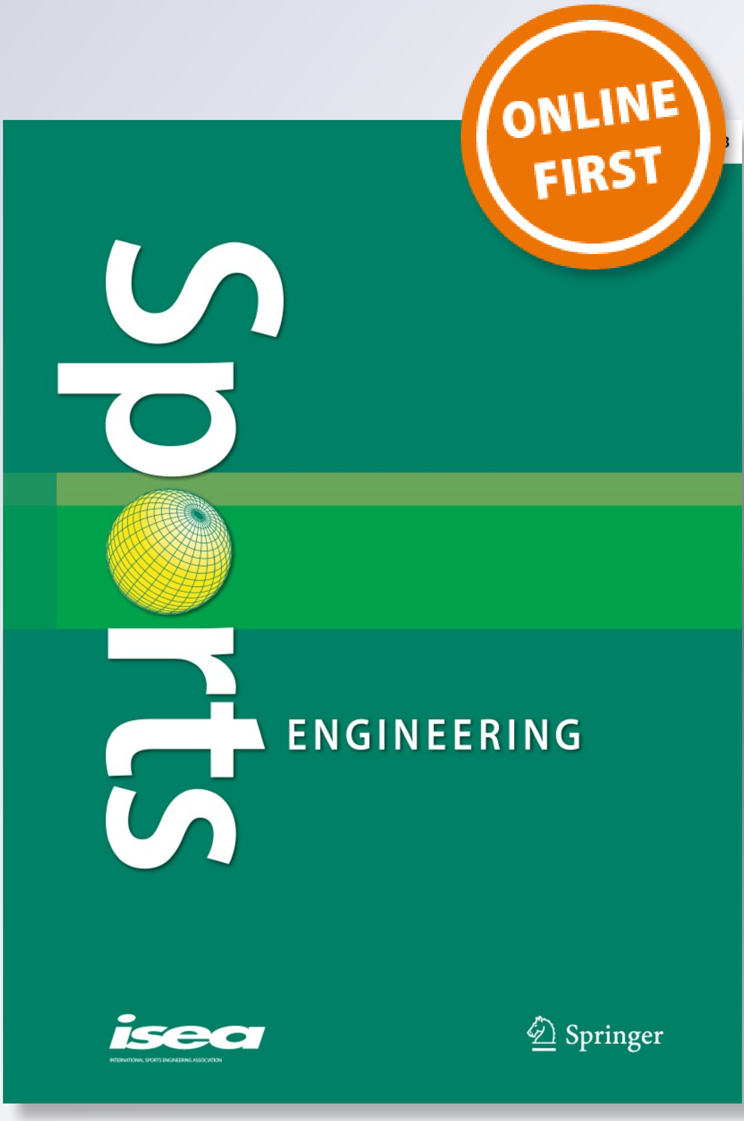
# Construction of an instrumented roller ski and validation of three-dimensional forces in the skating technique

**M. Hoset, A. B. Rognstad, T. Rølvåg, G. Ettema & Ø. Sandbakk**

**Sports Engineering**

ISSN 1369-7072

Sports Eng
DOI 10.1007/s12283-013-0130-2




Springer

Sports Eng
DOI 10.1007/s12283-013-0130-2

RESEARCH PAPER

# Construction of an instrumented roller ski and validation of three-dimensional forces in the skating technique

M. Hoset · A. B. Rognstad · T. Rølvåg ·
G. Ettema · Ø. Sandbakk



**Abstract** The purposes of the present investigation were to construct an instrumented roller ski, validate the force measurements and resolve the forces into three dimensions. To demonstrate the practical applications of the system, this study aimed to distinguish cycle characteristics and kinetics between skiers with different technical characteristics and between skating with and without poling while roller ski skating on a treadmill. It was shown that a roller ski with full bridge strain gauges could provide valid measurements of one-dimensional forces. By recording the orientation of the skis in space using the Qualisys motion capture system, the one-dimensional forces were converted into three dimensions according to the global coordinate system. However, some corrections are still required to obtain valid three-dimensional forces. It was possible to distinguish clear differences in cycle characteristics and roller ski forces between the two skiers with different characteristics and between skating with and without poling. Overall, this instrumented roller ski can be useful for future research and when monitoring elite athletes' technical development.

**Keywords** Cross-country skiing · Cycle characteristics · Elite skiers · Kinematics · Kinetics

M. Hoset · A. B. Rognstad · G. Ettema · Ø. Sandbakk (✉)
Department of Human Movement Science, Center for Elite Sports Research, Norwegian University of Science and Technology, 7491 Trondheim, Norway
e-mail: oyvind.sandbakk@svt.ntnu.no

M. Hoset · A. B. Rognstad · T. Rølvåg
Department of Product Development and Materials, Norwegian University of Science and Technology, Trondheim, Norway

Published online: 24 August 2013

## 1 Introduction

Cross-country skiing involves two main techniques, classical and skating, and demands an effective employment of upper and lower extremities to convert metabolic energy into external work. In the ski skating technique different sub-techniques are used at varying speeds and terrains and are designated as gears (G) from one to seven [1]. G4 is used on level terrain and includes a symmetrical double pole push in connection with every other leg push. Here, the leg push-off is performed perpendicular to the gliding direction of the sideways angled and edged skis, synchronous with a poling push-off on the so-called "strong side" [2]. Hence, the combination of pushing-off and poling propels the skier forward in a "zig-zag" movement.

To measure technique in more detail, ski-specific laboratory testing using roller skis on treadmills has served as a model for cross-country skiing since the early 1990s [3]. Testing during roller skiing provides a valid and reliable test model for skiing [4], where it is easier to accurately quantify the forces acting between the ski and the ground than in skiing on-snow. Compared to cross-country skis, roller skis have a more suitable geometry for analyzing the actual ski forces. The magnitude and direction of the ground reaction forces from roller skis and poles acting on the center of mass determine the changes in the body's kinetic energy. Several studies have measured pole forces in the different skating techniques when roller skiing [5–9], and roller ski forces have been estimated from pressure distribution in Pedar insoles [9] or two-dimensionally by strain gauges in a force platform [10]. All these approaches have inherent weaknesses. The pressure measurements so far only provide forces in one unknown direction, but more importantly they may be unreliable as one cannot ensure that the insole detects all forces transferred between the foot and the boot. The force platform used previously [10] measures forces in one dimension and is relatively heavy which thereby may affect the performance of the athlete. Thus, to the best of our knowledge, no system has so far been developed that measures the magnitude and orientation of the forces acting between the ski and the ground.

Accordingly, the purpose of the present investigation was to construct an instrumented roller ski, validate the force measurements and resolve the forces into three dimensions in the global coordinate system. To demonstrate the practical applications of the system, this study aimed to distinguish cycle characteristics and kinetics between skiers with different technical characteristics and between skating with and without poling while roller ski skating on a treadmill.

## 2 Methods

### 2.1 Overall design

An instrumented roller ski was constructed by mounting full bridge strain gauges connected to a wireless sensor node with a radio transmitter. To convert the one-dimensional forces into three dimensions according to the global coordinate system, the orientation of the skis in space was recorded using the Qualisys motion capture system. The magnitude and direction of the forces were validated against two three-dimensional Kistler force platforms, with one wheel on each platform. Thereafter, the practical applications of the system were demonstrated by analyzing cycle characteristics and ski kinetics between two skiers with different skating techniques and between skating with and without poling, while roller skiing on a treadmill.

### 2.2 Construction

The measurement system consists of two aluminum roller skis (Start Skating 80, Startex, Hollola, Finland), each instrumented with two full bridge strain gauges (VY 41-3/350, HBM Gmbh, Darmstadt, Germany). A wireless analog sensor node with an internal battery and a radio transmitter (V-Link MXRS, Microstrain Inc, Williston, VT, USA) on the top of each ski provided excitation for the full bridge strain gauges and could log and transmit the data wirelessly to a base station. All data were acquired by the accompanying software NodeCommander 2.3.0.

The V-Link mass was 140 g and placed between the binding and the front wheel on top of both roller skis. Subsequently, the center of gravity for the roller ski was moved 26 mm forward. With a total ski mass of 900 g this led to a torque of 0.23 Nm, which was regarded as negligible. To measure the applied forces, the strain gauges were placed under the ski, with one in front of the binding and one behind the heel. The strain gauges were connected with the V-link by shielded wiring and covered by a layer of a kneading compound (ABM 75, HBM Gmbh, Darmstadt, Germany) protecting the strain gauges from water or collision. The design of the roller ski measurement system is illustrated in Fig. 1.

#### 2.2.1 Calculation of forces

Strain gauges measure the bending strain ($\varepsilon_x$) at a given point under the roller ski with the distance ($L$) from the force ($F$) that acts between the wheel and the ground (Fig. 2). The maximum values of strain applied to the aluminum ski were measured to be <1/3 of the yield strain; hence linear elastic material models were applied. The forces could be derived with equation $F = \frac{EI_x\varepsilon_x}{(h/2)L}$, where $E$ is Young's modulus of the roller ski material, $I_x$ is the second moment of area for the roller ski which has the shape of a hollow rectangular beam $I_x = \frac{b_{\mathrm{outer}}h^3_{\mathrm{outer}}}{12} - \frac{b_{\mathrm{inner}}h^3_{\mathrm{inner}}}{12}$, where $b$ is the width of the roller ski and $h$ the height of the roller ski beam.

The three-dimensional forces between the wheel and the ground were determined by measuring the orientation of the roller skis in a global coordinate system. Thereto, reflective markers were placed in a triangular fashion on the outside of each ski (Fig. 1). The positions of these markers were sampled at 500 Hz using the Qualisys Pro Reflex system (Qualisys AB, Gothenburg, Sweden). Determination of the angling and edging of the skis (defined in Fig. 3) allowed expressing the forces measured in $z$-direction of the local coordinate system as three-dimensional force components, $F_x$, $F_y$, $F_z$, in the global coordinate system.

### 2.3 Calibration

The roller ski forces were calibrated on two three-dimensional Kistler force plates (Type 9286AA, Kistler Instrumente AG, Winterthur, Switzerland). First, five balance tests with varying applied forces were conducted for each ski. One test subject (70 kg) with equipment (additional 2 kg) was standing on one roller ski with one wheel on each force plate. The subject held weights of 0, 5, 10, 15, and 20 kg in the hands and stood with full weight on the roller ski, while the other foot was lifted. Thus, the tests were carried out with average applied forces of 706, 755, 804, 853 and 903 N. The force plate measured the forces in three directions ($x$, $y$ and $z$) in its local coordinate system, and the resultant forces of the roller ski should be equal to the resultant forces measured on the force plate. Thus,

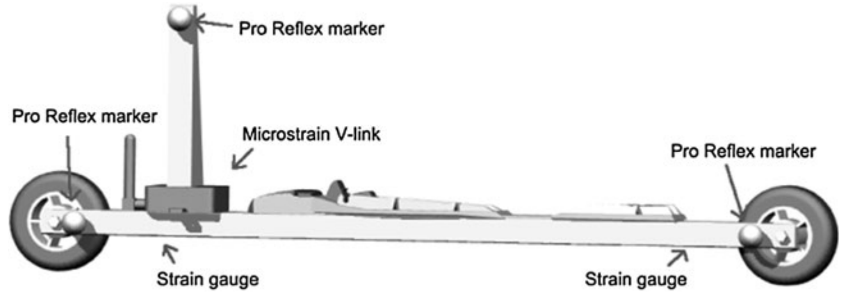



**Fig. 1** A three-dimensional model of the instrumented roller ski. The upper marker is placed on a lightweight stiff styrofoam beam, glued on top of the V-link

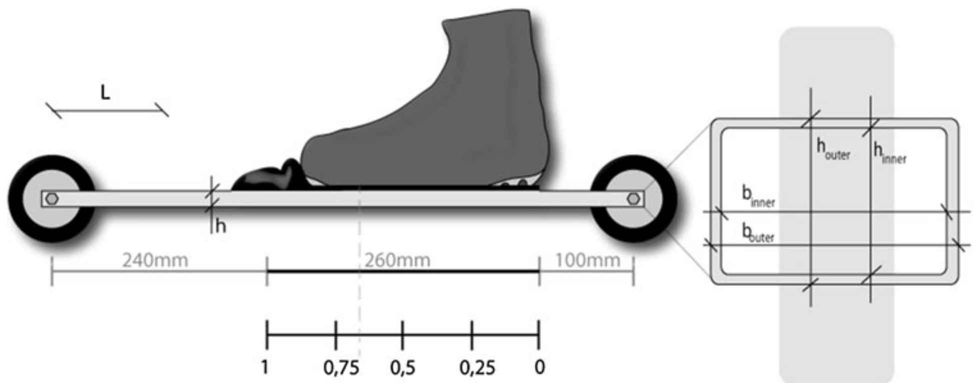



**Fig. 2** Definition of the calculated center of pressure and geometric values for calculating forces. *L* is the distance from the wheel to where the strain gauge is applied and *h* the height of the roller ski beam. The CoP found from the strain values in the front and back in the ski is recalculated into the fraction-value as shown in the figure, assuming a standard EU size 43 ski boot

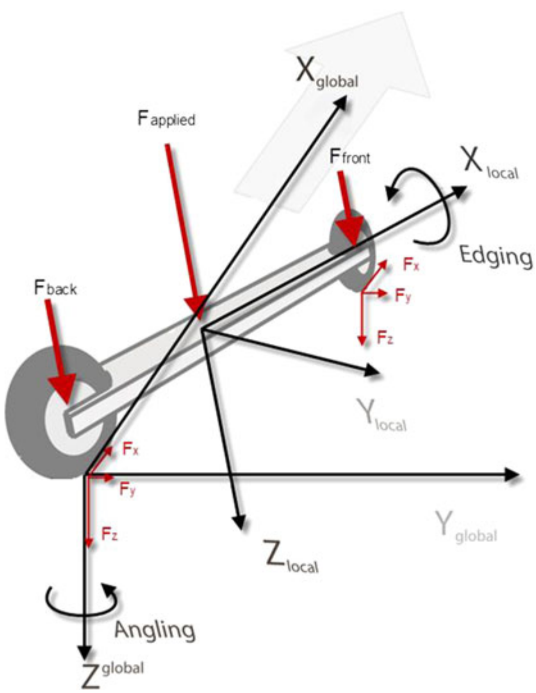



**Fig. 3** Definitions of roller ski angling and edging, and how the applied forces are resolved in the two different coordinate systems. The *x*-axis of the global coordinate system is parallel to the "forward" direction of the treadmill. The global *y*-axis is perpendicular to the *x*-axis in plane of the treadmill surface, while the *z*-axis is perpendicular to both global *x*- and *y*-axis, pointing out of the treadmill. The local coordinate system follows the ski's movement. Angling is defined as rotation about the global *z*-direction, and edging as rotation about the local *x*-direction

**Table 1** Calculated calibration coefficients for the four strain gauges applied on the roller skis

| Strain gauge | Calibration coefficient |
|---|---|
| Left roller ski, back | 0.9460 |
| Left roller ski, front | 0.8941 |
| Right roller ski, back | 0.9182 |
| Right roller ski, front | 0.9003 |

When the calculated forces are multiplied with these constants the forces will be within the standard deviations shown in Table 2

$F_{z\text{–rollerski}} = \sqrt{F_x^2 + F_y^2 + F_z^2}$ where $F_x$, $F_y$ and $F_z$ were measured directly on the force plate and smoothed in MATLAB using a 15-point moving average. Based on this, a calibration coefficient for each strain gauge was found, with which the calculated forces were multiplied (Table 1). The comparison of forces from the instrumented roller skis and the force plate for the left ski is illustrated in Fig. 4. The accuracy of the instrumented roller ski measurements was quantified by calculating the standard deviation ($\sigma$) and coefficient of variation ($C_v$) for the absolute difference in forces between the instrumented roller ski and the Kistler force plate (Table 2).

### 2.3.1 *Validation of three-dimensional forces*

To validate whether the forces found in Sect. 2.2.1 are also applied when resolved into three directions, the orientation

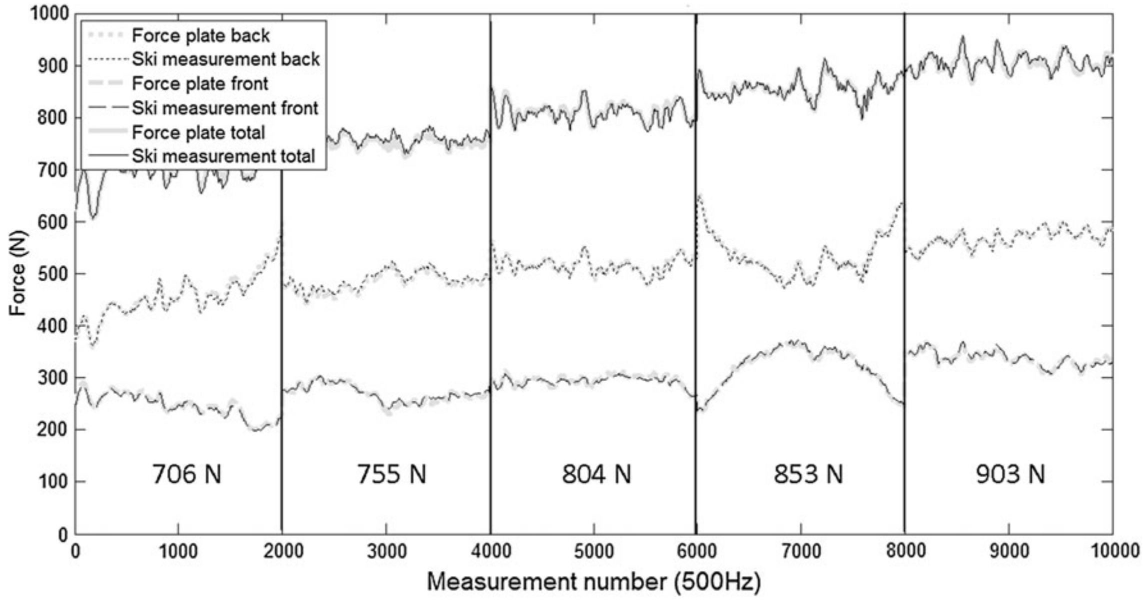



**Fig. 4** Comparisons of the roller ski and the force plate measurements, left ski. Five separate 4-s balance tests (the mass of subject with equipment is 72 kg) with ascending weights. The total applied forces in the five sections of the graph were 706, 755, 804, 853 and 903 N. The *graphs* show the values from the force plate and the strain gauge system mounted on the left ski

**Table 2** Standard deviation ($\sigma$) and coefficient of variation ($C_v$) calculated for the absolute difference in forces between the instrumented roller ski (calibrated forces) and the Kistler force plate

| | Left ski, back | Left ski, front | Right ski, back | Right ski, front |
|---|---|---|---|---|
| $\sigma_{mean}$ (N) | 3.22 | 2.24 | 3.71 | 3.77 |
| $C_{vmean}$ | 0.0062 | 0.0079 | 0.0072 | 0.0128 |
| $\sigma_{72\ kg}$ (N) | 3.63 | 2.51 | 3.26 | 2.69 |
| $C_{v72\ kg}$ | 0.0083 | 0.0093 | 0.0071 | 0.0109 |
| $\sigma_{77\ kg}$ (N) | 1.81 | 2.11 | 2.46 | 3.93 |
| $C_{v77\ kg}$ | 0.0037 | 0.0080 | 0.0051 | 0.0146 |
| $\sigma_{82\ kg}$ (N) | 2.70 | 1.52 | 1.85 | 3.55 |
| $C_{v82\ kg}$ | 0.0050 | 0.0058 | 0.0036 | 0.0120 |
| $\sigma_{87\ kg}$ (N) | 4.37 | 2.30 | 1.70 | 2.46 |
| $C_{v87\ kg}$ | 0.0078 | 0.0077 | 0.0032 | 0.0077 |
| $\sigma_{92\ kg}$ (N) | 2.08 | 1.98 | 2.74 | 2.36 |
| $C_{v82\ kg}$ | 0.0037 | 0.0061 | 0.0048 | 0.0100 |

**Table 3** Standard deviation ($\sigma$) and coefficient of variation ($C_v$) calculated for the absolute difference in three-dimensionally resolved forces between the instrumented roller ski (calibrated forces) and the Kistler force plate

| | Left ski, back | Left ski, front |
|---|---|---|
| $F_x$ | | |
| $\sigma_{mean}$ (N) | 9.8 | 5.3 |
| $C_{vmean}$ | 0.0728 | 0.0685 |
| $F_y$ | | |
| $\sigma_{mean}$ (N) | 12.2 | 12.5 |
| $C_{vmean}$ | 0.1334 | 0.2391 |
| $F_z$ | | |
| $\sigma_{mean}$ (N) | 10.2 | 4.8 |
| $C_{vmean}$ | 0.0183 | 0.0148 |

of the skis was measured during testing on the Kistler force plates. Here, the Qualisys Pro Reflex system monitored the three-dimensional motion of the roller skis and the data were collected by the Qualisys software program (Qualisys Track Manager) as previously done in our laboratory [2]. By synchronizing the Node Commander and the QTM data, the forces were resolved into the global $x$-, $y$- and $z$-directions. The synchronization of the skis was done by tramping the skis on the force plate to identify a narrow peak in the two force measurement systems and a spike in the measured $z$-values in Pro Reflex. The data from all measurement systems were evaluated using a self-written MATLAB 7.12.0(R2011a) program.

Thereafter, three tests for each ski were performed as follows; the test subject simulated skating push-offs on the force plates. The three-dimensional forces from the force plates were compared with the calculated three-dimensional forces from the skis. Table 3 shows the standard deviation and coefficient of variation calculated for the absolute difference in 3-dimensionally resolved forces between the instrumented roller ski (calibrated values) and the Kistler force plate.

### 2.4 "In vivo" measurements

To demonstrate the practical significance of the measurement system, two male world-class skiers were roller skiing on a treadmill using the instrumented roller skis. From a dataset of 17 elite skiers, these two were chosen by an expert panel consisting of national coaches and cross-country skiing researchers due to their distinct different technical characteristics. The subjects had a similar body mass and were both on the Norwegian national team 2011/2012. Skier A was regarded a typical "upper-body skier" with an effective poling movement, but with limited employment of legwork in skating. Skier B was considered a typical "leg skier" with an effective skating push-off, but with less effective poling. All roller ski tests were carried out on a 6 × 3-m motor-driven treadmill (Bonte Technology, Zwolle, The Netherlands) with 2 % incline and a velocity of 20 km/h using G4 skating with (G4-P) and without poling (G4-NP). The surface of the treadmill belt was covered with non-slip rubber and the subjects used their own poles (with a length of 90 % of body height for both subjects) with special carbide tips. Before the measurements, each subject had a 15 min warm-up at low-intensity roller skiing for familiarization reasons and to eliminate changes in rolling resistance during testing since the rolling friction is significantly higher when the wheels are cold [11]. The G4 skating technique which is also referred to as Gunde skate [12], Open Field Skate [10] and 2-Skate [13], is used in relatively flat terrain and characterized by a "strong side" with synchronous poling and leg push-off and a "weak side" with only the leg push-off. In G4-NP, the skiers were told to simulate G4-P without poling. This technique is frequently used as a training mode by cross-country skiers. The two different skiers were compared when skiing in the G4-P technique, whereas the impact of using poles on the measurements was analyzed by comparing G4-P and G4-NP for one skier (Skier B).

In MATLAB, the strain measurements from the Node Commander and positional measurements from QTM were synchronized using distinct events in the force measurement and movements of the markers on the skis during a skating push-off. Kinetic- and kinematical variables were all recorded simultaneously. One cycle was defined as encompassing one right and one left skating step. The cycle began at ski lift-off of the left ski and ended at the next lift-off of the left ski. All variables were averaged over ten complete cycles. Cycle time was defined as the duration of one cycle, and cycle rate was expressed as 1/cycle time. Cycle length was the covered distance on the treadmill during one cycle which was calculated as speed divided by cycle time. Ground contact time was the time during which the skis were on the ground. Swing time for the skis was defined as cycle time minus ground contact time. Ski angles in relationship to the forward direction of the treadmill belt were calculated from the three markers on each roller ski during ground contact. Ski orientation angle was defined as the rotation of the roller ski about the global *z*-axis and ski edging around the local *x*-axis, as described in Fig. 3. Center of pressure (CoP) was calculated in the local *x*-direction of the ski from the measured force in the front and at the back of the binding (50 % back and 50 % front wheel force distribution resulted in a CoP in the middle of the ski). Thereafter, the CoP value was defined from 0 (heel) to 1 (toe) using a standard EU size 43 shoe as shown in Fig. 2. The applied force is the mean value per cycle of the total measured forces during the ten cycles. Applied force/body weight gives the relative values of the applied force. Peak force is the maximal value measured, and peak force/body weight describes the relative values of the peak force. Force impulse is the total force produced during the phase from force minimum to ski lift-off and calculated as the integral of force over this time. Mean $F_x$, $F_y$ and $F_z$ are the calculated resolved forces. As described in detail in Fig. 5, a within-cycle analysis of the variables speed of ski, ski edging, ski angle, COP, and applied ski force was calculated at distinct points and phases during a cycle.

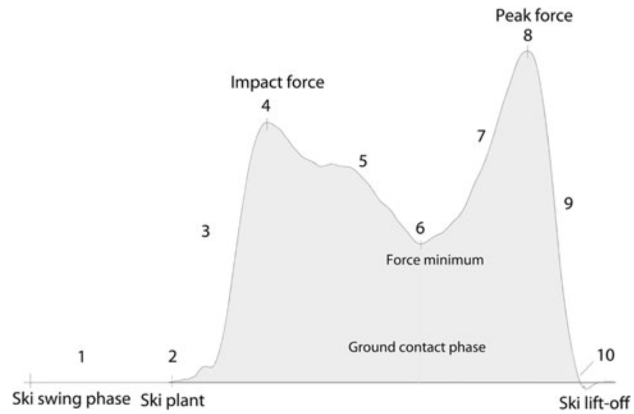



**Fig. 5** Definition of the different phases of a skating push-off. The force plot for one ski during a complete cycle divided in two phases; swing phase and ground contact phase. The peak force is defined as the largest force in the push off-phase (*8*). Force values, center of pressure, edging, angling and the speed of the skis are calculated for each of the distinct points *2*, *4*, *6*, *8* and *10*, as well as average values between these points; *1*, *3*, *5*, *7* and *9*

## 3 Results

### 3.1 Validation

There were no differences in calibrated forces between the left and right ski, but the calibration coefficients for the different strain gauges varied by 0.9 ± 2.8 %. The highest coefficient of variation for the absolute difference in forces between the instrumented roller ski (calibrated forces) and the Kistler force plate was 0.015 (Table 2).

For the three-dimensional forces, the roller ski system matched the Kistler force plate recordings within 7.3, 24.0 and 1.8 % for $F_x$, $F_y$ and $F_z$, respectively (Table 3). The standard deviation did not differ between the *x*- and *z*-directions but was somewhat higher for the *y*-direction. The coefficient of variation was smaller for $F_z$ when compared to $F_x$ and $F_y$.

### 3.2 Comparison of two skiers in the G4 technique

When the two skiers with different characteristics were compared at 20 km/h, distinct differences between their cycle characteristics and ski kinetics were observed (Table 4; Fig. 6). Skier B demonstrated higher peak force, especially on the strong side, when compared to Skier A, and had a 54 % greater force impulse per cycle. Skier A compensated with an 8 % higher frequency to maintain the same treadmill speed. The average CoP position was further posterior in Skier B but showed a more steady forward movement during the cycle as compared to Skier A (Fig. 6).

Skier B skied more symmetrically than Skier A in regard to the forces produced, ski angling, and the CoP placement during each cycle (Fig. 6). Skier B had relatively equal leg push-offs for the strong and weak sides (Fig. 7b), while Skier A had a more pronounced leg push-off on the weak side (Fig. 7a).

### 3.3 Comparison of the G4 technique with and without poling

When comparing the G4-P (Fig. 7b) and G4-NP (Fig. 7c) techniques in Skier B, the peak force was higher for G4-NP, whereas the cycle rate was higher with G4-NP. The angling was generally greater and the edging of the skis increased considerably more through the cycle G4-NP when compared to G4-P (Fig. 6).

## 4 Discussion

The present investigation constructed and validated an instrumented roller ski, in which forces were resolved into three dimensions. Thereafter, the practical applications of the system were demonstrated by testing two skiers with different skating techniques and by comparing G4 skating with and without poling. It was shown that a roller ski with full bridge strain gauges could provide valid measurements of forces in the ski's local coordinate system. Subsequently, the orientations of the skis from reflective markers were incorporated to obtain three-dimensional forces in the global coordinate system. Here, some corrections are still

**Table 4** Comparison of two skiers with different characteristics (Subject A and B) in the skating G4 technique (G4-P), and Subject B using G4 skating with (G4-P) and without poling (G4-NP)

| Subject | Subject A | | Subject B | | | |
|---|---|---|---|---|---|---|
| Technique | G4-P | | G4-P | | G4-NP | |
| Side | Strong | Weak | Strong | Weak | Strong | Weak |
| Cycle time (s) | 1.53 ± 0.07 | | 1.62 ± 0.08 | | 1.58 ± 0.06 | |
| Cycle rate (Hz) | 0.66 ± 0.03 | | 0.61 ± 0.03 | | 0.63 ± 0.02 | |
| Cycle length (m) | 8.49 ± 0.39 | | 9.04 ± 0.48 | | 8.79 ± 0.32 | |
| Ground contact time (s) | 1.09 ± 0.10 | 0.97 ± 0.05 | 0.97 ± 0.08 | 1.06 ± 0.07 | 0.94 ± 0.06 | 1.01 ± 0.04 |
| Swing time (s) | 0.47 ± 0.04 | 0.61 ± 0.06 | 0.64 ± 0.05 | 0.59 ± 0.08 | 0.64 ± 0.05 | 0.57 ± 0.05 |
| Ski orientation angle (°) | 6.30 ± 0.51 | 8.25 ± 0.69 | 6.62 ± 1.14 | 7.37 ± 0.56 | 8.97 ± 1.37 | 9.38 ± 0.67 |
| Ski edging (°) | 14.1 ± 2.1 | 11.5 ± 2.2 | 16.2 ± 2.9 | 11.8 ± 1.8 | 17.3 ± 1.8 | 12.4 ± 1.8 |
| Center of pressure (heel:toe ratio) | 0.67 ± 0.07 | 0.58 ± 0.04 | 0.44 ± 0.07 | 0.49 ± 0.05 | 0.47 ± 0.07 | 0.54 ± 0.06 |
| Applied force (N) | 381 ± 23 | 374 ± 25 | 387 ± 21 | 407 ± 21 | 401 ± 19 | 423 ± 21 |
| Applied force/body weight (BW) | 0.50 ± 0.03 | 0.49 ± 0.03 | 0.50 ± 0.03 | 0.52 ± 0.03 | 0.51 ± 0.03 | 0.54 ± 0.03 |
| Peak force (N) | 866 ± 57 | 1084 ± 30 | 1192 ± 77 | 1171 ± 47 | 1423 ± 79 | 1405 ± 44 |
| Peak force/body weight (BW) | 1.13 ± 0.07 | 1.41 ± 0.04 | 1.53 ± 0.10 | 1.50 ± 0.06 | 1.83 ± 0.10 | 1.80 ± 0.06 |
| Force impulse in push-off (N s) | 243 ± 30 | 196 ± 13 | 325 ± 77 | 350 ± 37 | 333 ± 35 | 387 ± 31 |
| Force impulse in *x*-direction in push-off (N s) | 9.7 ± 1.5 | 12.0 ± 2.2 | 12.2 ± 3.4 | 11.0 ± 1.9 | 23.6 ± 5.8 | 18.7 ± 3.6 |
| Mean $F_x$ (N) | 10.5 ± 1.7 | 12.8 ± 2.7 | 9.8 ± 3.6 | 5.9 ± 2.0 | 17.8 ± 4.1 | 11.3 ± 3.1 |
| Mean $F_y$ (N) | 85 ± 11 | 66 ± 14 | 107 ± 17.7 | 80 ± 14 | 125 ± 11 | 94.5 ± 15 |
| Mean $F_z$ (N) | 367 ± 24 | 364 ± 26 | 365 ± 25 | 393 ± 22 | 371 ± 24 | 405 ± 23 |

Values are presented are mean ± standard deviation over ten cycles. See more detailed description of each of the variables in the manuscript

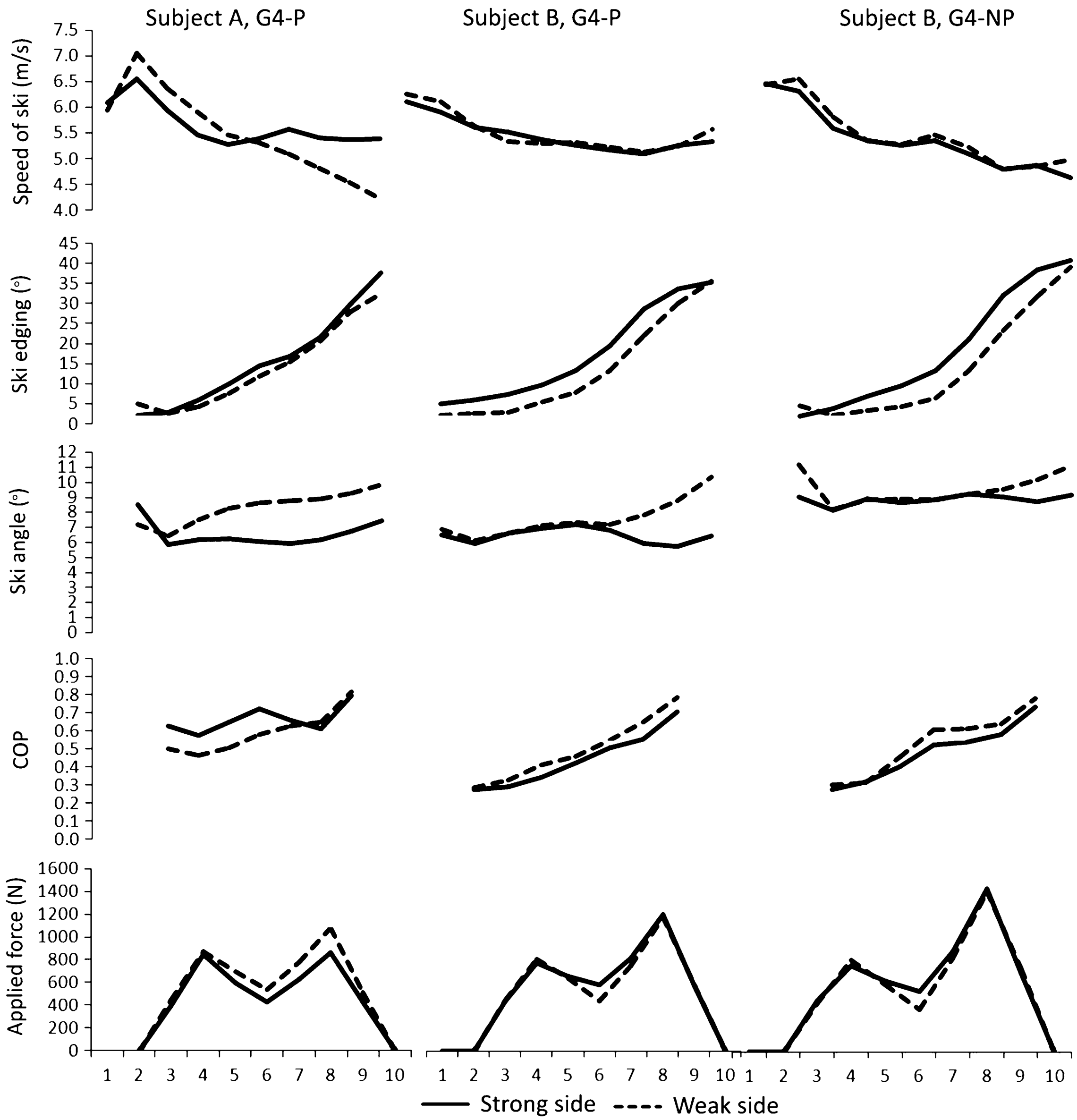



**Fig. 6** Comparisons of Skier A and B in the G4 skating technique (G4-P), as well as G4-P and G4 skating without poling (G4-NP) for Skier B during ten defined phases of the skating cycle. The skiing cycle are divided into ten segments according to Fig. 5. The applied force is the mean value of the measured forces during the ten cycles. Center of pressure (CoP) is defined from 0 (heel) to 1 (toe) using a standard EU size 43 shoe. Ski angle is the rotation of the roller ski about the global $z$-axis and ski edging around the local $x$-axis. Ski velocity is calculated in the local $x$-direction

required to obtain valid values. It was possible to distinguish clear differences in cycle characteristics and kinetics between skiers with different characteristics and between the different skating techniques.

### 4.1 Construction of an instrumented roller ski

Although strain gauges, telemetry technology and positional data have been combined for decades, this was to the best of our knowledge, the first scientific study with a combined implementation in roller skis. Furthermore, the weight reduction as compared to earlier systems [10] for measuring ski forces is an advantage here which allows skiers to roller ski with their normal skating technique. The current system is wireless, which eliminates disturbing elements such as backpacks with equipment or wires on the body, and allows quick changes from one athlete to the next. A further development of the system would be to employ inertial navigation measurement technology to monitor the movements of the skier and the skis three-

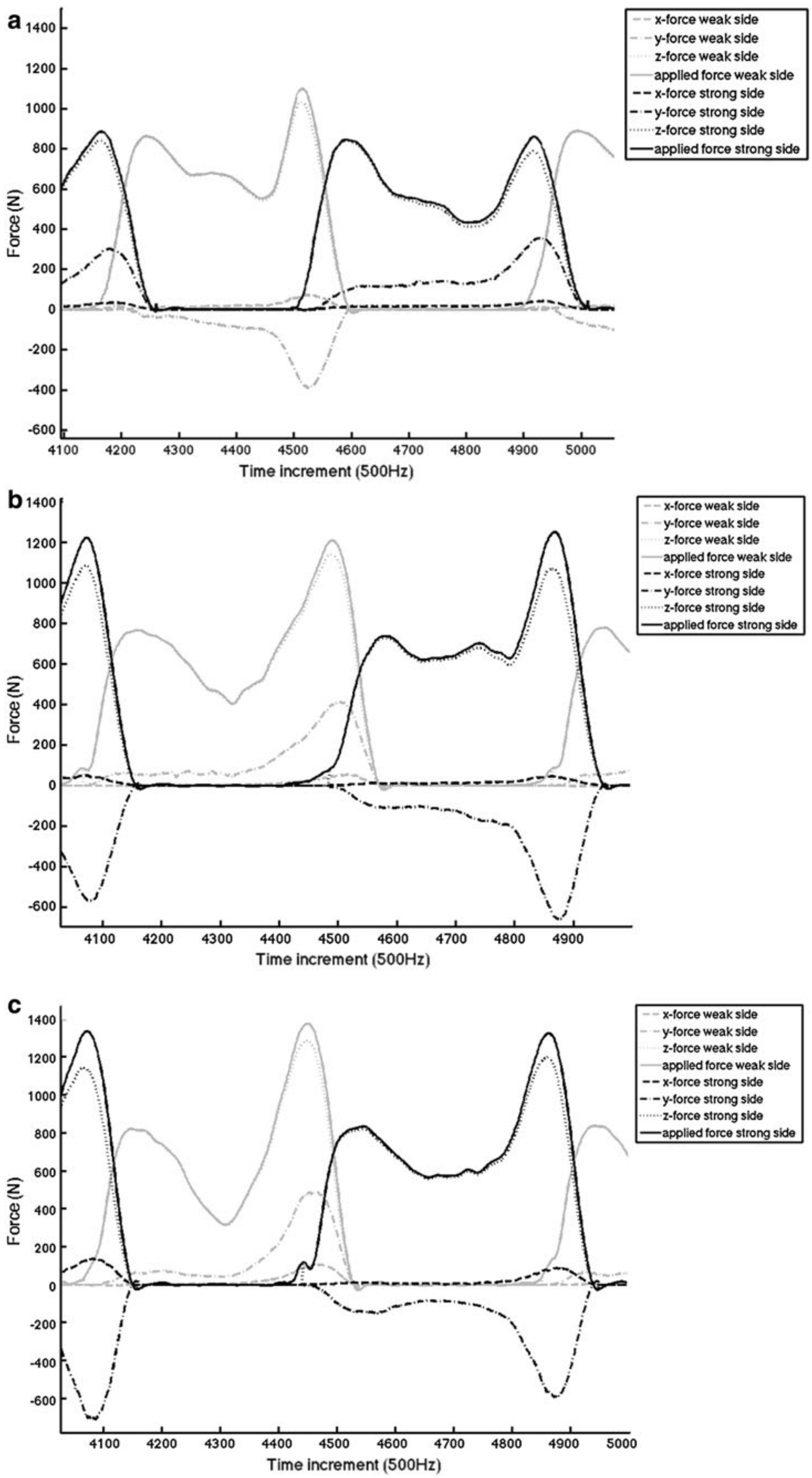



**Fig. 7** **a–c** The one- and three-dimensional forces plotted for **a** Subject A and **b** Subject B while skiing in the G4 technique, and for **c** Subject B in the G4 technique without poling at 20 km/h with 2 % incline

dimensionally in the field. Finally, future examinations should develop force measurement systems for skiing on-snow.

### 4.2 Validation of the magnitude and direction of forces

When comparing the one-dimensional roller ski forces with forces from a Kistler force platform (used as the golden standard here), the measurements indicate that the differences in magnitude of forces are linear, and can therefore be removed by multiplying with a calibration coefficient for each strain gauge. However, it is notable that each strain gauge needs individual calibration. Repeated measurements showed a low coefficient of variation, and there were no differences between the force plate and calibrated roller ski forces between the left and right ski. Together, this indicates a high reproducibility of the system which is important for future research and monitoring of athletes.

The errors for the forces resolved in the global coordinate system were larger than in the local system. This is likely caused by the direction of the applied forces that are not completely perpendicular to the skis since skiers seem to edge the skis slightly differently than the forces are applied. The relative small errors in the ski orientation measurement may have rather large effects on the calculated forces; however, this factor is probably different for skiers and speeds. Thus, there will be some side forces which are unaccounted for by the strain gauge measurements. These forces are probably small, but since they work in the *xy*-plane they may cause significant errors for the forces calculated in the *x*- and *y*-directions. By mounting strain gauges on the side of the ski, to measure the sideways loading, it might be possible to measure the local $F_y$ and thereby correct the global $F_x$ and $F_y$ force components. However, this aspect requires further examination.

### 4.3 The practical significance of the instrumented roller ski

The current study demonstrated clear kinematic and kinetic differences between the two skiers with different technical characteristics that quantify their strengths and weaknesses previously observed by their coaches. For example, Skier B, who is regarded the superior one with regard to roller ski skating, demonstrated a significantly higher peak force and more than 50 % higher force impulse. This lead to a longer cycle length, a factor that earlier has been shown to correlate with skiing efficiency [14]. Throughout the push-off, Skier B got a steady forward movement of the CoP during a cycle, whereas Skier A showed an unstable placement of the CoP. Whether these aspects of skiing can be used to characterize skiers of different standards needs further examination with multiple subjects.

Another interesting finding is that Skier B was more symmetrical for both legs than Skier A, regarding the forces, angling of the skis and the CoP during a cycle. Thus, it seems that Skier B has more similar leg push-offs for the strong and weak sides, while Skier A has a pronounced leg push-off on the weak side but relies more on poling for the strong side. This supports the fact that Skier A is a typical upper-body skier as characterized by the coaches.

When comparing the G4-P and the G4-NP techniques, the peak forces are substantially higher for G4-NP as a consequence of the higher propulsion required by the legs when poling is eliminated. This is especially pronounced on the strong side where poling supports the legwork in G4-P. This is accompanied by distinct differences in the CoP between techniques. To maintain the treadmill speed when propulsion from poling was eliminated in G4-NP, the cycle rate was increased. Furthermore, the angling and edging of the skis were increased in G4-NP when compared to G4-P. This characterization of ski forces when G4 skating and the effects of adding poling in this technique are novel data that provides background for future studies on a larger sample of subjects.

## 5 Conclusions

The current study shows that implementing strain gauges on roller skis is a valid and reliable method for measuring the magnitude of forces in roller ski skating. The reflective markers on the roller skis provide accurate measurements of the orientation of the roller skis. However, the validity of forces derived in three directions has some limitations, probably due to differences between the direction of applied forces and the orientation of the roller skis. This leads to inaccurate calculation of forces in the *x*- and *y*-direction, and thus requires further investigation. Although roller ski and on-snow ski skating is similar, some distinct technical differences are apparent and the current results cannot directly be applied to on-snow skiing. However, due to their geometrical and material properties, roller skis are more suited for testing purposes. Furthermore, a steady laboratory situation induces a higher grade of repeatability. By showing distinct differences between skating techniques and different types of skiers, it was demonstrated that this instrumented roller ski can be useful for future research and when monitoring elite athletes' technical development.

**Acknowledgments** The authors would like to thank Christina Åsan Grasaas, Erik Grasaas and Ann Magdalen Hegge for assistance in the laboratory tests, as well as the athletes and coaches for their enthusiasm and support. The authors have no conflicts of interest or financial disclosures to report.

## References


1. Andersson E, Supej M, Sandbakk O, Sperlich B, Stoggl T, Holmberg HC (2010) Analysis of sprint cross-country skiing using a differential global navigation satellite system. Eur J Appl Physiol 110(3):585–595
2. Sandbakk O, Ettema G, Holmberg HC (2012) The influence of incline and speed on work rate, gross efficiency and kinematics of roller ski skating. Eur J Appl Physiol 112(8):2829–2838
3. Watts PB, Hoffman MD, Sulentic JE, Drobish KM, Gibbons TP, Newbury VS, Mittelstadt SW, O'Hagan KP, Clifford PS (1993) Physiological responses to specific maximal exercise tests for cross-country skiing. Can J Appl Physiol 18(4):359–365
4. Sandbakk O, Ettema G, Leirdal S, Jakobsen V, Holmberg HC (2011) Analysis of a sprint ski race and associated laboratory determinants of world-class performance. Eur J Appl Physiol 111(6):947–957
5. Millet GY, Hoffman MD, Candau RB, Buckwalter JB, Clifford PS (1998) Cycle rate variations in roller ski skating: effects on oxygen uptake and poling forces. Int J Sports Med 19(8):521–525
6. Millet GY, Hoffman MD, Candau RB, Buckwalter JB, Clifford PS (1998) Effect of rolling resistance on poling forces and metabolic demands of roller skiing. Med Sci Sports Exerc 30(5):755–762
7. Millet GY, Hoffman MD, Candau RB, Clifford PS (1998) Poling forces during roller skiing: effects of technique and speed. Med Sci Sports Exerc 30(11):1645–1653
8. Millet GY, Hoffman MD, Candau RB, Clifford PS (1998) Poling forces during roller skiing: effects of grade. Med Sci Sports Exerc 30(11):1637–1644
9. Stoggl T, Muller E, Ainegren M, Holmberg HC (2011) General strength and kinetics: fundamental to sprinting faster in cross country skiing? Scand J Med Sci Sports 21(6):791–803
10. Smith GA (1992) Biomechanical analysis of cross-country skiing techniques. Med Sci Sports Exerc 24(9):1015–1022
11. Ainegren M, Carlsson P, Tinnsten M (2008) Rolling resistance for treadmill roller skiing. Sports Eng 11:23–29
12. Boulay MR, Serresse O, Almeras N, Tremblay A (1994) Energy expenditure measurement in male cross-country skiers: comparison of two field methods. Med Sci Sports Exerc 26(2):248–253
13. Bilodeau B, Boulay MR, Roy B (1992) Propulsive and gliding phases in four cross-country skiing techniques. Med Sci Sports Exerc 24(8):917–925
14. Sandbakk O, Holmberg HC, Leirdal S, Ettema G (2010) Metabolic rate and gross efficiency at high work rates in world class and national level sprint skiers. Eur J Appl Physiol 109(3):473–481