain. All subjects were able to ski sub-maximally and recover anaerobic energy stores during the flat (2%) and downhill segments, whereas the uphill (12%) segments required supramaximal intensities and therefore a significant contribution from the anaerobic energy systems. **5)** Skiers with a relatively higher $\dot{V}O_{2peak}$ produced enough aerobic energy to exceed the energy demand of flat sections (2%) and sections at moderate incline (5%). They also covered a bigger proportion of the energy demand uphill (12%) aerobically compared to the other skiers and performed better (TTE) in the finishing all-out sprint.

<u>Accumulated whole race energy contributions</u>

It was hypothesized that the supramaximal intensities uphill would make XC skiers utilize a greater whole-race anaerobic contribution in comparison to other endurance sports of similar race time. The current study reported accumulated whole race contributions of ~93-94% from the aerobic energy system, and accordingly ~7-6% from the anaerobic systems with exclusion of the downhill segments. Contradictory to the hypothesis, these findings imply a somewhat similar whole-race energy system contribution between the active sections of mass start distance skiing and the ~92-96% aerobic system and ~8-4% anaerobic systems reported by Gastin (26) on track running with similar race-time. The current study's reported whole race aerobic energy contributions were additionally in the upper tier of Sandbakk and Holmberg's assumed distance skiing contribution of ~85-95% from the aerobic energy seystem (27), even without the inclusion of downhill segment. However, our study's high aerobic energy values seemed to be the result of long periods of submaximal intensities in a pre-set protocol, allowing for severe anaerobic recovery and shorter high intensity steep inclines (discussed more thoroughly further down). Making it comparable to an outdoor mass start were athletes ski in groups to save energy in lower intensities, and "attack" in the uphill segments.

The findings were even more contradictory to the authors hypothesis when we included the metabolic cost of downhill (G7) segments (estimated from the pilot test). Reporting whole race energy system contribution of ~108% from the aerobic system and ~ -8 % from the anaerobic systems. However, negative values of anaerobic energy were assumed to be anaerobic energy recovery in the current study, as it was the result of the calculated aerobic energy contribution exceeding the energy demand. These calculations further depended on the extrapolated values of submaximal PO-$VO_2$ relationship of each sub-technique to be constant throughout the competition course, and similar between submaximal and supramaximal competition intensities. Additionally, we do not know the actual metabolic cost of downhills, and if it differs between rested skiers and during competitions, with competition skiers being affected by previous intensities, muscular fatigue, turns and surrounding opponents. Nonetheless, these whole-race energy contributions seamed misleading, as we assume more skiers to finish without breaks if they were rested to the extent of 0% (or less) anaerobic energy contribution, with skiers additionally reporting full exhaustion after the finishing sprint. Accordingly, we assumed our whole-race aerobic energy contributions (when including downhill) to be untrustworthy. Although, there is still much we do not know about the relationship between energy fatigue and muscular fatigue, and further studies are necessary to understand the actual energy system contributions of downhill skiing.

Nevertheless, this study and several others (1, 3, 4, 7, 8) discovered a severe anaerobic recovery during the competition, supporting the statement of a great absolute anaerobic utilization in XC skiing if we exclude the anaerobic recovery. The current study reported the $\sum O_2$-deficit off all dynamic course sections to be 149 ± 19 $mL \cdot kg^{-1}$ for the mass start, which is approximately half of the 299 ± 49 $mL \cdot kg^{-1}$ from the 15-km individual start reported by Gløersen et al. (3). The difference between studies seems to be affected by competition duration, participants and format (mass start vs individual start), with our skiers being forced to ski at a set speed and incline, whereas the skiers of Gløersen (3) were encouraged to increase the speed if the intensity was too low. These assumptions were further supported when our $\sum O_2$-deficit increased to 180 ± 15 $mL \cdot kg^{-1}$ for the MAOD-method and to 40 ± 8 kJ for the GE-method when all recovery values were excluded, suggesting large possibilities for recovery during the active sections of the course and less time spent on supramaximal intensities. Accordingly, our findings supported the great absolute anaerobic utilization assumed in XC skiing, despite having similar active relative energy system contributions to other endurance sports of similar race time.

Fluctuations in energy system contribution

The fluctuations in energy distribution during the simulated mass start competition were highly affected by the changing terrain (Figure 3, Table 4). We reported significant differences in metabolic cost between all segment inclines, with the metabolic cost increasing with steeper inclinations. This was somewhat expected based on the pre-set protocol, and the skiers verbally communicated that the competition course felt realistic. The 8 finishing skiers without breaks were able to ski sub-maximally during the flat sections (2%), and therefore recover the anaerobic energy stores. While the moderate incline (5%) demanded supplementary anaerobic energy contribution in the first part of the segment, much likely because of the drop in aerobic energy production during the prior downhill. Unsurprisingly, all skier performed at supramaximal intensities with high anaerobic energy contributions in the steep inclines (12%), which was in agreement with other studies on individual starts (1, 3, 4, 6).

Interestingly, we observed a fluctuation of aerobic energy contribution which, if possible, stabilised above the segment demands to allow recovery of anaerobic energy stores, and specifically for this course; prepared the skiers for the steep incline (12%). The greatest anaerobic recovery was observed in the downhill segments, and thus supported the claim of XC skiers executing supramaximal intensities uphill because of the low metabolic cost downhill (1, 4, 7, 8) also in the mass start events. Notably, we visually observed a change in the G7 sub-technique (downhill) during the competition, and skiers seemed to stretch their legs in the downhills to avoid accumulation of lactic acid. This could be highly influential in an outdoor competition, as the increased air drag of standing up would reduce the speed of the skier and negatively affects their performance. However, simulated mass starts events are less affected by this compared to simulated individual starts, as skiers avoid drag by siting behind opponents or stand up to prevent gliding into the skier in front of them when skiing in groups.

From the 12 participating athletes, were 4 skiers excluded in the segment calculations because they could not follow the protocol and utilized additional breaks. So compared to an individual start, are the segmental values of the current study based on the skiers which was strong enough to ski on the pre-set course, and thus the skiers with a relatively higher aerobic energy contribution. During a competition, this would plausibly be the leading group of more homogenic skiers, who produces enough aerobic power to survive every steep incline (12%) and avoid contributions from the lactic anaerobic contribution mentioned by Gløersen el al. (3), described by Gastin et al. (26) and discussed further below. Ultimately, our results imply energy system fluctuations similar to those of individual starts (1, 3, 4, 6). With recovery in the downhill and flat segment, and supramaximal intensities utilized on steep inclines, also in the mass start competitions.

Individual skier variations

The competition performance was measured by TTE in the all-out sprint. Results from the current study reported a strong association between TTE and $\dot{V}O_{2peak}$, which in agreement with several other studies (9, 10, 16, 18-23), suggests $\dot{V}O_{2peak}$ to be a strong predictor of distance skiing performance. These finding also support the authors hypothesis of "individual variations in performance based on aerobic power. With the better skiers utilizing a lower anaerobic energy contribution in the uphill segments, ultimately providing them with a more anaerobic energy storage for the finishing sprint." By analysing the skier with the best TTE, the skier with the worst TTE of the 8 finishers and the skier with the most breaks (Figure 4), there are clear fluctuational differences in energy system contribution between the skiers. The best skier had a less anaerobic energy contribution in the steep incline (12%), with the aerobic energy system providing aerobic powers equivalent to a bigger proportion of the total energy demand. Unlike the worst skier, who plausibly went above his preferred utilization of 0-50% maximal anaerobic storage (3), in the steep inclines (12%). Thus, relying on a greater utilization of the lactic anaerobic energy system, which has a longer required recovery time compared to the alactic anaerobic energy systems (32, 33), resulting in 3 additional breaks (lap 5-7).

The better performing skiers also seemed to have a longer recovery timespan. Their aerobic energy systems covered the demand of the moderate inclines (5%), in addition to the flat (2%) and downhill segments, allowing them to ski on lower intensities throughout the competition. Based on the whole competition energy system contributions of Table 2, there is a slightly higher relative aerobic contribution in the 8 finishers compared to all 12 participants, even though the 4 worst skiers had additional breaks. These group-related relative energy system contributions might have been more similar in a self-paced individual start; with the better skiers utilizing more anaerobic power and reducing their surplus of anaerobic recovery, and the worse skiers pacing themselves within their preferred intensity, unaffected by the leading group.

Based on the fluctuating energy contributions of individual skiers (Figure 4), one could assume that the skiers performed better TTE's because they had more anaerobic energy left and lower levels of muscular H+-ions (which is regarded to cause fatigue) (32, 33) when the all-out sprint started. The anaerobic storage is important for the required power production of accelerations and top speeds in sprint finishes, although based on the current study it is unclear if this was the primary factor. Based on Figure 4, it seemed like the all-out sprint started at a somewhat low speed, and the best performing skier was able to cover the energy demands of the first sprint intensities aerobically, thus making it a long-distance sprint. Ultimately, forcing the more explosive anaerobic skiers above their submaximal intensities for a longer period of time in the all-out sprint, compared to more aerobic skiers. Unsurprisingly, our distance-competition course and all-out sprint seemed to favour the more aerobic skiers, as they were able to ski on lower intensities during the competition and cover more of the uphill and sprint energy demands aerobically.

Difference between methods

The current study included both the GE- and MAOD-method, to compare the result of the two methods. There was no statistically significant difference in anaerobic capacity between the two calculation methods and a trivial effect size was reported ($t(7) = 0.38$, $p = 0.72$, $ES = 0.13$), which was similar to earlier research of Andersson et al. (39) on classical skiing. There is still no certainty on which calculation method is the most accurate. Although, the GE-method is the less time consuming of the two, whereas the MAOD-method enabled an inclusion of downhill energy cost for the current study, which the GE-method was not able to do.

Methodical considerations

The two methods (GE and MAOD) for calculating anaerobic energy contribution depend on the sub-maximally measured GE or PO-$\dot{V}O_2$ relationship to be constant throughout the whole competition. To date, there are no studies on the change in GE and PO-$\dot{V}O_2$ relationship during XC skiing**,** but a drop in actual GE during cycle time-trials has been reported (40), and might cause an overestimation of the aerobic contribution. The course protocol was simulated with long periods of submaximal intensities, with steep inclines (12%) being the only supramaximal intensity for some skiers, which plausibly resulted in unrealistically short durations of anaerobic utilization in the current study. Furthermore, the metabolic costs of G7 (downhill) were measured on a pilot group, which might not be representative of the competition group, and there is little knowledge regarding the metabolic cost differences between rested G7 and exhausted G7. Lastly, the skiers were allowed to choose sub-technique freely during the competition course, and both G2 and G3 were observed on the steep inclines (12%). Steep inclines (12%) were only performed with G2 on day 1, and GE was therefore calculated accordingly. No additional testing was performed, based on the findings of Losnegard et al. (11), reporting similar $O_2$-costs between G2 and G3 on steep inclines.

## Conclusion

This is the first study to investigate the whole race energy system contributions of mass start distance skiing. The current study reported a high relative aerobic energy contribution of ~93-94% (downhill excluded) in mass start distance skiing competitions. These highly aerobic energy system contributions were not significantly affected by the anaerobic calculation method, but rather interpreted as the result of long periods of submaximal intensities. The study's simulated mass start competition showed similar terrain-inflicted energy system contributions as previously seen in individual starts, with submaximal intensities on the flat segments (2%) and supramaximal intensities during the steep inclines (12%), suggesting temporal changes between high utilization and recovery of the anaerobic energy stores in XC skiing. The individual variations in performance between skiers was strongly correlated to $\dot{V}O_{2peak}$, were the best skiers covered more of the energy demand aerobically and performed better in the final all-out sprint. Future research on outdoor mass start competition seems essential to understand the real fluctuation in energy system contribution, implementing how the skier's pace themselves, interact and react to other skiers, and how the downhills actually affects the energy contribution during competitions.

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