Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Medicine and Health Sciences
Department of Circulation and Medical Imaging

Marte Vik

# Metabolic Rate and Gross Efficiency in G2 and G3 Roller Ski Skating: Effect of Incline and Work Rate

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# GROSS EFFICIENCY IN G2 VS G3 SKATING STYLE CROSS COUNTRY SKIING

G2; offset
G3; double dance

## PURPOSE

TO INVESTIGATE POSSIBLE DIFFERENCES BETWEEN G2 AND G3 IN GROSS EFFICIENCY (GE) AND IN THE METABOLIC RATE - WORK RATE RELATIONSHIP AT TWO INCLINES, CONSTANT SPEED, AND ACROSS A RANGE OF WORK RATES, WHERE WORK RATE WAS EQUAL ACROSS INCLINES.

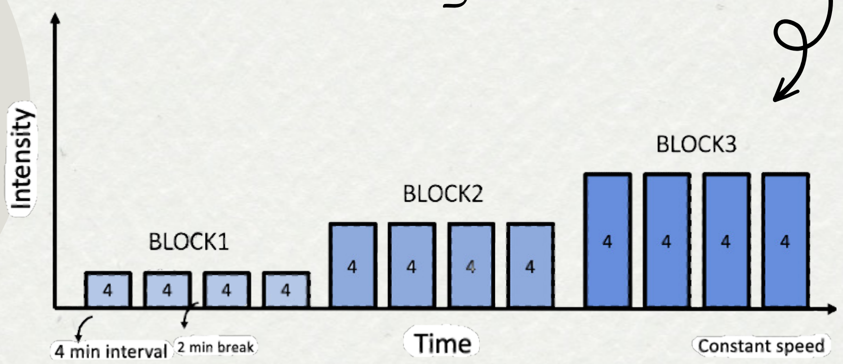
## METHODS

12 CROSS COUNTRY SKIERS
AGE: 24 ± 3 (yrs)
BODY MASS: 73 ± 4 (kg)
BODY HEIGHT: 179 ± 5 (cm)

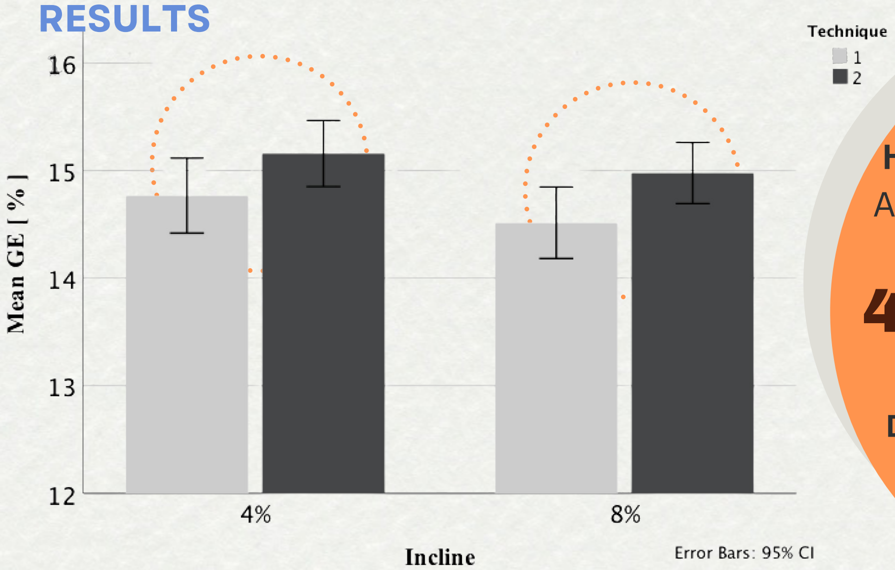
WORK RATE ADJUSTED BY PULLEY WEIGHT

PERFORMED ROLLER SKIING ON A 3 X 5 MOTORIZED TREADMILL

**3** INTENSITIES (BLOCKS)
**2** INCLINES (4% AND 8%)
**2** TECHNIQUES (G2 AND G3)
} **12 INTERVALS IN TOTAL**




## RESULTS




**G2** INDUCED A **HIGHER GE** THAN G3 OVER ALL BLOCKS, AND INCLINES

**4%** INCLINE GAVE **HIGHEST** VALUES OF **GE**

**DIFFERENCES IN GE** BETWEEN TECHNIQUES SEEMS TO **DIMINISH** AT HIGH WORK RATES

## CONCLUSION

THE FINDINGS OF THE STUDY WAS THAT G2 WAS MORE EFFICIENT THAN G3 AT BOTH INCLINES. HOWEVER, SIGNIFICANT INTERACTION EFFECT INDICATES THAT THESE DIFFERENCES IN GE DIMINISH AT HIGHER WORK RATES (280-300W+).

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## Abstract
**Background:** In skating style cross-country (XC) skiing, there is speculation of the benefits of using either the G2 or G3 technique, especially in moderate uphill terrain with low speed, which may favor both techniques approximately equally. However, in both practice and research, it is not fully clear whether gross efficiency (GE), or other physiological variables differ between G2 and G3, or whether differences are due to incline, technique, or work rate (WR).
**Purpose:** To investigate possible differences between G2 and G3 in GE and in the metabolic rate – WR relationship at two inclines, constant speed, and across a range of WRs, with equal WR across inclines.
**Methods:** 12 XC skiers (age 23.8 ± 2.9, body mass 73.1 ± 4.3, height 179.3 ± 4.8) performed 12 trials consisting of G2 and G3 treadmill roller ski skating at two inclines (4% and 8%), three intensities, and at a constant speed. WR was regulated by a purpose-made pulley system, and by regulating pull force and WR, three intensity levels (blocks) were established as well as enforcing equal WRs at the two inclines. Each trial lasted 4 minutes, with a two-minute break in-between. Blood lactate concentration and rated perceived exertion were measured after each trial, while oxygen uptake, respiratory exchange ratio, minute ventilation, and heart rate were measured continuously.
**Results:** At each BLOCK (1,2 and 3), G2 was more efficient than G3 at both 4% and 8% incline (~0.4%pts, $p<.01$; incline x technique interaction, $p>.2$). GE was also higher at 4% than 8% incline (~0.2%pts [0.0, 0.4], $p<.05$). Moreover, a significant interaction effect between technique and WR was found at both inclines ($p<.05$), where differences in GE diminished at the highest WRs. G2 induced an overall lower physiological response than G3.
**Conclusion:** The results of this study indicate that G2 was more efficient than G3 during submaximal skiing at both 4% and 8% incline. However, this difference appears to diminish at higher WRs.

## Sammendrag

**Bakgrunn:** I skøytestil i langrenn er det spekulasjoner om fordeler ved å bruke enten G2- eller G3- teknikk, spesielt i moderat oppoverbakke med lav fart, hvor begge teknikkene favoriseres omtrent likt. Likevel, er det noe uklarhet i både praksis og forskning om effektivitet (gross efficiency; GE) eller andre fysiologiske variabler differensierer mellom G2 og G3, eller om forskjellene skyldes stigning, teknikk eller arbeidsrate.

**Formål:** Å undersøkte mulige forskjeller mellom G2 og G3, i GE og i forholdet mellom metabolsk rate og arbeidsrate, ved to stigninger, konstant hastighet, og over en rekke arbeidsrater, hvor arbeidsraten var lik over stigninger.

**Metode:** 12 langrennsløpere (alder 23.8 ± 2.9, kroppsvekt 73.1 ± 4.3, høyde 179.3 ± 4.8) utførte 12 drag på rulleski på tredemølle, med både G2- og G3- teknikk ved to stigninger (4% og 8%) og tre intensiteter (blokker), med konstant hastighet. Arbeidsraten ble regulert av et spesiallaget system, slik at tre intensitetsnivåer ble satt ved å regulere trekkraften og arbeidsrate, samt opprettholde like arbeidsrater ved begge stigningene. Hvert drag hadde en varighet på 4 minutter, med en to-minutters pause imellom. Blodlaktatkonsentrasjon og opplevd grad av anstrengelse ble målt etter hvert drag, mens oksygenopptak, respiratorisk utvekslingskvotient, minuttventilasjon og puls ble målt kontinuerlig.

**Resultat:** For hver BLOKK (1, 2 og 3) var G2 var mer effektiv enn G3 ved både 4% og 8% stigning (~0.4%pts, $p<.01$; stigning- x teknikkinteraksjon, $p>.2$). GE var også høyere ved 4% enn ved 8% stigning (~0.2%pts [0.0, 0.4], $p<.05$). I tillegg ble det funnet en signifikant interaksjonseffekt mellom teknikk og arbeidsrate ved begge stigningene ($p<.05$), hvor forskjellene i GE ble redusert ved de høyeste arbeidsratene. G2 induserte en generell lavere fysiologisk respons enn G3.

**Konklusjon:** Resultatene i denne studien indikerer at G2 var mer effektiv enn G3 under submaksimale drag i langrenn ved både 4% og 8% stigning. Imidlertid så denne forskjellen ut til å avta ved høyere arbeidsrate.

## Acknowledgements

First of all, I would like to thank my supervisor, Jørgen Danielsen, for helping and guiding me with his wide expertise in this field of study, and for always being available and supportive, throughout the year but especially in the final rush. Also, I would like to thank my co-supervisor Knut Skovereng for practical guidance in the lab from early on in the process.

I would also like to thank all the participants for being open-minded and joining my project. Not to forget the employees at Senter for Toppidrettsforskning in Granåsen for welcoming us students. Last but not least I would like to thank all my fellow students for all discussions, frustrations, revelations, support, and fun during our studies.

Thank you,

Marte Vik

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## Abbreviations

| | |
|---|---|
| XC | Cross country |
| G2 | Gear 2; Skating technique, offset |
| G3 | Gear 3; Skating technique, double poling |
| GE | Gross efficiency |
| WR | Work rate |
| $VO_2$ | Oxygen uptake |
| RER | Respiratory exchange ratio |
| MR | Metabolic rate |
| BLa | Blood lactate concentration |
| HR | Heart rate |
| RPE | Rating of perceived exertion |
| %pts | Percentage points |

## 1.0 Introduction

Choice of technique can be crucial for performance in cross country (XC) skiing, as the skier is dependent on using metabolic energy to produce work in the most efficient way (1). Over the last decades, since the skating technique arrived, it has developed and changed the sport. The skating technique is shown to be 13,4-16,3 percent quicker than the classical technique on average in a 3.04 km race (2).

XC skiing requires a combination of different techniques to navigate through varying terrain and conditions (e.g., flat or uphill, plus or minus degrees, etc.), and there are multiple techniques within both the skating and classical styles, each of them with different characteristics and challenges (3). In this thesis, we focus on the two most commonly used skating style techniques; G2 and G3. G3, also referred to as V2, two skate, or double dance, involves a synchronous left and right pole push for each ski push, and is most commonly used on flat to moderately uphill terrain and for speed increases. G2, also known as V1 or offset skiing, is a less synchronous technique than G3, involving a left and right pole push on every second ski push, commonly used on uphill terrain.

Given that skiers spend half of their competition time on uphill segments (4), the physiological responses associated with the use of G2 and G3 on such terrain have become a topic of debate. Traditionally G2 has been the main technique for uphill skiing, but in practice, it is often recommended by coaches that skiers should maintain G3 for as long as possible during a race, and it is now used to a greater extent also in steeper uphill´s (4). It is known that faster skiers use more G3 than G2 throughout a given track. However, it is not really known if this is due to the faster skiers choosing a more (or less) efficient technique, being more efficient at any technique, or if their total physiological (and technical) capacity enables them to use a "faster" technique while skiing faster.

Mechanical efficiency is of importance for performance in XC skiing (5). The challenge is to measure work rate (WR) accurately, however, using ski-specific testing in the labratory on a roller ski treadmill makes it possible to measure metabolic responses and WR under controlled conditions. To measure whole-body efficiency, gross efficiency (GE) is most commonly used and can be defined as the ratio of work done during a specific activity to the total energy expended, and is usually expressed as percentage (6). A small improvement of GE can make a considerable difference in a race for elite athletes, and maybe an even greater difference for less skilled athletes (6). A study by Wilkinson and Kram (7) performed on cyclists, found ~0.3 percentage points (%pts) to make a significant difference, corresponding to a ~26 s improvement up a 13.8 km climb (Alpe d Huez). Despite the fact that the study was carried out on cyclists, it showed that a minimal increase in %pts can make a relatively large difference in the outcome of a race. XC skiing has more complex and technically challenging movements than cycling. A difference of 0.5%pts have been shown to clearly separate world-class from national-level XC skiers (8).

Sandbakk et al. (1) observed a linear increase in metabolic rate (MR) with WR at a 5% incline, however, in that study skiers used G2 at a 12% incline and G3 at a 5% incline, so one cannot (clearly) separate technique from incline effects. Further, there were no significant differences in GE between genders, even though men had higher WRs and MRs, and athletes with higher rankings had higher GE (1). One likely reason for there being a relationship betweeen performance level and GE is due to the technical complexity of XC skiing, which may result in differences in the magnitude of muscle power transferred into external power and speed (5).

Bilodeau et al. (2) investigated various techniques in 3 km skating and found no clear difference in speed between G2 and G3, however, the G2 technique was slightly faster during the uphill parts. Boulay et al. (9) found similar results, G2 and G3 at 6% incline had no clear speed difference, however, the difference was significant at 9% and 12% incline. At a 5% incline using G3 with a speed of 14 km/h, Sandbakk et al. (8) found a significant difference in GE of ~1 %pt between national-level and world-class XC skiers, the difference were significant but smaller at higher speeds. When keeping speed constant across inclines (~7-11%), Losnegård et al. (10) found no difference in oxygen cost between G2 and G3. This is in contrast to Kvamme et al. (4) who found – at identical inclines – that G3 had a higher oxygen cost than G2 at inclines >~7%. In summary, it is not fully clear whether G2 or G3 skating is more efficient than the other. Also, it is not fully known whether possible differences are due to incline, technique, or power output.

Two of these factors; incline, speed, or WR, were modified in a previous study by Løkkeborg and Ettema (11). They suggested that incline can be a factor for technique selection, and WR played a minor role. However, WR was associated with changes in speed and/or incline, which makes the isolated role of WR less clear. Modifying only one factor (WR, speed, or incline), allows us to examine in greater detail to what extent each factor influences technique in XC skiing. We adjusted WR, by use of resistive force (pulley) that can give similar effects as different friction (e.g., glide, air) while maintaining a constant speed and over two inclines. To the authors knowledge, the effect of adjusted WR, where WR was constant across incline and technique, for a range of intensities, has not been investigated. Therefore, this study aimed to compare MR and GE of G2 and G3 at two different inclines across a range of WRs, where WR was kept constant at both techniques by use of a pulley system. It was hypothesized that GE is higher for G3 at 4% incline and for G2 at 8% incline.

# 2.0 Methods

## 2.1 Participants

12 XC skiers participated in the study, of which eleven males and one female. The participants consisted of a selection from semi-hobby practitioners to national-level skiers, where all skiers have been or is still active at a national level. They were all deemed to be highly skilled at roller skiing and in XC skate skiing style. Table 1 displays the mean and standard deviation (SD) for age, body height, and body mass of the participants. The participants volunteered in the study and gave written informed consent to participate. The Norwegian Centre for Research Data (NSD) approved the study.

***Table 1.*** *Characteristics of the participants (mean ± SD)*

| | |
|---|---|
| Age [years] | 23.75 ± 2.86 |
| Body height [cm] | 179.25 ± 4.83 |
| Body mass [kg] | 73.07 ± 4.32 |

## 2.2 Experimental design

The experimental design involved a repeated measure comparison of the G2 and G3 skating techniques at two different inclines and three intensities. The intensities were regulated by a pulley weight, and the individual participant used a constant speed for the entire test. All participants came to the laboratory on a scheduled day, free of injury and illness, and the test was carried out within one and a half hour including warm-up. The test was performed roller ski skating on a treadmill, making it possible to standardize the execution of the test and giving the ability to manipulate the workload for the individual participant.

## 2.3 Instruments and materials

The entire test was conducted on a 3 x 5 m motorized treadmill (Forcelink Technology, Culemborg, Netherlands), and all skiers used the same set of roller skis with wheels of category 2 resistance (IDT Sports, Lena, Norway), but their own set of shoes and poles with preferable length. The spikes on the poles were replaced with special carbide tips with non-slip rubber which ensures better grip on the belt of the treadmill. A towing test was used to find the coefficient of rolling resistance (μ) between the wheels of the roller skis and the belt of the treadmill, and μ equaled to ~0,02.

An open-circuit indirect calorimetry apparatus with a mixing chamber (Vyntus CPX, JAEGER, CareFusion, Germany 234 GmbH) was connected to a breathing tube and a mouthpiece and was used to continuously measure respiratory variables for each condition. An automatic pump built into the Vyntus CPX calibrated the respiratory flow transducer. The $VO_2$ and $CO_2$ gas analyzers of the Vyntus were calibrated against a known mixture of gases ( 5% $CO_2$ and 15% $O_2$) and were calibrated before each participant. A system specifically designed for using a pulley weight were used to regulate the workload (see Figure 2). The system is adding resistance to the skier's movements. It comprises a belt that is worn around the hips, close to the center of mass, with a rope attached to it. The rope extends to the system located behind the treadmill, positioned above the wheel at the top. Adjustable weights are attached to the end of the rope, which gravity pulls towards the floor. The weights consisted of custom weight bags and plates which could easily be added or removed from the rope. The system was adjusted to a suitable length according to where the athlete placed himself on the treadmill during movement.

Heart rate (HR) was measured continuously by a chest-worn HR belt during the whole test and the average HR of the last 30 s was read off the connected watch. The participants rated perceived exertion (RPE) on the Borg scale from 6-20 (12). Blood lactate concentration (BLa) was measured by collecting 20 µL of blood from the fingertip of the participant immediately after the completion of each interval and analyzed in Biosen C-Line Sport Lactate measurement system (EKF Industrial Electronics, Magdeburg, Germany). Body weight and height were measured before the test started.

### 2.4 Test protocol

The sessions started with a warmup procedure that lasted for 5-10 min, and they alternated between the different techniques (G2/G3) and inclines (4%/8%) to prepare for the test. They got familiar with the treadmill and the roller skis got warmed up. The trials were performed with either 8 or 10 km/h at a constant speed according to the performance level of the skiers and were assessed during the warmup procedure by HR and the participants' evaluation.

Subsequently, the test started, which consisted of three intensity blocks with four intervals in each BLOCK (see Figure 1). The different blocks, also referred to as intensities, were divided into BLOCK1, BLOCK2, and BLOCK3, all below the lactate threshold. Each interval had a duration of four minutes, which resulted in an active interval time of 48 minutes for the entire test. The breaks had a duration of approximately two minutes. The intervals were performed on the predetermined speed and inclines, with an adjusted pulley weight concerning the body mass of the individual participant. The increase in resistive force was either 10W or 15W where a judgement was made according to the HR and RPE of the participant at BLOCK1. The incline was exchanged between 4% and 8% by two intervals each, and the technique was exchanged for every interval, starting in counterbalanced order to avoid order effects. The test leader controlled the panel for speed and incline. The average $VO_2$ of the last minute was used, and a blood sample was taken within the two-minute break.

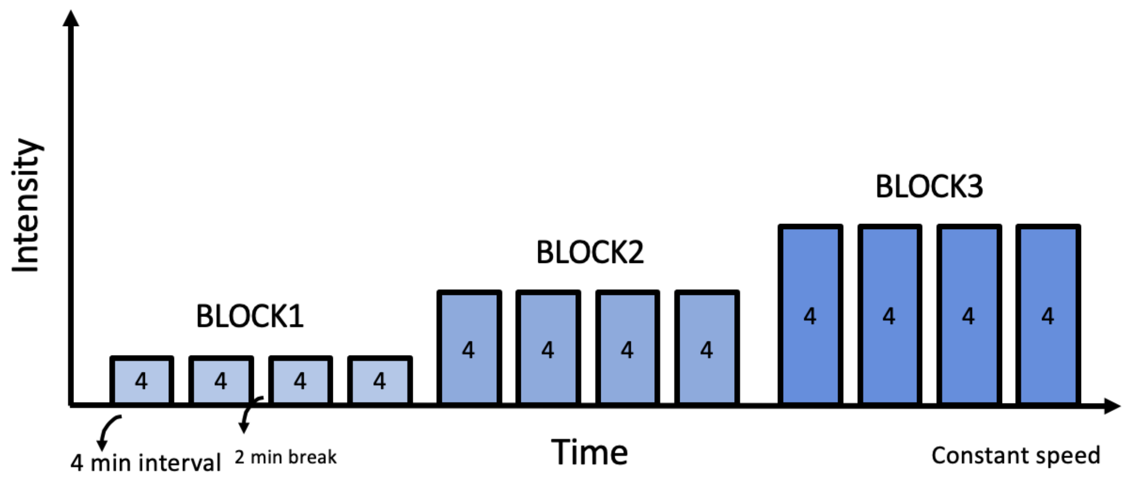


***Figure 1.*** *The protocol of the test day. Every other interval consists of G3 and G2, starting in counterbalanced order, with constant speed. Exchanged incline (4% and 8%) after two intervals throughout the test.*

### 2.5 Data analysis

The data analysis was carried out in Microsoft Excel for Mac (Version 16.71, 2023 Microsoft), IBM SPSS Statistics for Mac (Version 28.0.1.0 (142)), and R Studio (Version 2022.12.0+353, Posit Software, PBC).

2.5.1 Calculation of work rate, metabolic rate, and gross efficiency

WR was calculated as the sum of power against gravity ($P_g$), power against friction ($P_f$), and the power against the pulley weight ($P_p$), hence the sum of forces:

$P_g = m \bullet g \bullet \sin(\alpha) \bullet v$
$P_f = m \bullet g \bullet \cos(\alpha) \bullet \mu \bullet v$
$P_p = m_p \bullet g \bullet v$

$WR = P_g + P_f + P_p$

where m is the skier's body mass, g is the gravitational constant (acceleration), $\alpha$ is the angle of the treadmill, v is the speed of the treadmill belt, $\mu$ ($\approx$.02) is the frictional coefficient, and $m_p$ is the mass of the pulley weight.

Metabolic rate was calculated by the following formula: MR = ($VO_2$ (L/min) • kCal • 4184 J) / 60, where kCal is the energetic equivalent of oxygen corresponding to the given RER value (13), 4184 is the constant converting kCal to Joules, and divided by 60 to get Joules per second (Watts, W). To calculate GE, the external WR of whole-body movement was divided by MR and is expressed in percentage.

2.5.2 Calculation of pulley mass

Pulley mass was calculated to achieve the same watts on the different conditions at the same blocks/intensities according to: $m_p = P_p / g \bullet v$. This was based on the lowest WR possible given body mass and speed, at BLOCK1 and 8 %incline. For example, for a 75 kg participant skiing at 8 km/h, the 8% incline at BLOCK1 equals a WR of 163W. At 4% incline, a speed of 8 km/h equals a WR of 98W. This means that $P_p$ must be 65W, which equals a pulley mass of 3 kg. The same equation was applied to deduce the needed pulley mass for all subsequent conditions.

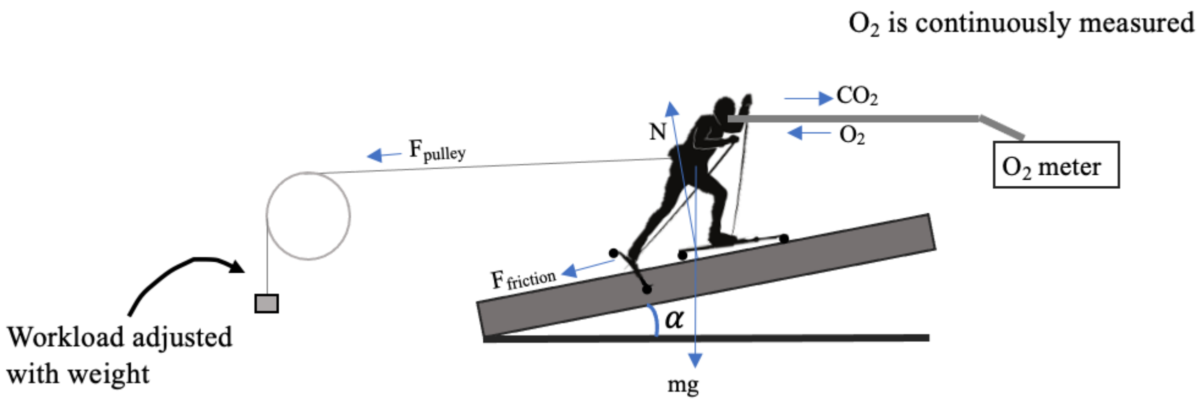


***Figure 2.*** *Illustrates the setup for testing and the various components involved in the calculation of GE.*

### 2.6 Statistical analysis

IBM SPSS Statistics (Version 28.0.1.0 (142)) was used to perform all the statistical analysis. Linear mixed effects models, with participant ID specific as a random factor (intercept only) due to repeated measure data per participant were used to test for effects of technique, incline, and/or BLOCK on the various outcome variables (primary variable was GE) with technique and BLOCK as fixed effects. The main interest was the effect of technique, and the analysis was mainly run separately for each technique. However, we used a linear mixed effects model to include incline as a fixed effect in some cases to compare the possible influences of incline. A linear mixed effects model was also fitted to examine the MR-WR relationship, mainly by testing for interaction effects between technique and WR. For GE, data was also categorized per BLOCK. The residuals of the model(s) were visually inspected for normality using Q-Q plots. Data are presented as mean ± SD unless otherwise stated. Statistical significance was set at $p<.05$. There were no missing data, $n=12$ for all trials.

## 3.0 Results

Figure 3 shows the physiological responses during the test for the range of intensities (BLOCK1, BLOCK2, and BLOCK3), divided into inclines of 4% and 8%. WR is identical for 4% and 8% incline at the different intensities (see Figure 3), as it was adjusted for by the pulley weight which increases gradually for both inclines. For all variables in Figure 3, there was no significant interaction between BLOCK and technique at either incline (all $F_{2,55} < 1.4$, $p > .2$). Overall, G2 induced a lower physiological response than G3 (see Table 2 and Figure 3). For $VO_2$, there was a mean difference (overall blocks) at both inclines, and $VO_2$ increases approximately linearly with BLOCK (~2.6 ml/kg/min, main effect of BLOCK: $p < .001$). For all blocks, there was no significant mean difference of RER and RPE ($p > .05$) between G3 and G2 applicable for both inclines, either for HR at 4% incline. However, the mean difference for HR at 8% incline was ~2.2 beats/minute ($p = .009$). It was a tendency of BLa ($p < .1$) for both inclines, the mean difference was 0.3 mmol/L, and at both inclines it increases ~0.5 mmol/L for each block (main effect of block $p < .001$).

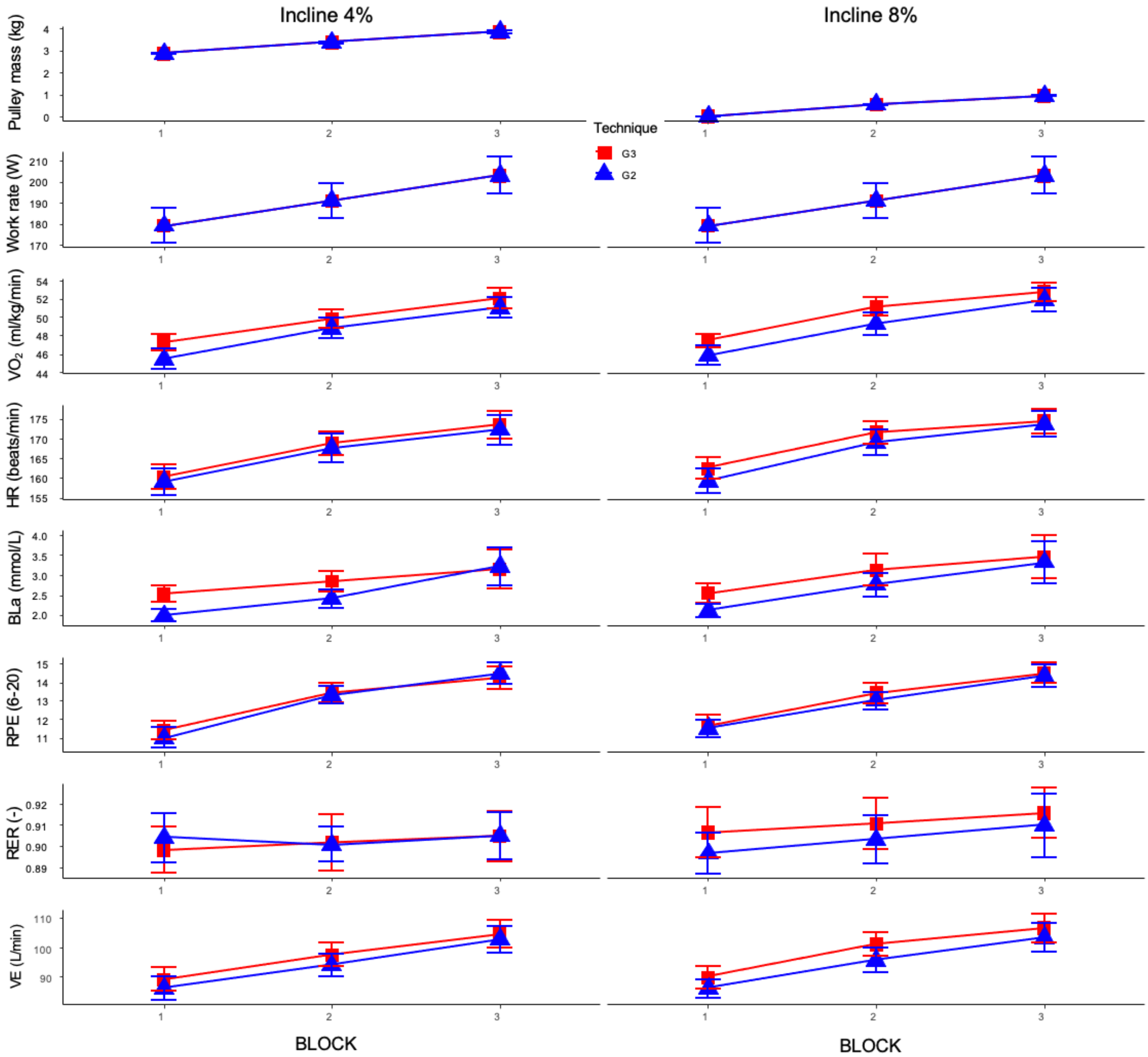


***Figure 3.*** *G3 versus G2 skating; Comparison of load and physiological responses across three different blocks (intensities) on fixed inclines of 4% and 8% while roller skiing on a treadmill.*

***Table 2.*** *Physiological responses for 12 XC skiers over all blocks.*

| Incline | Variable | G3 | G2 | Difference between G2 and G3 [95%CI] |
|---|---|---|---|---|
| 4% | $VO_2$ (ml/kg/min) | 49.7±4.0 | 48.4±4.4 | 1.3 [0.7, 1.8] |
| | RER | 0.90±0.04 | 0.90±0.04 | -0.00 [-0.01, 0.01] |
| | VE (L/min) | 97±16 | 94±15 | 2.9 [0.1, 5.7] |
| | HR (beats/min) | 168±12 | 166±13 | 1.3 [-0.5, 3.0] |
| | BLa (mmol/L) | 2.8±1.2 | 2.5±1.2 | 0.3 [-0.0, 0.6] |
| | RPE (6-20) | 13±2 | 13±2 | -0.3 [-1.0, 0.5] |
| 8% | $VO_2$ (ml/kg/min) | 50.5±3.9 | 49.0±4.7 | 1.4 [0.8, 2.0] |
| | RER | 0.91±0.04 | 0.90±0.04 | 0.01 [-0.00, 0.02] |
| | VE (L/min) | 99±16 | 95±16 | 4.1 [1.2, 7.1] |
| | HR (beats/min) | 170±11 | 167±12 | 2.2 [0.6, 3.9] |
| | BLa (mmol/L) | 3.0±1.5 | 2.7±4.8 | 0.3 [-0.1, 0.7] |
| | RPE (6-20) | 13±2 | 13±2 | 0.2 [-0.6, 1.0] |

*Data presented as mean ± SD. VO2=oxygen uptake, RER=respiratory exchange ratio, VE=minute ventilation, HR=heart rate, BLa=blood lactate concentration, RPE=rating of perceived exertion.*

A linear relationship between MR and WR is demonstrated in Figure 4 for a 4% incline and Figure 5 for 8% incline. At inclines of 4%, there was a significant interaction between WR and technique ($F_{1,57}$=4.1, p=.047), with a steeper slope for G2 (5.6W [95%CI 4.9, 6.2]) than for G3 (5.1W [95%CI 4.5, 5.8]) in addition to significant differences between offsets (192W for G2 and 313W for G3, p=.009). The same applies to 8% incline, where there was a significant interaction between WR and technique ($F_{1,55}$=7.7, p=.008), with a steeper slope for G2 (6.2W [95%CI 5.5, 6.9]) than for G3 (5.5W [95%CI 4.7, 6.2]) and significant differences between offsets (94W for G2 and 270W for G3, p<.001). This means that GE overall was higher for G2 than G3 at both inclines, but this difference became smaller when WR increased  (see Figures 4 and 5).

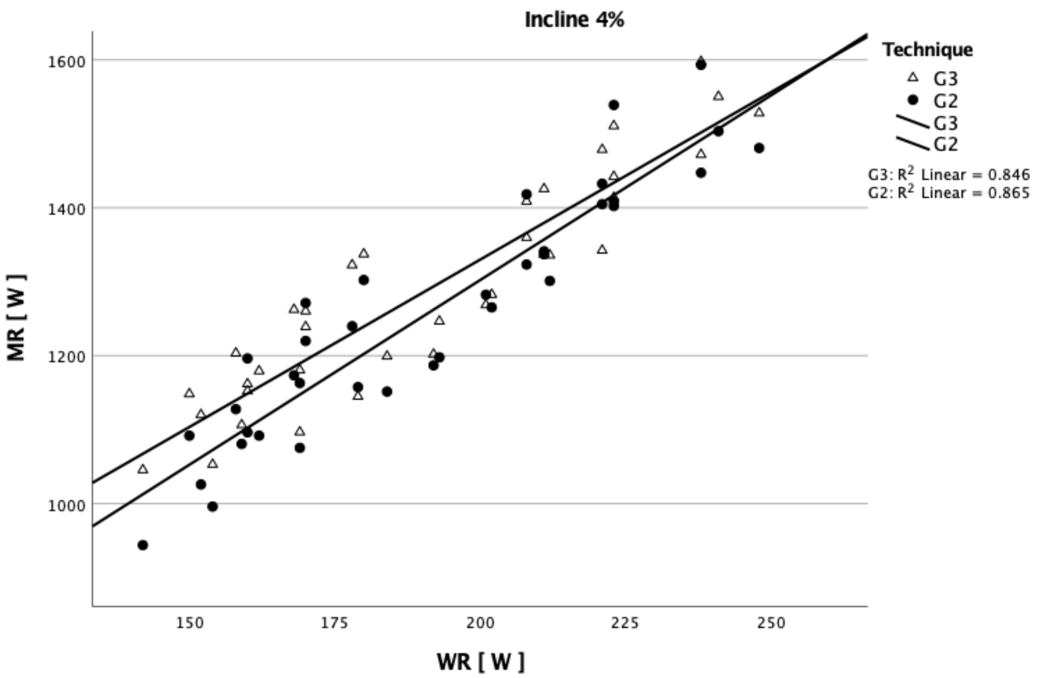


***Figure 4.*** *MR plotted against WR for individual data at a constant speed with adjusted WR at 4% inclination using G3 and G2 skating techniques. Trend lines are based on linear regression for G3 and G2 separately within the entire dataset.*

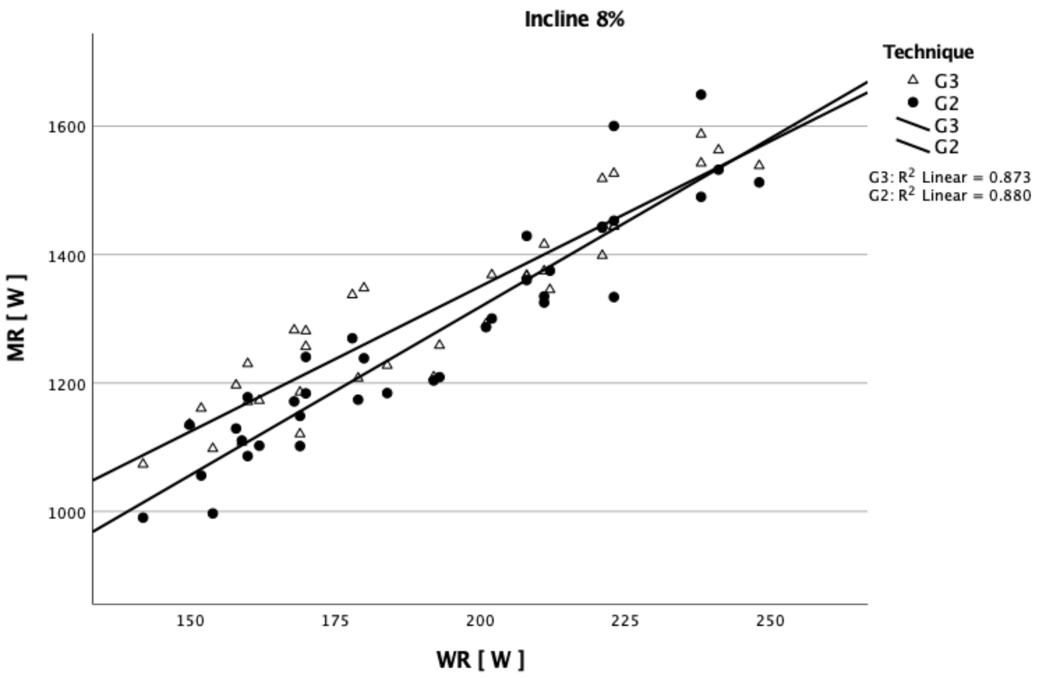


***Figure 5.*** *MR plotted against WR for individual data at a constant speed with adjusted WR at 8% inclination using G3 and G2 skating techniques. Trend lines are based on linear regression for G3 and G2 separately within the entire dataset.*

For GE at each BLOCK (Figure 6), we found no interaction between technique and incline ($F_{1,33}$<1.8, p>.184). For BLOCK1, GE was significantly higher for G2 compared to G3 (0.6%pts [95%CI 0.4, 0.8], p<.001) and had no effect of incline (0.1%pts [-0.1, 0.3], p=.323). GE was significantly higher for G2 compared to G3 for BLOCK2 and BLOCK3 as well (0.4%pts [95%CI 0.3, 0.6] p<.001 and 0.3%pts [95%CI 0.1, 0.5] p=.006, respectively). A significant mean difference of 0.3%pts [95%CI 0.1, 0.5], p<.05 was found between inclines for both BLOCK2 and BLOCK3. Mean values over all blocks for 4% and 8% incline were 15.2% and 15.0% for G2, and 14.8% and 14.5% for G3, respectively. Thus, G2 had an overall higher GE for all intensities, with 4% incline giving the highest values of GE compared to an 8% incline.

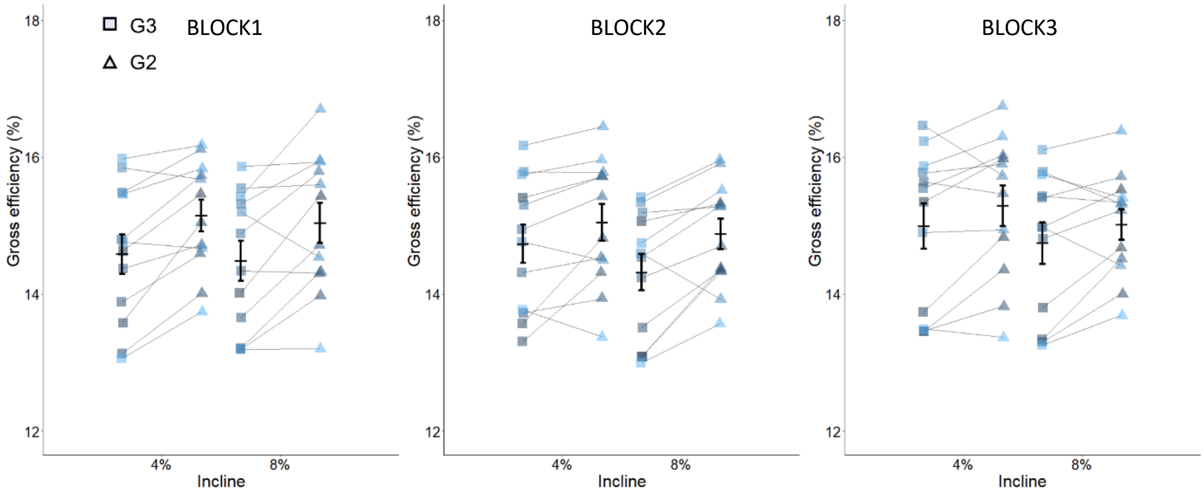


***Figure 6.*** *Mean, SD, and individual values of GE for BLOCK1, BLOCK2, and BLOCK3 distributed in 4% and 8% incline. Connecting lines apply to individual data for the same participant.*

## 4.0 Discussion

The purpose of the present study was to investigate differences in GE between G2 and G3 with increased external WR and controlled speed and incline, where WR was identical at the different inclines. The findings are that G2 was more efficient than G3 at both inclines (4% and 8%). However, the significant interaction effect between technique and WR showed that this difference in GE diminished at higher WRs. The fact that G2 was (clearly) more efficient than G3 at 4% was somewhat surprising and rejected our hypothesis, as we chose two inclines that we believed would favor each technique (4% G3, 8% G2). Lastly, there was a main effect of incline as well, with higher GE at 4% than 8%. The effect of incline was, however, consistently lower than the effect of technique. In race situations with the presented inclines and speeds, G2 and G3 are both used and investigating this can provide information about GE and physiological responses useful for technique selection.

### 4.1 Gross efficiency and metabolic rate

GE was expected to provide valuable insight for technique selection in the uphill sections of 4% and 8% inclination. The results showed that G2 had higher GE than G3 at all blocks (intensities), especially the lowest intensities. Hence, with constant WRs for each BLOCK, G2 seems to be of advantage at all intensities. GE was only significantly affected by incline at BLOCK2 and BLOCK3, but no effect by incline at BLOCK1. Suggesting that GE is similar at both inclines at the lowest intensity. Overall, 4% is giving the highest values of GE, indicating that the participants are more efficient at a 4% incline compared to an 8% incline. This is opposite to the findings of Sandbakk et al. (1) that found higher efficiency at steeper incline. One explanation for this may be the WR being constant for both inclines and techniques in our study, while they (1) used G3 at 5% and G2 at 12% incline, showing lower MRs and higher GE at 12% incline at matching WRs. However, it doesn't explain differences in technique on a given incline, only that a higher incline induced a higher efficiency, which can be explained by higher WRs at uphill terrain. Another explanation is the level of the skiers, as GE seems to be strongly correlated to the performance level of the skiers (1). Several studies conducted on world-class and national-level sprint skiers (8,14) suggested that world-class skiers have greater GE. However, only G3 was tested, and less is known about G2.

G2 had a steeper slope than G3 in the linear relationship between MR and WR, indicating that G2 becomes more metabolically costly for each increase in WR than G3 does. The regression lines had a lower intercept for G2 at both inclines compared to G3, and as WR increased, the difference between techniques was reduced. The WR in which GE seems to start favoring G3 over G2 is estimated to be about 280-300W+. This WR is high, and for most skiers, it will be above steady-state intensity. In any case, a large part of ski races is performed at non-steady-state intensities and high WRs. Therefore, according to these findings, it might be that GE favors different techniques during low-and-moderate-intensity training compared to high-intensity and race-like intensities. Other studies found corresponding results to our study showing lower MRs and higher GE for G2 than with G3 (1,8,15), only Stöggl et al. (15) with extra loading which had no effect on technique (G2 at ~14% and G3 at 9%). Different inclines are used in some of the studies, however, it appears that G2 generally induces higher efficiency than G3.

A previous study by Leirdal et al. (16) suggests that high WRs caused reduced efficiency and performance as a result of high frequency. The finding of higher GE for world-class than national-level skiers in Sandbakk et al. (8) was also related to the frequency which was higher in national-level- than world-class skiers at submaximal skiing. Losnegård et al. (10) found G3 to have a longer cycle length and lower cycle rate than G2 on moderate to steep inclines (~7-11%), the mean cycle rate was ~0.75 Hz for G2 and ~0.53 Hz for G3. In agreement, Stöggl et al. (17) also found longer cycle length and lower cycle rate for G3 than G2 at ~12-18% incline. Since G2, in general, has a lower frequency than G3 (counting each pole push in G3 as one cycle), it could be that part of the reason for the higher GE for G2 in this study, is to be found here. However, this study did not include measures of cycle length. Furthermore, it has been suggested that an increase in GE of 0.5%pts would influence performance in XC skiing (8). Previous studies (7,18) reported a 0.9%pts change and even a lower (~0.3%pts) change in GE for cyclists to be both statistically and practically meaningful in a performance setting. However, XC skiing has more complex movements than cycling, whereas technique might not be as decisive for cycling as it seems to be in XC skiing. Taking all this into consideration, the results of the present paper seem to suggest that skiers might benefit from choosing G2 more often than not over G3 at moderate uphills, contrary to what is often believed in practice.

**4.2 Physiological responses**

Overall, all other variables followed the same pattern and indicate the same thing, that G2 seems to induce a lower physiological response than G3 at the inclines and speeds used in the present study. For $VO_2$ there was a significant difference over all blocks at both inclines, and the linear increase of $VO_2$ with blocks naturally explains itself by increased intensity. Lower mean values of $VO_2$ for G2 were found at both inclines, which supports previous studies (4,19) and contrasts with the findings of Losnegård et al. (10) that found both G2 and G3 to be appropriate techniques for optimizing oxygen cost in moderate to steep inclines (~7-11%) in elite XC skiers. However, Kvamme et al. (4) suggested that G2 has a lower oxygen cost than G3 at an inclination steeper than ~7-9% and makes G3 of disadvantage. This number might be lower considering values of 4% incline in the present study. Millet et al. (19) compared G2 and G3 on snow for non-elite skiers and reported a higher oxygen cost in G3 than in G2, which reinforces our results. The study is conducted on-snow terrain and should be considered when comparing results. However, it also reinforces that roller skiing and on-snow skiing might not be that different, confirmed by several studies showing a strong correlation previously (20,21).

In the present study, there was only a tendency of mean differences in BLa between techniques at both inclines (~0.3mmol/L), with G2 giving the lowest values. However, the SD of the mean at 8% incline, indicated that individual differences may be explained by variations in the level and training volume of the skiers (not recorded). BLOCK was a stronger predictor for the increase in BLa which correlated well with the intensity increase. Kvamme et al. found higher BLa in G2 at inclines <~9%, and higher in G3 at higher inclines. They found a difference of 1 mmol/L between G2 and G3 at ~14% incline, and at ~7% incline only 0.1 mmol/L separated techniques. Regardless, both Kvamme et al. and the present study found G2 to have lower mean values of BLa at 8% up to 14% incline, indicating that G3 may hit the breaking point earlier, thus, leading to faster exhaustion at these inclines. In contrast, Losnegård et al. (10) found no difference in BLa at either incline (~7-11%), probably due to different levels of skiers than the present study and the study of Kvamme et al. (4). Elite XC skiers initially tolerate higher BLa and usually have lower values than less trained skiers, and technique may also play a role due to optimalization and efficiency.

Further, HR at 4% incline showed no significant effect of technique in the present study. However, at 8% incline, HR was lower for G2 than G3 at steeper inclines which are in accordance to findings of previous studies (4,9). Kvamme et al. (4) found a significant interaction between incline and HR responses in relation to technique. At ~5% incline, HR had the lowest mean values for G3, at ~7% incline HR had mean values slightly less for G2 than G3 (4), corresponding to 4% incline in our study with no significant mean difference of HR and technique. It may indicate that the intersection between the techniques in HR lies between 4-7% incline, however, several factors are involved. Previous studies (2,9) also compared HR and velocity of G2 and G3, and Bilodeau et al. (2) found no significant differences in HR and velocity between techniques throughout the course. While Boulay et al. (9) found G2 to be significantly faster at 9% and 12% incline and with a slightly lower HR compared to G3. Even though the present study had constant velocity, these findings confirm that G2 is appropriate for uphill skiing, with HRs lower for G2 than G3. In total, the present study's results highlight the care that should be taken when choosing what "physiological indices" or variables (for example, GE or HR) to infer which technique (or condition overall) is more effective or efficient than the other.

**4.3 Work rate and pulley weight**

A pulley weight system was used as a mechanism to change power independent of other factors such as incline and speed. WR was calculated to keep a constant load and to investigate how increased WR affects GE for technique at constant speed, at two different inclines. Potentially, it can elucidate essential mechanisms responsible for one technique being more efficient than the other. Ettema et al. (22) suggested that external resistive force plays a triggering role on a fixed incline. The technique was self-selected in that study and the sense of effort may have played a role in the change of technique, as increased external WR gave a sense of having to apply increased propulsive force (which indeed is the case). Interestingly, despite the "clearly" higher GE for G2, most of our participants preferred using G3 over G2 on most conditions, even though RPE had no significant difference between the techniques, and the individual values showed G3 to have higher HR, $VO_2$, and BLa. Thus, efficiency is higher using G2 and should be considered used to a greater extent, thereby, using less energy expenditure on the presented inclines and having more surplus energy for other parts of the race. This could result in an overall higher pace. When adding resistive force, changes in the activation patterns of local muscles may occur and also affect other factors, for example, adjustment of technique as it is unnatural to have a resistive force pulling you backward. Bolger et al. (23) found more lateral and vertical displacement on the weak side using G2 at steep inclines with the loading of the skis, which is not further investigated in this study, but an adaptation of the technique with increased load will probably occur.

**4.4 Methodological considerations**

In the present study, WR was calculated for each individual participant. However, $P_f$ is assumed to be constant and does not consider the force taken by the poles (24) or the movement direction of the roller skis during the skating technique. The treadmill belt and the skis do not move in the same direction, meaning that the distance and speed of the treadmill belt do not necessarily correspond to the actual distance and speed of the skier. This may affect the estimated GE, causing systematic errors. However, this effect is likely minimal, as discussed in Sandbakk et al. (8). The minimal effect is due to the participants using the same set of skis, using the same techniques and inclines, and with a constant speed throughout the entire test. The systematic error should be considered when interpreting the GE values reported between techniques as the orientation angle in relation to the forward direction may vary between the techniques.

In summary, for the present study, G2 seems to be beneficial over G3 for this group of participants considering the physiological responses at both inclines and all blocks. Further, G2 seemed to be more efficient than G3 at both inclines with the speeds examined here. Surprisingly at 4% incline, while more expected at 8% incline. However, the difference in GE decreases with higher WRs, indicating that G3 may become the most efficient at very high WRs. It should be noted that the GE changed from favoring G2 to G3 at WRs around 300W, and this was not for world-cup skiers. For really high-level skiers (world-cup) it could be that this change occurs at a lower or a higher WR, which needs further examination. Since the actual WRs XC races are competed at differ depending on the general performance level, the “optimal” choice of technique (G2 or G3) may depend on this performance level as well. This should be kept in mind when interpreting these results in a practical setting. We chose a speed that is natural for discussion, the same applies to incline. As the present study only used one speed level for each participant, future studies should do a range of speeds to expand the understanding of the role of speed. Possible differences in GE between G2 and G3 at a larger range of speeds, inclines, and WRs need further examination before clear recommendations relevant to actual XC ski racing can be given.

## 5.0 Conclusion

The current results of this study indicate that G2 was more efficient than G3 at both inclines. However, a significant interaction effect indicates that the differences in GE diminish at higher WRs. Moreover, other physiological variables (blood lactate, HR) generally moved in the positive direction of G2, thus considered the most appropriate technique selection for this group of participants at both inclines.

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