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Biomechanical analysis of the herringbone technique in classical cross-country skiing

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ABSTRACT

Purpose: To investigate the mechanics of the cross-country herringbone technique and to enhance the understanding of adaptations in kinematics and kinetics due to increasing velocity.

Method: Eleven male elite cross-country skiers performed the herringbone technique at three different velocities; moderate, high and maximal. The slope covered a total distance of 50 m. The first 35 m, at $\sim 7.5^\circ$ incline, was utilized for acceleration using the diagonal stride technique to reach the desired velocity, followed by an 8 m measuring section ($\sim 15^\circ$ incline) using the herringbone technique. All trials were filmed synchronously using two video cameras placed perpendicular along the section and one moving panning camera. Two photocells were used in order to obtain average section times and velocities. All subjects used ski poles that were constructed for force measurements and the forces directed along the poles was recorded with a sampling rate of 1500 Hz. Vertical plantar pressure was recorded at a rate of 100 Hz using the Pedar Mobile System. The plantar pressure was further converted to plantar ("leg") force.

Results: Cycle rate and cycle length increased synchronously from moderate to high velocity, whereas the increase from a high to a maximal velocity was achieved by a higher cycle rate. The poling and the leg thrust times decreased gradually as velocities increased, whereas the relative poling and leg thrust times were constant; $\sim 50\%$ and $\sim 40\%$. From moderate to maximal velocities the peak pole forces increased by 74%, in association with a 75% shorter time to peak force. The peak leg force increased by 7% from moderate to high velocity with no further changes at maximal velocity. The time to peak leg force decreased 24%, from moderate to maximal velocity. The force impulse ratio between pole and leg remained constant at $\sim 8\%$ from moderate to maximal velocity and the ratio for propulsion was $\sim 30\%$ due to the higher relative propulsive components from the poles. Changes in joint kinematics across the velocities were negligible, except for the total body lean and the lower leg angle. The angle of the lower leg, at end of the push off, decreased with increased velocity and was negatively correlated to maximal pole/leg force, cycle length and maximal velocity. Strength parameters correlated positively to force distribution between upper and lower body, as well as to maximal velocity.

Conclusions: The adaptation of herringbone velocity between moderate and high velocity was achieved by increased cycle rate and cycle length, whereas the adaptation from high to maximal velocity was achieved only by increased cycle rate. The latter is explained by increased force generation from the upper and lower body, despite decreased poling and leg thrust times, with a constant impulse ratio between the upper and lower body. Higher skiing velocity was primarily assisted by constant body segment and joint angles.

Key Words: CYCLE LENGTH, CYCLE RATE, HERRINGBONE, IMPULSE RATIO, LEG FORCE, POLE FORCE, PROPULSION

INTRODUCTION

Cross-country skiing is a challenging and complex sport due to the varying techniques and the necessity of adapting these techniques to changes in terrain topography and skiing velocity. In the classical style there are three major techniques: diagonal stride, double poling and double pole kick (double pole with a single leg kick) (Holmberg, 2005b). In addition, the herringbone technique is used on the steepest uphill climbs or when the skis are lacking sufficient ski grip for diagonal stride. Herringbone is a technique that to some extent resembles the three dimensional ski-skating motion. In this technique the arms and legs work in synchronized opposition, as in diagonal stride, but in order to maintain grip, the skis are angled laterally and edged as the leg thrusts are generated primarily backwards. The lateral ski angulations make this technique similar to the diagonal skating technique. The difference is that in herringbone the skis are stationary during the leg thrust and the use of grip wax enables the skier to push backwards, rather than solely sideways as in ski-skating (Nilsson et al., 2004; Holmberg, 1996).

A skier can adapt to increasing velocity within one technique by changing the cycle rate and/or the cycle length. Numerous studies (Smith., 1988; Bilodeau et al., 1996; Sandbakk et al., 2010; Andersson et al., 2010) have analyzed the relative contribution of cycle rate and cycle length to skiing performance and show that for both distance and sprint races, faster skiers use a longer cycle length versus slower skiers, whereas cycle rate has shown similarities between skiers of different performance levels. Stöggl et al., (2007) found that cycle length and cycle rate for diagonal stride was positively and negatively correlated to velocity, respectively, when analyzing simulated sprint skiing on a treadmill. Furthermore, the fastest skiers could produce higher propulsion at a specific cycle rate, i.e. generate longer cycle length as verified by Lindinger et al., (2009a). Higher maximal performance was explained by longer cycle length due to higher force impulse for the leg thrust generated over a shorter thrust time. Stöggl & Müller (2009) used an incremental grade test protocol, where the velocity was kept constant and the incline was raised 1° for every single stage. They found that skiers adapted to higher workloads exclusively by increased cycle rates, whereas cycle length decreased. Decreased cycle length can partly be explained by an altered mechanical situation with an increased incline, i.e. increased gravitational force. Nilsson et al., (2004) showed that skiers adapted their diagonal stride velocity mainly through changes in cycle rate while keeping cycle length relatively constant and Vähäsöyrinki et al., (2008) showed a simultaneous increase of both cycle length and cycle rate from low to high velocity, whereas only the cycle rate increased from high to maximal velocity.

The total vertical forces during the leg thrust when using diagonal stride are about 2-3 times the body weight (BW), while the propulsive force components are considerably smaller, 10-25% of BW (Komi, 1987; Smith, 2002). For an effective leg thrust, the transition from a primarily vertical reaction force during approximately the first third of the thrust has to be followed by a higher percentage of a horizontal reaction force comprised over the last two thirds of the thrust. The most important factors influencing the effectiveness of the leg thrust are: ski stiffness, grip wax and technique characteristics. An optimal leg thrust occurs when these factors are considered and aligned to the individual (Smith, 2002). Komi, (1987) showed that the contribution of the upper body in relation to the legs increases in diagonal stride with steeper incline. The tangential propulsive force component is proportional to both the absolute axial pole force and the pole inclination, with respect to the ground, given that the effectiveness of the axial pole force increases with increased pole angulation (Smith, 2002). To apply a high force impulse in the beginning of the poling cycle when the pole is in a relatively straight position is therefore ineffective. This is supported by Lindinger et al., (2009a) who showed that higher performance correlated positively with a later peak pole force. Furthermore, Pellegrini et al., (2010) found that the contribution of the poling power increased with higher slope gradients, together, with increased effectiveness of the applied pole force due to a more angulated pole during the poling cycle. The ratio between propulsive and total poling force varied from ~55-65% on 2-8° incline. Two studies have analyzed the vertical and horizontal force components of diagonal stride directly through the use of portable force plate systems (Komi, 1987; Vähäsöyrinki et al., 2008). Vähäsöyrinki et al., (2008) found that the contribution of the propulsive pole force in relation to the propulsive ski force decreased with increased velocity, i.e. higher contribution from the legs at higher velocity. At maximal velocity the propulsive force from the ski was ~15% of the vertical force.

For all classical techniques the time for force application through the poling and/or the leg thrust decreases with increasing cycle rate and velocity. Values down to ~0.20 s have been recently shown for the leg thrust in diagonal stride and for the poling time in double poling (Stöggl & Müller, 2009). To maintain or increase cycle length at a shorter time for force generation requires higher maximal forces and a higher rate of force development (Lindinger et al., 2009a). A present study (Stöggl et al., 2010) showed that several strength exercises were correlated to maximal skiing velocity. This supports earlier suggestions (Nilsson et al., 2004; Østerås et al., 2002) of the importance of a high maximal and explosive strength for a high maximal skiing velocity.

World Cup race courses are selected according to the FIS international guidelines for terrain topography (FIS, 2009) and must have a distribution of approximately 1/3 uphill, 1/3 downhill and 1/3 undulating to flat terrain. Uphills are divided into three different categories: A, B and

C climbs. The A climbs are the most common climbs, ~50% of total distance uphill, with grades from 9-18%. B climbs are short uphill and C climbs are long and steep uphill, >18% incline (FIS, 2009). On the steepest climbs the skiers decide whether to use the diagonal stride or the herringbone technique depending on 1) inclination, 2) ski grip, 3) the skiers' technical ability and 4) skiing velocity (Holmberg, 1996). For a traditional course, ~1/3 uphill terrain, the time spent in a distance race during climb is ~50% and in a sprint race ~45% (Bergh & Forsberg, 2000; Andersson et al., 2010). Therefore, on a FIS standard course the herringbone technique can be utilized approximately 2-3% of the total racing time. Relatively short and steep uphill climbs can therefore have an impact on the outcome of a race and in these sections the skier needs to master the technical challenges the herringbone technique present.

Since the late 1980s, several biomechanical studies of cross-country skiing techniques have been performed (Smith et al., 1988, 1989; Bilodeau et al., 1992, 1996; Nilsson et al., 2004). However, these studies have mainly used video analysis to assess adaptations in kinematics between different skiing techniques and velocities. Field studies with combined approaches using both kinematic and kinetic investigations are few (Komi, 1987; Vähäsöyrinki et al., 2008). No previous study has investigated the uphill climbing, herringbone technique used in the steepest terrain sections. Hence, to enhance the understanding of the mechanics of the herringbone technique, a study with combined analysis of kinematics and kinetics was performed on snow.

The aim of the study was to examine: (1) differences in kinematics and kinetics from moderate to maximal velocity when using the herringbone technique, (2) the force-impulse ratio of the arms and legs and (3) to analyze whether these two aspects are related to the athletes' strength.

Based on earlier findings in other cross-country techniques it was hypothesized that: 1) herringbone is a high-frequency technique due to the steep incline and absent gliding phase of the ski, therefore, cycle rate is expected as a major factor for adapting to higher velocities and 2) the muscle strength in both upper and lower body is related to the force impulse and peak force ratio between poles and legs when skiing at maximal herringbone velocity.

METHODS

Subjects

Eleven elite, Norwegian male cross-country skiers (including members of the Norwegian National Team), age 23.2 ± 4.4 years, body height 182.1 ± 5.1 cm, body mass 78.2 ± 7.5 kg, volunteered as subjects. The average VO_{2max} was 73.5 ± 5.2 mL·kg⁻¹·min⁻¹ (65–82), as measured during diagonal skiing on a treadmill using an ergospirometry system (AMIS 2001, Innovision A/S, Odense, Denmark). All the skiers were fully acquainted with the nature of the study before they gave their written informed consent to participate. The research techniques and the experimental protocol of the study were approved by the ethics committee of Umeå University, Umeå, Sweden.

Procedures

The study was performed on snow in one day at the end of the winter season. All skiers were tested on an uphill slope with steady inclines of $\sim 7.5^\circ$ and $\sim 15^\circ$ using the diagonal stride and herringbone techniques. The slope covered a total distance of 50 m. The first 35 m at $\sim 7.5^\circ$ incline and the last 10 m at $\sim 15^\circ$ incline. The section for analyses was the last 8 m (15° incline) of the slope. All skiers were informed to use diagonal stride for the 7.5° incline and herringbone in the steeper measuring section. The first part of the slope (7.5°) was used to enable the skiers to reach the desired velocity. All skiers performed three skiing trials at three different intensities; moderate (Mod, 65% of Max), high (Hi, 80% of Max) and maximal (Max) intensity. The subjects were familiar with the three selected skiing intensities since regularly applied in their training. The Mod and/or the Hi intensity trials were repeated after the Max trial if the skier deviated more than 5% from the instructed intensity. The time for acceleration to achieve the specific velocity was approximately 10 s and the time in the analyzing zone was 2.1–3.3 s. Between trials, 4 min of light active recovery at the lowest intensity zone ($\sim 40\%$ VO_{2max}) was allowed, giving a testing time of ~ 12 min for each skier. Two photocells (IVAR, LL Sport, Mora, Sweden) were used to obtain average section times and velocities.

Prior to testing, the skiers performed a 15 min light to moderate intensity warm-up. In order to standardize the grip- and gliding properties, all skiers used their own racing skis selected for current snow conditions. The grip and glide waxing was performed by a professional ski technician to achieve optimal grip for racing conditions and to minimize variations between the skiers. The weather conditions during the testing session were relatively stable; light

wind, with an air temperature varying from +1 to 3°C, snow temperature 0°C and a relative humidity of 92-96%. The slope was machine groomed the evening before the test day. To achieve constant firm snow conditions during testing salt was regularly applied to the ski track in order to avoid changing snow conditions (Supej et al., 2005).

Cycle definitions

Cycle time (CT) was defined as the period from the start of the right pole plant to the end of the right leg push-off. One herringbone poling cycle was divided into a poling phase representing the pole ground contact and a recovery phase. Leg actions were defined based on leg force data and were divided into a leg thrust and a recovery phase. Absolute and relative poling/leg thrust and recovery times (%cycle time), cycle rate (= 1/cycle time) and cycle length (= cycle time · velocity) were determined. All calculated pole and leg force data were averaged over four movement cycles and the average value of right and left leg/arm motions was used for each subject. The force generated by the leg thrust was defined as leg force and the force generated by the arms as pole force.

Pole and leg forces

All subjects used poles constructed for force measurements that were adjustable in length to optimally fit the skier (average pole length: 154 ± 5 cm equivalent to $85 \pm 3\%$ body height). The ground reaction forces directed along the pole were measured at rate of 1500 Hz by a strain gauge load cell (Hottinger – Baldwin Messtechnik GmbH, Darmstadt, Germany) weighing 15 g and fitting into a short (80 mm), lightweight (65 g) aluminum body mounted directly below the pole grip. Pole force data were amplified by a telemetric recording system (TeleMyo 2400T G2, Noraxon, Scottsdale, AZ, USA) and collected to a laptop computer via an A/D converter card.

Vertical plantar pressure was recorded for the right and left leg at a maximum rate of 100 Hz by the Pedar Mobile System (Novel GmbH, Munich, Germany). Conversion of plantar pressure to force was calculated as pressure multiplied with the area of the cell. For detailed analysis, the total foot area was divided into forefoot and rear-foot at 50% of foot length, respectively, and inside-foot and outside-foot at 50% of foot width, respectively. Relative force impulse of the forefoot and inside-foot was calculated by dividing the impulse of the forefoot and inside-foot with the total leg force impulse, respectively.

Absolute and relative peak force, time to peak force and average force were determined for the pole and leg motions, respectively. All relative force values were expressed as percent of body weight (%BW). Average leg force was calculated by dividing the leg force impulse by the leg thrust time and the procedure was replicated also for the pole. Force ratios were calculated by dividing the peak force by the average force for the leg and pole thrusts, respectively. A force impulse ratio (FI_{ratio}) was calculated by dividing the pole force impulse by the leg force impulse. A peak force ratio was calculated by dividing the peak pole force by the peak leg force. Relative time to peak pole force and relative time to peak leg force was calculated by dividing time to peak force by poling or leg thrust time. Rate of force development (RFD) was calculated by dividing the peak force by the time to peak force. When two peaks occurred the first peak after a steady build up of force was chosen. All data were processed using the IKE-Master Software (IKE-Software Solutions, Salzburg, Austria).

Validation of the pole and plantar system was performed according to the procedures described by Holmberg et al., (2005a) and insole calibration was performed using the Pedar calibration device. For synchronization of pole force and the Pedar system signals, a simultaneous lift and push off for the right ski and pole was performed before and after each skiing trial, when the skier was standing still. This synchronization procedure is not 100% accurate and cannot allow a detailed analysis of timing parameters between pole and leg plants. However, for the present study, the reason for synchronization was to identify corresponding pole and leg thrusts.

Total external power (P_{ext}) was calculated (Eq. 1) as the sum of power against gravity:

$$(1) P_{ext} = m \cdot g \cdot \sin(\alpha) \cdot v$$

With α being the grade; m , the body mass against gravity (g); and v , the average section velocity. The formula did not account for power against snow friction and air drag.

Normalization of force impulse was performed by multiplying the force impulse for the poling (IP) (Eq. 2) and leg thrust phase (ILT) (Eq. 3) over one cycle with the skiers individual cycle rate (CR) giving the force impulse over one second which is consequently equal, in value, to the average force over the same time period.

$$(2) IP_{1s} = IP \cdot CR$$

$$(3) ILT_{1s} = ILT \cdot CR$$

The total force impulse (total body) generated from leg thrusts and poling over one second ($ILTP_{1s}$) was calculated as:

$$(4) \quad ILTP_{1s} = 2(IP_{1s} + ILT_{1s})$$

For an estimation of the propulsive force impulse component from the poles over one second (PIP_{1s}), the angulation of the pole was measured with respect to the slope in the sagittal and lateral plane, according to the video analysis described below. These two angles were measured twice, at pole plant and at pole take off. Pole angles were averaged over four consecutive cycles. The average values for the pole angulation at pole plant and pole take off in the sagittal and lateral plane was used for calculation of the propulsive component (Eq. 5), assuming the center of mass is moving straight in the skier's direction of progression:

$$(5) \quad PIP_{1s} = (\sin(\alpha) \cdot IP_{1s}) \cdot \cos(\beta)$$

Where α is the lateral pole inclination and β is the sagittal pole inclination. The pole angles are illustrated in Figure 1A.

When a skier strides at constant velocity, force balance exists, resulting in equal propulsive force to gravity along the incline ($m \cdot g \cdot \sin(\alpha)$) with opposing forces. The estimation of propulsive pole force results in residual propulsion from the legs. Thus, to obtain an estimate for the propulsive force impulse from the leg thrust over one second ($PILT_{1s}$) the following calculation was performed (Eq. 6):

$$(6) \quad PILT_{1s} = (m \cdot g \cdot \sin(\alpha) - 2PIP_{1s})/2$$

With $m \cdot g \cdot \sin(\alpha)$ being the gravitational force along the slope, equals the impulse of gravitational force over one second.

Relative propulsive impulse, i.e. the propulsive component over the entire impulse, of pole force (PIP_{rel}) was calculated as PIP_{1s} over IP_{1s} and relative propulsive impulse of leg thrust force ($PILT_{rel}$) as $PILT_{1s}$ over ILT_{1s} . The propulsive force impulse ratio (PFI_{ratio}), i.e. ratio for propulsive pole and leg force impulse, was calculated as PIP_{1s} divided by $PILT_{1s}$.

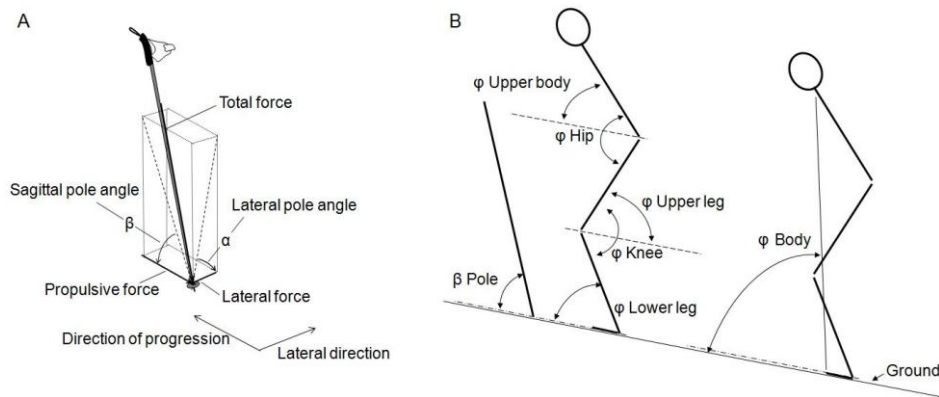


Figure 1. Illustration of the sagittal (β) and the lateral (α) pole angle (A), and joint and body segment angles from marker coordinate data (B).

Video analysis

All trials were filmed synchronously using three video cameras, one panning camera (Panasonic NV-GS 280) and two fixated cameras (Sony Handycam HDR-HC1E PAL). The panning camera was used to obtain the synchronization procedure. For the 3D video reconstruction, two perpendicular fixated video cameras were used. The first camera was positioned on the right side of the track, at a lateral distance of 17m from the center of the measurement area. The second camera was placed along the right side of the track, 13 m behind the measurement area. The shutter time of the cameras was set at 1/500 s to ensure high resolution. The videos obtained from the cameras were elaborated at 100Hz by using 3D video software for based measurements (Simi Reality Motion System; SIMI, Unterschleissheim, Germany). Both cameras were calibrated using 12 reference points positioned on the vertices and the sides of a parallelepiped covering an area of 3.5 m width, 8 m length and 2 m height. Eight fixed markers were set in the snow surface to check and correct for any movement in the position of the cameras. Calibration was performed using a Direct Linear Transformation-11 algorithm created in the SIMI motion software. The data extraction involved manually digitizing each camera view of the position of all selected points. The points of interest were marked by attaching bright orange lightweight spheres with a diameter of 38 mm to improve recognition. Skis and poles together with the right side of the skiers' body were identified during video analysis. For poles, markers were attached 0.4 m below pole handgrip and 0.20 m above pole tip to create well identified markers and improve recognition. For each ski, tip and tail were digitized. For body segment, markers were attached on the hip, the knee and the malleolus. After digitization, the data were available in 3D Cartesian coordinate values and used to calculate kinematic parameters.

Pole angles were calculated as the average of the left and right pole at the start (s) and the end (e) of the poling phase for each cycle, defined as the first frame where the pole meets the ground and the last frame where the pole was on the ground. Body segment angles were calculated at the start (s) and the end (e) of the right ski support phase. Body segment angles were also calculated for the aerial phase for the skier used in Figure 2. The pole angle to the front (sagittal plane) was defined as the pole angle (β) with respect to the ground (β_{ps} and β_{pe}) and lateral angulation was defined as the angle (α) of the pole at the frontal plane with respect to the ground (α_{ps} and α_{pe}) as shown in Figure 1A. Inclination of body segments with respect to the ground were calculated for total body (φ_{tbs} and φ_{tbe}), upper body (φ_{ubs} and φ_{ube}), upper leg (φ_{uls} and φ_{ule}) and lower leg (φ_{lls} and φ_{lle}) at the sagittal plane. Joint angles of hip (φ_{hs} and φ_{he}) and knee (φ_{ks} and φ_{ke}) were calculated on the sagittal plane as shown in Figure 1B. Lateral angulations of the skis (φ_{ski}) were obtained as the average ski angle between left and right ski. All kinematic parameters were analyzed over the same four movement cycles as the kinetic parameters were obtained.

Strength and jump tests

The upper, lower and total body strength and power were assessed with four relevant exercises for cross-country skiers, the bench pull, a concentric bench press, an isometric mid-thigh pull and a squat jump. The tests were performed one day after the on snow testing. The subjects were familiar with the movement patterns of the exercises as they were frequently used in everyday training. In addition, the subjects received specific instructions to perform the exercises prior to each test. The bench pull was performed with the subject lying in a prone position on an elevated bench while pulling a barbell towards the bench as described by Stöggl et al., (2010). The concentric bench press was also performed as described by Stöggl et al., (2010). The subject was instructed to use a narrow grip with the index finger perpendicular to the acromion. The bar was lowered with assistance to the subject's chest and on command from the test leader; the subject pressed the weight to extended arms. For both the bench pull and concentric bench press the subjects were allowed a warm-up at 30% of estimated 1RM for six to eight repetitions. The starting weight for data collection was set at ~50% of estimated 1 RM. Thereafter, the load increased by 2.5-5 kg per set until the weight for peak power had been established. Only single repetitions were performed at each load. The subjects were instructed to perform each set with maximal effort and speed with 1 min rest between sets. After failing to increase peak power the test was stopped and the test values obtained in the last successful attempt were used for further

analysis. The power was measured using a linear encoder (MuscleLab, Ergotest Technology AS, Langesund, Norway).

To assess the ability to generate maximal voluntary force into the ground, an isometric mid-thigh pull was performed on two force platforms (Kistler Instrument Corp., Amherst, NY, USA) similar to the procedures described by Haff et al., (1997) and Stone et al., (2004). The subject performed two maximal isometric repetitions separated by 3 min rest. Prior to the maximal effort, the subject was placed inside a squat rack with an adjustable height for the barbell. Each subject was placed with their feet under the bar at a knee angle of $144 \pm 5^\circ$ and a hip angle of $145 \pm 3^\circ$ and the subject placed his hands at shoulder width. The subject was instructed to pull the bar with maximal effort. For each repetition, total, right and left leg peak force was recorded.

In order to assess lower body vertical explosive force, a squat jump from both feet was performed on the force plate (Haff et al., 1997, Stone et al., 2004). During the squat jump the subject was instructed to have a starting position where the thigh was parallel to the ground while keeping his hands on hips and remaining in a still position until he is receiving a command to jump. The squat jump was performed for three repetitions each separated by 1 min between jumps. From the force plates, peak force, rate of force development, time to peak force, and time from initiation to flight was recorded.

Statistical analysis

Results are presented as mean and standard deviation (\pm SD). All data were checked for normality with the Kolmogorov–Smirnov analysis. One-way repeated measures ANOVA with Bonferroni correction were used for analyzing differences in the measured variables between the three skiing intensities. To assess relationships between variables Pearson's product-moment analysis was performed, in some cases also multiple regressions were used. The statistical significance level was set at $\text{Alpha} < 0.05$. All statistical tests were processed using Office Excel 2007 (Microsoft Corporation, Redmond, WA, USA) and SPSS 17.0 Software (SPSS Inc., Chicago, IL, USA).

RESULTS

Schematization of the herringbone technique and the corresponding pole/leg force curves over one cycle is shown for one skier at Hi velocity (82% of Max) in Figure 2A. The force curve shows that one pole mainly has ground support, whereas leg thrust have a short phase with no ground support, i.e. a short aerial phase in the transition between legs. It also shows that herringbone lacks a gliding phase and that the poling starts before the leg thrust phase. The mean velocities at the different intensities were as follows: Mod 2.4 ± 0.4 , Hi 3.0 ± 0.4 and Max $3.8 \pm 0.4 \text{ m}\cdot\text{s}^{-1}$, Mod and Hi representing 64.4 ± 2.6 and $80.7 \pm 3.2\%$ of Max. The estimated external work rates were: Mod 491 ± 101 , Hi 596 ± 122 and Max $735 \pm 142 \text{ W}$.

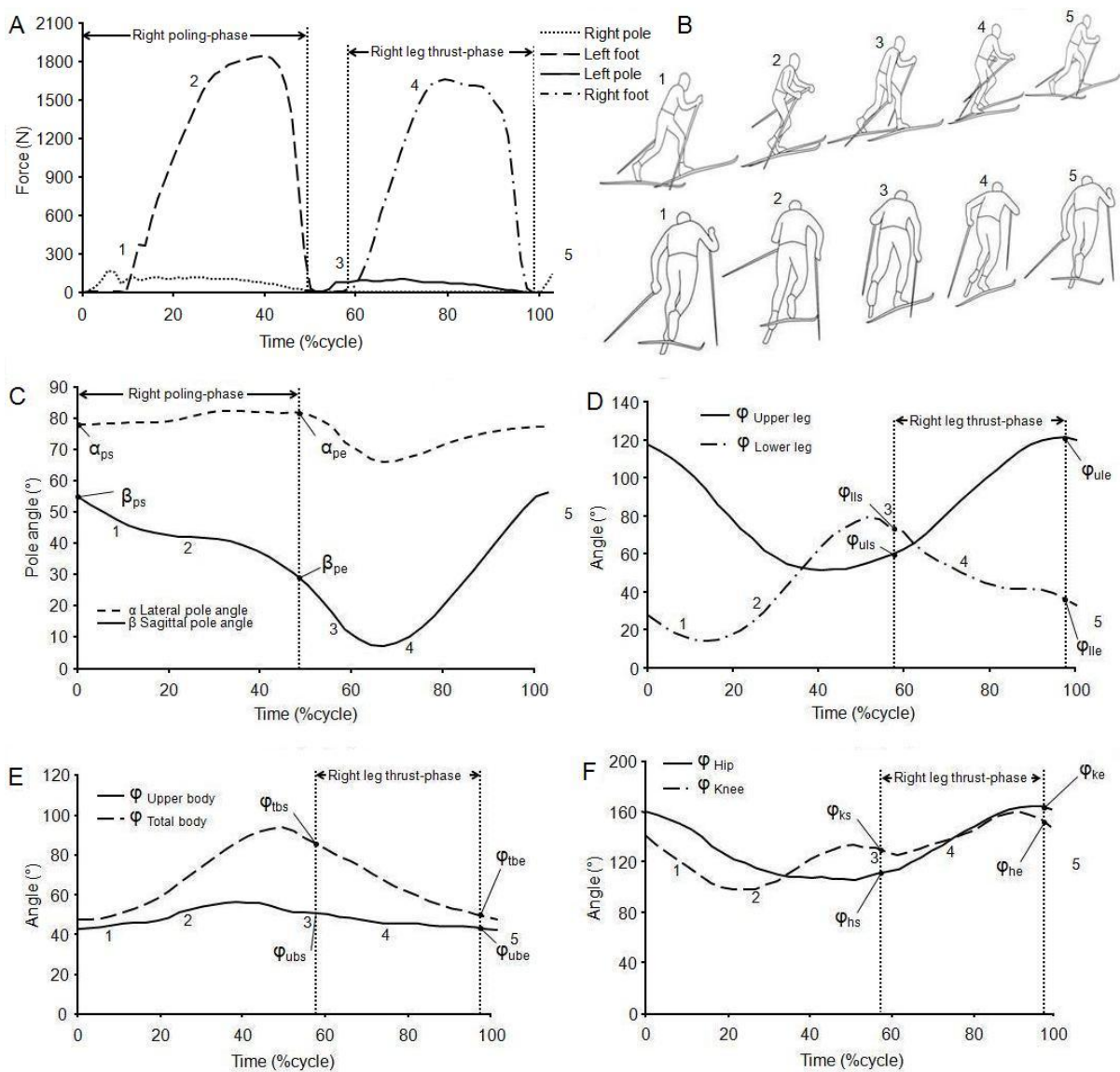


Figure 2. Kinetic and kinematic characteristics over one cycle for one subject skiing at moderate (82% of maximal) herringbone velocity. The included numbers (1-5) in all graphs shows different time phases for the skier (Fig. B). Time course of pole and leg thrust force (A); side view and back view of the skier at five different time phases (B); lateral and sagittal pole angle (C); upper and lower leg angle (D); upper and total body angle (E); and hip and knee angle (F). Data for joint and body segment angles including all subjects are presented in Table 1.

Cycle characteristics

Kinematics is shown in Table 1-2 and Figure 2-4. Cycle rate increased 35% (1.19 to 1.61 Hz) from Mod to Max (all $P < 0.05$). Cycle length increased 13% (2.04 to 2.31 m) between Mod to Hi ($P < 0.05$) with no further increase at Max. Cycle rate and cycle length increased similarly from Mod to Hi, where after cycle length reached a plateau and cycle rate continued to increase up to Max (Figure 3A). Cycle time decreased gradually from 0.85 s at Mod to 0.63 s at Max (Figure 3B). Relative poling and leg thrust times were constant over all velocities with ~50% poling and ~50% recovery time for the arms, and ~40% thrust phase and ~60% recovery time for the legs. The absolute values for the leg thrust and poling times gradually decreased as velocity increased ($P < 0.05$ in all cases) (Figure 4A-B).

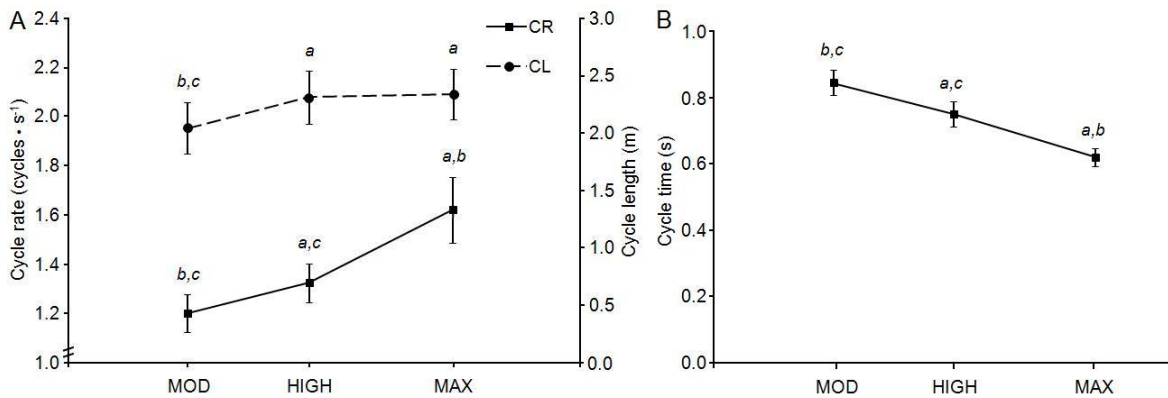


Figure 3. Cycle rate (CR), cycle length (CL) (A) and cycle time (B), at three different skiing velocities. Data expressed as means \pm SD. a, b and c indicates significantly different from MOD (a), HIGH (b) and MAX (c) velocity ($P < 0.05$).

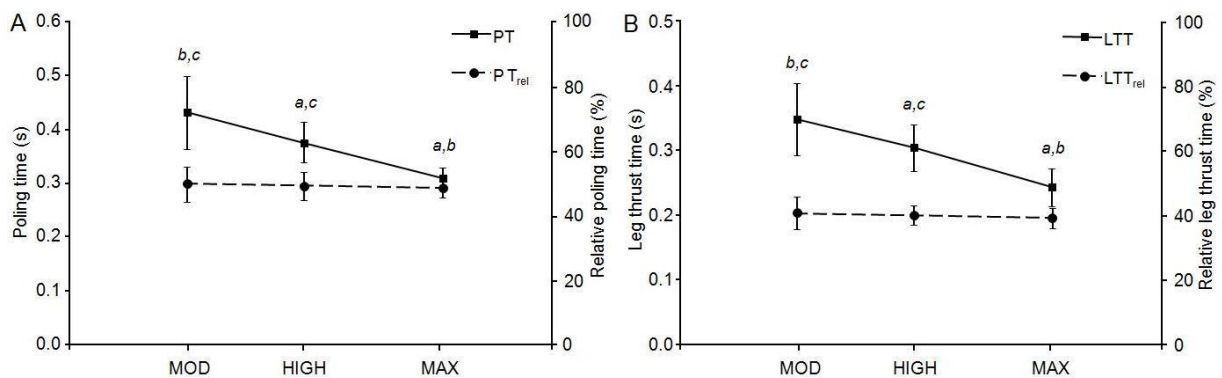


Figure 4. Absolute poling time (PT), relative poling time (PT_{rel}) (A), absolute leg thrust time (LTT) and relative leg thrust time (LTT_{rel}) (B), at three different skiing velocities. Data expressed as means \pm SD. a, b and c indicates significantly different from MOD (a), HIGH (b) and MAX (c) velocity ($P < 0.05$).

Joint kinematics

Joint and body segment angles demonstrated relatively constant patterns over the entire herringbone movement cycle at the three velocities (see Table 1). The lower leg angle and the forward lean of total body was an exception, which were less inclined at the end of the leg thrust at Max compared to Mod ($P < 0.05$). There was no difference in lateral ski angles between Mod and Hi, whereas the ski angles decreased from Hi to Max ($P < 0.05$).

Table 1. Kinematic characteristics of HB at the different velocities ($N = 11$); mean values \pm SD.

	Moderate	High	Maximal
β_{ps} ($^{\circ}$)	52.2 \pm 1.5	52.5 \pm 2.6	54.5 \pm 3.1
β_{pe} ($^{\circ}$)	35.2 \pm 1.1	35.2 \pm 1.6	34.9 \pm 2.0
α_{ps} ($^{\circ}$)	78.1 \pm 3.4	79.2 \pm 3.0	79.3 \pm 3.1
α_{pe} ($^{\circ}$)	80.6 \pm 3.7	80.8 \pm 3.2	82.3 \pm 4.3
φ_{ski} ($^{\circ}$)	30.2 \pm 11.4 ^c	29.4 \pm 7 ^c	24.6 \pm 4.4 ^{ab}
φ_{tbs} ($^{\circ}$)	92.6 \pm 2.4	92.7 \pm 3.0	92.0 \pm 2.9
φ_{tbe} ($^{\circ}$)	61.9 \pm 2.8 ^{bc}	59.3 \pm 2.5 ^a	59.3 \pm 2.6 ^a
φ_{ubs} ($^{\circ}$)	49.6 \pm 3.5	49.1 \pm 4.2	48.7 \pm 3.9
φ_{ube} ($^{\circ}$)	46.0 \pm 3.2 ^b	43.6 \pm 3.5 ^a	45.9 \pm 2.7
φ_{hs} ($^{\circ}$)	114.3 \pm 3.7	111.4 \pm 5.6	109.4 \pm 7.0
φ_{he} ($^{\circ}$)	164.3 \pm 5.6	162.4 \pm 6.6	163.9 \pm 6.1
φ_{uls} ($^{\circ}$)	64.7 \pm 3.7	62.4 \pm 4.6	60.6 \pm 4.6
φ_{ule} ($^{\circ}$)	118.3 \pm 4.9	118.8 \pm 5.4	118.0 \pm 5.9
φ_{ks} ($^{\circ}$)	138.9 \pm 5.2	135.5 \pm 5.5	133.2 \pm 6.6
φ_{ke} ($^{\circ}$)	159.3 \pm 4.3	156.3 \pm 6.1	152.7 \pm 7.6
φ_{lls} ($^{\circ}$)	74.2 \pm 3.8	73.1 \pm 3.0	72.6 \pm 5.5
φ_{lle} ($^{\circ}$)	41.0 \pm 4.8 ^c	37.5 \pm 4.3 ^c	34.7 \pm 3.6 ^{ab}

β_{ps} ($^{\circ}$), sagittal pole angle at the start of poling phase (PP_{start}); β_{pe} ($^{\circ}$), sagittal pole angle at the end of poling phase (PP_{end}); α_{ps} ($^{\circ}$), lateral pole angle at PP_{start}; α_{pe} ($^{\circ}$), lateral pole angle at PP_{end}; φ_{ski} ($^{\circ}$), lateral ski angle; φ_{tbs} ($^{\circ}$), forward lean of total body at the start of right ski support (RSS_{start}); φ_{tbe} ($^{\circ}$), forward lean of total body at the end of right ski support (RSS_{end}); φ_{ubs} ($^{\circ}$), upper-body angle at RSS_{start}; φ_{ube} ($^{\circ}$), upper-body angle at RSS_{end}; φ_{hs} ($^{\circ}$), hip angle at the RSS_{start}; φ_{he} ($^{\circ}$), hip angle at RSS_{end}; φ_{uls} ($^{\circ}$), upper leg angle at RSS_{start}; φ_{ule} ($^{\circ}$), upper leg angle at RSS_{end}; φ_{ks} ($^{\circ}$), knee angle at RSS_{start}; φ_{ke} ($^{\circ}$), knee angle at RSS_{end}; φ_{lls} ($^{\circ}$), lower leg angle at RSS_{start}; φ_{lle} ($^{\circ}$), lower leg angle at RSS_{end}.

Pole and leg force

Force variables are shown in Table 2 and in Figure 5-7. Relative peak pole force increased by 74% from Mod to Max, whereas time to peak pole force decreased by 75% (Figure 5A). Relative peak leg force increased by 7% from Mod to Hi ($P < 0.05$) and no significant changes were found from Hi to Max. Time to peak leg force decreased by 24 % from Mod to

Max (Figure 5B). The higher peak forces and the shorter time to peak force resulted in a nearly fourfold increase in RFD for the poles from Mod to Max ($P < 0.05$ in all cases), whereas a lower increase, 38%, was revealed for the leg thrust (all $P < 0.05$).

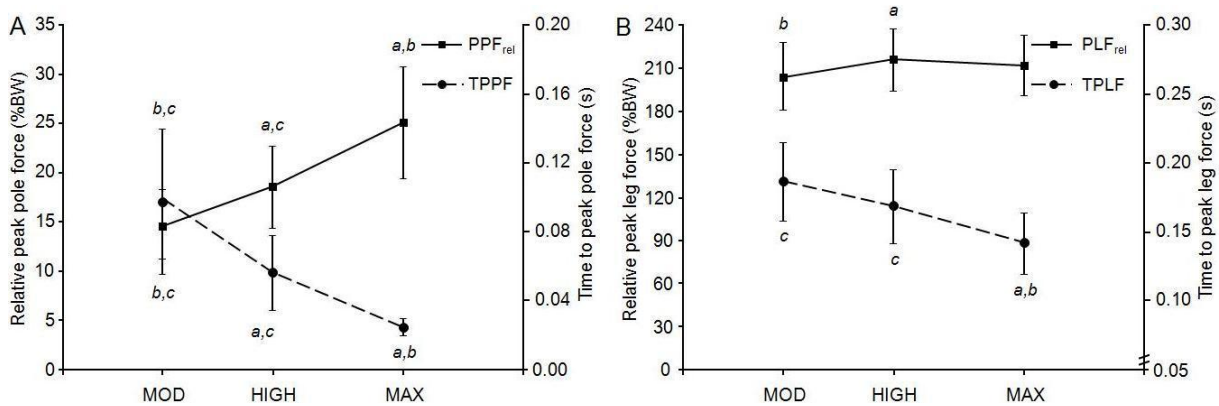


Figure 5. Relative peak pole force (PPF_{rel}), time to peak pole force (TPPF) (A), relative peak leg force (PLF_{rel}) and time to peak leg force (TPLF) (B), at three different skiing velocities. Data expressed as means \pm SD. *a*, *b* and *c* indicates significantly different from MOD (*a*), HIGH (*b*) and MAX (*c*) velocity ($P < 0.05$).

Relative time to peak pole force decreased from ~ 23 to 8% of poling time, whereas relative time to peak leg force was constant (~ 54 to 58%) (Figure 6A-B). The leg force ratio was constant from Mod to Hi but decreased at Max, whereas the pole force ratio increased from 180 to 287% of the average pole force (Figure 6A-B).

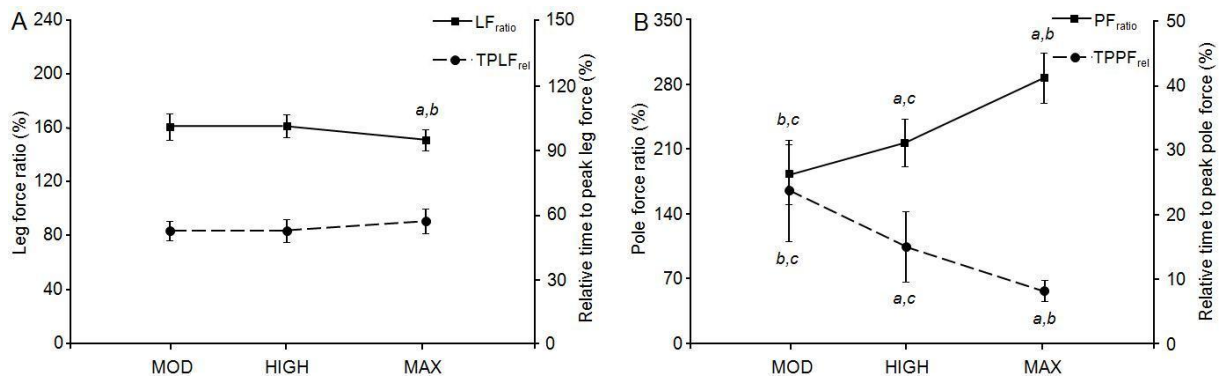


Figure 6. Leg force ratio (LF_{ratio}), relative time to peak leg force (TPLF_{rel}) (A), pole force ratio (PF_{ratio}), relative time to peak pole force (TPPF_{rel}) (B), at three different skiing velocities. Data expressed as means \pm SD. *a*, *b* and *c* indicates significantly different from MOD (*a*), HIGH (*b*) and MAX (*c*) velocity ($P < 0.05$).

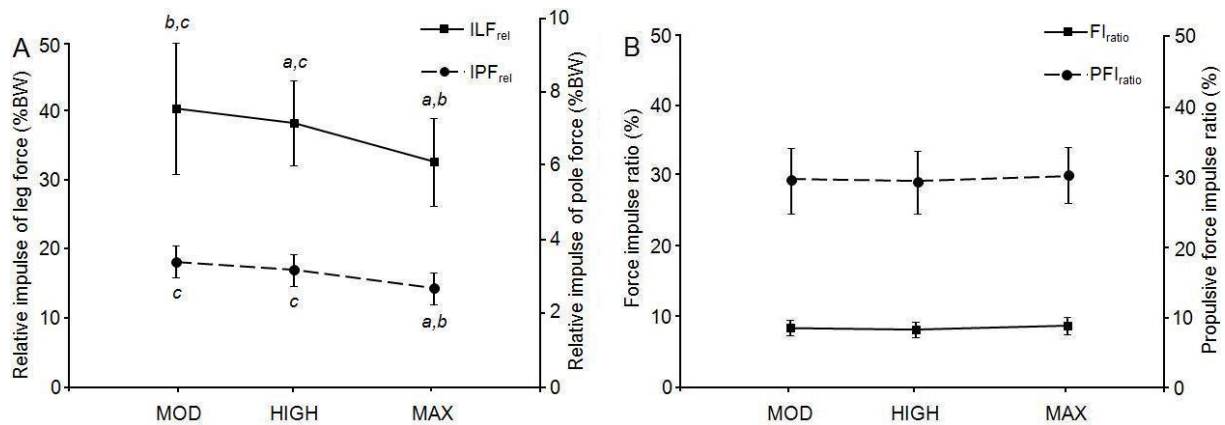


Figure 7. Relative impulse of leg force (ILF_{rel}), relative impulse of pole force (IPF_{rel}) (A), pole and leg force impulse ratio (FI_{ratio}), propulsive force impulse ratio (PFI_{ratio}) (B), at three different skiing velocities. Data expressed as means \pm SD. a, b and c indicates significantly different from MOD (a), HIGH (b) and MAX (c) velocity ($P < 0.05$).

The relative force impulse of every single pole and leg thrust decreased with increasing velocity, as shown in Figure 7A. ILTP_{1s} remained relatively constant with a slight increase of ~4% from Mod to Hi with no further increase from Hi to Max (Table 2). IP_{1s} showed no changes over the three velocities, whereas ILT_{1s} showed an increase from Mod to Hi ($P < 0.05$) with no further increase at Max. The FI_{ratio} remained constant over all velocities, with the IP being ~8% of the ILT (Figure 7B). PIP_{rel} was ~71% across the velocities and PILT_{rel} was about 20%. The PFI_{ratio} was ~30% across the velocities due to the ~3.6 times higher PIP_{rel} compared to PILT_{rel} (Figure 7B).

Analyzed differences between dominant/non-dominant arm and leg forces revealed no homogeneous pattern but the majority of skier's generated a higher force impulse with the dominant arm/leg. Individual side differences for each skier were relatively constant over the velocities.

Table 2. Force and cycle characteristics of herringbone at the different intensities ($N = 11$); mean values \pm SD.

	Moderate	High	Maximal
PRT _{rel} (%CT)	50.3 \pm 5.8	52.2 \pm 3.4	52.2 \pm 2.8
PPF (N)	111.9 \pm 23.8 ^{bc}	142.8 \pm 32.3 ^{ac}	194.3 \pm 43.5 ^{ab}
PF _{avg}	61.9 \pm 6.0 ^{bc}	66.1 \pm 6.4 ^a	68.3 \pm 7.6 ^a
TPPF _{rel} (%)	23.4 \pm 12.0 ^{bc}	14.9 \pm 7.7 ^{ac}	8.1 \pm 2.3 ^{ab}
RFD _{pole} (N s ⁻¹)	2281 \pm 1693 ^{bc}	4027 \pm 1744 ^{ac}	8737 \pm 2814 ^{ab}
IP (Ns)	26.1 \pm 2.5 ^c	24.4 \pm 3.6 ^c	20.8 \pm 3.7 ^{ab}
IP _{1s} (Ns)	31.0 \pm 3.4	32.0 \pm 4.6	33.4 \pm 6.3
PIP _{rel} (%)	70.9 \pm 1.3	71.0 \pm 1.8	70.1 \pm 2.7
IP _{DA/NDA} (%)	100.8 \pm 13.4	106.0 \pm 9.6	103.6 \pm 27.2
LRT _{rel} (%CT)	59.0 \pm 4.9	60.5 \pm 3.2	61.3 \pm 2.7
PLF (N)	1527.9 \pm 240.4 ^b	1643.9 \pm 216.1 ^a	1605.7 \pm 233.9
LF _{avg}	944.3 \pm 149.8 ^{bc}	1020.8 \pm 149.4 ^a	1040.5 \pm 170.0 ^a
TPLF _{rel} (%)	54.0 \pm 4.6 ^c	55.5 \pm 4.9	58.4 \pm 7.0 ^a
RFD _{leg} (N s ⁻¹)	8446.5 \pm 2094.9 ^{bc}	10116.2 \pm 2462.4 ^{ac}	11650.9 \pm 2253.2 ^{ab}
ILT (Ns)	326.6 \pm 66.8 ^{bc}	308.7 \pm 51.3 ^{ac}	252.5 \pm 50.9 ^{ab}
ILT _{1s} (Ns)	387.1 \pm 76.2 ^b	404.2 \pm 66.7 ^a	403.7 \pm 74.3
PILT _{rel} (%)	21.3 \pm 4.3 ^{bc}	19.5 \pm 3.3 ^a	19.4 \pm 3.3 ^a
ILT _{DL/NDL} (%)	107.6 \pm 22.1	108.9 \pm 19.2	106.8 \pm 18.7
IFF _{rel} (%)	84.7 \pm 6.4	87.5 \pm 5.6	88.3 \pm 6.7
IIF _{rel} (%)	77.8 \pm 7.2	76.8 \pm 6.5	75.0 \pm 7.6
ILTP _{1s} (Ns)	836.0 \pm 150.1	872.3 \pm 137.1	874.1 \pm 149.8

PRT_{rel} (%cycle time), relative poling recovery time; PPF (N), peak pole force; PF_{avg} (N), average pole force; TPPF_{rel} (%), relative time to peak pole force; RFD_{pole} (N s⁻¹), Rate of force development for the poling; IP (Ns), Impulse of pole force; IP_{1s} (Ns), impulse of pole force over 1s; PIP_{rel} (%), relative propulsive impulse of pole force; IP_{DA/NDA} (%), ratio for impulse of pole force between dominant and non-dominant arm; LRT_{rel} (%cycle time), relative leg recovery time; PLF (N), peak leg force; LF_{avg}, average leg force; TPLF_{rel} (%), relative time to peak leg force; RFD_{leg} (N s⁻¹), rate of force development for the leg; ILT (Ns), impulse of leg thrust force; ILT_{1s} (N s), Impulse of leg thrust force over 1s; PILT_{rel} (%), relative propulsive impulse of leg thrust force; ILT_{DL/NDL} (%), ratio for impulse of leg thrust force between dominant and non-dominant leg; IFF_{rel} (%), relative impulse of fore-foot force; IIF_{rel} (%), relative impulse of inside-foot force; ILTP_{1s} (Ns), total force impulse generated by pole and leg thrusts over 1s.

Variables related to skiing at maximal velocity

Both poling time and leg thrust time correlated negatively to velocity ($P < 0.05$ in both cases; $r = -0.79$ and -0.65). Leg RFD revealed a positive relationship against velocity, whereas the pole RFD showed a positive trend ($P < 0.05$; $r = 0.71$ and $P = 0.08$; $r = 0.55$). Peak leg force correlated positively to velocity ($P < 0.05$; $r = 0.76$), whereas peak pole force showed a positive trend to velocity ($P = 0.09$; $r = 0.54$). Relative time to peak leg force showed a positive correlation ($P < 0.05$; $r = 0.66$) against velocity, whereas relative time to peak pole force was negatively correlated to velocity ($P < 0.05$; $r = -0.64$). The total force impulse per body weight from pole and leg thrusts over one movement cycle at Max velocity showed a non-significant correlation to cycle length ($P = 0.10$; $r = 0.52$), whereas the estimated total propulsive force impulse per body weight at Max velocity showed a high positive correlation to cycle length ($P < 0.05$; $r = 0.95$).

Lateral angulation of the pole was highly negatively correlated with the lateral ski angulation at Max ($P < 0.05$; $r = -0.85$). However, no correlation was observed for the skiers with lateral ski angulations less than 24° . Angulation of the pole in the sagittal plane at pole plant was positively correlated to peak pole force at Max ($P < 0.05$; $r = 0.78$). $PILT_{rel}$ was highly positively correlated to the relative impulse of the inside-foot force at Max ($P < 0.05$; $r = 0.92$). The knee and the lower leg angle at the start of the leg thrust were negatively correlated to velocity at Max ($P < 0.05$ in both cases; $r = -0.68$ and -0.72). The lower leg angle at the end of the leg thrust was negatively correlated to cycle length, peak leg force, peak pole force and velocity at Max ($P < 0.05$ in all cases; $r = -0.80$, -0.67 , -0.80 and -0.88). Other joint and body segment angles showed low non-significant correlations to velocity at Max ($P > 0.56$; $r < 0.20$ in all cases).

Multiple regression analysis showed that for the PIP_{rel} value the average β pole angulation and α pole angulation showed semipartial correlations of $r = -0.94$ and $r = 0.27$, respectively, and beta values of -0.94 and 0.27 , respectively ($P < 0.05$). For Max velocity cycle rate and cycle length showed semipartial correlations of $r = 0.72$ and $r = 0.80$, respectively, and beta values of 0.72 and 0.81 , respectively, ($P < 0.05$).

Strength test results versus maximal performance on snow

The results of the strength and power tests were as follows: bench pull 59 ± 6 kg, 589 ± 110 W; concentric bench press 49 ± 8 kg, 399 ± 91 W; isometric mid-thigh pull peak force 1938 ± 331 N, for the dominant leg 1050 ± 176 N and for the non-dominant leg 952 ± 143 N; squat jump peak force 820 ± 162 N, jump height 0.33 ± 0.04 m, RFD 4514 ± 1840 N s⁻¹. Maximal power output in bench pull was highly positively correlated to the velocity at Max ($P < 0.05$, $r = 0.83$). The four strength exercises together were associated with velocity, cycle rate and cycle length at Max ($P < 0.05$ in all cases; $R^2 = 0.82$, 0.82 and 0.49). Isometric pull peak force, squat jump peak force and bench pull maximal power, were positively correlated to cycle rate at Max ($P < 0.05$ in all cases; $r = 0.63$, 0.79 and 0.68), but no significant correlations were found for cycle length. The ratio between peak force in the bench pull and the squat jump showed positive correlations against the FI_{ratio} and peak force ratio at Max velocity ($P < 0.05$ in both cases; $r = 0.64$ and 0.66).

DISCUSSION

The main findings of the present study investigating the herringbone technique in cross-country skiing on snow were: 1) the skiers adapted velocity from moderate to high intensity through a simultaneous increase in cycle rate and cycle length, whereas the higher velocity at maximal intensity was explained by increased cycle rate; 2) at higher skiing velocities the peak pole forces increased markedly, together with a shorter absolute and relative time to peak force. For the leg thrust, absolute time to peak force decreased whereas relative time to peak force and peak leg thrust force were relatively constant across the different velocities; 3) the pole and leg force impulse ratio were constant (~8%) across the velocities, and the propulsive ratio was about 30% due to the higher relative propulsive component from the poles versus the legs; and 4) strength parameters were positively associated with herringbone performance and the ratio between peak force in the bench pull and the squat correlated with the pole and leg force impulse ratio.

Intensities and external power

The intensity levels in the present study were selected according to the intensities used in competitions. The moderate, high and maximal velocities were meant to represent race intensities used in long distance (30-50 km), normal distance (15 km) and sprint races. If we postulate that the gross efficiency is similar to running, i.e., 23% (van Ingen Schenau et al., 1994), the generated external power generated by the maximal aerobic power of the athletes would be on average 471W. Consequently, the intensity levels at moderate, high and maximal velocity would represent about 100, 130 and 160% of the skiers' maximal aerobic power. Hence, when using the herringbone technique at steep short inclines a high anaerobic energy contribution can be assumed for normal distance and sprint distance races.

Cycle characteristics

In the current study, the skiers increased cycle rate and cycle length simultaneously from moderate to high velocity whereas increased velocity from high to maximal was only achieved by an increase in cycle rate. The increase in cycle rate with higher velocity is in line with previous research examining diagonal skiing (Stöggl & Müller, 2009) and double poling in elite skiers (Lindinger et al., 2009b). Vähäsöyrinki et al., (2008) showed a simultaneous

increase in both cycle rate and cycle length up to ~90% of maximal diagonal stride velocity and Lindinger et al., (2009b) showed a similar increase of cycle rate and cycle length up to ~95% of maximal velocity in double poling. As the cycle rate in the present study exceeds the cycle rates showed in previous skiing studies the herringbone technique can be classified as a “high frequency” technique. This might be explained by the steep inclination and the absence of a gliding phase. The adaptation to velocity in herringbone is similar to the adaptation in running (Weyand et al., 2000). In running, Weyand et al., (2000) showed a higher dependency of increases in cycle length for increasing velocity at the lower intensity range and cycle rate at the higher intensity range. The regulation of cycle rate and cycle length at maximal running velocity (4.5 m/s) at a steep incline (~17°) showed a similar relation between cycle length to cycle rate compared to herringbone at maximal intensity (Swanson & Caldwell, 2000).

In the current study, the relative leg thrust/poling and recovery times were constant over the different velocities. The major difference for the herringbone technique compared to other techniques is the absence of a gliding phase and thereby a shorter cycle length which needs to be compensated by a higher cycle rate. The latter could be a disadvantage due to higher alterations in kinetic energy between body segments which results in a higher energy cost (Frederick, 1992). The advantage of the lack of gliding phase is that it minimizes the changes in kinetic energy of the centre of mass during a movement cycle. Consequently, a “trade-off” probably exists between a high cycle rate and the steadier velocity of the centre of mass, for the total skiing economy.

When going from flat to uphill when skating, the relative time in propulsive phase increases whereas the relative time in gliding phase decreases. This is a technical solution that decreases the total deceleration over the movement cycle (Bilodeau et al., 1992; Smith, 2002). While ski-skating the skier is always forced to push in a right angle to the gliding direction which leads to a “zig-zag” movement. In comparison, herringbone is a technique that does not comprise a leg thrust on a gliding ski, due to the use of grip wax, and the skier’s center of mass is moving relatively straight in the direction of progression. For steep inclines herringbone can therefore be assumed to be an effective technique.

Joint kinematics

The increased velocity from moderate to maximal skiing intensity resulted in no differences for upper body, hip and upper leg angles whereas changes were observed for the forward lean of total body and the lower leg angle. At the end of the leg thrust the lower leg angle,

with respect to the ground, was smaller. This could indicate that the execution of the herringbone technique is relatively constant across the examined velocities for the upper body segments compared to lower body segments (Table 1). The decrease in the lower leg angle at higher velocities might be an outcome related to the higher force exertion. The negative correlations for the knee joint and the lower leg angle against maximal velocity revealed that the fastest skiers used a “deeper” position (smaller knee and lower leg angle at ski plant). This might be a beneficial technical strategy due to the possibility for a higher range of motion in the knee and ankle joint and thereof enhanced possibility to generate a high leg thrust force. Schache et al., (2010) showed that the work done at the ankle joint increased from a running velocity of 3.50 to 5.02 m/s whereas the work done at the knee joint remained constant, which might be similar in the present study.

Force characteristics

Pole forces increased approximately 72% from low to maximal intensity, changing more with velocity compared to leg force. The peak pole forces reported were 15-25% BW (112-193 N) at the three examined velocities. In comparison, Lindinger et al., (2009a) showed peak pole forces for diagonal skiing at racing velocity at 9° incline of 15% BW (109 N). In the current study, the steeper incline in combination with higher skiing velocities resulted in higher external work rates, explaining the higher peak pole forces. The peak pole forces found in the herringbone technique at maximal velocities are relatively high as compared to the peak pole forces of 30-35% BW observed in double poling, a technique with solely propulsion through the poles (Lindinger et al., 2009b). Pole and leg forces showed different patterns across velocities with a shorter relative time to peak pole force at the higher velocity, whereas the relative time to peak leg force was relatively constant. The pole force ratio (i.e. peak force divided by average force) increased markedly, 180 to 287%, from moderate to maximal velocity, whereas the leg force ratio was constant at about 160% from moderate to high velocity and decreased 7% at maximal velocity. This was revealed despite the constant pole and leg force impulse ratio over the different velocities. Thus, at higher velocities the higher peak pole forces contributed modestly to the total pole force impulse, explained by the short application time with a high force. As can be observed in Figure 1, the poling phase begins slightly before the leg thrust phase. Possibly to “secure grip” at higher velocities, the skier is forced to generate a high pole force earlier in the poling phase to reduce the early loading on the ski when the static friction has not yet reached its maximum.

Higher peak pole forces early in the poling cycle results in a lower relative propulsive pole force as compared to higher pole forces later in the poling cycle when the pole is more sagittally angulated (Lindinger et al., 2009a) but could be necessary to generate an effective leg thrust. The peak leg thrust forces for all velocities were on average about 2.1 times BW with a range from 1.5 to 2.7 times BW and is therefore similar to earlier studies on diagonal stride that have reported peak forces of 2-3 times BW (Smith, 2002; Lindinger et al., 2009a).

Impulse ratio of pole and leg force

The force impulse of poling was 8% of the leg thrust force impulse which can be seemed rather low in comparison to the leg thrust force impulse. However, the leg thrust force impulse involves a weight bearing non-propulsive component, i.e. the force impulse of body weight. If the force impulse of body weight were subtracted from the force impulse of the leg thrust, it would result in a ratio of about 40% between the pole and leg force impulses. The force impulse ratio between poles and legs were constant between the velocities despite the higher increase in peak pole forces as compared to the leg thrust forces. The explanation for that is the short duration with a high peak pole force at higher velocities. Thus, the markedly increased peak force contributes only modestly to the total pole force impulse. One more reason for a constant ratio might be related to low skiing velocities due to the steep incline.

It can be assumed that the contribution of the legs would increase with increased velocity in diagonal stride at lower inclines and in ski-skating G3 and G4 techniques used on level terrain. The higher velocity in flatter terrain when skating results in that the poling work must be performed more rapidly, arms must be moved as fast as the velocity of center of mass. The inverse relationship between contraction velocity and generated force means that the skiers' ability to generate power through the poles decreases at very high arm movement velocities. Vähäsöyrinki et al., (2008) showed a higher contribution of leg force impulse versus pole force impulse with increasing diagonal stride skiing velocities up to 5.6 m s^{-1} at a slight uphill slope of 2.5° . This adaptation is thought to be beneficial due to the higher muscle mass and strength in the legs compared to the arms that enables force generation at a high velocity. This suggestion is supported by Björklund et al., (2010), who found higher muscle activation (%MVC) in the arms compared to the legs while roller-skiing at $90\% \text{ VO}_{2\text{max}}$, which means that the legs have a higher "reserve" capacity to use at higher velocities.

Strength

The need of a high maximal and explosive strength can be assumed due to the requirements of a high maximal skiing velocity in modern cross-country skiing (Holmberg, 2005b). This implies shorter times for propulsion due to the stopping of the foot and/or the pole in the classical techniques leading to high requirements for rapid force generation. In the current study, poling times of 0.30 s and leg thrust times of 0.24 s were observed which is in line with previous findings for diagonal skiing at maximal velocity (Stöggl et al., 2010). To maintain cycle length when the push-off time decreases requires both an increase in the rate of force development as well as peak force (Lindinger et al., 2009a). A critical time limit may exist for maintenance of the force impulse during the push-off and when passing this limit the skier needs to compensate with cycle rate as were observed for some of the skiers in the present study at maximal velocity.

The selected strength tests were based on exercises regularly used by competitive elite cross-country skiers in their training. In the current study, positive correlations were observed for the ratio between lower and upper extremity in strength tests (bench pull and squat jump) and in herringbone (pole and leg thrust peak force and impulse). Thus, a ratio between highly relevant strength exercises has a transfer to the contribution of forces from the upper versus the lower body while skiing at maximal velocity. The power output in the bench pull was highly correlated to maximal skiing velocity and is in line with the previously shown correlation ($r = 0.71$) between bench pull peak power and maximal velocity in diagonal skiing (Stöggl et al., 2010). Isometric pull peak force, squat jump peak force and bench pull maximal power showed positive correlations to cycle rate. A high cycle rate has previously (Millet et al., 1998; Nilsson et al., 2004) been suggested to be most important for an increased skiing velocity, and the ability to maintain or increase cycle length at the highest cycle rates is probably related to maximal strength and power as well as to the coordination of force application.

In the present study, cycle length showed a positive relation to the results in the four strength exercises. However, this relation was lower compared to maximal velocity and cycle rate. The lower relation between strength and cycle length might be explained by the high inter-individual variability where the slowest skiers showed a modest cycle rate at a rather high cycle length, whereas the discriminating factor between the four fastest skiers were cycle length since all of them showed a similarly high cycle rate. The three fastest skiers in this study showed the ability to maintain or increase cycle length when cycle rate increased from ~1.35 Hz (Hi) to 1.65 Hz (Max), leg thrust time decreased by 27% (0.30 to 0.22 s) and poling

time decreased by 16% (0.35 to 0.29 s). To maintain or increase cycle length at these short times for force application requires high maximal strength that is rapidly generated. Furthermore, these skiers also showed the best results in the squat jump, bench pull and bench press, exercises which are relevant for cross-country skiers (Stöggl et al., 2010). The involvement of specific strength exercises aimed to increase maximal strength, power and rate of force development might enable the skier to maintain or increase cycle length at higher cycle rates and thus increase the maximal skiing velocity.

Force balance and propulsion

When skiing at a constant velocity, balance exists between the generated power and the dissipation by gravity, air drag and snow friction which means that the force balance is constant (de Koning & van Ingen Schenau, 2000; Frederick, 1992). This is in line with the results of the current study where the normalized pole and leg force impulse remained constant from moderate to maximal velocity. Gravity was considered as the main constraint against performance since snow friction and air drag was ignored. Snow friction was ignored due to the absence of a gliding phase in the herringbone technique and the air drag was estimated to be low (Leirdal et al., 2006).

Even though no significant changes were observed for the total normalized impulse of pole and leg force across the velocities a high inter- and intra-individual variation was observed. A slight increase in the total normalized impulse of pole and leg force could be expected at higher velocities explained by the velocity dependent air drag resistance. Another factor assumed to be related to the total normalized impulse of pole and leg force is the skiers' ability to generate a high percentage of propulsive force ("effectiveness of force application"). In the current study, the relative propulsive component of the leg force impulse decreased from ~21.3 to 19.5% from moderate to high velocity and remained constant at ~19.5% up to maximal velocity. The normalized leg force impulse increased ~4.5% from moderate to high velocity, with no further increase up to maximal velocity. No changes across the velocities were observed for the relative propulsive component of the pole force impulse and the normalized pole force impulse. Thus, the higher normalized leg force impulse might be related to both the lower propulsive component of the leg force impulse and the increased air drag. Consequently, the "effectiveness of force application" decreased for the leg force but remained constant for the pole force at higher velocities.

If the ratio of the propulsive component to the total force impulse is constant over the different velocities a slight increase of the force impulse due to the higher air drag would be

expected. Therefore, if the total normalized impulse of pole and leg force is constant or decreases an improved “effectiveness of force application” could be assumed. However, the differences in the percentage of the propulsive component from the poles versus the legs results in that a higher total force impulse needs to be generated for skiers that involves the legs to a higher extent compared to the arms. This makes the interpretation somewhat more complicated, but for skiers with similar upper and lower body contribution (impulse ratio arms versus legs) a higher “effectiveness of force application” could be expected for those who generate a lower total impulse at similar skiing velocity. Candotti et al., (2007) showed in cycling that the effective force was related to cycling economy at cadencies from 60 to 105 rev/min. Thus, in the present study a higher skiing economy can be expected for skiers with higher “effectiveness of force application”.

Propulsive forces

Herringbone differs from diagonal stride due to the absent gliding phase in combination with the lateral angulation of the skis. It can be argued that the transition to herringbone from diagonal stride at the steepest inclines can be beneficial due to the increased static friction between ski and snow which might enable the skier to maintain grip and generate a higher percentage of propulsive force components during the leg push-off compared to diagonal stride.

Video analysis revealed that the skiers centre of mass was moving relatively straight in the direction of progression in contrast to ski skating uphill, where the centre of mass is moving more side-ways during each leg stroke than during herringbone. The major advantage of the lateral ski placements in herringbone is probably the increased ability to generate static friction, i.e. grip, between ski and snow. In the present study, the lateral angulation of the skis was similar between moderate and high velocity, but decreased at maximal velocity. A wide range in lateral ski angulations were observed between the skiers at similar skiing velocities. This is most likely explained by differences in the timing and amount of pole force and variations in the application of leg force. Impulse of force on the fore- and inside-foot showed no significant change to higher velocity. Interestingly, the force impulse on the inside-foot correlated positively ($r = 0.92$) to the estimated percentage of propulsive leg thrust force at maximal velocity. It may be that higher pressure on the inside foot provides better grip and thus a more advantageous orientation of the force vector during the push off.

In ski-skating, as well as in ice-skating, the leg thrust direction is perpendicular to the gliding direction of the ski/skate. The direction of the generated force is perpendicular to the ski, through the centre of mass. The horizontal component of the leg thrust force results in a perpendicular acceleration to the other leg with its subsequent gliding phase. Both the magnitude of the leg thrust force and the angle between the leg thrust force and the horizontal component determines the following acceleration (van Ingen Schenau et al., 1994; de Koning & Schenau, 2000). When using the herringbone technique the propulsive component can, in principle, go in any direction in relation to the ski, how much backwards depends on grip. It can be assumed that if a skier is having a superior ski-grip the leg thrust is mainly directed backwards and the lateral ski placements are narrow. With decreasing ski-grip the skier is forced to push more sideways, using a wider lateral ski placement, without reaching the point where he/she starts to glide.

The estimated propulsive impulse per body weight from pole and leg thrusts at maximal velocity was highly correlated to cycle length, whereas the total force impulse showed a lower non-significant correlation. This result is in line with a recent study investigating sprint running performance who found that the orientation of the force in a propulsive direction is a higher determinant of performance than its amount (Morin et al., 2011). For all velocities the estimated propulsive forces of total forces were ~71 and 20% for the poling and leg thrust phase respectively. Pellegrini et al., (2010) showed that the ratio between propulsive and total force increased with grade and varied from 55% at 2° to 66% at 8°. When using herringbone the poles are more laterally angled compared to diagonal skiing which decreases the ratio between propulsive and total pole force. In contrast, the greater angulation of the pole in the sagittal plane at pole plant in the present study increases the relative propulsive force. Pellegrini et al., (2010) showed pole angulations at pole plant of ~70° at 8°, whereas the present study showed values of ~53°. The pole angulation at the end of the poling phase was similar in both studies (~35°).

Methodological considerations

External factors such as temperature, wind resistance and skiing velocity are complicated parameters to control when testing outdoors. This often results in that research studies are conducted in a standardized laboratory. In field studies, weather conditions can influence outcomes. However, in the current study these parameters were relatively stable and the snow conditions were controlled regularly. The majority of studies investigating cross-country skiing using combined approaches of both kinetics and kinematics have been performed in

controlled laboratory settings using treadmill roller skiing (Holmberg et al., 2005a; Lindinger et al., 2009a, 2009b; Stöggl et al., 2007; Stöggl & Müller, 2009). Herringbone technique cannot be performed indoor on a treadmill due to the inability to perform the technique accurately on roller skis. Limitations with controlled laboratory settings are often related to problems with external validity, whereas field studies are more sensitive to problems with internal validity. The major advantage with the current study is that it evaluates sport specific performance in its actual environment.

To standardize the self selected velocities (moderate, high and maximal) as much as possible the skier was re-tested for their moderate and/or high skiing trials if they were 5% faster or slower than instructed. The results showed average velocities of 64 and 81% of maximal for the moderate and high trials respectively, which shows that elite skiers are well able to find a certain velocity. The equipment used for assessment of pole and leg forces in the current study was validated according to the procedures described by Holmberg et al., (2005a) and can therefore be assumed to be valid. However, for the Pedar in-shoe system, studies (Barnett et al., 2001) have shown that different types of footwear can influence the magnitude of forces transmitted between the foot and the shoe. Hence, it cannot be excluded that different ski-boots could have decreased the validity of the measurements.

The estimation of the propulsive force components were based on the force balance between gravity force and the skiers generated propulsive force. However, when skiing at a constant velocity, force balance generally exists between gravity, snow friction, air drag and propulsive force (Frederick, 1992). In this study, snow friction and air drag was ignored because of the absence of a gliding phase and the low skiing velocities. Even though herringbone does not include a gliding phase a small energy loss due to snow deformation can be assumed when loading the ski during the leg thrust. However, this small component may be relatively constant for all skiers. The air drag in the present study was estimated to be ~2-4 N, when using an air drag coefficient ($0.5 \cdot \rho \cdot A \cdot C_d$) of 0.29 based on the results by Leirdal et al., (2006) who investigated the effect of different body positions in ski-skating and its influence on air drag and power output. This coefficient can be considered as valid due to the subject's similar body heights and joint angles as in the current study. An air resistance between 2 to 4 N from moderate to maximal velocity would only have underestimated the propulsive component by 1-2%.

The estimation of the propulsive component from the poles includes one main shortcoming. The propulsive force was calculated from the average pole angle, forward and sideward angle at pole plant and at the end of the poling phase and not from the entire pole angle curve during one skiing cycle. Therefore, an exact value was not observed for propulsion.

However, the value is likely relatively accurate due to the homogeneous change in pole inclinations over the entire herringbone stride-cycle for all skiers. Hence, the error is considered to be systematic. But the comparison of the propulsive component over the different velocities should be considered with caution due to the earlier relative peak pole force at higher velocities. This minimizes the relative propulsive component and the estimation used in this study does not account for this. Therefore, the propulsive component from the pole can be assumed to be slightly overestimated at higher velocities.

CONCLUSIONS

In conclusion, the present study showed that elite skiers adapted herringbone velocity through a simultaneous increase of cycle rate and cycle length from moderate to high velocity, whereas the further increase up to maximal velocity was explained by a higher cycle rate and maintained cycle length. The absent gliding phase in herringbone makes the leg motion similar to that of running and results in substantially higher cycle rates in comparison to other cross-country skiing techniques. Changes in body segment angles across velocities were only found for the knee joint and the lower leg, which decreased with higher velocity. The “deeper position” is probably a technical strategy for increased force generation during the leg thrust. The increase in cycle length from moderate to high velocity was achieved by higher average and peak forces for the pole and leg thrusts as well as to faster force generation. The timing of the peak forces also changed, with earlier peak pole forces at higher velocities. The force impulse ratio between poles and legs remained constant at ~8% across the different velocities and the ratio for propulsion was ~30% due to the higher relative propulsive component from the poles. Herringbone seems to be a technique where a higher velocity is explained by higher and faster force generation with relatively constant body segment angles. Both the upper and lower body strength variables were related to maximal herringbone velocity and there was a transfer between upper and lower body strength and the force impulse ratio when skiing.

This is the first study to analyze the herringbone technique on snow and the present findings have a direct value in the understanding of the technique used by elite skiers on the steepest uphill climbs. To increase the mechanical understanding of the sport, future studies should further use similar methodological approaches to investigate skiing performance.

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