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Comparison of physiological and biomechanical responses to flat and uphill cross-country sit-skiing in able-bodied athletes

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ABSTRACT

Purpose: To compare peak work rate (WR_{peak}) and associated physiological and biomechanical performance-determining variables between flat and uphill cross-country (XC) sit-skiing. ***Methods:*** Fifteen able-bodied male XC skiers completed two test sessions, each comprised of four 4-min submaximal stages, followed by an incremental test to exhaustion and a verification test in a sit-ski on a roller-ski treadmill. The test sessions were counterbalanced by incline, being either 0.5% (FLAT) or 5% (UPHILL). We compared WR_{peak} and peak oxygen uptake (VO_{2peak}), as well as physiological variables, rating of perceived exertion (RPE), gross efficiency, and cycle characteristics at identical submaximal WR, between FLAT and UPHILL. ***Results:*** In UPHILL, WR_{peak} was 35% higher compared to FLAT ($p < 0.001$), despite no difference in VO_{2peak} ($p = 0.9$). The higher WR_{peak} in UPHILL was achieved through more work per cycle, which was enabled by the twice as long poling time compared to FLAT ($p < 0.001$). Submaximal gross efficiency was 0.5-2 percentage points lower in FLAT compared to UPHILL ($p < 0.001$), with an increasing difference as WR increased ($p < 0.001$). Neither cycle rate nor work per cycle differed between inclines when compared at identical submaximal WR ($p > 0.16$). ***Conclusions:*** The longer poling times utilized in uphill XC sit-skiing enable more work per cycle and better gross efficiency, thereby allowing skiers to achieve a higher WR_{peak} compared to flat XC sit-skiing. However, the similar values of VO_{2peak} between inclines indicate that XC sit-skiers can tax their cardiorespiratory capacity similarly in both conditions.

Keywords: Paralympic cross-country skiing, oxygen uptake, exercise efficiency, work rate, kinematics

INTRODUCTION

During Para cross-country (XC) sit-skiing, athletes with impairments of the lower extremities and/or trunk propel themselves with the upper-body double poling technique using two poles, while sitting in a sledge mounted on two skis.[1, 2] The race courses consist of undulating terrain changing between uphill, flat and downhill sections,[3] in which ~50% of the time is spent in uphill terrain, where the largest performance-differences seem to occur.[1, 4, 5]

The varying terrain during Para XC sit-ski competitions leads to substantial variation in speed, where skiers must adjust their speed through regulation of cycle length (CL) and cycle rate (CR). When double poling, able-bodied XC skiers utilize longer poling times (PT) associated with lower speed in uphill compared to flat terrain. Longer PT allows a higher production of work per cycle ($\text{work}_{\text{cycle}}$) and thereby greater WR in uphill compared to flat terrain.[6] However, when double poling at identical work rates (WR), able-bodied XC skiers display a higher CR and less $\text{work}_{\text{cycle}}$ when skiing on uphill compared to flat terrain.[6, 7] In Para XC sit-skiing, previous studies have shown similar CR across terrains,[5] but WR, $\text{work}_{\text{cycle}}$, and other cycle characteristics have not yet been studied. These variables would provide important information for understanding the demands when athletes are skiing in different terrains.

Para XC sit-skiing performance will to some extent be limited by the skiers' disabilities. Even though physiological functioning and/or the ability to produce power may be reduced, the performance-determining variables are similar to those in other endurance sports, including peak oxygen uptake (VO_{2peak}) and the fractional utilization of VO_{2peak}, termed performance oxygen uptake, and efficiency.[8-10] Using different sub-techniques in uphill (diagonal stride) and flat (double poling) terrain, able-bodied XC skiers have shown ~10% lower VO_{2peak} in flat terrain,[11, 12] whereas VO_{2peak} achieved during double poling in flat and uphill terrain have not yet been compared in neither standing nor sitting XC skiing. In able-bodied XC skiers, gross efficiency (GE) is higher in uphill compared to flat terrain, which explains the ability to produce higher WR when skiing uphill.[13, 14] However, how these performance-determining variables are influenced by different terrain in Para XC sit-skiing, and their relation to the WR production remains to be investigated.

Therefore, the purpose of the current study was to compare peak WR and associated physiological and biomechanical performance-determining variables between flat and uphill using upper-body double poling when XC sit-skiing. We hypothesize that the ability to produce WR is higher uphill, in particular due to a higher GE compared to flat.

METHODS

Participants

Fifteen able-bodied male XC skiers participated in this study (mean ± SD, age 25 ± 4 years, body mass 79 ± 6 kg, body height 184 ± 6 cm, weekly training 9.3 ± 3.0 hours). In our approach, able-bodied XC skiers were chosen in order to reduce the high within-group differences in maximal aerobic capacity and power output found in Para XC sit-skiers with different disabilities,[15, 16] and thereby establish a baseline for further research on Para XC sit-skiers.
All participants signed an informed consent form prior to participation in the study and were made aware that they could withdraw from the study at any point without providing an explanation. The study was approved by the Norwegian Centre for Research Data (ID 419539) and conducted in line with the declaration of Helsinki.

Overall design

Every participant completed two test sessions of double poling in a XC sit-ski on a treadmill, each comprised of four submaximal stages with increasing speed, followed by an incremental test to exhaustion and a verification test. The test sessions were counterbalanced by incline, being either 0.5% (FLAT; submaximal speeds 10, 12, 14, and 16 $km \cdot h^{-1}$) or 5% (UPHILL; submaximal speeds 4, 5, 6, and 7 $km \cdot h^{-1}$). The speed-incline combinations were chosen to cover a range of intensities from low to moderate/high submaximal intensity. The WR from stage 1 and 2 in UPHILL overlapped with stage 2, 3 and 4 in FLAT. The time between test sessions was a minimum of 48 h and maximum of two weeks.

Methodology

Test protocol

After a standardized 10-min warm up (0.5% incline; 8-10 $km \cdot h^{-1}$), the skiers performed four 4-min stages separated by a 2-3-min break, in either FLAT or UPHILL. After a 5-min passive break and a 3-min active recovery (0.5%; 10 $km \cdot h^{-1}$), a continuous incremental test to exhaustion was completed. The velocity started at 14 $km \cdot h^{-1}$ in FLAT and 6 $km \cdot h^{-1}$ in UPHILL and was increased by 1 $km \cdot h^{-1}$ each minute. The test was stopped when the participant, despite strong verbal encouragement, involuntarily reduced the speed and passed a point marked on the treadmill. Then, after a 5-min passive break and a 3-min active recovery was conducted, a verification test was completed. The verification test was conducted at the highest work load reached during the incremental test until exhaustion, and was used to verify that no higher VO_{2peak} could be reached in this exercise mode.[17]

Respiratory variables (oxygen uptake (VO_2), respiratory exchange ratio (RER), minute ventilation (VE)) and heart rate (HR) were measured continuously throughout all tests. Motion capture data were recorded toward the end of each submaximal stage (2 x 30- s) and during each minute in the incremental test (1 x 30- s). After each submaximal stage, the incremental test and the verification test, the rating of perceived exertion (RPE) was recorded. One capillary blood sample taken from the fingertip was obtained after each submaximal stage, and two samples after termination (1- and 3- min) of both the incremental and verification test, for analysis of blood lactate (BLa). In addition to the verification test, maximal effort during the incremental test was verified through scoring on at least two of the following five criteria: 1) a plateau (three values within 2 $mL \cdot kg^{-1} \cdot min^{-1}$ measured every 10 second) or drop (> 2 $mL \cdot kg^{-1} \cdot min^{-1}$) in VO_2, 2) RER $\geq$ 1.05, 3) BLa $\geq$ 8 $mmol \cdot L^{-1}$, 4) RPE $\geq$ 17, and 5) peak HR (HR_{peak}) within 10 $beats \cdot min^{-1}$ of the individual age-predicted maximum (220-age-10[18]).

Instruments and materials

Respiratory variables were measured employing open-circuit indirect calorimetry (Oxycon Pro, Jeager GmbH, Hoechberg, Germany). Prior to collecting data of each participant, the VO_2 and CO_2 analyzers were calibrated using a mixture of gases (15.0 ± 0.04% O_2 and 5.0 ± 0.1% CO_2, Riessner-Gase GmbH & Co, Lichtenfels, Germany) and the expiratory flow meter was manually calibrated with a 3-L syringe (Hans Rudolph Inc., Kansas City, MO, USA). HR was measured with the Polar V800 watch, which was connected to a HR10 heart rate monitor (Polar Electro OY, Kempele, Finland). Capillary blood samples (20 µL) were analyzed for BLa using the Biosen C-Line lactate analyzer (Biosen, EKF Industrial Electronics, Magdeburg, Germany). RPE was recorded according to the Borg Scale (6-20).[19] Body mass was measured using a flat Seca 876 scale (Seca, Gmbh & co, Germany) and body height determined using a stadiometer Seca 213 (Seca, Gmbh & co, Germany) at the beginning of each test session.

The tests were performed on a 5 x 3 m motor-driven treadmill (Forcelink B.V., Culemborg, The Netherlands). All participants used the same XC sit-ski (SKENO, Oslo, Norway), attached to the same pair of classical roller-skis (resistance category 2; IDT Sports, Lena, Norway), with a “kneeing” sitting position and adjustable straps around the hips, thighs, and lower legs for individual adjustments. This “kneeing” sitting position is mostly used by Para-skiers classified as LW11.5 and LW12, who have full control of their trunk.[2, 20, 21] The front of the sit-ski was firmly attached to an aluminum crossbar of a custom-made safety-system, connected to rails on each side of the treadmill (Figure 1). Before study start, the coefficient of rolling resistance (μ) was determined as 0.018 using the towing test previously described by Sandbakk et al.[8] Rail-system friction was established by placing the crossbar of the safety-system at the front of the treadmill and incrementally increasing the incline until the bar began to move, determined as $F_{rail} = m_{xbar} \cdot g \cdot \sin\theta$, where m_{xbar} is the mass of the safety-system cross-bar, g the gravitational constant, and θ the angle of treadmill incline at which the crossbar first moves. The participants used Swix Triac 3.0 junior poles (Swix, Lillehammer, Norway) with carbide tips customized for treadmill roller-skiing. Pole length was selected to be within a range of 66 ± 2% of body height, together with the preference of each individual participant.

Figure 1

Nine infrared Oqus 400 cameras (Qualisys AB, Gothenburg, Sweden) captured three-dimensional position characteristics with a sampling frequency of 250 Hz. In total eight reflective markers (spherical, ⌀ 16 mm) were placed on the equipment: two markers on each ski (one 1 cm behind the front wheel and one 1 cm in front of the back wheel) and two markers on each pole (one ~5 cm below the bottom of the grip handle and one on the lateral side of the carbide tip). Before test start of each participant, the camera system was calibrated according to the manufacturer’s specifications.

Data processing and calculations

For each submaximal stage, respiratory variables and HR were calculated by averaging the values during the last two minutes. For the incremental and verification test, 30-s (with a 10-s data window) moving averages were calculated for the respiratory variables and 3-s moving average for HR. The highest respiratory values, RPE, and HR reached during either the incremental or verification test were defined as peak responses.

Metabolic rate (MR) was calculated from VO_2, associated measurements of RER, and a standard conversion table.[22] WR was calculated as the sum of power against gravity ($P_g = m_{body+equipment} \cdot g \cdot \sin\alpha \cdot v$), rolling friction ($P_{f-roll} = m_{body+equipment} \cdot g \cdot \cos\alpha \cdot v \cdot \mu$), and rail friction ($P_{f-rail} = F_{rail} \cdot v$), where $m_{body+equipment}$ is the mass of the skier and equipment, g the gravitational constant, α the angle of treadmill incline, v the belt speed, μ the coefficient of rolling resistance, and F_{rail} the rail-system friction. GE was calculated as the ratio of WR and MR, without any baseline subtraction.[23]

Kinematic data were registered in Qualisys Track Manager 2019.3 (Qualisys AB) and further processed in MATLAB R2019b (version 9.7.0.1190202, Mathworks, Natick, MA, USA). First, marker coordinates were rotated about the lateral axis by constant treadmill angle (corresponding to 0.5% for FLAT and 5% for UPHILL) and kinematic signals were spline interpolated where missing data gaps were ≤ 5 samples. Pole-belt contact (poling phase) was detected from unfiltered signals with a purpose-written algorithm using the right pole tip marker, determined as when the marker was simultaneously below a vertical position threshold (2.5 cm above belt) and a horizontal velocity threshold (~negative belt speed). Cycle time (CT) was calculated as the time between consecutive starts of pole-belt contact and CR as the reciprocal of CT. PT was defined as the period where the poles were in contact with the belt and ST as the period where the poles were off the belt. Relative PT and ST were calculated as percentage of CT. $\text{Work}_{\text{cycle}}$ was calculated as WR multiplied by CT. After the poling periods were detected, kinematic signals were low-pass filtered at 10 Hz with a fourth-order Butterworth filter. Next, instantaneous sit-ski velocity was obtained by numerical differentiation of a virtual marker representing the sit-ski (mean of all four ski markers), adding belt speed. Then, CL was calculated as the product of cycle mean sit-ski velocity and CT. Lastly, for each variable, the mean across all cycles was calculated. For each submaximal stage, cycles from the two measurements were combined before mean values were calculated.

During the submaximal stages, regression analyses were used to determine the relationship between absolute WR and the dependent variables for each individual participant. Linear regression analyses were used for the physiological variables, RPE, MR, and GE, and exponential regression analyses for BLa. Using inter- and extrapolation from the regression analyses, values of the dependent variables at a given absolute WR (60, 80, and 100 W) were calculated to compare FLAT and UPHILL at identical WR. The absolute WR at 60, 80, and 100 W corresponded to the velocities 10.8, 14.4, and 18.0 $\text{km}\cdot\text{h}^{-1}$ in FLAT and 3.6, 4.7, and 5.9 $\text{km}\cdot\text{h}^{-1}$ in UPHILL.

Statistical analysis

Data are presented as means ± SD. A linear mixed model with fixed coefficients and random intercept was employed to investigate the main effect of incline and intensity for each dependent variable (physiological variables, RPE, and cycle characteristics), as well as the interaction between incline and intensity during the submaximal stages. Post-hoc tests with Bonferroni correction were employed for pairwise comparisons between FLAT and UPHILL for each dependent variable at each absolute WR. Paired samples t-tests were used to investigate differences in peak values between FLAT and UPHILL. The assumption of normality of residuals (mixed models) and difference scores (paired t-tests) was tested with the Shapiro-Wilk W test. An alpha level of 0.05 was used to indicate statistical significance. IBM SPSS Statistics 24.0 (SPSS Inc., Chicago, IL, USA) was used for all statistical analyses.

RESULTS

Work rate, physiological variables and RPE

Comparison at a given submaximal WR. All physiological variables and RPE increased with increasing absolute WR (all $p < 0.02$). Most of the physiological variables and RPE were higher in FLAT compared to UPHILL (all of these $p < 0.04$). There was an interaction effect between incline and WR for most physiological variables and RPE (all of these $p < 0.01$; Figure 2): they increased more with increasing WR in FLAT compared to UPHILL. RER was not different between FLAT and UPHILL ($p = 0.35$; Figure 2). Accordingly, MR increased with increasing absolute WR ($p < 0.001$). Overall, MR was higher at a given WR in FLAT compared to UPHILL ($p < 0.001$). GE increased with increasing absolute WR in UPHILL ($p < 0.001$) but was not different between the different absolute WRs in FLAT ($p = 1.0$). In addition, GE was higher in UPHILL compared to FLAT ($p < 0.001$). There was an interaction effect between incline and WR for MR and GE (both $p < 0.001$). MR increased more with increasing WR in FLAT compared to UPHILL. GE was unchanged in FLAT compared to UPHILL (Figure 2).

Peak values. In UPHILL, WR_{peak} was 35% higher compared to FLAT ($p < 0.001$). There were no significant differences in peak physiological variables and RPE between UPHILL and FLAT (all $p > 0.3$; Table 1). Test duration was 147 ± 114 s longer in FLAT compared to UPHILL ($p < 0.001$).

Figure 2 and Table 1

Cycle characteristics

Comparison at a given submaximal WR. CR, CL, work$_{cycle}$, and relative ST increased with increasing absolute WR in FLAT and UPHILL (all $p < 0.001$), while the corresponding values for CT, PT, and relative PT decreased (all $p < 0.001$). ST was not affected by increasing absolute WR in FLAT and UPHILL ($p = 0.14$). Overall, CL, ST, and relative ST were shorter (all $p < 0.001$), whereas PT was longer, in UPHILL compared to FLAT (all $p < 0.001$). Overall, there was no difference in CR, CT, and work$_{cycle}$ between FLAT and UPHILL (all $p > 0.16$), but there was a small difference in CR and CT at 60 W between FLAT and UPHILL (both $p < 0.05$). There was an interaction effect between incline and WR for CL, ST, relative PT, and relative ST (all $p < 0.04$): CL and relative ST increased, and ST and relative PT decreased more with increasing absolute WR in FLAT compared to UPHILL (Figure 3).

Peak values. Compared to FLAT, in UPHILL CL was 2.6 ± 0.2 m shorter, PT was 0.14 ± 0.05 s longer, ST was 0.16 ± 0.10 s shorter, relative PT was 17 ± 3 percentage points higher, relative ST was 17 ± 3 percentage points lower, and work$_{cycle}$ was 34 ± 4% higher (all $p < 0.001$). There was no difference in CT and CR between FLAT and UPHILL (both $p > 0.8$; Table 1).

Figure 3

DISCUSSION

In this first investigation of double poling when XC sit-skiing on a treadmill, the ability to produce WR and associated physiological and biomechanical performance-determining variables were compared between flat and uphill. In UPHILL with 5% incline, WR$_{peak}$ was 35% higher compared to FLAT with 0.5% incline, which coincided with more work$_{cycle}$ and twice as long PT at 5% incline, whereas no difference in VO_{2peak} was found across conditions. When compared at identical WR, most physiological responses were lower, and GE was higher in UPHILL compared to FLAT.

Despite different test durations between FLAT and UPHILL, neither VO_{2peak}, RPE, nor any of the other peak physiological variables were different between conditions, which is in accordance with previous findings in seated upper-body poling.[24] This indicates that the cardio-vascular system was taxed equally and that similar levels of exhaustion were reached in both conditions. Further, in seated upper-body poling it has been shown that a 140 s longer incremental test to exhaustion is accompanied by 9% lower WR production.[24] Comparatively, in the current study, the incremental test to exhaustion was 147 s shorter in UPHILL than FLAT, accompanied by a 35% higher WR$_{peak}$. Consequently, most of the difference found in WR$_{peak}$ between UPHILL and FLAT can likely be explained by better efficiency in UPHILL and not the difference in test duration. In accordance with findings in able-bodied XC skiers,[6, 14, 25] the better efficiency found in UPHILL was accompanied by lower physiological and perceptual effort when working at an identical submaximal WR in UPHILL. In addition, the resting metabolic rate constitutes a smaller proportion of the overall metabolic rate and has a decreasing impact on GE as the WR increases. Thereby, as expected GE increased as WR became higher in UPHILL due to the decreasing impact of resting metabolic rate on GE.[23, 26] However, in FLAT, GE remained stable with increasing WR and the difference in GE between inclines therefore increased at higher WR. This difference in the WR-MR relationship between FLAT and UPHILL indicates that maintaining technique and efficiency when speed increases in flat terrain is technically more challenging and requires a greater metabolic rate to increase WR compared to the same WR increase in uphill terrain.

Furthermore, compared to flat terrain, a higher anaerobic contribution in uphill has previously been reported in both able-bodied XC skiing[13, 27] and running,[28] attributed to a different recruitment of muscle fibers and greater amount of active muscle mass. Together with the shorter test duration in UPHILL, it is likely that some of the difference in WR_{peak} found between FLAT and UPHILL could be connected to an earlier recruitment of fast twitch muscle-fibers and a higher anaerobic contribution in UPHILL compared to FLAT. However, if this difference in anaerobic contribution between inclines also occurs during XC sit-skiing, especially in the lower classes where trunk movement is limited, remains to be investigated.

The lower speed utilized when XC sit-skiing UPHILL enables a longer PT and production of larger $work_{cycle}$ and WR_{peak} compared to FLAT. This is, amongst other things, related to the higher contribution of work against gravity to total work in UPHILL.[25, 27] However, in line with what has previously been shown in a case study on a Para XC sit-skier during skiing on snow,[5] CR was similar in UPHILL and FLAT. In contrast, able-bodied XC skiers,[7] seem to display a higher CR in uphill terrain (between 4.5-8% at a given WR), which is likely related to the larger range of motion in the trunk and longer time to produce propulsion during able-bodied XC skiing compared to XC sit-skiing.

In our study, speed in the different inclines is solely regulated through changes in PT and ST. In UPHILL, accompanied by the slower speed, a longer PT was found, which enables longer time for generation of propulsive forces and production of WR.[6, 7] This is probably connected to both the muscles working in a more favorable range of the force-velocity relationship,[29] and a shorter swing time without any force production, which together might be the main mechanisms behind the better GE in UPHILL. In addition, in able-bodied XC skiing,[6] a greater force impulse and higher peak pole force later in the cycle have been demonstrated in uphill terrain. The higher WR_{peak} as well as the lower physiological variables and RPE at identical submaximal WR in UPHILL demonstrated in this study are likely connected to these mechanisms as well. However, this remains to be investigated in XC sit-skiing. Furthermore, Para XC sit-skiers have various movement limitations linked to their different disabilities. Thus, whether the differences in cycle characteristics between FLAT and UPHILL found in able-bodied XC sit-skiing also occur in Para XC sit-skiers needs to be further investigated.

Practical applications

The higher WR achieved by XC sit-skiers uphill is accompanied by a better efficiency compared to flat, demonstrating that the constraints when double poling uphill allow a more efficient technique where more of the metabolic energy goes to WR. The higher efficiency also implies that a given increase in WR would cost less metabolic energy in uphill compared to flat terrain, which could explain why most skiers find it beneficial to increase their effort in uphill terrain during competitions.[27, 30] Conversely, that XC sit-skiers are able to tax their aerobic capacity similarly in uphill and flat conditions (i.e., similar VO_{2peak} in FLAT and UPHILL), indicates that the physiological responses can be stimulated to the same degree during training in both types of terrain, even though the WR produced in flat terrain is much lower. Taken together, this establishes an important foundation for understanding the underlying mechanisms for choice of pacing strategy in Para XC sit-skiing. In addition, our data indicate that VO_{2peak} testing can be performed on both flat and uphill conditions. However, if the aim is to test efficiency, the external conditions must be standardized well as both WR and incline affect GE. Finally, the generalizability of our findings to Para XC sit-skiers with different disabilities and their different sitting positions (i.e., “kneeing” and “knee-high”) needs to be established, although the current data serve as a baseline for further research in the field of Para XC skiing.

CONCLUSION

The longer poling times utilized in uphill XC sit-skiing enable more work per cycle and better GE, thereby allowing skiers to achieve a higher WR_{peak} compared to flat XC sit-skiing. However, the similar values of VO_{2peak} between inclines indicate that XC sit-skiers can tax their cardiorespiratory capacity similarly in both conditions.

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FIGURE AND TABLES CAPTIONS

Table 1. Peak physiological variables, RPE, cycle characteristics and test duration during upper-body double poling in a cross-country sit-ski at 0.5% (FLAT) and 5% (UPHIILL) incline. The highest respiratory values, RPE, and HR reached during either the incremental or verification test were defined as peak responses (mean ± SD).

Variables	**FLAT**	**UPHILL**
WR_{peak} (W)	128 ± 9	197 ± 26 "
VO_{2peak} (mL·kg^{-1}·min^{-1})	46 ± 4	46 ± 5
VE_{peak} (L·min^{-1})	170 ± 32	169 ± 26
RER_{peak}	1.10 ± 0.10	1.08 ± 0.15
MR_{peak} (W)	1275 ± 171	1277 ± 170
HR_{peak} (beats·min^{-1})	178 ± 13	177 ± 7
BLa_{peak} (mmol·L^{-1})	10 ± 2	11 ± 2
RPE_{peak} (6-20)	18 ± 1	18 ± 1
CR (Hz)	1.2 ± 0.2	1.2 ± 0.2
CL (m)	5.2 ± 1.0	2.7 ± 0.5 "
CT (sec)	0.9 ± 0.1	0.9 ± 0.2
PT (sec)	0.2 ± 0.04	0.4 ± 0.06 "
ST (sec)	0.7 ± 0.1	0.5 ± 0.1 "
Relative PT (% of cycle)	25 ± 3	42 ± 5 "
Relative ST (% of cycle)	75 ± 3	58 ± 5 "
$Work_{cycle}$ (J)	113 ± 22	170 ± 23 "
Test duration (sec)	513 ± 100	366 ± 90 "

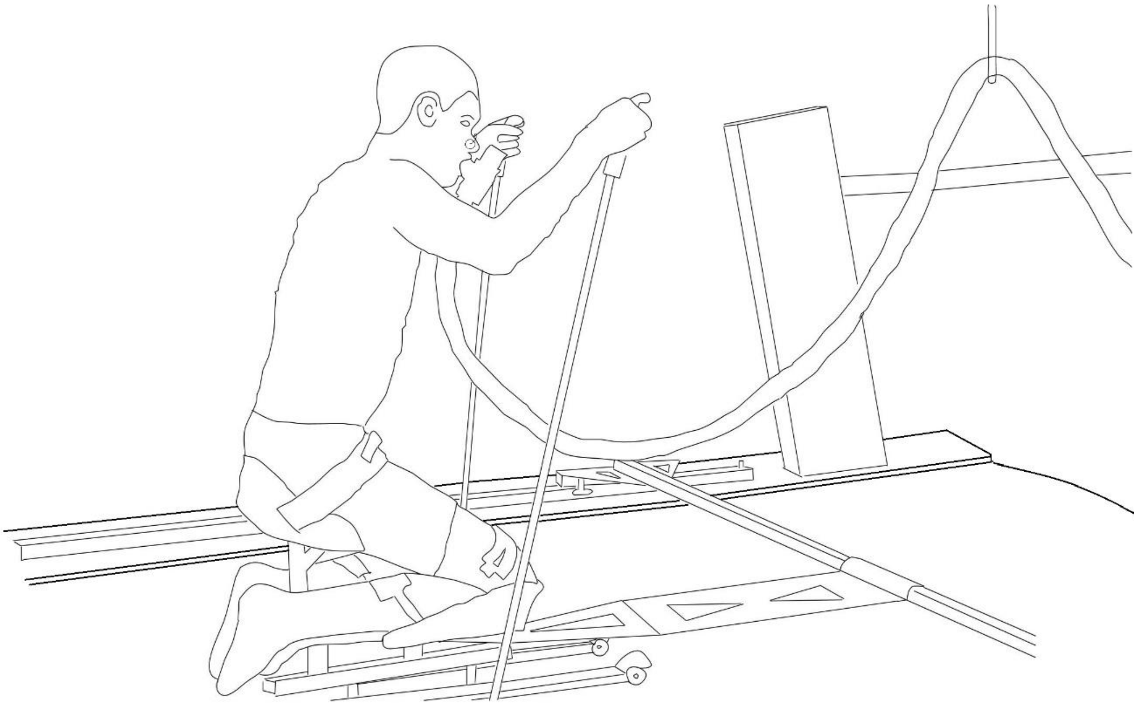
Peak work rate (WR_{peak}), peak oxygen uptake (VO_{2peak}), peak minute ventilation (VE_{peak}), peak respiratory exchange ratio (RER_{peak}), peak metabolic rate (MR_{peak}), peak heart rate (HR_{peak}), peak blood lactate concentration (BLa_{peak}), peak rating of perceived exertion (RPE_{peak}), cycle rate (CR), cycle length (CL), cycle time (CT), poling time (PT), swing time (ST), and work per cycle ($work_{cycle}$).

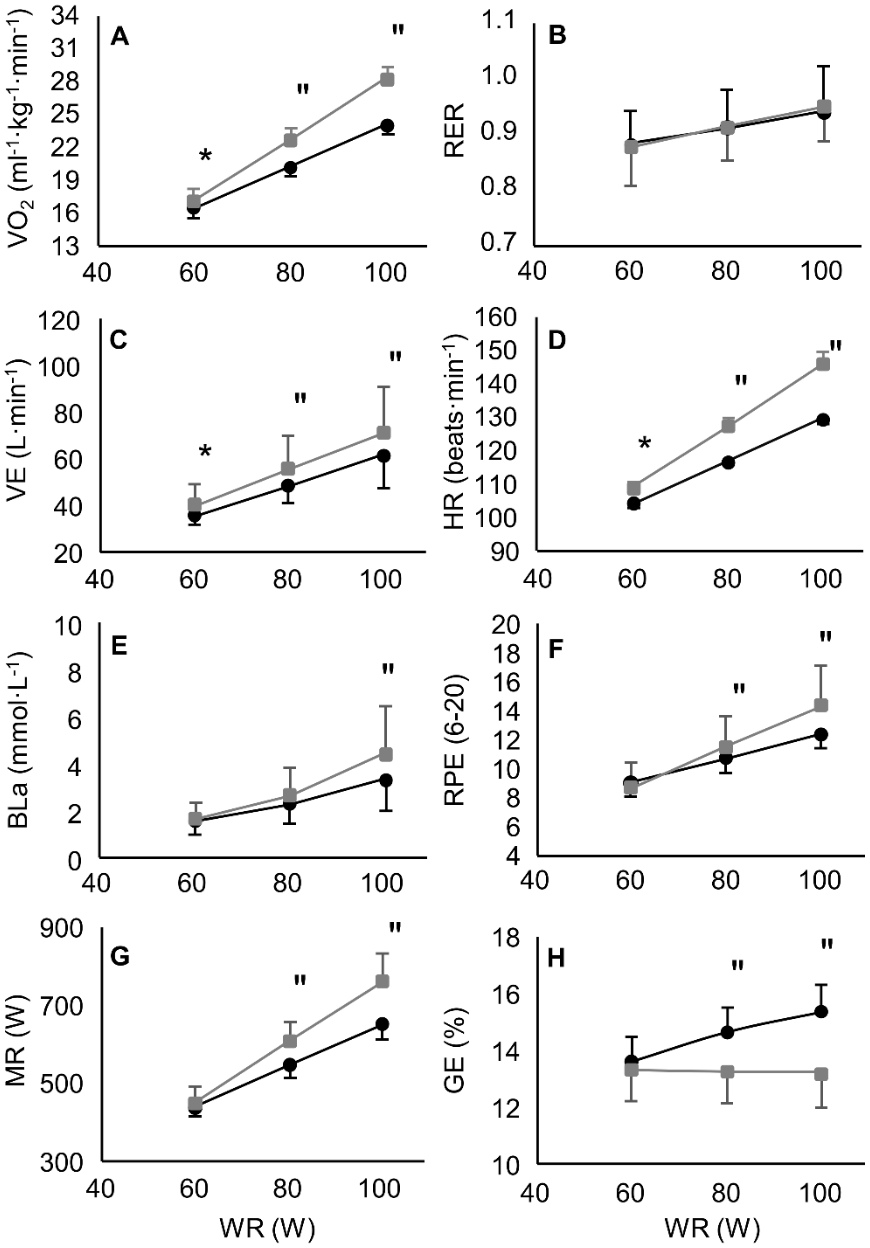
"Significantly higher in UPHILL compared to FLAT at an alpha level of 0.01.

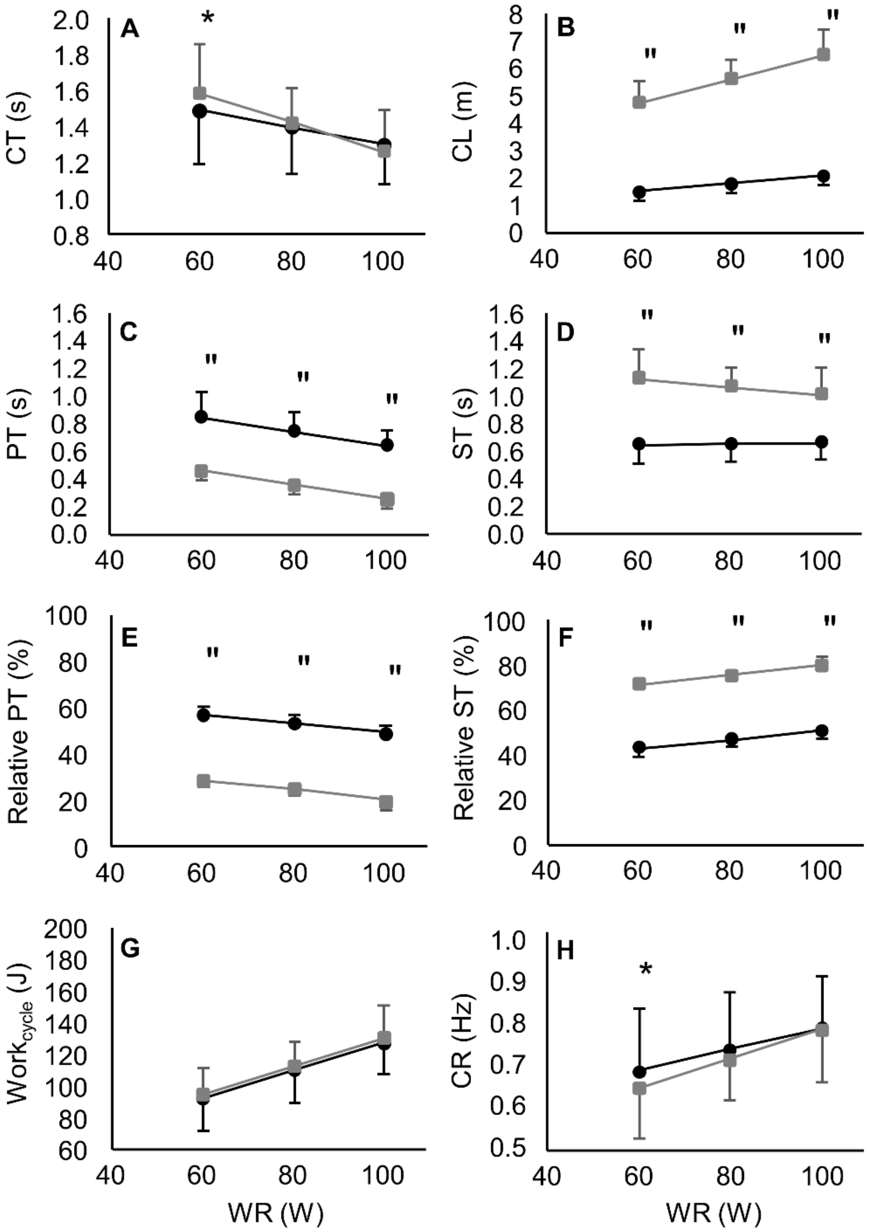
Figu Test set-up on the treadmill. The XC sit-ski was mounted on a pair of classical roller-skis, with a “kneeing” sitting position and adjustable straps around the hips, thighs, and lower legs that secured the participant to the sit-ski. The front of the sit-ski was firmly attached to an aluminum crossbar of a custom-made safety-system, connected to rails on each side of the treadmill, allowing the crossbar to move in the same direction as the sit-ski.

Figure 2. Oxygen uptake (VO_2), respiratory exchange ratio (RER), minute ventilation (VE), heart rate (HR), blood lactate concentration (BLa), rating of perceived exertion (RPE), metabolic rate (MR), and gross efficiency (GE) presented as mean ± SD at a given absolute work rate (60, 80 and 100 W) during upper-body double poling in a XC sit-ski at 0.5% incline (FLAT; grey squares and line) and 5% incline (UPHILL; black circles and line).
*Significant difference between FLAT and UPHILL at an alpha level of 0.05.
"Significant difference between FLAT and UPHILL at an alpha level of 0.01.

Figure 3. Cycle time (CT), cycle length (CL), poling time (PT), swing time (ST), relative PT, relative ST, work per cycle ($work_{cycle}$), and cycle rate (CR) presented as mean ± SD at a given absolute work rate (WR; 60, 80 and 100 W) during upper-body double poling in a XC sit-ski at 0.5% incline (FLAT; grey squares and line) and 5% incline (UPHILL; black circles and line).
*Significant difference between FLAT and UPHILL at an alpha level of 0.05.
"Significant difference between FLAT and UPHILL at an alpha level of 0.01.




A
VO$_2$ (ml^{-1}·kg^{-1}·min^{-1})
34
31
28
25
22
19
16
13
*
"
"
B
RER
1.1
1.0
0.9
0.8
0.7
C
VE (L·min^{-1})
120
100
80
60
40
20
*
"
"
D
HR (beats·min^{-1})
160
150
140
130
120
110
100
90
*
"
"
E
BLa (mmol·L^{-1})
10
8
6
4
2
0
"
F
RPE (6-20)
20
18
16
14
12
10
8
6
4
"
"
G
MR (W)
900
700
500
300
"
"
H
GE (%)
18
16
14
12
10
"
"
40
60
80
100
WR (W)
WR (W)


A
CT (s)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
*
B
CL (m)
8
7
6
5
4
3
2
1
0
"
C
PT (s)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
D
ST (s)
E
Relative PT (%)
100
80
60
40
20
0
F
Relative ST (%)
G
Work$_{cycle}$ (J)
200
180
160
140
120
100
80
60
H
CR (Hz)
1.0
0.9
0.8
0.7
0.6
0.5
40
60
80
100
WR (W)