The Effect of Speed, Incline and Work Rate on Technique Transition in Classical Roller-skiing

Espen Kveli

Abstract

Purpose: Cross-country skiers use three main classical sub-techniques to adapt to varying speed and incline during training and competition in order to ski as efficient as possible. The three main sub-techniques are diagonal stride (DIA), double poling with a kick (DK) and double poling (DP). The present study investigated the number and moment of occurrence for technique transitions at constant work rates with varying speed and incline combinations, as well as the effect of work rate in classical roller-skiing. Additionally, the total time distribution of the various sub-techniques was examined.

Methods: Eight male national level skiers (age 22.4 ± 1.7 years, body height 183.7 ± 4.4 cm, body mass 80.3 ± 7.7 kg and VO_2-max 73.9 ± 6.4 ml·kg^{-1}·min^{-1}) performed three test sessions of 23 minutes at respectively *low-, moderate-*, and *high* intensity while roller-skiing on a large treadmill. The protocols consisted of two main parts; I) 3 to 11%, with incremental increase of 1% each minute and II) 11 to 3% with incremental decrease of 1% each minute. Part I and II was separated by a 1-minute brake for lactate sample. Speed at every incline was calculated to keep a constant work rate. Physiological recordings (oxygen uptake and heart rate) and 3-D kinematics were synchronized and continuously recorded.

Results: Physiological values were different between *low-, moderate-* and *high* intensity (oxygen uptake 39.3 ± 1.2, 45.2 ± 1.2 and 52.0 ± 1.4 ml·kg^{-1}·min^{-1}, heart rate; 138 ± 12, 148 ± 8 and 166 ± 10 bpm (all $P < 0.01$). Total number of technique transitions for all subjects during the whole 23-minutes protocols showed a significantly decrease from *moderate-* (66) to *high* (45) intensity ($P = 0.04$). Moment of occurrence for technique transitions did not differ between *low-, moderate-* and *high* intensity (6 ± 1.2, 6 ± 0.8 and $6 \pm 0.8\%$ incline) for the transition from DK to DP. Speed values for DK to DP technique transition were respectively 9.8 ± 1.4, 11.6 ± 1.1 and 13.1 ± 1.3 km·h^{-1}. Total time distribution of DK increased significant from 282 ± 74 seconds at *low-* to 352 ± 108 seconds at *high* intensity ($P = 0.01$), whilst the *moderate* intensity did not differ from the two other work rates.

Conclusions: The current study indicates that incline rather than speed was the determining factor regarding technique transitions in the classical roller skiing technique. The highest work rate had significantly less technique transitions compared to the *moderate* intensity, but there were no linear trend in number of technique transitions with increasing intensity. The total time spent in DK showed a linear increase with increasing work rate, and was significantly higher at *high-* compared to *low* intensity.

Acknowledgement

This master thesis would not have been possible without important wisdom from my supervisors Gertjan Ettema and Øyvind Sandbakk. Thank you for good help and advice during all parts of the work process.

Additionally, I would like to thank the subjects for their attendance and contribution in this study and the employees at *The Norwegian Olympic Sports Center, Region Mid-Norway* for support and helping out with different issues during the project time.

I will also express my gratitude to my fellow student Magne Øksnes, for great teamwork regarding this project, from start to commissioning.

Trondheim, May 2015

Espen Kveli

Table of contents

Introduction

Cross-country skiing is a human movement where the whole body contribute in the propulsive force production (Vähäsöyrinki et al., 2008). Ski attached to the legs allows gliding on snow-covered surface and the poles cause efficient utilization of arms, which make cross-country skiing an effective way of human locomotion on snow. Cross-country ski training and competition is typically performed in varied terrain where skiers need to utilize different sub-techniques to maintain high speed in an efficient way. Transitions between the different sub-techniques can be considered as a gear system to adapt to changes in speed and incline (Nilsson, Tveit, & Eikrehagen, 2004).

Cross-country skiing involves both classic and skating technique. In the classical technique, the skis are parallel and follow a track, except during the sub-technique herringbone, where the skis are angled and edged to increase static friction. The other sub-techniques 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). Even though DIA follows the same movement pattern as walking, it is a biomechanically unique movement where arms and legs produce propulsive force simultaneously (Kehler, Hajkova, Holmberg, & Kram, 2014). 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. This makes DIA favorable when work against gravity increases, because the positive accelerations from propulsive forces comes more frequently and reduces the periods of negative acceleration. Pellegrini et al. (2013) found that the technique transition to DIA occurred around 9% inclination, and 100% of the subjects preferred DIA when slopes were steeper than 10.5%.

DP is a symmetrical and synchronous movement of both arms, where the propulsive forces are exerted 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 (Holmberg, Lindinger, Stöggl, Björklund, & Müller, 2006). High angular elbow- and hip-flexion velocity, a small minimum elbow, hip and knee angle, a high pole force and a short poling phase are characteristics which is found to differ good compared to less good DP technique (Holmberg et al., 2005).

DP is most frequently used in slight up- or down hills and flat terrain, but also in steeper uphills when the friction is low. Pellegrini et al. (2013) found that DP was preferred by all skiers at speeds >16 km·h^{-1} and incline ≤ 2% and almost never at slopes above 7% incline.

In DK, the upper body movement is quite similar to the movement in DP. In addition to the propulsive force from the upper limb, 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 are commonly used slightly uphill or if snow conditions cause high resistance in flat terrain (Smith, 2002). The inserted leg kick has the same characteristics as the lower limb movement in DIA (Lindinger, Göpfert, Stöggl, Müller, & 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). In addition to the large amount of propulsive phases, DK shows the lowest cycle rate among the sub-techniques in classical cross-country skiing. According to Pellegrini et al. (2013), DK was mostly used at slopes around 7% and the technique transition from DP occurred around 3.5-5% inclination.

Regarding choice of these sub-techniques, friction resistance, static friction, snow condition, individual strengths and abilities are important factors (Nilsson et al., 2004). In classical skiing, skiers would usually switch from DP to DK and thereafter to DIA as the incline rise (Pellegrini et al., 2013).Technique transitions in cross-country skiing separates from other known and described transitions in human and animals, because of both upper- and lower limbs involvements, where the propulsive forces are exerted through skis and poles. The upper- and lower limb movements are inter-correlated in several ways where also the contribution differs between the sub-techniques. This is a unique aspect of cross-country skiing and makes technique transitions complex. In skating it has been registered as much as 34 transitions between four different sub-techniques in a cross-country sprint time trial, during a 1425 m track (Andersson et al., 2010). However, this has not been investigated in classic.

Triggers that lead to a transition in gait are well investigated and mechanical stress, where either joints, muscles or ligaments reaches a threshold of strain are emphasized in several studies (Farley & Taylor, 1991; Hreljac, 1995; Neptune & Sasaki, 2005). Another hypothesis is that gait in human and animal locomotion are selected to minimize metabolic cost (Alexander, 1989; Mercier et al., 1994). A third suggestion is related to comfort criteria, where the subjective feeling of comfort is predominant over energy savings criteria (Daniels

& Newell, 2003; Prilutsky & Gregor, 2001; Thorstensson & Roberthson, 1987). Cignetti et al. (2009) investigated transitions in classical cross-country skiing by letting the skiers ski *as naturally as possible* while treadmill roller-skiing, were speed was constant (10 km·h^{-1}) and the incline increased by 1° every 30 second, form 0° to 7° and transitions were registered. Gradual changes in external conditions may lead to a shift from one attractor (preferred movement pattern) to another at a certain combination of speed and incline due to loss of stability (Cignetti, Schenab, Zanonec, & Rouarda, 2009; Kelso & Ding, 1993). Cignetti et al. (2009) suggested that limb movements of the skiers are attracted towards low-order frequency ratios (i.e. 1:1 and 2:1 movements) and in-phase – anti-phase relations. Increasing incline cause a technique transition by a loss of stability (Cignetti et al., 2009).

Pellegrini et al. (2013) used the same test setup as Cignetti et al. (2009), in addition to varying speed at constant incline. They tried to determine the main triggers regarding technique transition in classical cross-country skiing. The results from this study suggested two different primary triggers. They hypothesized that there is a limited force a skier would like to exert through the poles and the limit triggers a transition to a sub-technique where less of the propulsive forces are exerted through the poles (e.g. DIA). The other suggested trigger is related to transitions where the legs are involved (DIA and DK). This trigger is *leg thrust time* and is the time where the ski stands still during a leg stride. The muscle contracts faster and faster with increasing speed, and when the speed requires a muscle contraction ≤ 0.1 second, a technique transition is necessary to a further increase of speed. This corresponds to Nilsson et al. (2004) observations, where 0.15 seconds was the shortest LTT. A period of 0.1 second, or less, is shown to be too short to produce maximal power for lower limbs (Harridge et al., 1996). Even though Pellegrini et al. (2013) emphasized two triggers, they underline that a technique transition probably is triggered by several factors.

In addition to the hypothesis of minimalized metabolic cost, gait transitions in terrestrial locomotion are related to the regulation of speed (Hoyt & Taylor, 1981), and, thus, indirectly related to work rate. As far as this author knows, no previous study has investigated technique transitions at varying speeds and inclinations at constant work rates to emphasize the effect of speed and inclination itself, and not as an indirectly effect of increased work rate. Probably, increased work rate alone will lead to technique transitions.

The primary purpose of this study is therefore to investigate the number and moment of occurrence for technique transitions at constant work rates with varying speed and incline combinations, as well as the effect of work rate in classical roller-skiing. Additionally, the total time distribution of the various sub-techniques was examined.

Methods

Participants

Eight male 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 VO_2max 73.9 ± 6.4 $ml \cdot kg^{-1} \cdot min^{-1}$) volunteered to participate in this study. All procedures were explained verbally to each skier and written informed consent was obtained and signed. This study was pre-approved by the Regional Ethics Committee, Trondheim, Norway.

Experimental Design

Following a 17-minute low intensity warm-up, all subjects completed a 23-minutes session with constant work rate. This was done at three different work rates (*low-*, *moderate-* and *high* intensity) randomized on three different days while skiing as efficient as possible on a large treadmill optimized for roller-skiing. The protocols consisted of two main parts where recordings were done; I) 9 minutes of constant work rate where incline increased by 1% each minute, from 3 to 11% incline, and speed simultaneously decreased and II) 9 minutes of constant work rate where incline was reduced from 11 to 3% each minute, and increasing speed. The two parts were separated by a short break. A period of two minutes without any increments were added before each part (I and II) of the protocol, which make a total of three minutes for the first speed- and incline combination.

Physiological data were recorded using an open circuit indirect calorimetry (oxygen uptake), and heart rate monitor, and kinematical data were recorded using a motion capturing system. All data were synchronized and recorded continuously.
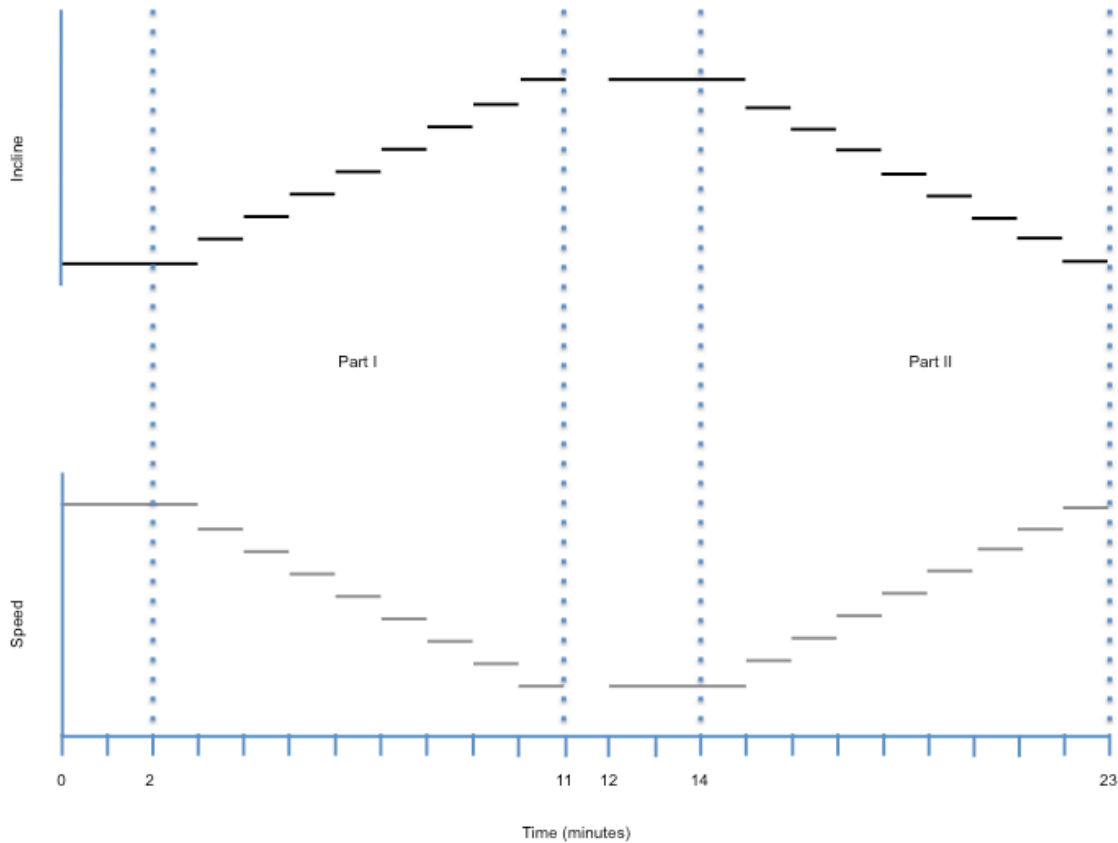
Figure 1. General overview of the protocols, separated in part I and II, expressed as speed- and incline changes of the treadmill with time, while roller-skiing at constant submaximal work rates in the classical technique. Incline increases in part I and decreases in part II while speed decreases in part I and decreases in part II, and thereby maintaining a constant work rate.

Instruments and Materials

The subjects skied on a 5x3-meter treadmill (Forcelink Technology, Zwolle, The Netherlands), optimized for roller-skiing. All subjects used the same pair of roller skis (Pro-Ski, Sterners, Nyhammar, Sweden) with wheels from IDT (IDT Sports, Lena, Norway, resistance category 2). Rolling friction force (F_f) of the roller skis was calculated by a towing test described previously (Sandbakk, Holmberg, Leirdal, & Ettema, 2010). The friction coefficient (μ) was calculated by dividing F_f by the normal force (N): $\mu = F_f \cdot N^{-1}$. The overall mean value was 0.022 and was included to calculate work rate. Poles (Madshus UHM 100, Biri, Norway) were available in five-centimeters intervals and the subjects chose the preferred length.

All three test-protocols where pre-programed in a computer program appurtenant to the treadmill (ForceLink B.V., Culemborg, The Netherlands). Three-dimensional movements of the roller-skis and poles, included incline of the treadmill, were monitored by the OQUS

system (Qualisys AB, Gothenburg, Sweden). Six cameras recorded 50 Hz of positions data from 6 passive reflective markers. One marker placed on each ski and pole and two markers placed on the frame of the treadmill. Each recording session lasted approximately 550 s. The coordinate system was calibrated with a wand and L-frame between every third participant to ensure precisely and correct data. Appurtenant software (Qualisys Track Manager, Qualisys AB, Gothenburg, Sweden) was used to collect the data, and the evaluation of data was completed in a self-written Matlab (8.4.0 R2014b, Mathworks Inc., Natick, MA, USA) script designed specifically for analysis of the classic technique and synchronized with the physiological measurements. A video camera (Canon Legria HF R206, Japan) taped the whole test sessions as a back up regarding transitions and other questionably situations during testing.

Oxygen uptake was calculated by using open-circuit indirect calorimetry (Oxygen Pro apparatus, Jaeger GmbH, Hoechberg, Germany). The VO_2 and VCO_2 analyzers were calibrated using a known mixture of gases ($16.00\% \pm 0.04\%$ O_2 and $5.0\% \pm 0.1\%$ 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), before each test-session. Heart rate was recorded with a heart-rate monitor (Garmin, USA), with a samplings rate of 1Hz (all values synchronized to a samplingsrate of 1Hz). Blood lactate samples was collected from the fingertip of the middle- or ring finger (20-μL) and analyzed by Biosen C_line lactate analyzer (EKF diagnostics GmbH, Magdeburg, Germany). The same person collected all lactate samples during testing to minimize variation in procedure.

Test protocols

All subjects completed a 5-minute self-paced familiarization period before a standardized 12-minute warm-up on varied terrain on roller-ski, where all three sub-techniques were employed. The experimental protocols (both at *low-, moderate-* and *high* intensities) lasted 23-minutes where speed and incline changed (figure 1). Part I started two minutes into the protocol to ensure the athletes reaching an aerobic metabolic steady state before the increments were initiated, and lasted in 9 minutes, with increasing incline from 3-11% by 1% each minute. Minute 11-14 separated part I and II by a 1-minute brake for a lactate sample, followed by 2 minutes of constant work rate to resume an aerobic metabolic steady state after the break. Part II lasted from minute 14 to 23, where incline decreased from 11-3% by 1% each minute. Detailed speed- and incline combinations for *low-, moderate-* and

7

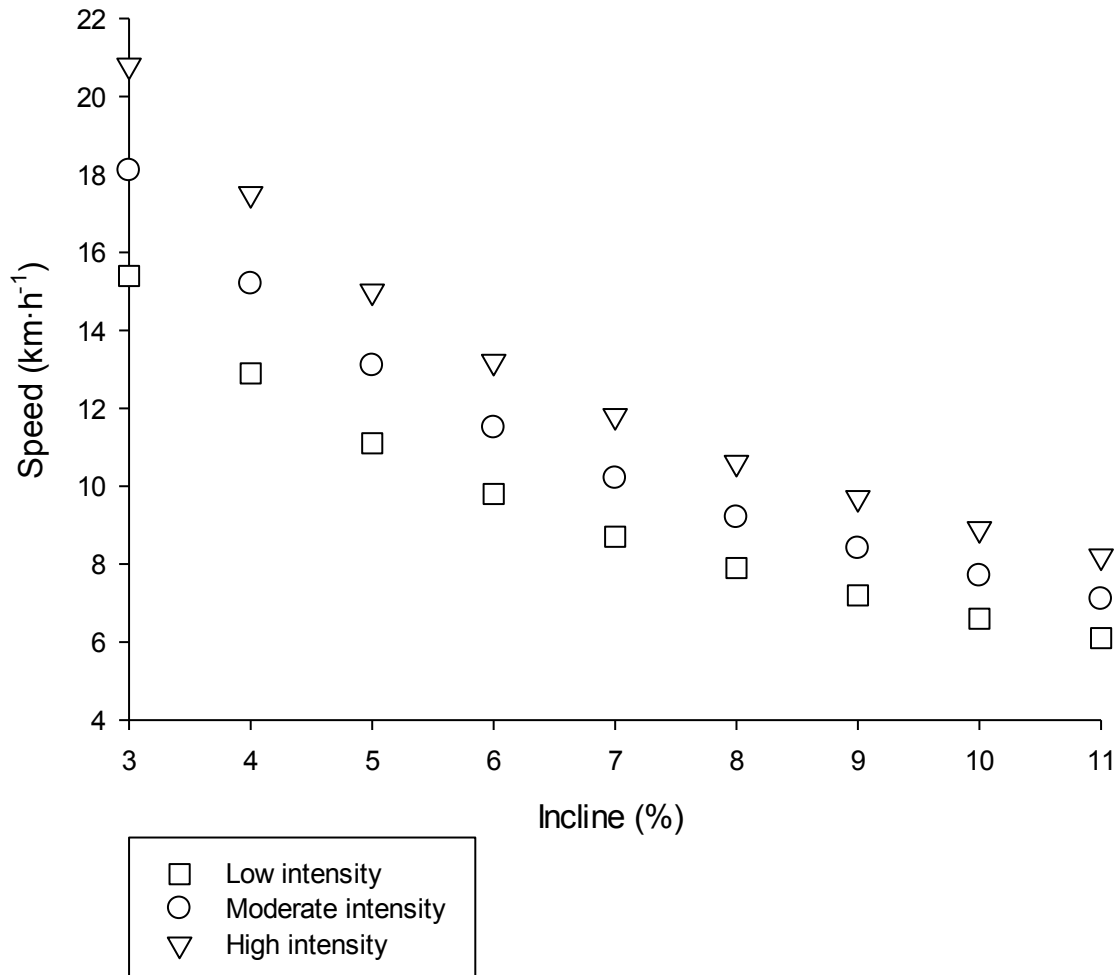*high* intensity are shown in figure 2. Each speed- and incline change of the treadmill lasted 2 seconds.

Figure 2. Detailed overview of the different speed- (km·h^{-1}) and incline (%) combinations of the treadmill at *low-, moderate-* and *high* intensity protocol while roller-skiing at constant submaximal work rates in the classical technique.

Respiratory variables were continually recorded during the 23-minutes. Kinematical recordings was continuously collected during part I and II, lasting 540 seconds each (9*60 seconds). Lactate samples were taken 5 minutes before and immediately after the protocol, in addition to the sample collected during the brake.

Calculation of work rate

Work rate was calculated as the sum of power against gravity (P_g) and friction (P_f):

$$P_g = m * g * \sin \alpha * v$$

$$P_f = m * g * \cos \alpha * \mu * v$$

where *m* is the body mass of the skier, *g* is the gravitational constant, *α* the angle of treadmill incline, *v* the speed of the treadmill belt, and *μ* the frictional coefficient (0.022). The respectively speed to each step of inclination was calculated from this formula to maintain a constant work rate (figure 2) which mean increasing inclination and reduced speed (and reduced inclination and enhanced speed). This makes different work rate between subjects as a result of different body mass, but in terms of a competitive situation, all skiers compete in the same tracks whether high or low body mass. The three different work rates were calculated to be 170, 200 and 230 watt for a skier with body mass equal to 78 kg (based on the groups' average body mass).

Kinematical variables

      Kinematical variables were collected during all recording session while roller-skiing. The registration of transitions was possible by data from the four reflex markers attached to skis and poles. Reflex markers were attached on the lateral side of the pole five centimeters below the handle and recorded the movements of the poles. Two reflex markers attached above the rear wheel recorded the ski movements. In addition to the four markers on poles and skis, there were two markers attached on the treadmill frame to ensure correct incline during the protocols.

      Determinations of sub-techniques: transitions were identified in Matlab using a continuous phase algorithm applied to the movements of the skis. Local minima and maxima of the relative movement of fore-aft direction identified each complete cycle. These movement cycles were normalized for amplitude. By observing the resultant signal sinusoidal in nature, where the amplitude signals were converted to continuous angles, the difference between left and right indicating the relative phase. Applying a moving average, with a window width of 5 complete movement cycles, smoothed this relative phase. A relative phase of > 2 rad was regarded as an out-of-phase ski movement and identified as DIA, ≤ 0.6 (in-phase movement) as DP and values between 0.6 and 2 as DK. The DK movement is partly in-phase and partly out-of-phase, which results in a continuous phase value around π. Transitions were identified as long lasting changes of the phase signal form one to another of the phase ranges mentioned above (figure 3).

      The algorithm was quality checked by comparing the computed technique transition times with technique transitions manually registered by the experimenters during the protocol

execution. A continuously running video camera was used as a control if any disagreements between the two previously mentioned methods. This was necessary only twice, and the video recordings showed that the algorithm was correct. Periods of one skiing sub-technique lasting less than two whole movement cycles, and the accompanying transitions were regarded as invalid, i.e. testing a new sub-technique and immediately go back to the previous sub-technique, and ignored in the statistical analysis. Technique transitions back to an earlier used sub-technique are determined as "temporarily technique transition". The "final technique transition", which is last time of use at each part of the protocol, is the analyzed technique transition in this study. The total number of technique transitions are a result of number of "temporarily technique transitions", since it is only possible with two "final technique transitions" at each part of the protocol.
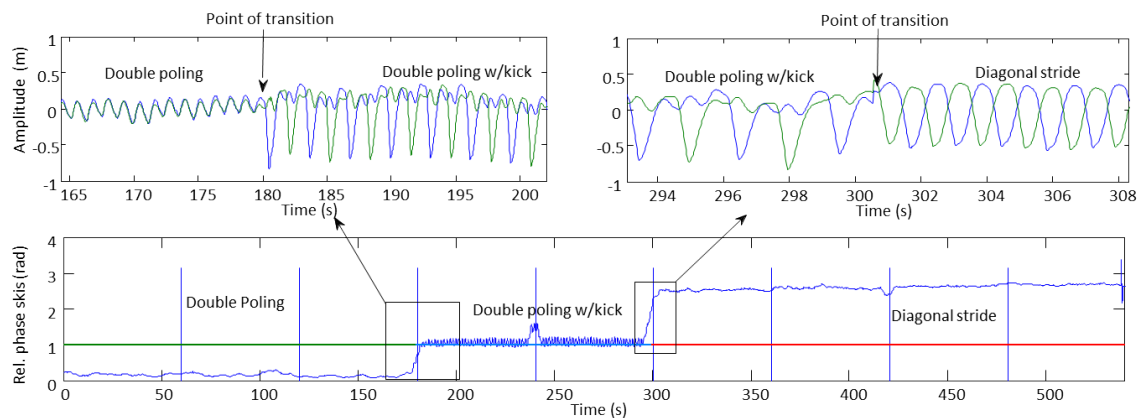

Figure 3. Overview of relative phases and identifications of the different sub-techniques based on ski movements. The amplitude (m) is in the movement direction (two top figures) relative to the treadmill, while the continuous differences in angles between left and right ski movement indicates the relative phase of the technique (bottom figure). Figure processed in Matlab

Statistical analysis

All data was checked for normality and presented as means and standard deviations (±SD). Coefficient of variation (CV) was determined for *number of technique transition* to give a detailed understanding of the variation within the group. To analyze differences in total time distribution and moment of occurrence for technique transitions between sub-techniques at the three different work rates, a two tailed repeated measures ANOVA was performed. The value of statistical significance was set at $P < 0.05$, and statistical tendency at $P < 0.1$. Statistical tests were conducted using Microsoft software for Mac (Excel 2011, 14.4.9, Microsoft Corporation, Redmond, WA, USA)

Results

Average oxygen uptake and heart rate at the three different work rates are significantly different from each other (P < 0.01). Continuous oxygen uptake at the different work rates throughout the protocol is presented in figure 4.
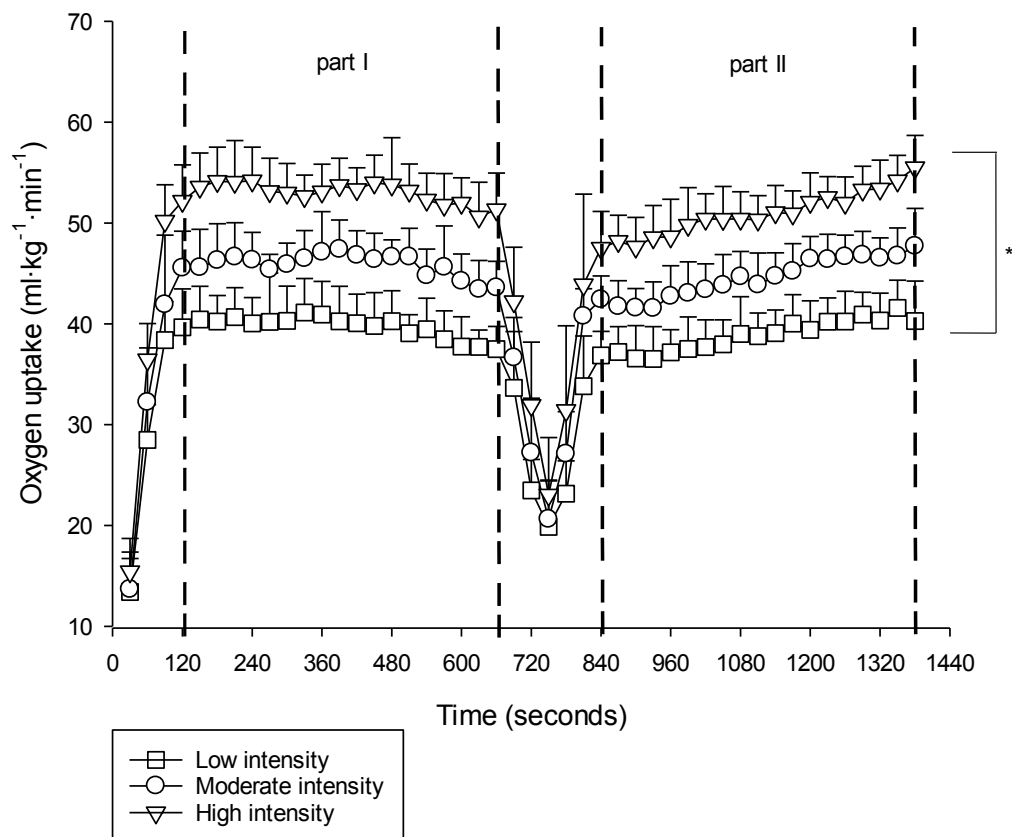

Figure 4. Oxygen uptake at *low-, moderate-* and *high* intensity during the whole 23-minute protocol (1380 seconds) while roller-skiing at constant submaximal work rates in the classical technique. Values between 0-120 and 660-840 seconds are excluded in the analysis, because of aerobic metabolic unsteady state. Star indicates a significant difference between the three work rates (P < 0.01). Values are expressed as mean + SD.

There were no linear trend in the average number of transitions between the three different work rates during part I and III of the protocol, but both SD and CV indicate that there is less variation in number of technique transitions among the subjects at the highest work rate. The total number of transitions is significantly lower at *high-* compared to *moderate* intensity (P = 0.04).

11

Table 1. *Total number of transitions* is the total number of transitions for all subjects at each work rate. *Transitions* are the average number of transitions for each subject at each work rate. The coefficient of variation (CV) indicates variation within all subjects. VO$_2$ (oxygen uptake), HR (heart rate) and LA (lactate) show the average value of all subjects. Lactate values are the average of the samples taken during the break between part I and II and after part II. Values are expressed as mean ($\pm$ SD), while roller-skiing at constant submaximal work rates in the classical technique.

Work rate	Low	Moderate	High
Total number of transitions	51	66	45*
Transitions $\pm$ SD	3 $\pm$ 2	4 $\pm$ 2	3 $\pm$ 1
CV	0.55	0.57	0.39
VO$_2$ (ml·kg^{-1}·min^{-1})	39.3 $\pm$ 1.2	45.2 $\pm$ 1.2	52 $\pm$ 1.4
HR (bpm)	138 $\pm$12	148 $\pm$ 8	166 $\pm$ 10
LA (mmol/L)	1.7 $\pm$ 0.8	2.1 $\pm$ 0.8	4.4 $\pm$ 1.5

Star indicates a significant difference in total number of technique transitions between *moderate-* and *high* intensity ($P = 0.05$).

Moment of occurrence for technique transitions (figure 5) shows small variation between *low-*, *moderate-* and *high* intensity, especially from DK to DP (6 $\pm$ 1.2, 6 $\pm$ 0.8, and 6 $\pm$ 0.8% incline). Speed values for the transition from DK to DP are for instance 9.8 $\pm$ 1.4, 11.6 $\pm$ 1.1 and 13.1 $\pm$ 1.3 km·h^{-1}. Incline values for the other transitions: from DP to DK; 6 $\pm$ 3.1, 6 $\pm$ 1.6 and 5 $\pm$ 1.1%, from DK to DIA; 7 $\pm$ 1.5, 8 $\pm$ 1.3 and 8 $\pm$ 1.2%, from DIA to DK; 8 $\pm$ 1.5, 9 $\pm$ 1.1 and 9 $\pm$ 1.4% incline.
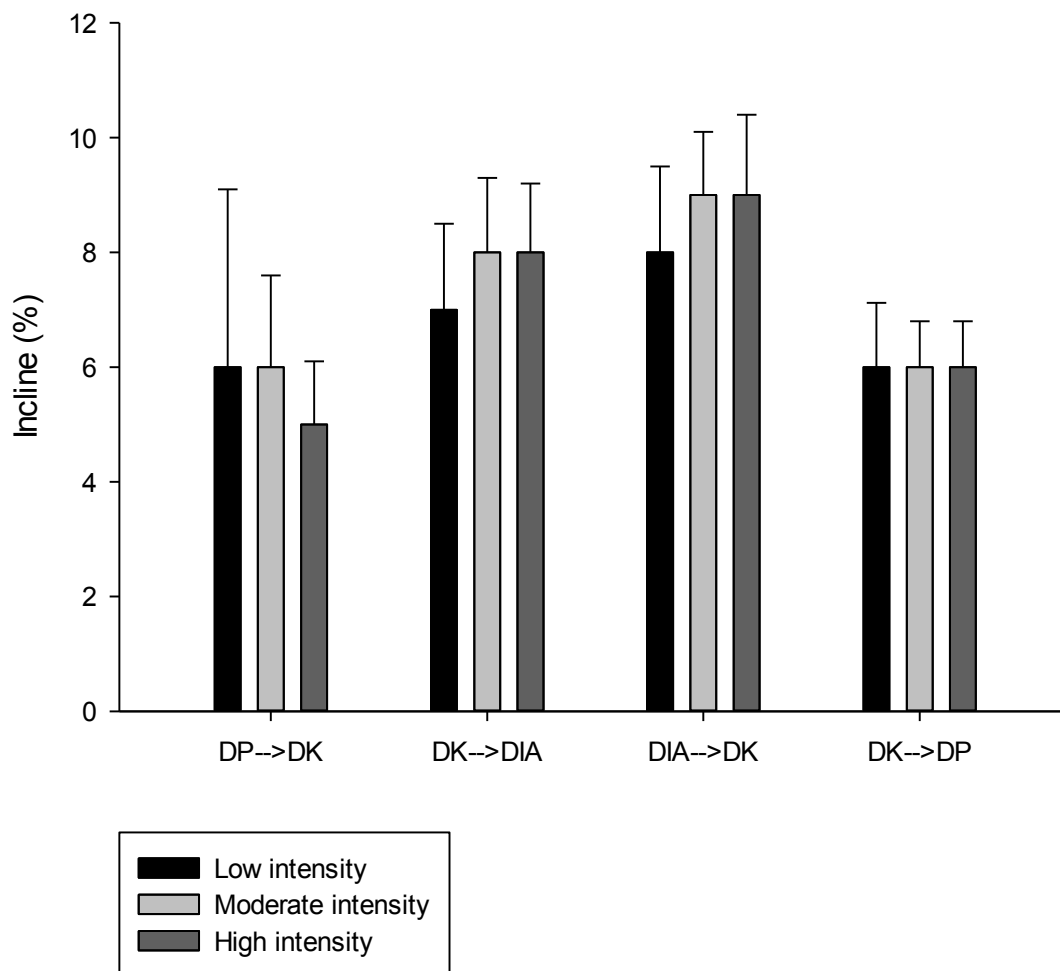
Figure 5. Moment of occurrence for technique transitions for the four different observed technique transitions during the protocol while roller-skiing at constant submaximal work rates in the classical technique. Y-axis refers to incline (%) of treadmill, which follows the same incline increments at *low-, moderate-* and *high* intensity. Values are expressed as mean + SD.

DP→DK, technique transition from double poling to double poling with kick; DK→DIA, technique transition from double poling with kick to diagonal stride; DIA→DK, technique transition from diagonal stride to double poling with kick; DK→DP, technique transition from double poling with kick to double poling.

Total time distribution of DP does not change considerably between work rates (451 ± 66 seconds, 419 ± 147 seconds and 415 ± 107 seconds) at respectively *low-, moderate,* and *high* intensity, but DK and DIA change with increased work rate (figure 6). Total time distribution of DK shows a significant increase with increasing work rate (237 ± 66 seconds, 282 ± 45 seconds and 375 ± 49 seconds, P = 0.01 from *low-* to *high* intensity), while total time distribution of DIA tend to decrease (434 ± 114 seconds, 377 ± 48 seconds and 336 ± 59 seconds), but the result is not significant. By separating the protocols in part I and II (table 2),

it is possible to see that average total time distribution of DP differs between the parts. 42% = 228 seconds in part I compared to 38% = 201 seconds in part II, but the great variation result in no significant differences (P = 0.17). DK show a tendency towards a higher amount of use in part II (35% = 156 seconds compared to 25% = 129 seconds in part I) with P = 0.08. DIA does not change between part I and II (34% at both parts).
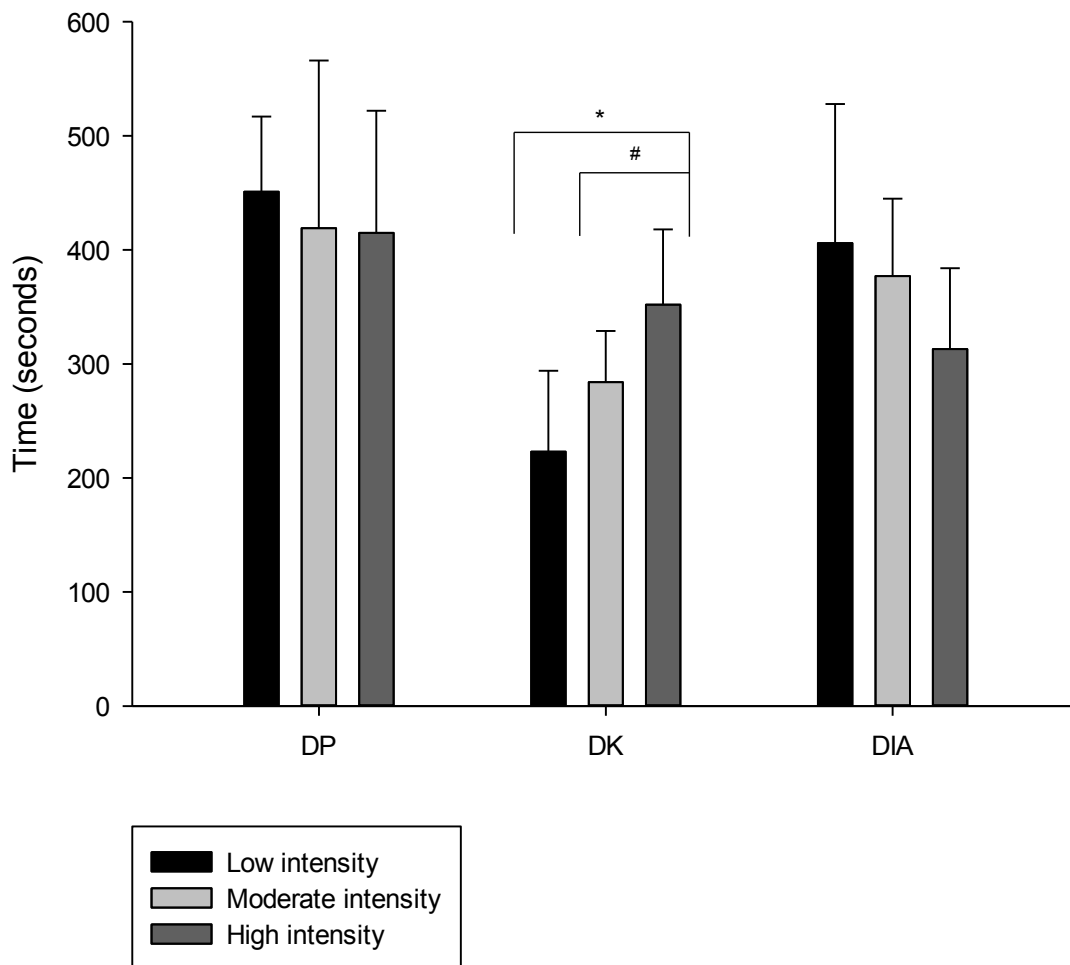

Figure 6. Total time distribution of DP, DK and DIA at *low-, moderate-* and *high* intensity, expressed in seconds, during part I and II of the protocol while roller-skiing at constant submaximal work rates in the classical technique. Star indicate P = 0.01 and square P = 0.06. Values are expressed as mean + SD.

DP, double poling; DK, double poling with kick; DIA, diagonal stride

Table 2. Total time distribution separated in part I and II while roller-skiing at constant submaximal work rates in the classical technique. The letter behind the sub-technique (L, M and H) refers to *low-, moderate-* and *high* intensity. Incline (%) increases during part I and decreases during part II. Values are expressed as mean in percent (%) of total protocol time ± SD.

	Part I	Part II
DP$_L$	45 ± 34%	38 ± 21%
DP$_M$	40 ± 14%	37 ± 11%
DP$_H$	41 ± 27%	36 ± 11%
DK$_L$	18 ± 13%	24 ± 13%
DK$_M$	25 ± 7%	28 ± 10%
DK$_H$	30 ± 15%	35 ± 9%
DIA$_L$	37 ± 27%	38 ± 19%
DIA$_M$	35 ± 16%	35 ± 10%
DIA$_H$	29 ± 16%	29 ± 11%

DP, double poling; DK, double poling with kick; DIA, diagonal stride

Discussion

The present study aimed to investigate the number and moment of occurrence for technique transitions at constant work rates with varying speed and incline combinations, as well as the effect of work rate in classical roller-skiing. Additionally, the total time distribution of the various sub-techniques was examined. One main finding in this study was that incline rather than speed was the determining factor regarding technique transitions. The *high* intensity had significantly less technique transitions compared to *moderate* intensity, but there were no linear trend in number of technique transitions with increasing intensity. Total time distribution of DK showed a linear increase with increasing work rate, and was significantly higher at *high-* compared to *low* intensity.

Existing literature on the topic have investigated transitions among sub-techniques by a method where work rate increases (Cignetti et al., 2009; Pellegrini et al., 2013). In this study the aim was to see to what extent incline and speed determined technique transition in classical skiing. To ensure that transition was not a result of increasing work rate, the protocol was designed so speed and incline varied at three constant work rates (performed at *low-, moderate-* and *high* intensity). It was therefore possible to see whether speed or incline *per se* was the determining factor regarding technique transition, independent of work rate. This contributes with novel information compared to existing research material on the topic.

In the current study the *high* intensity had significantly fewer technique transitions than *moderate* intensity, and was the work rate that showed less variation in number of technique transitions among the subjects. However, there was no linear trend in number of technique transitions between *low-, moderate-* and *high* intensity. The findings at the *high* intensity correspond to an assumption of less variation with increased work rate because of enhanced demands to keep up the current speed by reducing *degrees of freedom* to perform at required level, as shown in a study on table tennis where fatigue was found to reduced *degrees of freedom* (Aune, Ingvaldsen, & Ettema, 2008). Why this effect only are found between *moderate-* and *high* intensity may partly be explained by the fact that some subjects did not change sub-technique at any time during part I of the protocol at the *low* intensity, and thereby influenced the number of technique transitions. The lack of technique transition showed by some subjects here might be explained by the theory of comfort criteria (Daniels & Newell, 2003; Prilutsky & Gregor, 2001; Thorstensson & Roberthson, 1987), because DP is a sub-technique where the lower limbs do not move considerably, and may result in an enhanced threshold of involving the lower limbs, i.e. DK and DIA, and thereby stays in DP.

There were no differences in moment of occurrence for technique transitions between work rates in this study, which means that technique transitions are executed at varied speeds between different work rates. This result emphasizes the effect of incline rather than speed in technique transition. Cignetti et al. (2009) have previously shown that gradually increasing incline lead to loss of stability and result in a technique transition to a "lower gear" even though speed is unchanged. However, the actual technique transition trigger might be increased work rate as well as incline. The transition itself leads to instability, and as shown in table 2, time spent in DP and DK is influenced of whether the subjects start in- or shift to the actual sub-technique. However, there were great variations between the subjects. This trend corresponds to a dynamical system perspective, where you maintain the ongoing movement pattern as long as possible, to avoid the instability a transition cause (Cignetti et al., 2009). There are also research showing that speed is a determinant factor regarding choice of sub-technique (Pellegrini et al., 2013), but the differences in speed found in this study emphasize incline as the major determining factor.

In the current study, work rate affects the choice of sub-technique. There is a significant increased amount of DK from *low*- to *high* intensity, while the time spent in DP was almost unchanged and DIA tended to decrease. It is previously shown that DK has a propulsive phase of about 52% of a cycle (including legs and poles), which is considerably higher than that of DP at similar speeds, with a propulsive phase of 30-38% of a cycle (Göpfert et al., 2012). The high portion of the propulsive phase results in lowered recovery phase, and might influence usage of DK in various ways. Low recovery time might at some speed- and incline combinations feel to "expensive", compared to DIA or DP, for instance at low work rates. Low cycle rate, which also is a characteristic of DK compared to other classical sub-techniques (Göpfert et al., 2012), can also enhance that feeling, even though lower cycle rates have been shown to cost less VO$_2$ (Lindinger & Holmberg, 2011). The "expensive" feeling might be one possible explanation for lower amount of DK at the *low* intensity. Thus, shorter recovery time combined with lower cycle rates may be the main reason using DK at moderate inclines (Göpfert et al., 2012), which also was the main area of application found in this study.

At higher work rates, the amount of required propulsive force production increases compared to lower work rates and the large portion of the propulsive phase in DK make it possible to produce the required amount of propulsive force over a longer time period, compared to a more explosive force exertion in DP. A result of this can be a reduced subjective feeling of effort, because the skier works at a lower percentage of the maximal

force production abilities, and thereby chose DK as preferred sub-technique in a greater extent at higher work rates, because the subjective feeling of comfort is suggested to be more important than the actual metabolic cost (Daniels & Newell, 2003; Prilutsky & Gregor, 2001; Thorstensson & Roberthson, 1987). Although increased work rate affects choice of sub-technique by increasing the amount of DK, primarily at the sacrifice of DIA, the great variation among the subjects result in no significant differences in DIA. This effect might partly be explained of the fact that some subjects used DP 100% of part I of the *low* intensity protocol, which result in a downgrading of the other two sub-techniques, compared to *moderate-* and *high* intensity protocols.

The results in this study showed a great between- and within-subject variation in total time distribution, the number- and moment of occurrence for technique transition. This underlines the complexity and individuality regarding technique transitions in cross-country- and roller-skiing. This finding is in accordance to previous research investigating technique transitions in cross-country skating (Andersson et al., 2010) where the number of technique transitions showed a great variation. In the present study, there were for instance three subjects who chose to use DP all the way up to 11% inclination, which is in contrast to Pellegrini et al. (2013) were all subjects preferred DIA at inclines steeper than 10.5%. One explanation for this can be the many different factors that contribute in the choice of sub-technique. Factors as friction resistance, static friction and individual strengths and abilities (Nilsson et al., 2004) are all important in the choice of which sub-technique to use. The subjective feeling of comfort is suggested to be more important than the actual metabolic cost (Daniels & Newell, 2003; Prilutsky & Gregor, 2001; Thorstensson & Roberthson, 1987) which also probably are the explanation regarding use of DP at inclines higher than shown in a previous study (Pellegrini et al., 2013), despite enhanced metabolic cost.

Methodological considerations

This study was conducted at the autumn, pre-season for the subjects, a time of the year when the skiers have been roller-skiing for several months, and were highly familiarized to the equipment. Thus, technique transitions observed in this study are most likely not a result of accidental circumstances. One mentioned factor regarding the choice of sub-technique is static friction, and the static friction is complete in roller-skiing, which might influence the use of DK and DIA compared to cross-country skiing. The advantage compared to cross-country skiing is the controlled test setting by doing research on the treadmill. Thus, the fact

19

that the protocols were pre-programmed, resulted in a highly standardized execution of all protocols, and also made it possible for the experimenters to have an enhanced focus on the subjects and registrations during testing. However, another result might have been shown on snow, dependent of snow conditions.

Due to software limitations, the treadmill had small perturbations in work rate during change of speed and incline, because it was impossible to adjust more than one variable at time. Speed was adjusted first, and inclination accordingly, during a 2 seconds process. This resulted in a short period of lowered work rate during part I of the protocol, and enhanced work rate during part II. It was possible to hear when these perturbations occurred, which might affect technique transitions by make the subjects' conscious of changes in external conditions. In a real situation, training and competition, the skiers always get input either the slope is changing or not.

Therefore, these perturbations make the subjects consider a technique transition, or not, every minute of the protocol, and thereby it is reasonable to believe that *moment of occurrence for technique transition* is a highly conscious decision. Though, it would have been interesting to see the outcome of a protocol with continuously gradual changing speed and incline, and should be implemented in a future study.

Another aspect of the protocol is that all speed values are within the subjects' comfort zone, and thereby *leg thrust time* may not be as important as previously shown (Pellegrini et al., 2013). At higher speeds, l*eg thrust time* might be a limiting factor as the muscle contraction time come close to 0.1 second, as previously shown (Harridge et al., 1996).

Conclusions

In the current study, incline tend to be a more determining factor for where technique transitions occur than speed, although there is great individual variation. The highest work rate had significantly fewer technique transitions than the *moderate* intensity, indicating less variation and more consistent choice of sub-technique at high work rates. DK show an increased *total time distribution* with higher work rates.

Further research should implement a higher range of speeds and inclines, (especially higher speeds) to get a more detailed understanding of both total time distribution and determining factors regarding technique transitions, in addition to a protocol without perturbations during changing of speed and incline.

References

Alexander, R. M. (1989). Optimization and gaits in the locomotion of vertebrates. *Physiological Reviews, 69*(4), 1199-1227.

Andersson, E., Supej, M., Sandbakk, O., Sperlich, B., Stoggl, T., & Holmberg, H. C. (2010). Analysis of sprint cross-country skiing using a differential global navigation satellite system. *European Journal of Applied Physiology, 110*(3), 585-595. doi: 10.1007/s00421-010-1535-2

Aune, T. K., Ingvaldsen, R. P., & Ettema, G. J. (2008). Effect of physical fatigue on motor control at different skill levels. *Percept Mot Skills, 106*(2), 371-386. doi: 10.2466/pms.106.2.371-386

Cignetti, F., Schenab, F., Zanonec, P. G., & Rouarda, A. (2009). Dynamics of coordination in cross-country skiing. *Human Movement Science, 28*(2), 204-217. doi: http://dx.doi.org/10.1016/j.humov.2008.11.002

Daniels, G. L., & Newell, K. M. (2003). Attentional focus influences the walk-run transition in human locomotion. *Biological Psychology, 63*(2), 163-178. doi: 10.1016/s0301-0511(03)00024-3

Farley, C. T., & Taylor, C. R. (1991). A mechanical trigger for the trot-gallop transition in horses. *Science, 253*(5017), 306-308. doi: 10.1126/science.1857965

Göpfert, C., Holmberg, H. C., Stöggl, T., Müller, E., & Lindinger, S. J. (2012). Biomechanical characteristics and speed adaptation during kick double poling on roller skis in elite cross-country skiers. *Sports Biomechanics, 12*(2), 154-174. doi: 10.1080/14763141.2012.749939

Harridge, S. D., Bottinelli, R., Canepari, M., Pellegrino, M. A., Reggiani, C., Esbjornsson, M., & Saltin, B. (1996). Whole-muscle and single-fibre contractile properties and myosin heavy chain isoforms in humans. *Pflugers Arch, 432*(5), 913-920.

Holmberg, H. C., Lindinger, S., Stoggl, T., Eitzlmair, E., & Muller, E. (2005). Biomechanical analysis of double poling in elite cross-country skiers. *Med Sci Sports Exerc, 37*(5), 807-818.

Holmberg, H. C., Lindinger, S., Stöggl, T., Björklund, G., & Müller, E. (2006). Contribution of the legs to double-poling performance in elite cross-country skiers. *Medicine and science in sports and exercise, 38*(10), 1853-1860.

Hoyt, D. F., & Taylor, C. R. (1981). Gait and the energetics of locomotion in horses. *Nature, 292*(5820), 239-240. doi: 10.1038/292239a0

Hreljac, A. (1995). Determinants of the gait transitions speed during human locomotion – kinematic factors. *Journal of Biomechanics, 28*(6), 669-677. doi: 10.1016/0021-9290(94)00120-s

Kehler, A. L., Hajkova, E., Holmberg, H. C., & Kram, R. (2014). Forces and mechanical energy fluctuations during diagonal stride roller skiing; running on wheels? *Journal of Experimental Biology, 217*(21), 3779-3785. doi: 10.1242/jeb.107714

Kelso, J. A. S., & Ding, M. (1993). Fluctuations, intermittency and controllable chaos in biological coordination. *Human Kinetics Publishers*, 291–316.

Lindinger, S. J., Göpfert, C., Stöggl, T., Müller, E., & Holmberg, H. C. (2009). Biomechanical pole and leg characteristics during uphill diagonal roller skiing. *Sports Biomechanics, 8*(4), 318-333. doi: 10.1080/14763140903414417

Lindinger, S. J., & Holmberg, H. C. (2011). How do elite cross-country skiers adapt to different double poling frequencies at low to high speeds? *European Journal of Applied Physiology, 111*(6), 1103-1119. doi: 10.1007/s00421-010-1736-8

Mercier, J., Legallais, D., Durand, M., Goudal, C., Micallef, J. P., & Prefaut, C. (1994). Energy-expenditure and cardiorespiratory responses at the transition between walking and running. *European Journal of Applied Physiology and Occupational Physiology, 69*(6), 525-529. doi: 10.1007/bf00239870

Neptune, R. R., & Sasaki, K. (2005). Ankle plantar flexor force production is an important determinant of the preferred walk-to-run transition speed. *Journal of Experimental Biology, 208*(5), 799-808. doi: 10.1242/jeb.01435

Nilsson, J., Tveit, P., & Eikrehagen, O. (2004). Effects of speed on temporal patterns in classical style and freestyle cross-country skiing. *Sports Biomech, 3*(1), 85-107. doi: 10.1080/14763140408522832

Pellegrini, B., Zoppirolli, C., Bortolan, L., Holmberg, H. C., Zamparo, P., & Schena, F. (2013). Biomechanical and energetic determinants of technique selection in classical cross-country skiing. *Human Movement Science, 32*(6), 1415-1429. doi: http://dx.doi.org/10.1016/j.humov.2013.07.010

Prilutsky, B. I., & Gregor, R. J. (2001). Swing- and support-related muscle actions differentially trigger human walk-run and run-walk transitions. *Journal of Experimental Biology, 204*(13), 2277-2287.

Sandbakk, O., Holmberg, H.-C., Leirdal, S., & Ettema, G. (2010). Metabolic rate and gross efficiency at high work rates in world class and national level sprint skiers. *European Journal of Applied Physiology, 109*(3), 473-481. doi: 10.1007/s00421-010-1372-3

Smith, G. A. (2002). Biomechanics of cross country skiing. *Handbook of Sports Medicine and Science: Cross Country Skiing*, 32-61. doi: 10.1002/9780470693834.ch2

Thorstensson, A., & Roberthson, H. (1987). Adaptations to changing speed in human locomotion – speed of transition between walking and running. *Acta Physiologica Scandinavica, 131*(2), 211-214. doi: 10.1111/j.1748-1716.1987.tb08228.x

Vähäsöyrinki, P., Komi, P. V., Seppala, S., Ishikawa, M., Kolehmainen, V., Salmi, J. A., & Linnamo, V. (2008). Effect of skiing speed on ski and pole forces in cross-country skiing. *Med Sci Sports Exerc, 40*(6), 1111-1116. doi: 10.1249/MSS.0b013e3181666a88