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Title:

Kinematical analysis of the V2 ski skating technique: a longitudinal study

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Abstract

To characterize timing of movements and evaluate performance effects of technique alterations in V2 ski skating, thirteen elite male cross-country skiers (age, 23 ± 2 years; stature, 182 ± 6 cm; body mass, 76 ± 8 kg; V2 $\dot{V}O_{2max}$, 79.3 ± 4.4 $mL \cdot kg^{-1} \cdot min^{-1}$) were tested four times during the preparation and competition phase on a roller ski treadmill. Each test consisted of submaximal intensities of exercise for determination of oxygen cost followed by one 1000-m performance test. Hip movement (from accelerometer data) and joint angles (2D video) were determined for high-intensity exercise (6° and 3.5 $m \cdot s^{-1}$; ~ 97–100% of $\dot{V}O_{2peak}$). Each ski thrust consisted of three phases: Gliding phase (18–50% of cycle time); poling phase (50–70% of cycle time); and kick phase (70–78% of cycle time). Flexion/extension of the hip initiated all phases, followed by the respective joints in legs and arms. Mixed-model analysis, adjusting for systematic time-point effects, identified that both reduced vertical hip acceleration and increased cycle time gave a small likely reduction in oxygen cost and 1000-m time. In conclusion, well-developed hip movement is a key characteristic of the V2 technique for elite-standard skiers' long-term performance development.

Introduction

Cross-country skiing consists of two main techniques: classic and skating. The skating technique is a complex cyclic movement with many degrees of freedom. As the mean speed in World-cup races has increased markedly over the last two decades, the V2 technique (poling phase for every ski thrust; also called “Gear 3”) has become the most commonly-used technique in race events (Losnegard, 2013; Stöggl & Müller, 2008). Thus, improvements in the V2 technique are of high priority for competitive skiers.

Several studies have used cycle characteristics to describe the V2 technique and the consensus is that speed is related to cycle length (e.g. Bilodeau, Rundell, Roy, & Boulay, 1996; Losnegard, Myklebust, & Hallén, 2012). However, from a kinematical perspective, only a limited number of studies have investigated why skiers demonstrate this pattern. Sandbakk, Ettema, and Holmberg (2013) compared the V2 technique with and without contribution from the poles at constant speed. They demonstrated that poling reduced the centre-of-mass sideways range of motion, while cycle time and the vertical centre-of-mass range of motion increased. Moreover, a high centre-of-mass position before at the initiation of the poling phase has been suggested as important to increase propulsion both for the V2 and the classic style double-poling technique (e.g. Danielsen, Sandbakk, Holmberg, & Ettema, 2015; Myklebust, Losnegard, & Hallén, 2014). As hip movement and vertical displacement of the centre-of-mass seem to be determinants of the skiers' oxygen cost during double poling (Zoppirolli, Pellegrini, Bortolan, & Schena, 2015; Losnegard et al., 2016), hip movement is likely an important factor for effective V2 technique.

In double poling, the joints are engaged in a sequential pattern (proximal to distal joints) before and during the poling phase (Holmberg, Lindinger, Stöggl, Eitzlmair, & Müller, 2005). Skiers show similar sagittal-plane lowering of centre-of-mass during the pole thrust in double poling and V2 techniques (Myklebust et al., 2014). Hence, a distinct proximal-to-distal joint sequence could also be important in the V2 technique. From a practical point of view, timing of force application is considered to constitute one of the most important characteristics of effective technique (Holmberg et al., 2005; Stöggl, Müller, Ainegren, & Holmberg, 2011). Hence, description of timing characteristics is mandatory to understand how techniques are optimally executed in cross-country skiers. However, timing characteristics are rarely described in the literature.

The overall goal of technique alterations for a competitive athlete is to improve performance. Therefore, the need to evaluate whether its use leads to such improvement is important, but interventions or combined longitudinal and physiological studies are rare in biomechanical analyses (Lees, 2002). Although different standard skiers show different movement patterns and physiological responses at the same skiing speed (Sandbakk, Holmberg, Leirdal, & Ettema, 2010), it is not clear if imitating better skiers’ technique leads to enhanced performance. An alternative approach is to follow the same skiers during a training period. Recently, we showed by use of a single inertial measurement unit (IMU), that skiers have their individual movement patterns and that the differences between skiers persist over several months (Myklebust et al., 2014). Hence, an IMU should be able to evaluate effects of skiers' technical alterations on performance.

In a group of elite-standard skiers, we found reduced oxygen cost and improved performance during treadmill skiing (V2 technique) over an eight-month training period leading up to the main goal of the season (Losnegard, Myklebust, Spencer, & Hallén, 2013). In the present study, we used the same skiers to evaluate if the enhanced performance and exercise economy are related to kinematical alterations identified by IMU-data and video analysis. Especially, timing of joint movement, cycle characteristic and hip accelerations were analysed. We hypothesized that: (I) The V2 technique is characterized by distinct timing sequences where the movement starts with the hip joint and is followed by joints in the legs and arms. (II) Hip movement is an essential factor for effective V2 technique; (III) Hip IMU data can quantify essential technique alterations that affect economy of exercise and performance of elite-standard skiers.

Methods

Participants.

Thirteen elite-standard men senior cross-country skiers (age, 23 ± 2 years; stature 182 ± 6 cm; body mass 76 ± 8 kg) were recruited and completed. All had regularly participated in rollerski treadmill testing over the previous 2–4 years. Their V2 $\dot{V}O_{2max}$ (the highest individual $\dot{V}O_{2peak}$ during the season) was 79.3 ± 4.4 mL·kg^{-1}·min^{-1}. Training history for the annual training cycle (12 months) and competition results of the participants has been presented (Losnegard et al., 2013). The Regional Ethics Committee of Southern Norway approved the study, and participants gave their written consent before entering the study.

Experimental design.

To characterize timing of movements and evaluate effects of technique alterations, eleven participants performed an identical protocol four times during an annual training year (June, August, October and January). Additionally, two of the eleven skiers were tested the following June, and two additionally skiers were tested in October and January. Hence, in total 50 tests were included for the accelerometer analyses, whereas 44 tests were included for joint movement's analyses.

Procedures.

The participants performed 4–6 submaximal bouts of exercise (3.5–6.0°, 3.0 $m \cdot s^{-1}$), each of 5 min duration with 2 min breaks. The individual oxygen cost (measured between 2.5 and 4.5 minutes at each trial) was calculated as the mean from three bouts (3.5, 4.5 and 5.0°, completed at all tests). Participants then performed a 1000-m time-trial test including assessment of $\dot{V}O_{2peak}$. The 1000-m test was performed at 6°. The speed between 0–100 m, 101-200 m, and after 200 m was 3.25 $m \cdot s^{-1}$, 3.50 $m \cdot s^{-1}$, and self-selected, respectively. Video and accelerometer data captured between 101–200 m (6.0° and 3.5 $m \cdot s^{-1}$) were analysed for all tests. This speed was the greatest that was performed identically at all tests, and corresponded to an oxygen demand of ~74–76 $mL \cdot kg^{-1} \cdot min^{-1}$ and ~97–100% of $\dot{V}O_{2peak}$. Changes in physiological responses and performance have been reported (Losnegard et al., 2013). Briefly, from June to January 1000-m time (-7.4% ± 1.9% [mean ± 90% confidence limits], effect size = 1.37, $P < 0.05$) and oxygen cost (-3.0% ± 1.2% [mean ± 90% confidence limits], effect size = 0.63, units: $mL \cdot kg^{-1} \cdot min^{-1}$, $P < 0.05$) reduced, whereas $\dot{V}O_{2peak}$ did not change systematically (1.3% ± 2.4% [mean ± 90% confidence limits], effect size = 0.17, units: $mL \cdot kg^{-1} \cdot min^{-1}$, $P > 0.05$). The temperature during testing was automatically logged. It was between 21-24°C for all individual tests, and not systematically different between test occasions.

Movement capturing.

All tests were performed on a rollerski treadmill (Rodby, Sodertalje, Sweden). The skiers used Swix CT1 poles (Swix, Lillehammer, Norway) and Swenor Skate rollerskis (Swenor, Sarpsborg, Norway) with wheel type 1 ($\mu = 0.020$). Each skier used the same pole length at all tests (165 ± 6 cm, ~91 ± 1% of stature). The skiers wore an IMU system from PLUX Wireless Biosignals S.A. (Lisbon, Portugal). It included one accelerometer at each pole and ski boot for analyzing timing of the pole and ski ground contact hits and liftoffs, and a fifth accelerometer adhered directly to the skin at the os sacrum, vertebra 1 (hip). Data were transmitted via Bluetooth for logging on a computer at 1000 Hz (boot and hip accelerations) and 125 Hz (pole accelerations; sampling rate limited by data acquisition unit). For further details, see Myklebust et al. (2014), as the system and setup was identical. Video was captured at a distance of 6.6 meters perpendicular to the skiing direction (Sony DCR-TRV900E; Sony, Tokyo, Japan).

Accelerometer data analysis.

Data were post-processed using Matlab R2012b (MathWorks Inc., Natick, MA, USA). Timing of limb ground contact was automatically derived from pole and boot accelerometers. The procedure has better accuracy than a 50Hz video reference system, except for ski plants that have accuracy and precision of 0.047 ± 0.074 s (Myklebust et al., 2014). In the present study, the cycle started (0%) and ended (100%) at the right pole plant during the left ski thrust. Cycle time, poling time, and reposition time, were defined as time between every second right pole plant, a pole plant and subsequent pole liftoff, and from pole liftoff to subsequent pole plant, respectively. Because of technical problems, hip movements from six tests were lost. The following analysing steps, except step 6, were identical to the "IMU-G" method validated by Myklebust, Gløersen, and Hallén (2015):

1. Defining the laboratory reference frame (XYZ) as right-handed, moving along the surface with constant speed, with horizontal XY-plane and anterior direction as positive Y-axis.
2. Conversion to *g*-units using offset and scaling factors.
3. Filtering data using a 30 Hz low-pass second order Butterworth recursive digital filter. The cut-off frequency was selected based on a residual analysis.
4. Applying a rotation matrix to meet the assumption that mean horizontal acceleration is zero at constant speeds.
5. Time-normalizing data to a full cycle automatically derived from pole accelerometers.
6. Adjusting for intra-cycle rotations using the V2-specific rotational pattern presented by Myklebust et al. (2015).
7. Subtracting gravity (1.0 g) from vertical acceleration values before calculating resultant accelerations (vector norm - independent of direction).
8. Applying a cumulative trapezoidal numerical integration twice, to obtain the hip displacement. For each integration step, the mean was subtracted from the data since the speed was controlled and constant.

Since gyroscope data were not available in the present study, step 6 was included and order of analysing steps slightly changed from the IMU-G method validated Myklebust et al. (2015). Use of the present method on the data presented by Myklebust et al. (2015) identified root-mean-squared errors within a cycle of 1.7 ± 0.9 cm, 1.3 ± 0.5 cm, 0.3 ± 0.2 cm, for the X, Y, Z axes respectively. Range of displacement errors were -0.3 ±4.6 cm, 0.2 ± 1.6 cm, 0.2 ± 0.6 cm, for the X, Y, and Z axes respectively. Presented results are based on individual skiers' mean curve calculated from 10 subsequent time-normalized cycles. Acceleration in the different cycle phases was quantified as root-mean-squared acceleration for each orthogonal direction and the resultant vector norm. In addition to acceleration, curves showing displacement from the corresponding cycle's mean location on the treadmill are presented.

Joint kinematics.

Right side joint angles were calculated from video (25 Hz) using Tracker 4.84 (Douglas Brown, Open Source Physics). The pole tip and six joint centers (wrist, elbow, shoulder, hip, knee and ankle) were manually marked. Then, coordinates for each of five subsequent cycles were time-normalized, using a third-order 101-point interpolation, before joint angle calculations and means for the five cycles were recorded for further analyses. The participants were analysed one by one in chronological order. Note that angles presented are from the 2D projection to the sagittal plane through the represented joint (Figure 1). Further, the ankle angle is not the true foot angle, but calculated from the knee and ankle coordinates and the horizontal plane thru the ankle joint (Figure 1). During the right ski thrust, the horizontal distance between the pole tip and the ankle joint at pole plant was defined as forward pole plant. The right ski thrust was divided into three visually distinct phases: gliding phase (right ski hit to pole hit); poling phase (pole hit to pole leave); and kick phase (from the end of poling phase to the end of ski thrust).

<<FIG 1 NEAR HERE>>

Statistical Analyses.

All data are presented as mean ± standard deviation if not otherwise stated. The results in June and January are focused to highlight the main changes over the training period. Changes were determined using a two-tailed paired t-test, and magnitude of differences was expressed as standardized mean differences (Cohen's *d* effect size). Thresholds for interpreting differences as small, moderate, large and very large effect size were 0.2, 0.6, 1.2, 2.0, respectively (Hopkins et al., 2009). Since measurement error is a factor (e.g. oxygen cost error is ± 3%), all raw data (except joint angle data) were log-transformed to ensure uniformity of error residuals prior to further analysis. Pearson's Product Moment Correlation was calculated between both raw data and change scores from June to January. Thresholds used for small, moderate, large, very large and extremely large correlation coefficients were 0.1, 0.3, 0.5, 0.7, and 0.9, respectively (Hopkins, Marshall, Batterham, & Hanin, 2009), and a relationship was stated as clear if the confidence limits did not cover both positive and negative relations > 0.1, which means $r \geq + 0.4$ or ≤ -0.4 for the number of participants tested. Statistical calculations were performed with, Microsoft Excel (Redmond, WA) and SigmaPlot 11.0 (San Jose, CA). A level of $P < 0.05$ was considered significant, while $P < 0.1$ was considered a tendency.

To evaluate effects of technique alterations on performance, mixed-model analysis (IBM SPSS Statistics 21) was used to allow for repeated measurements (two to four tests), missing data, individual responses, and adjustment for time-point effects (e.g. because of physiological effects of adjusted training loads etc.). Changes of log-transformed scores from each individual's mean of available tests ensured uniformity and retrieved relative changes. The oxygen cost (units: $mL \cdot min^{-1}$) was a strong mediator for the technical variables' effects on performance. Hence, oxygen cost was used as dependent variable. The model allowed for random effect of participants, and adjusted for time point of testing (June, August, October, January, May) and changes in body mass (including equipment mass). One by one, a technical variable was then included in the model. Relative change slopes (% per % after back-transformation) with ± 90% confidence limits, within-participant variation over the whole season, and model residuals for each variable are presented. A reduced effect of test time point and/or reduced model residual was anticipated for important technical variables. Using magnitude thresholds presented by Hopkins et al. (2009), the smallest worthwhile effect of 1.1-1.4 % of ski racing times reported by Spencer, Losnegard, Hallén, and Hopkins (2014), and adjusting for oxygen cost's effect of performance, resulted in magnitude thresholds of 0.5%, 1.6%, 2.8%, and 4.3% of oxygen cost, for small, moderate, large and very large performance effect, respectively. This scale was used for probabilistic description of clear effects: <0.5%, most unlikely; 0.5%–5%, very unlikely; 6%–25%, unlikely; 26%–75%, possibly; 76%–95%, likely; 96%–99.5%, very likely; 99.6%–100%, most likely (Hopkins et al., 2009).

Results

***Kinematic analyses of the V2 technique*.**

The right ski thrust occurred at 18-78% of cycle time with the gliding phase from 18-50%, poling phase from 50-70% and kick phase from 70-78% of the cycle time (Figure 2). The gliding phase included an overlap with the left ski kick phase (ending ~28%) and a pure glide phase (28–50% of cycle time). The end of poling phase and the whole kick phase overlapped with the left ski gliding phase (starting ~67% of cycle time). During the gliding phase, the hip was elevated 14 ± 2 cm and this phase was initiated by a peak in vertical hip acceleration and ended with a nadir of vertical hip acceleration (Figure 3). The hip elevation was a result of hip, knee and ankle joint extensions starting at ~19%, ~22% and ~29% of cycle time, respectively (Figure 2). The arm movements in this gliding phase involved the backward arm swing with shoulder and elbow extensions before the arms were moved forward. During poling phase, the hip was lowered (Figure 3). Before pole plant, hip-flexion was initiated (~45 % of cycle time), while knee and ankle joint flexions started approximately at pole plant (~49% and ~50% of cycle time, respectively, Figure 5). Shoulder joint extension started slightly after pole plant (~52% of cycle time), while elbow flexion continued into the poling phase until elbow extension started at ~57% of cycle time (Figure 5). The kick phase was characterized by a rapid hip, knee and ankle extension. However, the hip and knee joint extensions started before the defined kick phase (~64% and ~66% of cycle time, respectively), while the ankle joint extension started just after pole liftoff (~72% of cycle time). Ankle and knee joint extensions finished at the end of the kick phase, while the hip joint extension continued into the gliding phase of the opposite leg.

<<FIG 2–3 AND TABLE 1 NEAR HERE>>

Kinematic alterations.

There were no clear relationships between cycle time and 1000-m time, or cycle time and oxygen cost at any test time point. However, cycle time increased from June to January because of increased durations of poling and reposition time (Table 1). The increased poling time was mainly a consequence of more forward pole plant relative to the ankle, and the increased reposition time occurred because of increased pure-glide time (28-50% of cycle time) (Table 1). While sideways displacement increased, vertical and anterior-posterior displacements did not change from June to January (Table 1, Figure 3). Full-cycle root-mean-squared accelerations were reduced in vertical and anterior-posterior directions, but did not change in the sideway direction. During the pure-glide phase, root-mean-squared accelerations were reduced in all directions (Table 1).

A linear mixed-model that adjusted for a fixed effect of time point and random effect of participants, distinguished between-participants variation of 9.7% in oxygen cost and an unexplained residual of 5.2%. Change in body-mass had a moderate (90% confidence limits: small to large) positive effect on oxygen cost and performance. Changes in body mass also reduced the residual to 3.9%, and were included when the technical variables were included one by one (Table 2). Changes in poling time and vertical root-mean-squared acceleration had the greatest likelihood (91% negative and 84% positive, respectively) for a substantial effect on oxygen cost and performance. Figure 4 illustrates seasonal decreases in oxygen cost that was explained by alterations in cycle time or vertical acceleration.

<<FIG 4 AND TABLE 2 NEAR HERE>>

In January compared with June, hip angle was less at the start of the gliding phase, while there were no changes in knee and ankle angles. Hence, the trunk was leaning more forward relative to the horizontal in January than in June ($P < 0.05$), and the hip joint tended to have greater range of motion during the gliding phase ($P = 0.11$, Fig 2)., Throughout the poling phase, the knee and ankle joint were more extended in January than June ($P < 0.05$). In addition, the minimum flexion-angle in the knee joint tended to occur later in January than June (~67% vs. 65% of cycle time, $P = 0.07$). At pole plant, elbow extension and shoulder flexion were greater in January than

June (both $P < 0.05$). Elbow flexion was coordinated with the pole plant, with an associated increase in range of motion ($P < 0.05$), whereas the subsequent elbow extension range of motion did not change. Furthermore, the maximum flexion in the elbow joint occurred later in the poling phase (~59% vs. 57% of cycle time, $P < 0.05$) and shoulder extension range of motion increased from June to January ($P < 0.05$). Changes in elbow flexion and shoulder extension range of motions had large and very large correlations (r = 0.67 and 0.85, respectively, both $P < 0.05$) with changes in cycle time from June to January. Further, changes in elbow flexion range of motion had a large correlation (r = 0.64, $P < 0.05$) with changes in forward pole plant. During the kick phase, hip, knee and ankle range of motion were reduced from June to January (all $P \leq 0.06$). At ski liftoff, the hip and knee joint were less extended in January compared to June ($P < 0.05$).

Discussion

The present study adds to previous work on technique analysis in cross-country skiing by integrating a longitudinal, physiological and biomechanical perspective in a group of elite-standard athletes. The principal findings were: (I) The V2 technique was characterized by consistent sequences of joint movement, starting with the hip and followed by joints in the legs and arms; (II) During the season, both smoother hip movements (reduced root-mean-squared accelerations) and increased cycle time gave a small likely reduction in 1000-m time and oxygen cost.

Kinematic analyses of the V2 technique.

The V2 technique consists of two symmetrical ski thrusts with a double-poling action superimposed in the last half of both ski thrusts. We divided each ski thrust into three visually distinct phases. The primary goal of the pure gliding phase is to reposition body segments and raise the body's centre-of-mass with a minimum loss of momentum to provide recovery of propulsive muscles. In the poling phase, the hip and upper-body are lowered and forward tilted (Figure 2, Figure 3). This prolongs poling time and hence, impulse, as found in double poling (Lindinger & Holmberg, 2011). In the kick phase the hip extension starts before pole liftoff, followed by knee and ankle extension. Hence, the poling phase and ski thrust is characterized by a body extension-flexion-extension pattern initiated by the hip, followed by knee and ankle movements in a “first in – first out” pattern (Figure 5). The arms follow the same timing, with shoulder and elbow joint movements occurring after the initial movement of the hip. A similar coordination pattern distinguishes among elite-standard skiers during double poling (Holmberg et al., 2005). This implies that coaches and athletes should have special focus on the timing of hip movement, since initiation of the hip seems fundamental for other joint movements in the V2 technique. However, we need more studies to investigate specific training models for optimizing the timing of joint movements.

Kinematic alterations.

The hip was more flexed, while the knee and ankle joint were similar at the start of the gliding phase in January than in June. Thus, the skiers demonstrated increased forward lean of the trunk, relative to horizontal. During the poling phase, the knee and ankle angles were greater in January, while the hip angle was similar. Further, the minimum knee flexion angle tended to occur later in the poling phase in January than June (Figure 5). These changes in timing of the joint movement were combined with reduced hip accelerations, especially in the vertical direction and during the pure glide phase. The possibly small positive effect of pure glide vertical root-mean-squared acceleration on performance (Table 2), suggest that the changed timing of the joint movement is an example of optimal force application between poles and skis. Furthermore, such improved timing could smooth whole-body movement and consequently reduce the oxygen cost of movement.

<<Figure 5 near here>>

The overall goal for these skier' training preparations was to optimize performance for the main events held in January. Since physical condition partly alters skiers' technique, we cannot draw causal relationships between changes in technique variables and performance without caution. However, the mixed-model adjusted for overall changes over time. After these adjustments, there were still relationships between oxygen cost and technical variables. This strengthens the assumption of causality between the changes in technique and change in performance. Figure 4 illustrates seasonal changes in oxygen cost and the amounts accounted for by technical variables. Small likely negative and positive effects on oxygen cost occurred for cycle time and vertical acceleration, respectively. Hence, technical modifications for smoother movements with reduced vertical acceleration seem favourable for oxygen cost and performance. An effect of cycle time on performance (Table 2) has not been reported at an individual level for the V2 technique. Leirdal, Sandbakk and Ettema (2013) used a cross-over design, but did not find any effect on oxygen cost by experimentally altering frequency (cycle time). It is possible that longitudinal adaptations are functional and have different effects to acute forced alterations in technique.

Notably, in our model vertical root-mean-squared acceleration in the latter part of the pure glide phase, affected oxygen cost and performance to the same extent as the full-cycle vertical root-mean-squared acceleration (Table 2). During this part of the glide phase, only one ski is in contact with the ground and balance is important. An improved balance might reduce accelerations. Possible performance enhancing implications of better balance are: (1) sufficient time and less energy demanding for repositioning segments and equipment; (2) more time for recovery of propulsive muscles; and (3) possibly reduced friction on snow because of a flatter oriented ski.

Technical considerations.

The 2D video analysis of the 3D nature of ski skating is a major limitation. However, the overall goal of this study was to characterize timing of movements, and analyse changes in technique during a season along with changes in performance. We find the longitudinal approach with mixed-modelling and analyses of 2D video and accelerometer data, well suited for this purpose. To minimize the limitations of 2D video analysis, a skilled physiotherapist performed all video analyses chronologically for one participant at a time. The recording camera was positioned perpendicular to the skiing direction, and two laser beams forced the skiers to position at the middle of the treadmill. Evaluation of upper arm, lower arm and leg length did not indicate any systematic errors (e.g. shoulder abduction) due to in-depth distance from the camera. Increased range of shoulder motion and greater extension of the elbow at pole plant, leads to a more forward pole plant and longer poling distance at constant speed. The video analysis and the poling time calculated from pole accelerometers confirmed this finding.

Conclusions

The data in the present study were collected from elite-standard skiers and provide a framework for understanding and developing an efficient skiing technique. First, the V2 technique used by these skiers, has distinct timing sequences of the joint movements, starting with the hip and followed by joints in the legs and arms. Together with the finding of a small likely effect of vertical acceleration and cycle time on performance, an improved timing of the joint movement seems to be important for skiers to develop their technique and performance. Finally, the findings of the present study indicate that IMU data evaluate alterations of technique.

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Table 1: Performance, physiological measures, and the technical parameters including full-cycle timing of phases, range of displacement (ROD) and root-mean-squared (RMS) acceleration in June and January at a fixed demand (6°, 3.5 $m \cdot s^{-1}$).

	June		**January**			**Magnitude of differences (ES)**	
1000-m time (s)	270	± 14	250	± 10	*	-1.63	Large
O_2-cost (mL/min)	4050	± 368	3769	± 388	*	-0.75	Moderate
Total mass (kg)	79.8	± 8.7	78.3	± 8.0	*	-0.18	Trivial
$\dot{V}O_{2peak}$ (mL/min)	5812	± 531	5776	± 522		-0.07	Trivial
Cycle time (s)	1.69	± 0.10	1.80	± 0.07	*	1.39	Large
Poling time (s)	0.70	± 0.04	0.75	± 0.04	*	1.16	Moderate
Poling time (% of cycle time)	42	± 2	42	± 2		-0.01	Trivial
Reposition time (s)	0.98	± 0.07	1.05	± 0.06	*	1.10	Moderate
Reposition time (% of cycle time)	57	± 1	57	± 2		0.07	Trivial
Kick time (s)	0.25	± 0.03	0.25	± 0.04		0.05	Trivial
Pure glide time (s)	0.73	± 0.05	0.80	± 0.06	*	1.24	Large
Poling distance (cm)	122	± 7	129	± 8	#	0.99	Moderate
Forward pole plant (cm)	18	± 9	24	± 8	*	0.78	Moderate
ROD sideways (cm)	32	± 8	40	± 6	*	1.14	Moderate
ROD AP (cm)	15	± 2	13	± 2		-0.78	Moderate
ROD vertical (cm)	14	± 3	14	± 2		0.15	Trivial
RMS sideways acceleration ($m \cdot s^{-2}$)	2.9	± 0.3	2.9	± 0.3		-0.14	Trivial
RMS AP acceleration ($m \cdot s^{-2}$)	3.4	± 0.5	3.1	± 0.3	*	-0.56	Small
RMS vertical acceleration ($m \cdot s^{-2}$)	3.0	± 0.3	2.7	± 0.4	*	-0.89	Moderate
RMS resultant acceleration ($m \cdot s^{-2}$)	5.6	± 0.5	5.2	± 0.4	*	-0.86	Moderate
RMS resultant acceleration pure glide ($m \cdot s^{-2}$)	4.4	± 0.5	3.9	± 0.4	*	-1.11	Moderate
RMS resultant acceleration poling ($m \cdot s^{-2}$)	6.1	± 0.8	5.7	± 0.7		-0.40	Small
RMS resultant acceleration kick ($m \cdot s^{-2}$)	7.1	± 0.7	7.0	± 0.7		-0.22	Small

Note: Data are mean ± standard deviation. AP = anterior-posterior direction. All technical parameters are from accelerometer analyses except for forward pole plant (relative to ankle position) which was calculated from video analysis. Total mass is body mass + equipment mass. ES = effect size. *Different from June ($P < 0.05$). # $P = 0.051$. N = 11, except for ROD and RMS accelerations where N = 10.

Table 2: Effect of altered technical variables on O_2-cost (Slope) and performance (Effect size) derived from a mixed model that allows for individual responses, and adjusts for fixed effects of test time-point and changes in total mass

	Slope % per %	CV (%)	Effect size ± 90 % CL		Residual (%)
Test time point					5.2
Total mass	0.92 ± 0.49	1.2	2.21 ± 1.18	moderate	3.9
Cycle time	-0.18 ± 0.17	4.3	-1.50 ± 1.40	small	3.5
Poling time	-0.16 ± 0.15	5.0	-1.52 ± 1.28	small	3.4
Pole reposition time	-0.13 ± 0.17	4.3	-1.08 ± 1.41	small	3.7
Kick phase time		6.2	-0.13 ± 1.08	unclear	4.0
Pure glide time	-0.09 ± 0.12	5.9	-1.08 ± 1.43	small	3.7
RMS acc sideways	0.06 ± 0.17	4.0	0.47 ± 1.32	unclear	3.9
RMS acc antero-posterior		7.3	-0.01 ± 1.26	unclear	4.0
RMS acc vertical	0.10 ± 0.11	6.7	1.30 ± 1.36	small	3.6
RMS acc resultant	0.09 ± 0.14	5.3	0.90 ± 1.45	unclear, possibly trivial to small	3.8
RMS acc vertical pure glide	0.05 ± 0.07	10.0	0.98 ± 1.26	small, possibly clear	3.7
RMS acc vertical late pure glide	0.03 ± 0.04	21.5	1.36 ± 1.48	small	3.6
RMS acc vertical poling	0.04 ± 0.08	7.9	0.61 ± 1.18	unclear, possibly trivial to small	3.9
RMS acc vertical kick	0.06 ± 0.08	7.2	0.85 ± 1.12	small, possibly clear	3.8
RMS acc resultant pure glide	0.08 ± 0.10	7.7	1.18 ± 1.49	small	3.7
RMS acc resultant middle pure glide	0.05 ± 0.07	12.1	1.10 ± 1.53	small, possibly clear	3.8
RMS acc resultant poling		6.0	0.43 ± 1.21	unclear	3.9
RMS acc resultant kick		4.8	0.19 ± 1.12	unclear	4.0
Sideways ROD	-0.05 ± 0.05	13.0	-1.15 ± 1.30	small	3.7
Anterior-posterior ROD		15.2	-0.70 ± 1.29	unclear	3.9
Vertical ROD		7.2	-0.38 ± 1.31	unclear	4.0

Note: Data are mean ± 90% confidence limits. RMS acc = root-mean-squared hip acceleration. ROD = hip range of displacement. Total mass is body mass + equipment. CV is within- participants variation over the whole season and magnitude of effect size is calculated according to Hopkins et al. (2009) and Spencer et al. (2014). Probability of effect size is "75%-95%, likely" if no other probabilistic term is noted. One technical variable was included at the time.

Figure legends.

Figure 1: Illustration of the examined joint angles. A = elbow, B = shoulder, C = hip, D = knee, E = ankle. Ankle joint angle was calculated from the following reference points: knee, ankle and the horizontal plane through the ankle joint.

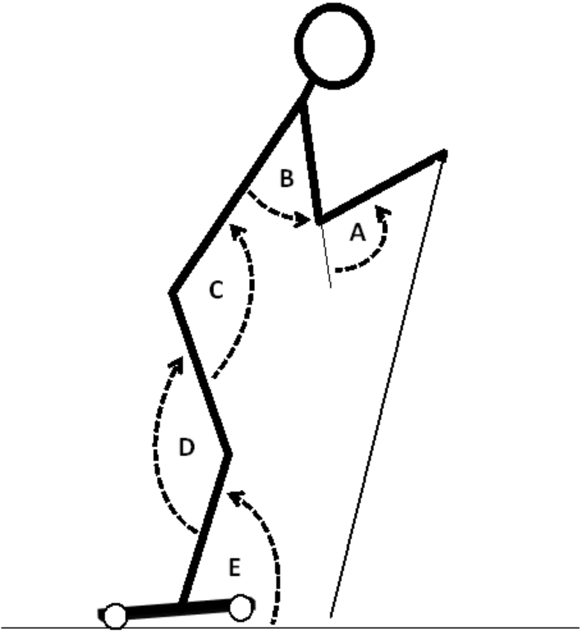
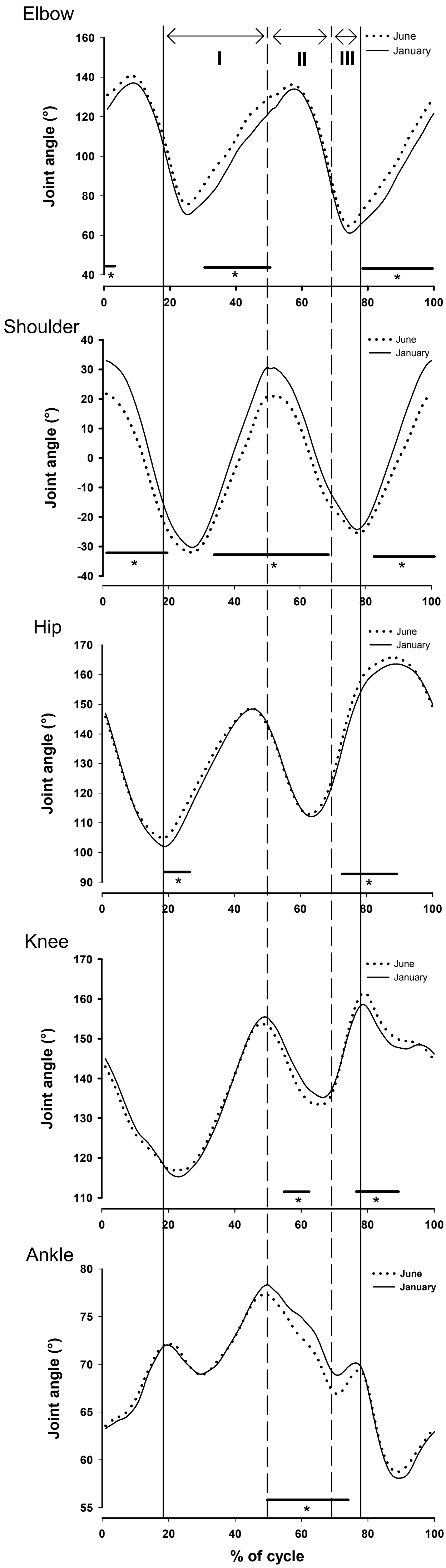
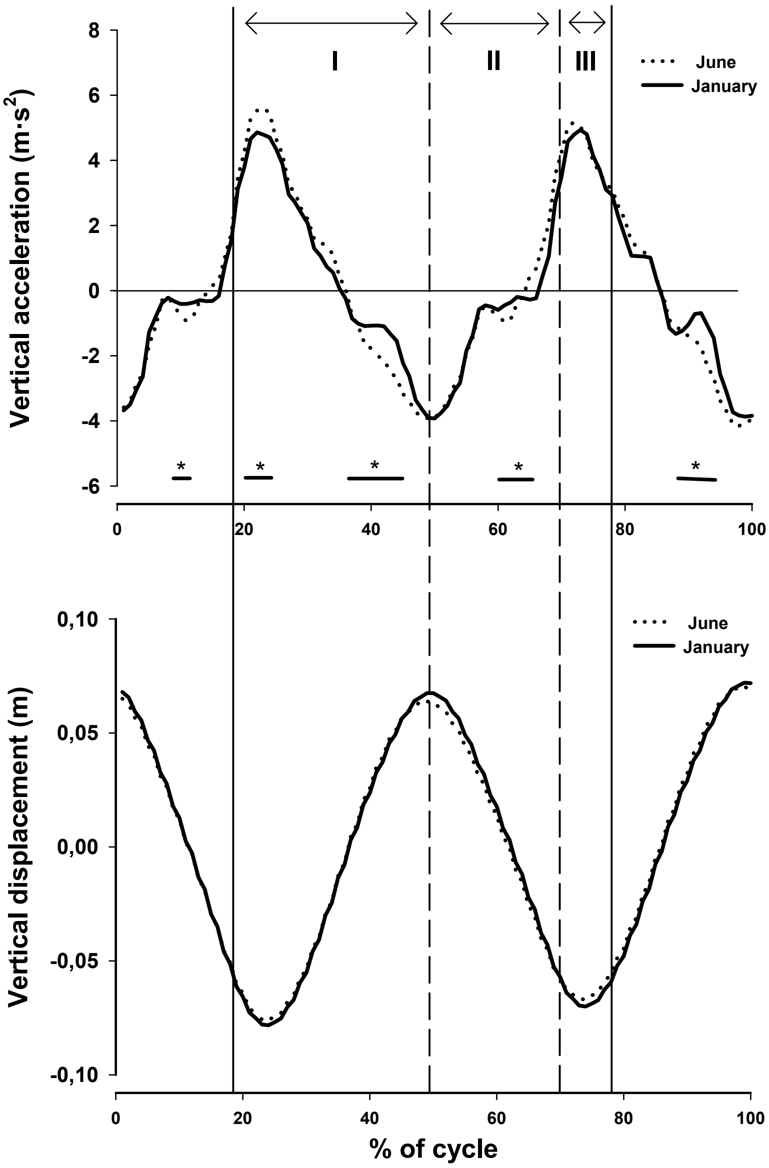

B
A
C
D
E

Figure 2: Group mean joint angle characteristics for the elbow, shoulder, hip, knee and ankle during a full cycle in June and January. The cycle starts (0%) and ends (100%) at right pole plant during left ski thrust. The vertical full lines are right ski plant (18%) and liftoff (78 %). The vertical dotted lines are right pole plant (50%) and liftoff (70%). The right ski thrust phases are: I = gliding phase including the pure glide phase from ~28%, II = poling phase, and III = kick phase. The horizontal full line shows the area of differences between the June and January curves (paired t-test, $P < 0.05$, N=11).



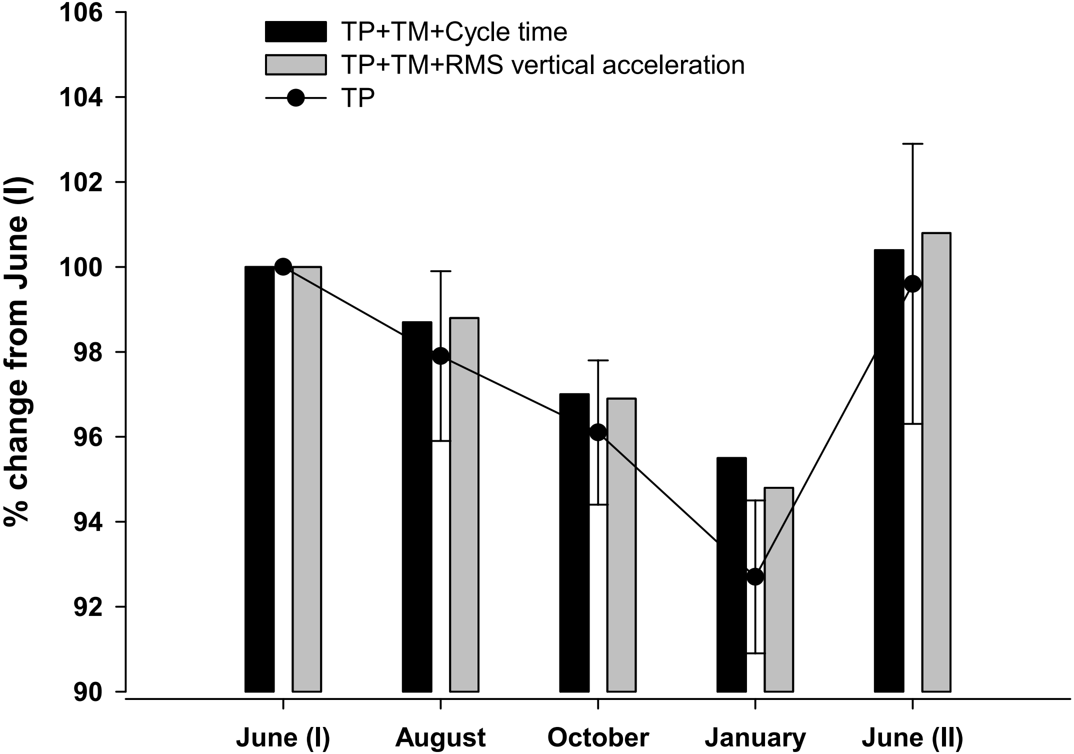
Elbow
I
II
III
June
January
Joint angle (°)
*
Shoulder
Hip
Knee
Ankle
% of cycle

Figure 3: Group mean curve of vertical acceleration (upper panel) and displacement (lower panel) measured by an accelerometer at the os sacrum (hip) in June and January. The cycle starts (0%) and ends (100%) at right pole plant during left ski thrust. The vertical full lines are right ski plant (18%) and liftoff (78 %). The vertical dotted lines are right pole plant (50%) and liftoff (70%). The right ski thrust phases are: I = gliding phase including the pure glide phase from ~28%, II = poling phase, and III = kick phase. The horizontal full line shows the area of differences between the June and January curves (paired t-test, $P < 0.05$, N=10).



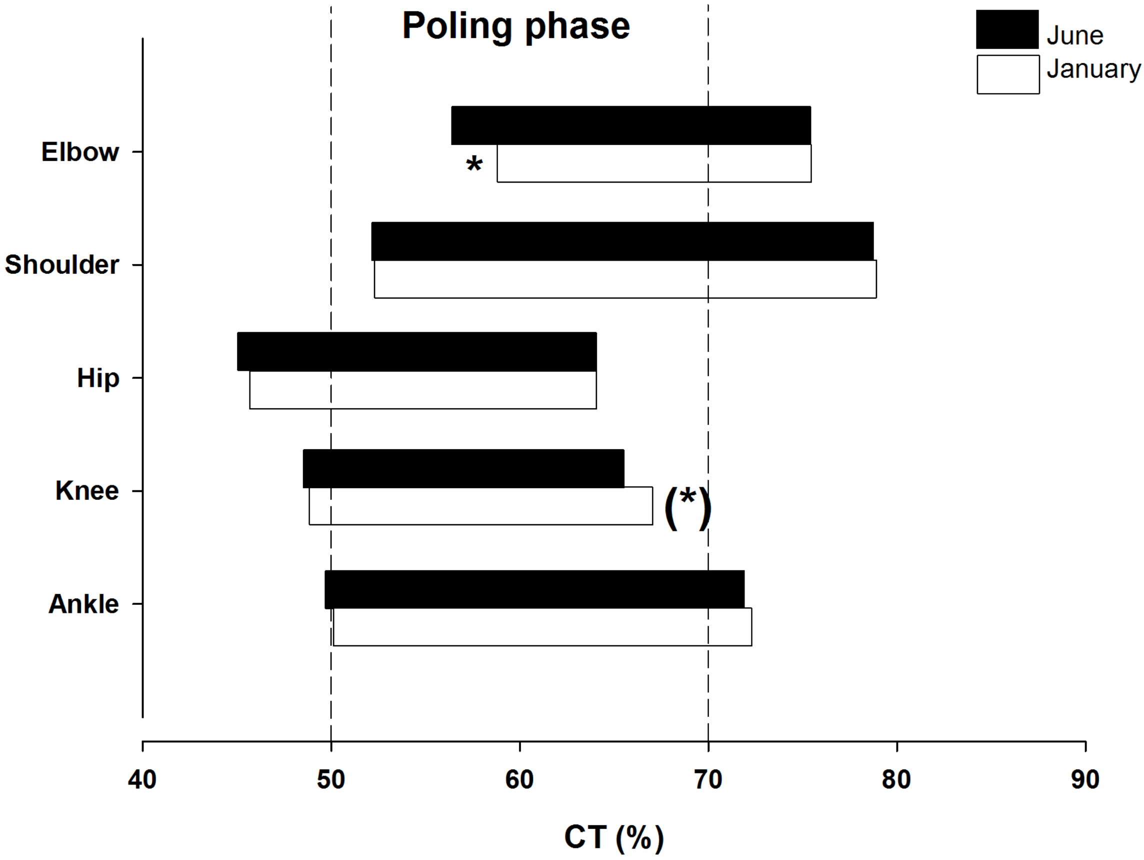
Vertical acceleration (m·s^2)
8
6
4
2
0
-2
-4
-6
I
II
III
June
January
*
*
*
*
*
0
20
40
60
80
100
Vertical displacement (m)
0,10
0,05
0,00
-0,05
-0,10
June
January
0
20
40
60
80
100
% of cycle

Figure 4: O_2-cost at different test time-points (black line; mean ± 90% confidence limits; TP) and how models adjusting for total mass (body mass + equipment mass; TM), and technical factors (cycle time or root-mean-squared (RMS) vertical acceleration) modified the time-point effect. Remark that only two skiers were analyzed in June (II).



106
104
102
100
98
96
94
92
90
% change from June (I)
TP+TM+Cycle time
TP+TM+RMS vertical acceleration
TP
June (I)
August
October
January
June (II)

Figure 5: Coordination pattern of the joints during the right pole plant (50%) and liftoff (70%) in June and January. The horizontal bars illustrate the initiation and duration of the flexion phase in hip, knee and ankle. In shoulder and elbow the horizontal bars illustrate the extension phase. Note that the shoulder and elbow extension during poling phase is followed by a backward arm swing after pole liftoff. * Differences between the June and January curves (paired t-test, $P < 0.05$, N=11). (*) Tendency towards differences between the June and January curves (paired t-test, $P < 0.1$, N=11).


Poling phase
June
January
Elbow
Shoulder
Hip
Knee
Ankle
*
(*)
40
50
60
70
80
90
CT (%)