Manuscript Details

Manuscript number	HMS_2017_242
Title	The Role of Speed and Incline in the Spontaneous Choice of Technique in Classical Roller-Skiing
Article type	Full length article

Abstract

Cross-country skiers change technique depending on terrain (incline) and effort (work rate; speed at a particular incline or resistance). The literature is not unequivocal about the influence of incline or speed on the choice of technique, i.e., which of these act as a 'control parameter'. Identifying task related control parameters for spontaneous technique shifts assists elucidating which mechanisms are active for triggering technique transitions. The aim of this study was to investigate whether speed or incline acted as such control parameter for technique shifts during classic style roller skiing. In this study, we kept the exercise intensity constant while changing two potential control parameters (speed and incline). Thus, any effect of work rate was excluded. Eight male competitive cross-country skiers performed roller skiing on a treadmill while incline was altered from 3 to 11% and back to 3% each minute by 1% and speed changed accordingly to obtain a constant work rate. This protocol was performed at three submaximal work rates (170, 200, and 230 W) to obtain various combinations of speed and incline. The athletes were free to choose their technique (double poling, double poling with kick and diagonal stride), which was identified using continuous phase analysis on the motion of the skis. Physiological response (heart rate, oxygen uptake) was recorded continuously. The incline seemed to affect choice of technique shift more than speed: the ANOVA for repeated measures on all work rates showed no significant effect of incline ($p > 0.2$) and an effect for speed ($p < 0.001$). No effect of protocol order (increasing versus decreasing incline) was found for transitions. The physiological response was lowest for conditions of steep incline-low speed and was affected by protocol order. Cycle rate was affected by incline only in the double poling technique. Possible mechanisms related to the triggering of technique transitions are discussed.

Keywords	Cross-country skiing; phase transitions; coordination
Taxonomy	Sport, Movement

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The Role of Speed and Incline in the Spontaneous Choice of Technique in Classical Roller-Skiing

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Eight male competitive cross-country skiers performed roller skiing on a treadmill while incline was altered from 3 to 11% and back to 3% each minute by 1% and speed changed accordingly to obtain a constant work rate. This protocol was performed at three submaximal work rates (170, 200, and 230 W) to obtain various combinations of speed and incline.

The athletes were free to choose their technique (double poling, double poling with kick and diagonal stride), which was identified using continuous phase analysis on the motion of the skis. Physiological response (heart rate, oxygen uptake) was recorded continuously.

The incline seemed to affect choice of technique shift more than speed: the ANOVA for repeated measures on all work rates showed no significant effect of incline ($p > 0.2$) and an effect for speed ($p < 0.001$). No effect of protocol order (increasing versus decreasing incline) was found for transitions. The physiological response was lowest for conditions of steep incline-low speed and was affected by protocol order. Cycle rate was affected by incline only in the double poling technique.

Possible mechanisms related to the triggering of technique transitions are discussed.

Highlights

- Technique transitions in classical style cross-country skiing are guided by incline, not speed.
- The incline at which technique shifts occur does not depend on the direction of change.
- When exercising at a constant work rate in classic cross-country skiing, energy consumption is lowest at steep incline – low speed condition.

1. Introduction

Cross-country ski training and competition is typically performed in varied terrain where skiers use different techniques, both in freestyle (skating) and classical style, primarily depending on that terrain. The different techniques are considered as a gear system to adapt to changes in speed and incline (e.g., Nilsson, Tveit, & Eikrehagen, 2004), possibly in a similar way as different gait forms (running vs walking) are preferred depending primarily on speed. Parameters that trigger transitions in gait in general are well investigated. Metabolic rate (Alexander, 1989; Hoyt & Taylor, 1981; Mercier et al., 1994), mechanical stress (Farley & Taylor, 1991; Hreljac, 1995; Neptune & Sasaki, 2005) and subjective feeling of comfort (Daniels & Newell, 2003; Prilutsky & Gregor, 2001; Thorstensson & Roberthson, 1987) have been proposed as parameters that, when reaching critical values, trigger transitions.

In cross-country skiing in the classic style, the main techniques applied are diagonal stride (DIA), double poling with a kick (DK) and double poling (DP). DIA follows a diagonal coordinated pattern as known from walking and running, where arms and legs move contralateral (Pellegrini et al., 2013). The DIA technique is primarily used in moderate to steep uphill slopes, where the high propulsive phase ratio (the relation between propulsive phase and recovery phase) provides advantages (Dahl, Sandbakk, Danielsen, & Ettema, 2017; Pellegrini et al., 2013). DP is a symmetrical and synchronous movement of both arms, where the propulsive forces are exerted only through the poles. The propulsion is supported by considerable trunk flexion (Holmberg, Lindinger, Stoggl, Eitzlmair, & Muller, 2005). The lower limbs contribute in the production of propulsive forces by elevating center-of-mass by extending ankle- and knee joints, resulting in an increase of potential energy (Dahl et al., 2017; Danielsen, Sandbakk, Holmberg, & Ettema, 2015; Holmberg, Lindinger, Stoggl, Bjorklund, & Muller, 2006). DP is most frequently used in slight uphill, slight downhill and flat terrain, but in recent years also in steeper uphill terrain when the friction is low and the snow is hard-packed and allows for effective poling. In DK, the upper body movement is quite similar to the movement in DP. In addition to the propulsive force from the poles, DK is supported by propulsion from either a left or right leg kick, inserted between the double poling actions to enhance the propulsive phase. DK is a combination of DIA and DP and is commonly used slightly uphill or if snow conditions cause high resistance in flat terrain (Smith, 2003). The inserted leg kick has the same characteristics as the lower limb movement in DIA (Lindinger, Gopfert, Stoggl, Muller, & Holmberg, 2009). DK has a large propulsive phase of about 52% of a cycle, including leg- and pole push offs. This is considerably higher than that of DP at similar speeds, with a propulsive phase of 30-38% of a cycle (Göpfert, Holmberg, Stöggl, Müller, & Lindinger, 2012), but lower than DIA with a phase of about 80% at high speed (Dahl et al., 2017). In addition to the large amount of propulsive phases, DK shows the lowest cycle rate among the sub-techniques in classical cross-country skiing.

Although the conditions under which particular techniques are preferred are reasonably well known, most studies that target this issue were not designed to identify, independently of workload, the task related control parameter, i.e., slope or speed, for the transition of technique. For example, Cignetti, Schena, Zanone, and Rouard (2009) investigated transitions in classical cross-country skiing by letting the skiers ski “as naturally as possible” while roller-skiing on a treadmill where speed was constant (10 km h^{-1}) and the incline increased by 1° every 30 second, from 0° to 7°. Cignetti et al. (2009) suggested that increasing incline caused a technique transition by a loss of stability. Pellegrini et al. (2013) used the same test setup as Cignetti et al. (2009), but in addition varied speed at a constant incline. In addition, they tried to identify the main trigger parameters regarding technique transition in classical cross-country skiing. The results from this study suggested two different primary parameters. They hypothesized that there is a limited force a skier would like to exert through the poles and approaching this limit triggers a transition to another technique where less of the propulsive forces are exerted through the poles. The other suggested parameter was leg thrust time, i.e., the time where the ski stands still during a leg stride. The thrust time was suggested to have a lower limit (0.1 s), which, if approached, would trigger a technique transition allowing longer thrust time. This corresponds to Nilsson et al. (2004) observations, where 0.15 seconds was the shortest leg thrust time. Although these studies provide valuable information about the control parameter(s) that may play central roles in shifts of technique, they are not (and cannot be) conclusive about whether incline and/or speed is the key control parameter that determines technique shifts in varying terrain. Therefore, it was our aim to explore this issue further by a protocol that changed both incline and speed simultaneously to keep workload unaltered. By performing this protocol at different workloads, i.e., studying different combinations of incline and speed, we attempted to determine which of these two parameters, if any, could be regarded as the control parameter for technique shifts. We recorded motion of skis and poles to identify the different techniques and changes thereof, and cycle rate was determined to shed light on possible mechanisms behind technique shifts. Furthermore, we recorded the physiological response continuously to investigate if metabolic demand was altered throughout this protocol.

2. Methods

2.1. Participants

Eight male national level competitive cross-country skiers (age 22.4 ± 1.7 years, body height 183.7 ± 4.4 cm, body mass 80.3 ± 7.7 kg, and $\dot{V}O_{2\max}$ 73.9 ± 6.4 ml kg^{-1} min^{-1}) volunteered to participate in this study. All procedures were explained verbally to each skier and written informed consent was obtained and signed. All participants were informed that could withdraw at any time without giving any reason. The study was registered, and approved by

Norwegian Social Science Data Services. The study was conducted in accordance with the Declaration of Helsinki.

2.2. Experimental Design

All participants completed three sessions of warm-up and a test protocol at constant work rate. The warm up was performed on the treadmill and consisted of a 5-minute self-paced familiarization period before a standardized 12-minute warm-up at varying speed and incline during which techniques could be employed. The test sequences (Figure 1A) were done at three different submaximal aerobic work rates (target: 170, 200, and 230 Watts) in randomized order and were executed on three different days. First, 11 minutes of constant work rate where incline increased by 1% each minute from 3 to 11% incline, and speed simultaneously decreased accordingly to obtain the same and constant external workload ('upward' protocol). The first incline-speed combination was maintained 3 minutes rather than one to give the athlete time to obtain steady state physiological conditions. Each shift of incline and speed took about 2 seconds to complete. After a short 1-minute break, this was followed by 11 minutes of the same work rate with decreasing incline (from 11 to 3%) and corresponding increasing speed ('downward' protocol).

The speeds to obtain the target work rates were calculated according to Sandbakk, Holmberg, Leirdal, and Ettema (2010):

$$P_{target} = mg\ v\ (sin\alpha + \mu\ cos\alpha) \leftrightarrow v = P_{target}\ (mg\ (sin\alpha + \mu\ cos\alpha))^{-1}$$

With P_{target} the targeted work rate, v the target speed, m the participants' expected average body mass (78 kg), μ (≈0.022) the friction coefficient as established by a towing test (Sandbakk et al., 2010), g gravitational acceleration, and α incline. Thus, slightly different work rates were used for each athlete depending on their body mass. This approach was preferred above using identical workloads for all participants for practical reasons as well as because this would resemble the usual testing and competitive situations in which all participants undergo the same protocols based on speed and incline.

2.3. Instruments and Materials

The participants skied on a 5x3-meter treadmill (Forcelink Technology, Zwolle, The Netherlands), optimized for roller skiing. All athletes used the same pair of roller skis (Pro¬Ski, Sterners, Nyhammar, Sweden) with wheels from IDT (IDT Sports, Lena, Norway, resistance category 2). The poles (Madshus UHM 100, Biri, Norway) were available in five-centimeter incremental lengths and all participants were allowed to choose their preferred length, which subsequently was used in all tests. All three test-protocols where pre-programmed using the treadmill's software.

2.3.1. Physiological variables

Oxygen uptake ($\dot{V}O_2$) was measured by using open-circuit indirect calorimetry (Oxygen Pro apparatus, Jaeger GmbH, Hoechberg, Germany). The aerobic metabolic rate was calculated as the product of $\dot{V}O_2$ and the oxygen energetic equivalent using the associated respiratory exchange ratio (*RER*) and standard equations based on the conversion tables in Peronnet and Massicotte (1991). Before each test- session, the system was calibrated using a known mixture of gases (16.00% ± 0.04% O_2 and 5.0% ± 0.1% CO_2, Riessner-Gase GmbH & Co, Lichtenfels, Germany), and the expiratory flowmeter was calibrated with a 3-liter pump (Hans Rudolph Inc, Kansas City, MO). Heart rate was recorded with a heart-rate monitor (Garmin, USA), at a samplings rate of 1Hz. Respiratory variables were recorded continuously during the entire session. Gross efficiency (*GE*) was calculated as the ratio of external work rate, i.e., P_{target}, over aerobic metabolic rate.

2.3.2. Kinematical variables and technique identification

Kinematic data were collected during the periods of interest, i.e., 9 minutes during upward and downward protocol using the Oqus motion capture system with six cameras (Qualisys AB, Gothenburg, Sweden) at 50 Hz. Six passive reflective markers, one on each ski (rear), one on each pole (about five cm below the pole grip), and two on the treadmill in longitudinal direction. Figure 2 depicts the procedure for identification of skiing technique (DP, DK, DIA) and cycle rate (*CR*): in a specially written script in Matlab (8.4.0 R2014b, Mathworks Inc., Natick, MA, USA), the mean continuous phase between the skis was determined for a complete cycle (phase ≤ 30 degrees, in-phase = DP; phase≥120, out-of-phase = DIA; 30<phase<120 usually about 60 degrees phase = DK). Movement cycles were identified by finding local minima and maxima of the ski movement in fore-aft direction relative to the moving belt. These movement cycles (that were sinusoidal in nature) were normalized for amplitude before being transformed to angle. The relative phase was determined as the difference between the two angles. A moving average, with a window width of five complete movement cycles was applied to the relative phase trace to handle noise. The relative phase for DIA and DP is very consistent with little variation because the phase hardly changes within one cycle. However, in DK, the phase changes within one cycle from out-of-phase to in-phase, which after smoothing appears as a 'band' (Figure 2). Occasionally, an athlete would switch to another technique to return to the original one within a few movement cycles. Such shifts were ignored and only lasting shift, i.e., leading to the use of another technique for at least three whole cycles were considered in further analysis.

The algorithm was quality checked by comparing the computed technique transition times with the times that were registered during the experiments. A continuously running video camera was used as a control if any disagreement between the two previously mentioned methods. This was necessary only twice, and the video recordings showed that the algorithm was correct.

2.4. Statistical analysis

All data were checked for normality and presented as means and standard deviations. To test whether incline and/or speed were the control parameter, both incline and corresponding speed at which technique shifts occurred were compared as outcome variables in a 2-way ANOVA for repeated measures (three work rates × two incline-speed orders) using the Statistical Package for the Social Sciences (SPSS 24; IBM Corp., Armonk, NY). Local differences between work rates were checked using ‘difference’ contrasts. Physiological response variables were analyzed with respect to change over time (condition) during the protocol using linear regression analysis, and order of protocol using Student’s t-test for paired comparisons.

3. Results

Figure 3 exemplifies the time trace results for one participant. Permanent technique shifts always occurred during or within a few seconds of a change of incline and speed. For all athletes, no techniques shifts between DP and DIA occurred, only between DP-DK and DK-DIA. In all cases DP was applied at the slighter inclines (higher speeds), DIA at the steeper inclines (lower speeds), and DK at intermediate inclines and speed. In three (out of 54) occasions, DIA was not applied.

3.1. Technique shifts

The incline and speed at which the two technique shifts (DP-DK and DK-DIA) occurred are shown in Figure 4A. The effect of work rate on incline-of-shift was not significant (DP-DK p=0.886; DK-DIA p=0.212). No order effect was found (DP-DK p=0.084; DK-DIA p=0.239).

The effect of work rate on speed-of-shift was highly significant ($p<0.001$ for both shifts), and no order effect was found (DP-DK $p=0.469$; DK-DIA $p=0.371$). All local differences (contrasts) for work rate were significant ($p \leq 0.027$). Because the protocol was designed to obtain constant work rate, and speed was based on given inclines, small differences in the programmed speeds between work rates existed. Thus, speeds of technique transition could be similar but never identical between work rates (as inclines could be). To check if this affected the statistical outcome, the same procedure was applied to the rounded speed values (in whole km h^{-1}, which contained identical values between work rates). The mean difference between actual and rounded speed amounted to 0.23 km h^{-1}, with a maximal difference of 0.5 km h^{-1}. For these rounded speeds, a similar outcome was obtained as for the original speed values (main work rate effect $p<0.001$ for both shifts; interaction DP-DK $p=0.368$; DK-DIA $p=0.482$). This basically implies that the differences in speed among the three work rates where technique shifts occurred was larger than the sensitivity introduced by the protocol.

3.2. Cycle rate

Changes in *CR* driven by incline-speed settings (as apparent in Figure 3) are small in comparison to the changes driven by choice of technique. Furthermore, *CR* in DK and DIA are very similar. Because *CR* is strongly affected by technique, the effect of incline-speed combination was tested within each technique employed by the athletes. For DIA (four inclines), no effect of incline was found; for DK the dataset with congruent inclines was too small, i.e., too few athletes applied DK at same inclines for this purpose; for DP (two inclines) a significant effect of incline was found ($p=0.003$), for work rate ($p=0.042$), as well as interaction ($p=0.007$): *CR* increased with incline, except for the highest work rate where there was no effect.

3.3. Physiological response

The physiological response shows relatively steady conditions during the period of statistical analysis, but gradual changes occur that are consistent among athletes. Fig. 5 shows the physiological response (for ‘upward’ and ‘downward’ protocol, against incline-speed condition in the protocol). The rate of change in the physiological response was small but significant and depended on incline-speed condition rather than time per sé. Expressed as mean ± S.D. for all work rate and protocol order combinations, rate of change for $\dot{V}O_2$ amounted to 0.59 ±0.35 ml kg^{-1} min^{-2}, *HR* to 1.24 ±1.14 beats min^{-2} (significant only in ‘downward’ protocol), and *GE* to 0.25 ±0.13 % min^{-1}. Noticeably, for all work rates, the steep incline – low speed condition resulted in in the lower metabolic cost and higher efficiency. Protocol order effects, i.e., ‘upward’ and ‘downward’ data deviating from each other, were identified for most of the protocol. Generally, the ‘downward’ protocol led to lower physiological response, particularly at the steep incline- low speed conditions. *RER* never exceeded 1.0, indicating the exercise conditions were aerobic.

4. Discussion

The main findings of this study were that the spontaneous shifts between techniques in the classic style in submaximal and constant work rate cross-country skiing is steered by incline rather than speed. The protocol order did not influence the conditions of shifts, ruling out large hysteresis effects or duration of the exercise. Furthermore, almost all transitions occurred instantaneously at incline-speed changes, and were in line with findings by Cignetti et al. (2009). Cycle rate was mostly determined by the choice of technique and affected by incline-speed condition only in DP. The physiological response was affected by the incline-speed combination: the steeper incline with lower speed combination tended to show lower

$\dot{V}O_2$ and *HR*, and higher *GE*. The protocol order affected the physiological response, with the second ('downward') protocol leading to a lower response $\dot{V}O_2$ and higher *GE*.

4.1. Choice of technique

The first purpose of this study was to examine if incline or speed was the control parameter for any transition in technique during constant work rate classic roller skiing. The results clearly indicate that incline is the steering parameter. Our results regarding incline-speed combinations and technique preferences seem to agree with findings by Pellegrini et al. (2013). However, the fact that speed does not seem to play a role of significance contradicts suggestions made by these authors and by Dahl et al. (2017) with regard to the mechanism that may explain the choice of using DIA (and DK). Pellegrini et al. (2013) argue that with increasing speed the time to propel becomes too short for ski propulsion using DIA. If speed and related time for leg thrust is a key determinant, we cannot explain our findings depicted in Figure 4: if the speed at which the shift to DIA occurs at 170 W is critical (i.e., it is less than 8 km h^{-1} for DIA), the shift at 230 at about 10 km h^{-1} cannot be explained. The same applies for the shift to DK for which attainable conditions are to be met at higher speeds (Pellegrini et al., 2013).

The reason for why incline is the main steering parameter for techniques choice is open for debate, but some suggestions are given here. The incline most likely affects the positioning of the body relative to the ground surface. For example, small differences in joint angles may exist depending on incline, which will affect dynamics and energy consumption (e.g., Stöggl & Holmberg, 2016). A more straightforward aspect of incline is the effect via the resistive component of gravity placing demands on propulsion forces. A way of approaching such incline effect is that by di Prampero et al. (2005) who compared accelerated running (i.e., demanding high propulsion force for acceleration) with running uphill at constant speed. In both cases, the acceleration vector of propulsion is obliquely oriented with regard to gravity, creating mechanical similarities between these two conditions. Similarly, accelerated skiing on the flat, like at the start of a race, may be mechanically comparable with skiing steep uphill at a constant speed. At the start of a classic style race when acceleration is high, skiers tend to start in DIA to change into DP after about 20-30 m (observations in world cup races). It is likely that the magnitude of acceleration diminishes and at about 20 m in the race ‘resembles’ a lesser incline at which skiers prefer DP. In DP, the propulsive force (and power) required for a large acceleration vector, regardless its purpose (horizontal acceleration or opposing gravity) can only be provided through the poles. It is tempting to argue that the arms may be a limiting factor. However, Dahl et al. (2017) showed only marginal increases in peak pole forces and strongly reduced peak pole power when increasing incline from 5% to 12% in DP at 200 Watts, indicating such limitations are not met in the current study. This is substantiated by the large amount of power residing for the lower extremity in DP (e.g., Danielsen et al., 2015; Holmberg et al., 2006; Holmberg et al., 2005; Pellegrini, Zoppirolli, Bortolan, Zamparo, & Schena, 2014). However, the utilization of this contribution via the body’s mechanical energy may actually be another candidate that explains the preference of technique at steep inclines. It may well be that in accelerated skiing the direction of acceleration (and thus pole forces) limits the generation and/or utilization of this mechanical energy. In other words, the perpendicular up- and downward motion of the body may be restricted, posing a limitation on the musculature that is available for power generation in the upper body only. Note that power generation (whole body) and transformation into propulsion via the poles are two closely related but essentially different aspects of the DP technique. Obviously, more research is required to test this idea.

Interestingly, no statistical indication for hysteresis was found. That is, the ‘upward’ and ‘downward’ protocol led to very similar inclines of technique shift. On basis of theory of motor control (e.g., Turvey, 1990), hysteresis was expected: a technique shift tends to occur when the ‘disadvantage’ of the current technique (by which ever variable this disadvantage may be indicated) exceeds the drawbacks of going through an unstable transition period with high energy demand (Usherwood & Bertram, 2003). Thus, the point of transition lies past the point of equality, and will therefore depend on the direction of transition (e.g., Dutt-Mazumder & Newell, 2017; Hreljac, 1993; Raynor, Yi, Abernethy, & Jong, 2002; Turvey, 1990; Turvey, Holt, Lafiandra, & Fonseca, 1999). Our study was not designed to investigate this issue in detail. Rather, by using both the ‘upward’ and ‘downward’ protocol, we ensured that history or duration of the exercise did not play a role of importance. Still, if hysteresis exists, it was not revealed because it apparently is smaller than the sensitivity in this study (1% incline).

4.2. Physiological response

In addition to the obvious effect of work rate, it is difficult to determine if incline or speed guided the details of the physiological response. In the current study, we could have attempted this in a similar way as for technique shifts. However, we cannot ascertain that the exercise history (protocol) did not affect the instantaneous physiological response, i.e., if the response resembled a physiological steady state. Even though the rate of change in response was low and near-constant response was achieved, the protocol order affected the response in a significant manner. This makes it merely impossible to judge whether incline or speed is responsible for the details in physiological response and even more difficult to generalize such conclusions beyond the current experiment. Interestingly, where a clear effect of protocol order was observed on the physiological response, this was not apparent for technique shifts. In other words, the role that the technique shifts may have played for the physiological response is difficult to ascertain. Still, the present results showed that skiing at a steep incline at low speed (primarily using DIA) was done at lower physiological load than at a small incline with high speed (using DP). This is in agreement with previous findings for in classic style (Dahl et al., 2017), as well as in freestyle (Sandbakk, Ettema, & Holmberg, 2012; Sandbakk, Hegge, & Ettema, 2013). Thus, even though in this study the efficiency differences are associated with technique (DP versus DIA), it may well be that the effect of incline-speed condition on efficiency is actually independent of technique, which warrants further investigation. This finding may have implications for practice with regard to pacing strategies. If an athlete paces according to physiological load (or perceived rate of exertion), the external work rate will not be constant and depend on the terrain.

The possible role of force-velocity (power-velocity) characteristics of skeletal muscle have not yet been discussed. It may be well so that the different techniques allow for changes of joint and related muscle shortening velocities (not recorded in this study) at the same speed of movement. However, the minor but very clear incline dependent changes in *CR* within one technique (DP) do not advocate this idea. In case that moving at energetic optimal joint velocities, this is apparently handled by adjusting *CR*.

The current study dealt with constant work rate conditions and changes in the task conditions were predictable. This may have, as in many others studies, affected the outcome. Thus, extrapolating our findings to less predictable conditions like varying terrain should be done with caution.

Acknowledgements

The authors wish to thank the athletes in participating in this study.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors

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Figure captions:

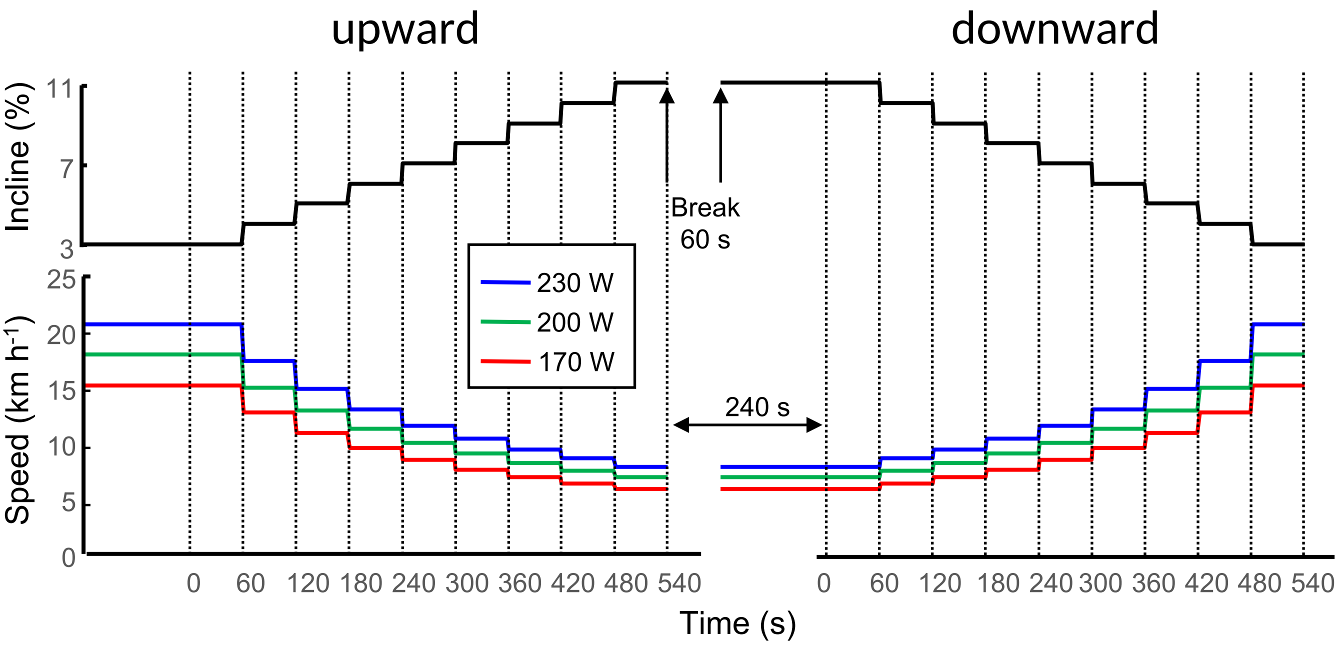
Figure 1. Description of the protocol. Time line showing how incline and speed are changed at three work rates in two orders (‘upward’ and ‘downward’).

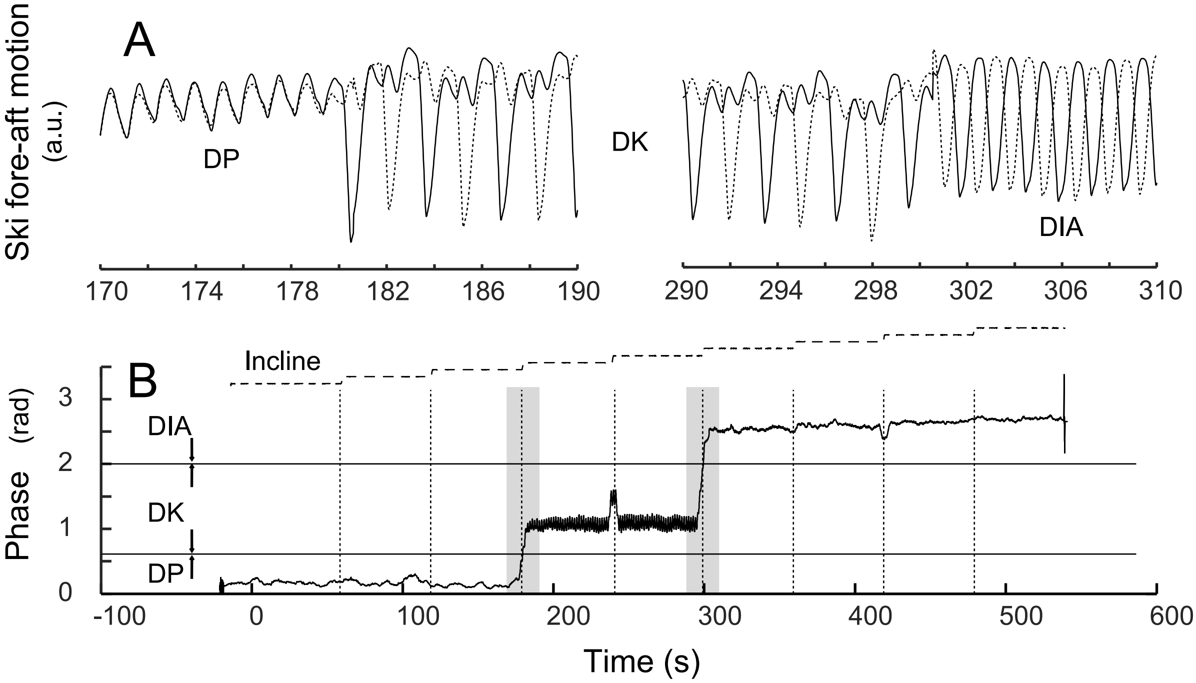
Figure 2. Analysis of continuous phase and technique determination. A. Time trace of position of left and right skis relative to the moving belt in two periods in which transitions occur. B. Time trace of relative phase (i.e., the difference between angle of left and right amplitude, after normalization within each cycle – giving amplitudes between -1 and 1). Grey areas depict the transition periods shown in detail in A. Horizontal lines indicate the critical values determining which technique is applied.

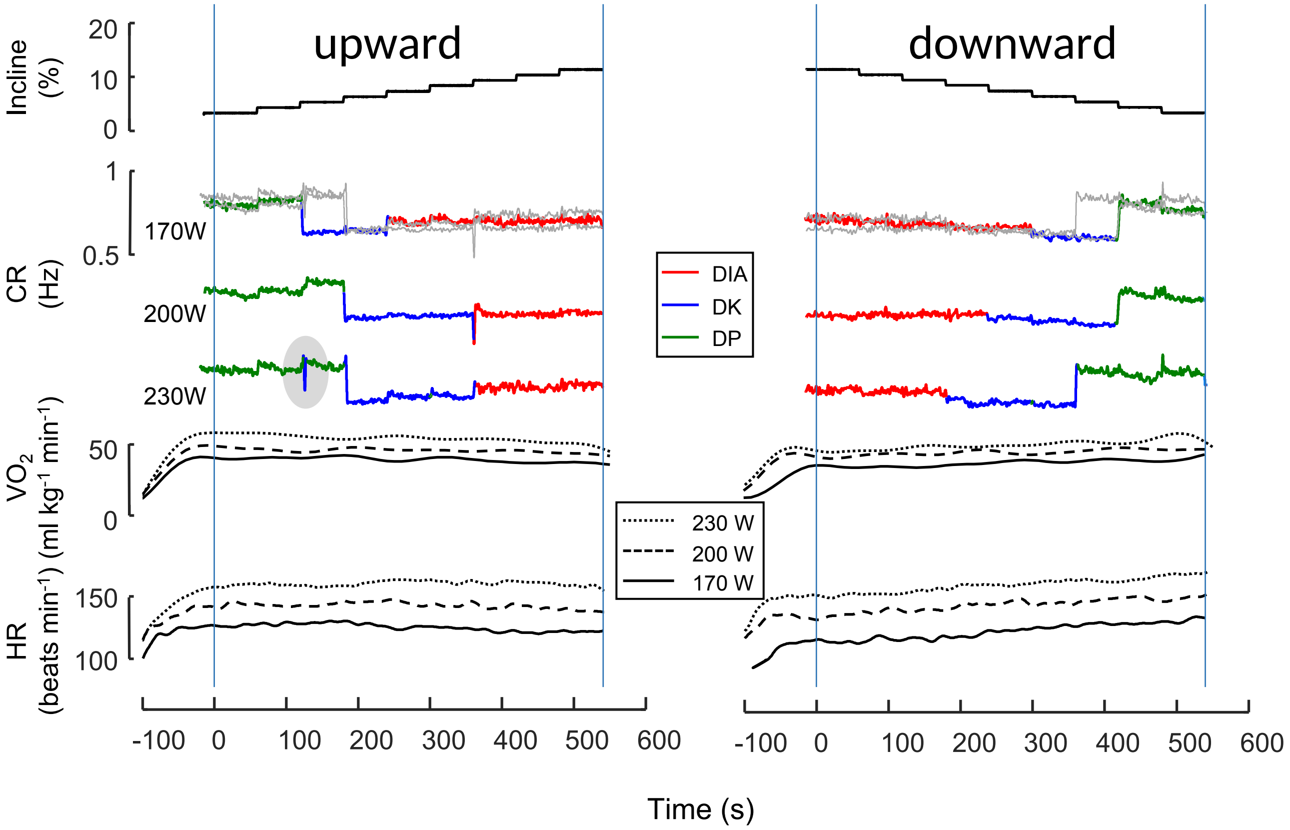
Figure 3. Time traces of one athlete for ‘upward’ and ‘downward’ protocol. *CR* shows technique by color signature for three work rates. Top diagram (170 W) also shows the *CR* for other work rates in grey for comparison. Bottom diagrams showing $V\square O_2$ and *HR*, respectively. Thin vertical lines indicate the 9-minute periods of analysis. Grey circle indicates a brief but not permanent shift; during a change of incline-speed, the athlete briefly shifts from DP to DK, but returns to DP almost immediately. Such shifts occasionally occurred for other athletes as well, and were not considered in the statistical analysis.

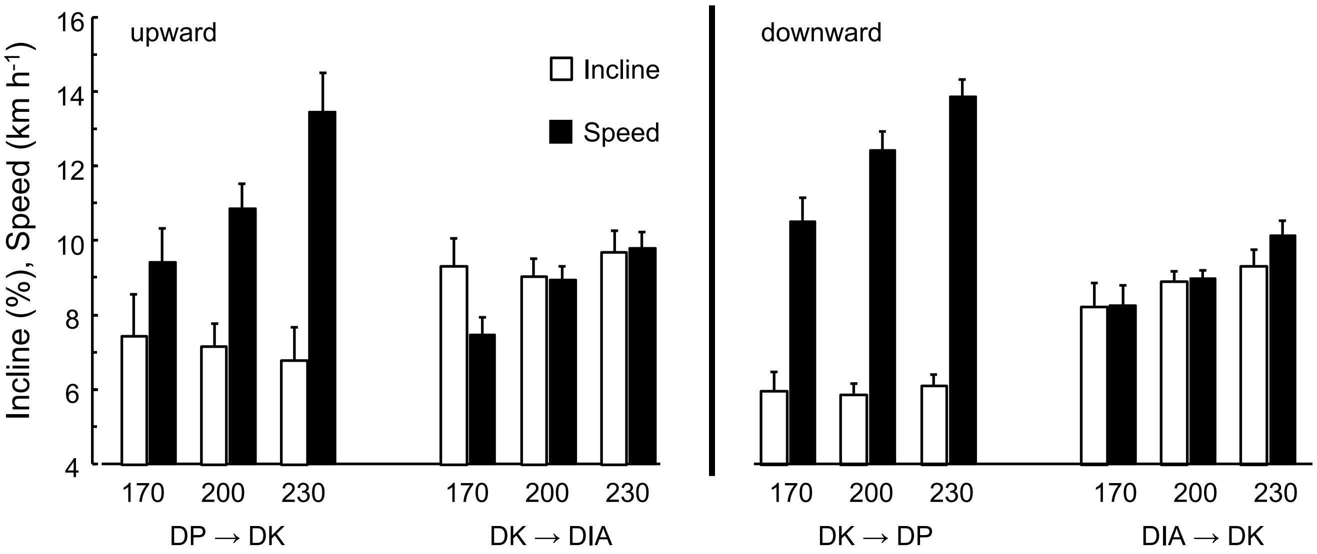
Figure 4. Mean and SD (N=8) of transition point expressed as incline and speed at all intensities and protocols (‘upward’ and ‘downward’).

Figure 5. Physiological response and gross efficiency as a function of protocol condition. Protocol order is depicted by small arrows on top of the traces. Significant differences between order are indicated by □ ($p<0.05$ for all work rates) and † ($p<0.05$ for two out of three work rates).

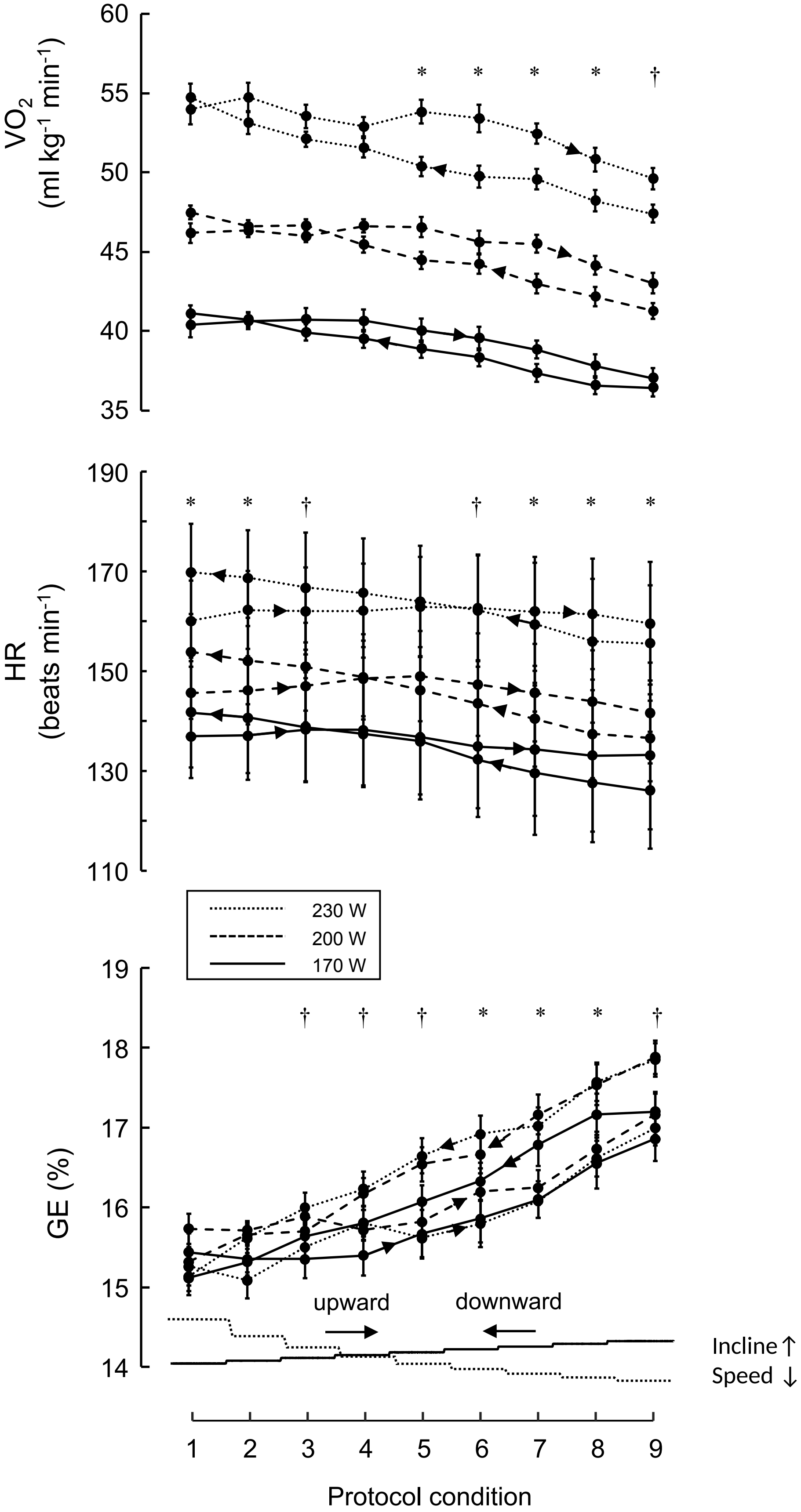

upward
downward
Incline (%)
11
7
3
Break
60 s
Speed (km h-1)
25
20
15
10
5
0
230 W
200 W
170 W
240 s
0
60
120
180
240
300
360
420
480
540
0
60
120
180
240
300
360
420
480
540
Time (s)


A
Ski fore-aft motion
(a.u.)
DP
DK
DIA
170
174
178
182
186
190
290
294
298
302
306
310
B
Incline
Phase (rad)
DIA
DK
DP
3
2
1
0
-100
0
100
200
300
400
500
600
Time (s)


upward
downward
Incline (%)
20
10
0
CR (Hz)
1
0.5
170W
200W
230W
DIA
DK
DP
VO2 (ml kg-1 min-1)
50
0
230 W
200 W
170 W
HR (beats min-1)
150
100
-100
0
100
200
300
400
500
600
Time (s)



upward
downward
☐ Incline
■ Speed
Incline (%), Speed (km h^{-1})
16
14
12
10
8
6
4
170
200
230
DP → DK
DK → DIA
DK → DP
DIA → DK


60
55
50
45
40
35
VO2 (ml kg-1 min-1)
* * * * †
190
170
150
130
110
HR (beats min-1)
* * † † * * *
230 W
200 W
170 W
19
18
17
16
15
14
GE (%)
† † † * * * †
upward
downward
Incline ↑
Speed ↓
1
2
3
4
5
6
7
8
9
Protocol condition