

**Downhill Turn Techniques and  
Performance  
in Cross-Country Skiing:**

Associations with Mechanical  
and Physical Parameters

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## ABSTRACT

Downhill turns in cross-country skiing are performed in widely varying conditions. In order to perform well, i.e. effectively utilize potential energy and accelerating forces from the leg push-off, skiers must adapt their entrance velocity, the trajectories throughout the turns and the employment of techniques. The aims of this study were to characterize the main techniques utilized in downhill turns among female elite cross-country skiers and to examine how downhill turn performance is influenced by technique distribution, mechanical parameters and the skiers' maximal strength and power. Twelve female elite cross-country skiers performed six highly standardized, subsequent turns using a freely chosen technique. The subjects were continuously monitored by a high-end real time kinematics GNSS and one camcorder. From here, the measured trajectory was used for calculating total and intersection times, velocity and energy dissipation at each point of observation. Video analysis was used to determine the distribution of techniques. In the laboratory, maximal isometric squats and counter-movement jumps were performed to characterize the athletes' peak strength and power. Side-stepping, skidding and ploughing were identified as the three main techniques utilized in different phases of downhill turns in cross-country skiing. The faster skiers in downhill turns preferred skidding to ploughing in decelerating parts of the turns and showed an earlier initiation and overall greater use of the accelerating side-stepping technique (all  $p < 0.05$ ). Furthermore, better performance in the turns was related both to higher velocity and shorter trajectory (all  $p < 0.01$ ). Peak force, time to peak force and rate of force development in a countermovement jump were most strongly correlated with performance (all  $p < 0.05$ ). Overall, the current study identified side-stepping, skidding and ploughing as the main techniques distributed in cross-country skiing downhill turns. Better skiers featured a greater portion of the side-stepping technique, which was initiated earlier in the turn and at a higher velocity. These technical patterns lead to higher velocities at shorter trajectories throughout the turn, in association with higher peak leg power.

## SAMMENDRAG PÅ NORSK

Svinger i nedoverbakker i langrenn blir gjennomført under varierende forhold. For å prestere godt, altså utnytte potensiell energi og akselererende krefter fra frasparkene på en effektiv måte, må løperne tilpasse inngangshastigheten, linjen gjennom svingen og bruken av teknikk. Målene med denne studien var å karakterisere hovedteknikkene som blir brukt i langrennssvinger i nedoverbakker blant kvinnelige eliteløpere og å undersøke hvordan prestasjonen blir påvirket av teknikkdistribusjon, mekaniske parameter og løpernes maksimale styrke og eksplosivitet. Tolv kvinnelige eliteløpere gjennomførte seks høyt standardiserte, påfølgende svinger med fritt valgt teknikk. Subjektene ble kontinuerlig målt med en RTK GNSS og et videokamera. Løpernes målte linje ble brukt for å kalkulere totaltid, tid i hver seksjon, fart og energitap eller gevinst. Videoanalyser ble brukt for å bestemme teknikkdistribusjonen. Isometrisk knebøy og svikthopp ble analysert i laboratoriet for å karakterisere løpernes maksimale styrke og spenst. Teknikkene som ble identifisert og brukt i de ulike fasene gjennom langrennssvingene i nedoverbakker var skøytesving (side-steg), skrensing og plogging. De beste løperne foretrakk skrensing over plogging i bremsefasen og hadde en tidligere overgang og totalt større bruk av den akselererende skøyteteknikken (alle  $p < 0.05$ ). Videre var god prestasjon relatert til både høyere fart og kortere linje gjennom svingen (begge  $p < 0.01$ ). Høyeste kraft, tid til høyeste kraft, og kraftutviklingsrate i svikthoppet korrelerte sterkest med svingprestasjonen (alle  $p < 0.05$ ). Sammenfattende identifiserte denne studien skøytesving, skrensing og plogging som hovedteknikkene som brukes i langrennssvinger i nedoverbakke. De beste løperne brukte en større andel av skøytesving og klarte å begynne å skøyte på et tidligere tidspunkt og på høyere fart. Disse tekniske mønstre og løpernes bedre eksplosive styrke i beina førte til høyere fart ved en kortere linje gjennom svingen.

## INTRODUCTION

Cross-country skiing competitions are carried out at high exercise intensities, on varying terrain and at widely varying velocities. Consequently, the sport of cross-country skiing is regarded as both physically and technically demanding (Smith 1992; Saltin 1997). In most races, uphill, flat and downhill terrains are equally proportioned over the race distance (Bergh and Forsberg 2000; Sandbakk et al. 2011a; Andersson et al. 2010). A majority of research in cross-country skiing has focused on performance on uphill and flat terrain, which has been shown to be the two most differentiating terrain sections in a race (Bergh and Forsberg, 2000; Sandbakk et al. 2011b; Andersson et al. 2010). Downhill sections are generally regarded to be of relatively low significance to overall performance, and their role primarily associated with recovery. On the other hand, in shorter races and in the finish-phase of mass start events, downhill turns are more important and can be the deciding factor in whether one wins or loses the race. In the study by Sandbakk et al. (2011b), a demanding turn section in the race was strongly related to time-trial performance in sprint cross-country skiing. No studies have, however, investigated downhill turns in cross-country skiing specifically.

From a mechanical point of view, acceleration in a downhill turn (i.e., an increase in kinetic energy) is the result of both the utilization of potential energy (i.e., gravity) and the possible addition of propulsive forces during the leg push-off. In order to optimize the kinetic energy of motion, skiers must adapt the level of entrance velocity, the trajectories throughout the turns and employ different techniques. In cross-country skiing, neither performance, mechanical parameters or technique distribution employed in turns have been scientifically investigated.

Coaching literature (e.g. Nymoen and Andersen 1991) and anecdotal observations in cross-country skiing indicate that there are three main strategies that are utilized in downhill turns: side-stepping, skidding and ploughing techniques. These techniques are also identified in alpine skiing (Howe 2001). The aims of these turning techniques are to reduce or increase velocity and change direction. The proportional use of the different techniques depends upon velocity, the turns' radii, snow conditions and the skier's physical abilities (Howe 2001). Because the skis run smoothly when side-

stepping, it might be suggested that energy dissipation is higher when skidding and ploughing, which generate more friction when edging the skis (Howe 2001; Supej 2008). Skidding movements may be a more effective technique than ploughing for deceleration, as more friction can be generated when lowering of the centre of mass, thereby producing a deeper penetration of the skis into the snow (Howe 2001). However, the skis' orientation in the ploughing technique can generate a larger support area and may therefore be a safer deceleration strategy. Consequently, it is reasonable to assume that better downhill turn performance in cross-country skiing turns is associated with an overall greater use of the accelerating side-stepping technique and more effective skidding.

Rationally, the intersection time in a turn is the product of mean velocity and the trajectory length. Their proportional impact on performance in cross-country skiing turns remains to be examined. In alpine skiing, high mean velocity is shown to be more important than short trajectories for performance (Supej 2008; Supej et al. 2011). It is therefore suggested that maintaining high velocity throughout the turn may be the main discriminating factor for performance in cross-country skiing turns.

Maximal strength and power have been shown to be critical determinants of modern cross-country skiing performance, most notably in association with maximal velocity and work economy (Andersson et al. 2010; Stöggl et al. 2006; 2007; 2011; Alsobrook and Heil 2009; Hoff et al. 1999 and 2002; Østerås et al. 2002). The impact of strength characteristics on performance in specific skiing techniques or aspects of a race has generally been linked to strength capacities with similar movement characteristics (Stöggl et al. 2011). The relevance of the leg's strength to downhill turn performance has been examined in alpine skiing, where maximal leg strength is significantly correlated with performance in both the downhill and giant slalom events (Andersen and Montgomery 1988; Berg et al. 1995). Compared to athletes in other sports, alpine skiers demonstrate extremely high leg strength, particularly at relatively slow contraction velocity (White and Johnson 1993; Berg and Eiken 1999). However, the requirements of maximal strength at low contraction velocity might be different in cross-country skiing due to lower racing velocities, different equipment and subsequently more active use of side-steps. Thereby, kinetic energy may be

influenced considerably by muscular power from the leg push-off in side-stepping techniques.

The purpose of the current study was to investigate performance, techniques and mechanical characteristics in downhill turns among female elite cross-country skiers. It was aimed to characterize the main techniques utilized in downhill turns and to examine how downhill turn performance is influenced by technique distribution, mechanical parameters and maximal strength and power characteristics. The main hypotheses were that high velocity throughout the turn is most important for downhill turn performance, and that a technique distribution featuring a greater possibility to maintain speed throughout the turn is advantageous. Furthermore, it is suggested that these abilities are related to the athletes' explosive leg power.

## METHODS

### *Subjects*

Nine Norwegian and three Swiss female elite cross-country skiers, including three national team skiers (mean  $\pm$  standard deviation: age  $20 \pm 3$  years; body height  $168 \pm 5$  cm; weight  $60 \pm 6$  kg;  $VO_{2max}$   $59 \pm 5$  ml·min<sup>-1</sup>·kg<sup>-1</sup>) volunteered to participate in this study. This study was pre-approved by the Regional Ethics Committee of Umeå, Sweden (#208-31M), and all subjects were fully informed of its nature before providing their written consent to participate.

### *Overall design of the study*

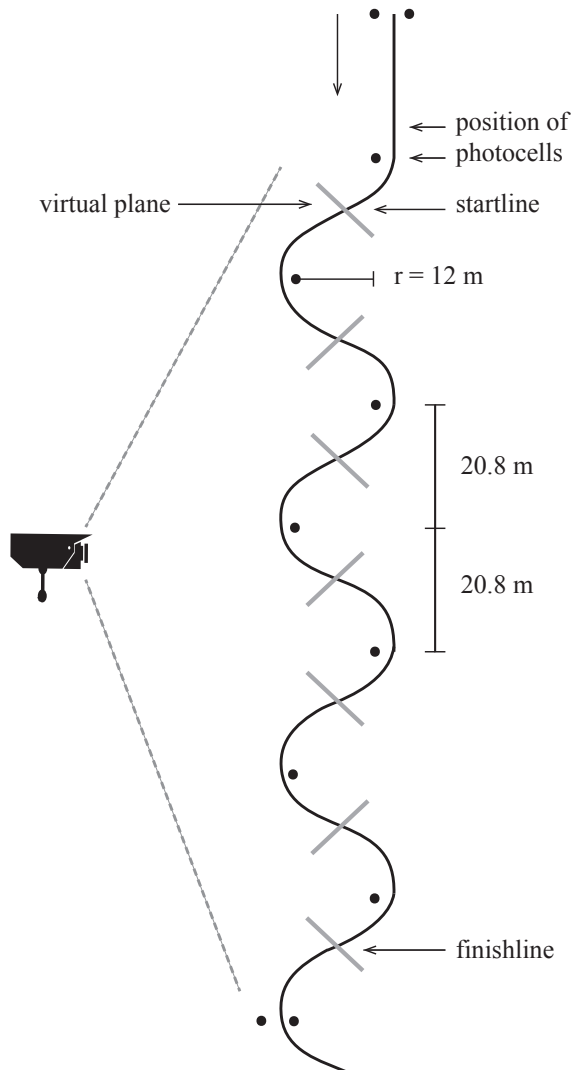
Initially, typical turns and main techniques applied in cross-country skiing World Cup competitions were identified. Thereafter, a relevant course with six standardized turns was developed (Figure 1), pre-tested by elite skiers and used in the experiment. Data were collected by measurements of real time kinematic GNSS monitoring, photocells and camcorders. From here, performance was measured by time to complete the total course (will be referred to overall performance in the following sections), the techniques used during the run were identified and relevant mechanical parameters were calculated. Finally, peak strength and power were determined in the laboratory.

### *Experimental set-up*

The experiment was carried out in Meråker (Norway) on snow. All skiers performed a giant slalom competition (Figure 1) on a 166.4 m downhill slope with a mean decline of  $10.6^\circ$ , using ordinary cross-country skiing equipment and a freely chosen technique. The course consisted of eight gates, resulting in six highly standardized turns for analysis. The run-in was 20.8 m and entrance speed prior to the first gate was set to  $7.5$  m·s<sup>-1</sup>  $\pm$  5 % (i.e. between  $7.1$  and  $7.9$  m·s<sup>-1</sup>) and controlled by photocells (TC-Timer, Bower Timing Systems, Draper, Utah). The gates were set up in a matter that a skier could ski radii of 12 m, and entrance and exit angles of  $60^\circ$ . The weather conditions were stable, light wind, with an air temperature varying between  $+1$  and  $+3^\circ\text{C}$ , snow temperature of  $0^\circ\text{C}$  and a relative humidity of 92-96%. The skiers were continuously monitored by a high-end real time kinematics GNSS (RTK GNSS) (Leica Geosystems AG, Heerbrugg, Switzerland) and filmed with one camcorder



(Panasonic NV-GS 280) from a fixed tripod. To minimize errors from the RTK GNSS measurements, the course was chosen to be in open terrain without adjacent forest. Subjects performed an individual warm up and used their own racing poles ( $90 \pm 1\%$  of body height in length) and skis ( $105 \pm 2\%$  of body height). The slope was machine groomed and salted before the experiment. To minimize the influence of different gliding properties, all the skis had a similar stone-grind and were waxed by a professional ski technician with the same fluorine wax.



**Figure 1.** Gate set-up of the course.

### *Instruments*

The rover and reference station for the RTK GNSS system are shown in Figure 2. The system simultaneously receives signals from both the United States' and Russian global navigation systems (GPS and GLONASS) and surveys positions with 1 cm + 1

ppm and  $2 \text{ cm} + 1 \text{ ppm}$  horizontal and vertical accuracy respectively, at a 20 Hz sampling rate in the real time kinematics (RTK) mode. During the measurements, the reference station stood on a fixed tripod  $< 150 \text{ m}$  from all surveyed points to assure maximum accuracy. The rover was placed in a specially designed small backpack carried by the skiers (total weight  $\sim 1.64 \text{ kg}$ ). The antenna was positioned at the height of the skier's upper back (level Th2-Th4) to ensure minimum disturbance to the skiers and that the sensor was well visible to the satellites. To survey the terrain properties and the gate set-up of the course, the RTK GNSS antenna was attached to a 2 m long carbon geodetic pole with onboard inclinometer (Leica Geosystems AG, Heerbrugg, Switzerland). All tests were carried out between 9 AM and 11 PM. This time frame had the highest satellite availability and resulted in 7 to 13 visible satellites above the  $15^\circ$  azimuth angle during all measurements and a Geometric Dilution of Precision (GDOP) value between 1.5 and 3.4. Before each measurement, satellite availability and GDOP were verified. The RTK GNSS system and the video were synchronized by an isolated rapid vertical squat movement by the skier prior to the measurement.



**Figure 2.** The RTK GNSS system, consisting of: 1) Leica GX1230 GG, 72 channel, dual frequency L1/L2 receivers, 2) Leica AX1202 GG survey antennas and 3) Leica GFU14 Satelline 3AS radio modems (Leica Geosystems AG, Heerbrugg, Switzerland).

### *Data processing*

The skiers' trajectory and the reference pole positions were surveyed by the RTK GNSS and were used to calculate time, velocity and energy dissipation. The trajectory's motion is described point by point in a three-dimensional Cartesian coordinate system. A two-way Kalman filter was used on the surveyed trajectory with boundary conditions, so that each filtered position on the trajectory would be within the known error for each position point provided by the RTK GNSS. Vertical body movement was removed by orthogonal projection to the slope surface. Moreover, the coordinates were rotated two-dimensionally around the z-axis, so the x-axis points in the direction of the fall line, perpendicular to the z-axis pointing upright against gravity. The result is a rotated coordinate system  $(x_n, y_n, z)$ , where index n refigures the new coordinate system,  $x_n$  the forward motion,  $y_n$  the lateral displacement and  $z$  the altitude. Virtual vertical planes were constructed to segregate the turns at  $90^\circ$  angles to moving direction precisely in between gates. The starting line was set between the first and second gate, and the finish was line between gates seven and eight. Overall performance time was calculated from the skier's trajectory intersecting the first plane and the last plane. Performance in each turn was calculated in all six intersections. A linear interpolation on the trajectory was used to arrive at a more precise intersection time. The entrance velocity ( $v_{in}$ ) and the exit velocity ( $v_{out}$ ) were calculated at the corresponding intersection times. Linear interpolation was again used on velocity to calculate each point of the turning cycle from 0 to 100%. Following the same analogy, mechanical energy ( $e_{mech}$ ) and differential mechanical energy ( $diff(e_{mech})$ ) was calculated at the entrance and exit points and at each point of the turning cycle as described elsewhere (Supej 2008). The length of the skier's trajectory was approached by the sum of linear displacement between each point of measurement. All calculations were conducted in Office Excel 2007 (Microsoft Corporation, Redmond, WA, USA) and Matlab 2007a (Mathworks, Natick, MA, USA).

### *Video analysis and technique classification*

For synchronization of kinematics and technique, the PAL video recordings were first transformed to 50 Hz via a frame-to-field method using two open source video-editing software packages (Avi Synth 2.5, Virtualdub 1.5). Technique analysis was

carried out in Dartfish ProSuite 4.5 (DartFish Ltd., Fribourg, Switzerland). The lowest squat position was detected on the videos and synchronized with the corresponding RTK GNSS measurement by identifying the trajectories' change in vertical velocity from downward to upward. The different techniques were classified by two independent observers and modified to cross-country skiing according to the terminology used in alpine skiing (Howe 1983). The criteria for classification were as follows: The side-stepping technique started at the moment when the inner ski was lifted or when a marked initiation for extension of the outer leg for push-off occurred and ended when the lifted ski was back at a parallel position after the last step was taken. Parallel skidding technique started when the skis were in a parallel position and pressure was added to the surface (i.e. a distinct lowering of the centre of mass) and ended when lifting one ski (i.e. transition to side-stepping) or the skis pointed in forward direction again (i.e. transition to gliding). Plough technique started when the skis were in V-formation and pressure was added to the surface (distinct lowering of the centre of mass) and ended when the skis were back in parallel position (i.e. transition to skidding or parallel gliding). Moreover, other movements were reported for classification purposes. Examples included parallel gliding, where the skis pointed in a forward direction without actual movement for either acceleration or deceleration, or movements that were used for the compensation of imbalances without the purpose of deceleration, acceleration or change of direction. From the measured trajectories, acceleration and energy dissipation were calculated for all technique sections  $\geq 15\%$  of a turn. Technique sections leading to imbalances were excluded. Energy dissipation within a technique section was calculated as the difference in mechanical energy from the beginning to the end of each technique section, normalized for the corresponding entrance velocity and the length of the section, based on the methods of Supej et al. (2011).

### *Laboratory tests*

Anthropometry and physical characteristics were tested in the laboratory on a separate day. Body mass without equipment was measured on the Kistler force plate and body height was calibrated on a stadiometer (Holtain Ltd., Crosswell, UK).  $VO_{2max}$  was tested during uphill running at 10% incline with an initial speed of  $6 \text{ km} \cdot \text{h}^{-1}$  and increases by  $1 \text{ km} \cdot \text{h}^{-1}$  every minute thereafter, until exhaustion was reached. This test

was considered to represent maximal effort if the following three criteria were met: 1) a plateau in  $\text{VO}_2$  with increasing exercise intensity, 2) a RER value above 1.10, and 3) blood lactate concentration exceeding  $8 \text{ mmol} \cdot \text{L}^{-1}$ .  $\text{VO}_2$  was measured continuously and the average of the three highest consecutive 10-s values designated as  $\text{VO}_{2\text{max}}$ . The blood lactate concentration was measured 1 and 3 min after termination of the test. Respiratory parameters employing open-circuit indirect calorimetry and spirometry were assessed with an Oxycon Pro apparatus (Jaeger GmbH, Hoechberg, Germany). Prior to each measurement, the  $\text{VO}_2$  and  $\text{VCO}_2$  analyzers were calibrated using a known mixture of gases ( $16.00 \pm 0.04 \% \text{ O}_2$  and  $5.00 \pm 0.1 \% \text{ CO}_2$ , Riessner-Gase GmbH & Co, Lichtenfels, Germany) and the expiratory flow meter calibrated with a 3-L syringe (Hans Rudolph Inc., Kansas City, MO). Heart rate was followed with a heart rate monitor (Polar RS800, Polar Electro OY, Kempele, Finland). Blood samples ( $20 \mu\text{L}$ ) were taken from the fingertip and used for determination of blood lactate concentration by Biosen 5140 (EKF diagnostic GmbH, Magdeburg, Germany).

Peak leg strength and power characteristics were tested on a Kistler force plate (Kistler 9286AA, Kistler Instrument Corp., Winterthur, Switzerland). The subjects were familiar with the movement patterns in the tested exercises as they are tests that are frequently used in everyday training. In addition, the subjects received specific instructions prior to each exercise. Maximal isometric squat was performed under a fixed metal bar in order to determine maximal isometric leg strength. The bar was regulated for each subject to fit a knee angle of  $125^\circ$ , close to where maximal strength in a knee extension is reported to be obtained (Hay 1992). The skiers were instructed to push maximally for 3 s. Peak force was taken as the highest average force over one second. The test was performed three times and the highest peak force value was used for further analyzes. In order to assess lower body vertical explosive power, countermovement jumps (CMJ) were performed. For the CMJ, the subject was instructed to keep their hands on their hips, to start in an upright position, squat down and immediately engage in a vertical jumping motion in order to use the muscles elastic properties. The subjects initiated the CMJ on own volition and were allowed to self-select the squat depth prior to jumping. The CMJ were performed for three repetitions, each repetition separated by 1 min between the jumps and the values from the highest jump was used for further analyses. In the CMJ, the concentric push-off phase was defined as the time period of upward movement. During the push-off

phase, the vertical velocity of the center of mass was determined by integration over time of the acceleration, which, in turn, was calculated from the vertical ground reaction forces. Position of center of mass was determined by time integration of the vertical velocity, and the highest position determined jump height. Peak force, time to peak force and rate of force development (i.e. peak force divided by time to peak force) were analyzed.

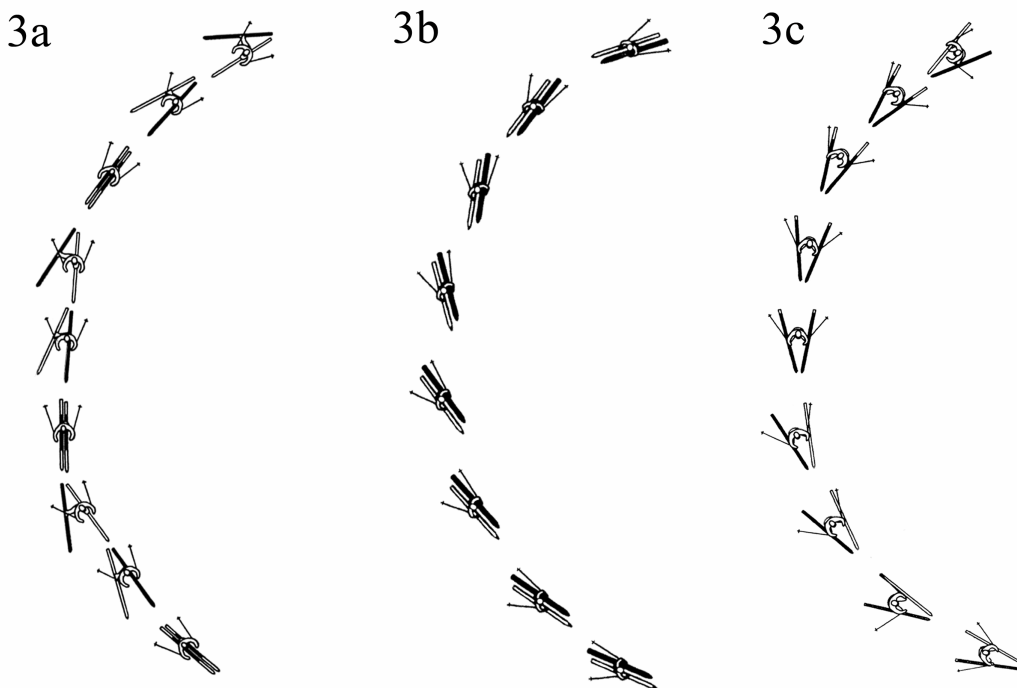
### *Statistics*

All data were shown to be normally distributed with a Shapiro-Wilks test and are presented as means and standard deviations (SD). Correlations between the various parameters were analyzed using Pearson's product-moment correlation coefficient test and simple linear regression were used to draw trend lines. Intersection differences in mechanical parameters and technique distribution between the different turns were tested using a one-way ANOVA for repeated measures, with turn as a between-subjects factor. Stepwise multiple regression was employed to predict overall performance. Potential interactions and confounders were examined according to Kleinbaum and coworkers (1998). These regression analyses are presented as non-standardized and standardized coefficients. Statistical significance was set at  $\alpha$  value of  $< 0.05$ . All statistical tests were processed using SPSS 17.0 Software (SPSS Inc., Chicago, IL, USA) and Office Excel 2007 (Microsoft Corporation, Redmond, WA, USA).

## RESULTS

### *Technique distribution*

Three main techniques with distinctively different movement patterns were employed: side-stepping, parallel skidding and ploughing. The side-stepping technique (Figure 3a) was performed by changing direction in the turn whilst rapidly changing between gliding and stepping with the skis and gradually changing the direction of the skis' movement through the turn. The skidding technique (Figure 3b) was performed while putting pressure on the parallel edged skis, thereby changing direction. The plough technique (Figure 3c) was performed while angling of the skis in a reverse V-formation, thereby increasing friction and changing direction.



**Figure 3.** The three main techniques used in cross-country downhill turns: 3a) side-stepping technique, 3b) skidding technique and 3c) ploughing technique.

Overall performance (i.e., time during the total giant slalom competition) and technique distribution for the individual athletes is shown in Table 2. Their overall performance was strongly related to the relative use of side-steps ( $r = -0.89$ ;  $p < 0.01$ ) and ploughing ( $r = 0.83$ ;  $p < 0.01$ ). The use of skidding and other movements showed no significant correlation with overall performance. For all athletes throughout the entire course, the side-stepping technique was characterized by an increase in velocity

( $0.75 \text{ m}\cdot\text{s}^{-2}$ ) and a lower energy dissipation ( $\Delta e_{\text{mech}}/v_{\text{in}} -2.27 \text{ J}\cdot\text{s}^{-1} \cdot \text{kg}^{-1}\cdot\text{m}^{-1}$ ) compared to skidding ( $-0.60 \text{ m}\cdot\text{s}^{-2}$  and  $\Delta e_{\text{mech}}/v_{\text{in}} -7.70 \text{ J}\cdot\text{s}^{-1}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$ ) and ploughing ( $-0.37 \text{ m}\cdot\text{s}^{-2}$  and  $\Delta e_{\text{mech}}/v_{\text{in}} -5.60 \text{ J}\cdot\text{s}^{-1}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$ ).

**Table 2.** Twelve subjects ranked for overall performance (time) in the entire course..

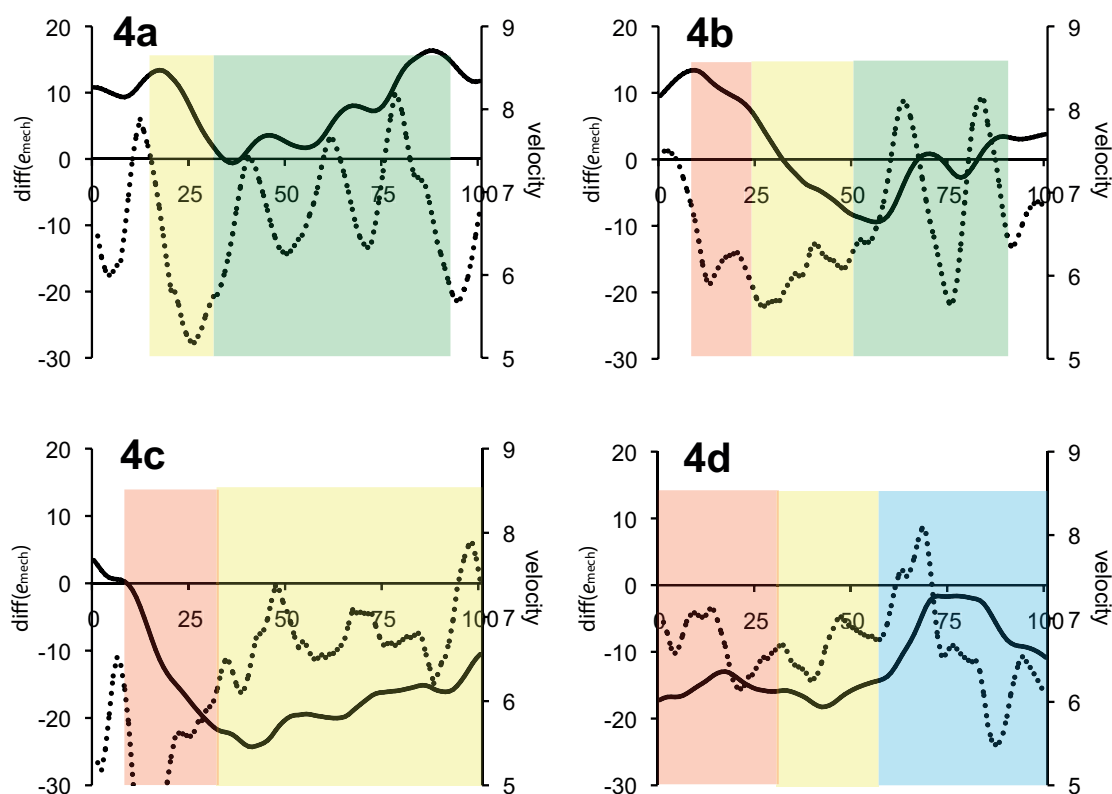
Subject	Time (s)	SS (%)	SK (%)	P (%)	O (%)
1	19.89	58	23	2	17
2	20.28	48	31	0	21
3	20.59	48	36	0	16
4	20.83	35	38	5	22
5	20.95	35	30	10	25
6	21.93	24	40	14	22
7	21.98	27	38	18	17
8	22.18	37	29	15	19
9	24.01	14	46	12	28
10	24.45	28	34	30	8
11	24.51	15	6	49	30
12	25.43	3	41	27	29

Technique distribution is presented as proportional use of side-stepping (SS), skidding (SK), ploughing (P) and other movements (O)

Based on overall performance, the subjects were divided into three different groups (time:  $20.5 \pm 0.4 \text{ s}$ ,  $22.0 \pm 0.1 \text{ s}$ , and  $24.6 \pm 0.6 \text{ s}$ ; all  $p < 0.05$ ). Technique distribution, the subsequent differential mechanical energy  $\text{diff}(e_{\text{mech}})$  and velocity throughout typical turns for these groups are illustrated in Figure 4. Typical technique distribution for the best five subjects was a short phase of skidding at the beginning of the turns, followed by an early transition to and overall greater proportion of side-stepping (Figure 4a). Energy dissipation ( $\Delta e_{\text{mech}}/v_{\text{in}}$ ) was  $-2.17 \text{ J}\cdot\text{s}^{-1}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$  while side-stepping and  $-8.37 \text{ J}\cdot\text{s}^{-1}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$  while skidding. The three mid-level subjects featured the same general pattern as the five best subjects, but the skidding phase was more often prefaced by a short section of ploughing, and the transition to side-stepping was initiated at a later point leading to an overall shorter phase of side-stepping (Figure 4b). Energy dissipation ( $\Delta e_{\text{mech}}/v_{\text{in}}$ ) for this group was  $-2.53 \text{ J}\cdot\text{s}^{-1}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$  while side-stepping and  $-7.49 \text{ J}\cdot\text{s}^{-1}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$  while skidding. The four least performing subjects primarily used skidding and ploughing throughout the whole turn, and additionally featured a high amount of imbalances. Figure 4c illustrates a turn with only plowing and skidding and Figure 4d a turn with ploughing and skidding followed by major imbalances. Only small parts of side-stepping were used by the least performing



athletes. Energy dissipation ( $\Delta e_{\text{mech}}/v_{\text{in}}$ ) was  $-3.02 \text{ J}\cdot\text{s}^{-1}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$  while side-stepping and  $-7.02 \text{ J}\cdot\text{s}^{-1}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$  while skidding. Note that it may be problematic to compare energy dissipation within techniques between these groups statistically, as they may be executed at different positions in the course and with different length.



**Figure 4.** Typical strategies for three groups with different level of downhill turn performances: 4a) typical turn for the five best subjects with a short phase of skidding, an early transition to and overall greater proportion of side-stepping; 4b) typical turn for the three mid-level subjects with a shorter phase of side-stepping at lower velocity, prefaced by a longer phase of ploughing and skidding; 4c) typical turn for the four least performing subjects with only ploughing and skidding at overall lower velocity; 4d) turn for the least performing subjects with imbalance at the second half of the turn. The bold line refers to the primary y-axis and denotes velocity ( $\text{m}\cdot\text{s}^{-1}$ ) and the dotted line refers to the secondary y-axis and denotes differential mechanical energy  $\text{diff}(e_{\text{mech}})$  ( $\text{J}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$ ) at each point of observation in the turning cycle from 0 to 100 % (x-axis). Side-stepping technique is marked green, skidding technique yellow, ploughing technique red and imbalances blue.

#### *Mechanical parameters and their relation to performance*

Individual and mean values of the mechanical parameters for all six turns combined are depicted in Table 4. Based on the abovementioned technique analyses, a deceleration and an acceleration phase could be identified by the shift from

decelerating techniques (i.e. skidding and ploughing) to accelerating techniques (i.e. side-stepping) or to parallel gliding. The point of the transition (TRS) between these phases and its corresponding velocity ( $V_{\text{TRS}}$ ) were calculated (Table 3).

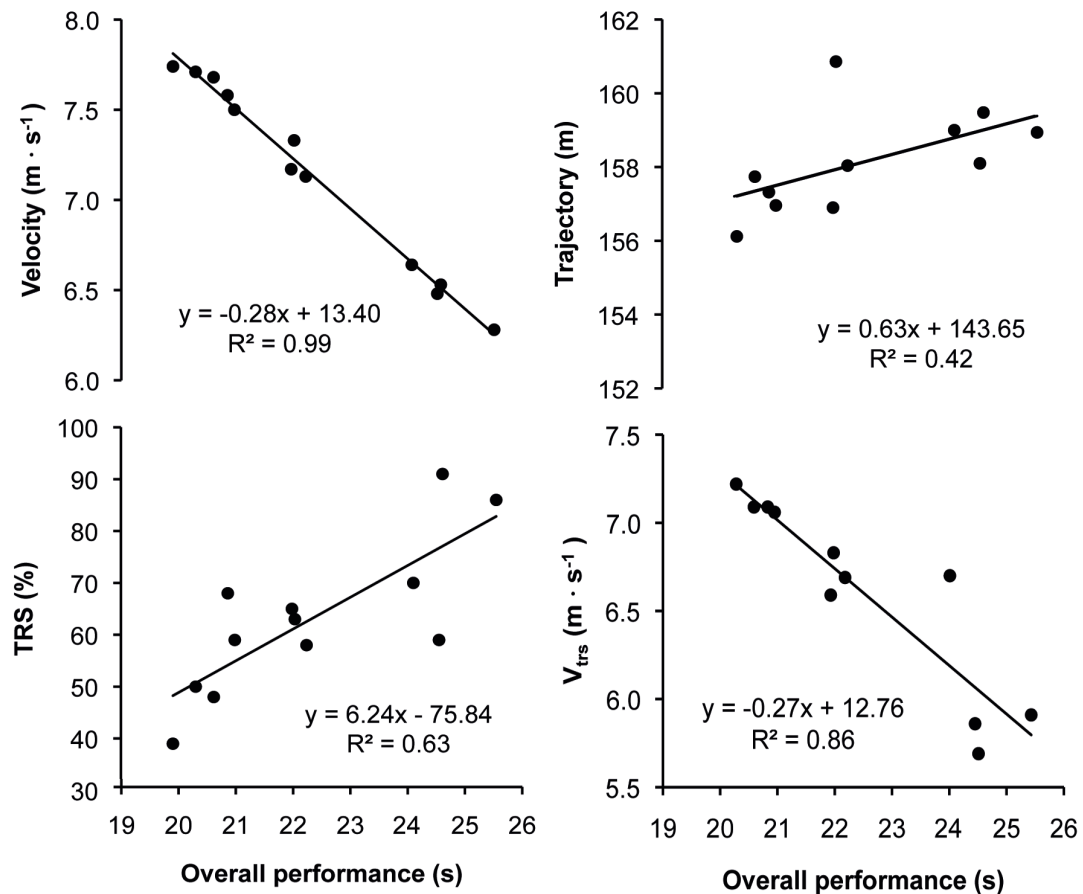
**Table 3.** Mechanical parameters for 12 female cross-country skiers ranked for overall performance for all six turns (mean and SD).

Subject	Intersection time (s)	Velocity ( $\text{m} \cdot \text{s}^{-1}$ )	Trajectory (m)	TRS (%)	$V_{\text{TRS}}$ ( $\text{m} \cdot \text{s}^{-1}$ )
1	3.32 ± 0.16	7.74 ± 0.33	25.59 ± 0.18	39 ± 6	7.30 ± 0.52
2	3.38 ± 0.10	7.71 ± 0.19	26.02 ± 0.28	50 ± 10	7.22 ± 0.20
3	3.43 ± 0.19	7.68 ± 0.32	26.29 ± 0.46	48 ± 10	7.09 ± 0.24
4	3.47 ± 0.23	7.58 ± 0.44	26.22 ± 0.46	68 ± 17	7.09 ± 0.54
5	3.49 ± 0.13	7.50 ± 0.27	26.16 ± 0.08	59 ± 11	7.06 ± 0.45
6	3.65 ± 0.18	7.17 ± 0.31	26.15 ± 0.23	65 ± 13	6.59 ± 0.40
7	3.66 ± 0.11	7.33 ± 0.21	26.81 ± 0.48	63 ± 19	6.83 ± 0.21
8	3.70 ± 0.11	7.13 ± 0.18	26.34 ± 0.55	58 ± 9	6.69 ± 0.40
9	4.00 ± 0.18	6.64 ± 0.33	26.50 ± 0.25	70 ± 17	6.70 ± 0.11
10	4.07 ± 0.20	6.48 ± 0.26	26.35 ± 0.40	59 ± 13	5.86 ± 0.42
11	4.08 ± 0.26	6.53 ± 0.33	26.58 ± 0.61	91 ± 12	5.69 ± 0.61
12	4.24 ± 0.34	6.28 ± 0.39	26.49 ± 0.67	86 ± 15	5.91 ± 0.82
Mean	3.71 ± 0.35	7.15 ± 0.59	26.29 ± 0.49	63 ± 19	6.67 ± 0.68

Intersection time refers to mean turn time, velocity to mean velocity per turn, trajectory to the trajectory length per turn, TRS to the point of transition between deceleration and acceleration and  $V_{\text{TRS}}$  to the velocity at this point.

Better overall performance was related to higher mean velocity, shorter trajectory, earlier TRS and higher  $V_{\text{TRS}}$  (Figure 5; all  $p < 0.05$ ). Stepwise multiple regression analysis employing overall performance as the dependent variable and velocity and trajectory ( $R^2 = 1.00$ ,  $p < 0.01$ ) as the independent variables shows a higher impact of velocity compared to trajectory in predicting performance. The corresponding linear regression formula with non-standardized [and standardized] coefficients was as follows:

$$\begin{aligned} \text{Total time (s)} &= 29.28 \\ &- 3.31 [0.94] \cdot \text{velocity (m} \cdot \text{s}^{-1}) \\ &+ 0.11 [0.10] \cdot \text{trajectory (m)} \end{aligned}$$



**Figure 5.** Correlations of overall performance and mechanical parameters.

The one-way ANOVA revealed no differences between the different turns' time, mean velocity, entrance- and exit velocity, trajectory and the transition point and velocity. Intersection analysis of all six turns revealed strong correlations between all intersection times and overall performance ( $r = 0.84 - 0.95$ ,  $p < 0.01$  for all).

### *Strength and power*

In the counter-movement jump (CMJ), the mean value for jump height was  $0.32 \pm 0.03$  m, the jump time was  $0.43 \pm 0.08$  s, time to peak force was  $0.18 \pm 0.04$  s, peak forces in absolute values and relative to body mass were  $786 \pm 103$  N and  $12.5 \pm 1.3$   $\text{N} \cdot \text{kg}^{-1}$  and rate of force development in absolute values and relative to body mass were  $4574 \pm 1321$   $\text{N} \cdot \text{s}^{-1}$  and  $72.6 \pm 20.6$   $\text{N} \cdot \text{s}^{-1} \cdot \text{kg}^{-1}$ . During the isometric squat, the athletes' peak forces were  $1174 \pm 442$  N and  $18.9 \pm 6.8$   $\text{N} \cdot \text{kg}^{-1}$ .

Correlations for kinematics and technique distribution versus peak strength and power characteristics are shown in Table 6. Overall performance correlated with time to peak force and rate of force development in CMJ in both absolute and relative values (all  $p < 0.01$ ). Mean velocity, trajectory, TRS and  $V_{\text{TRS}}$  revealed correlations with CMJ time to peak force, rate of force development (all  $p < 0.01$ ) and partly with absolute and relative peak force (specified in Table 4). Employment of the side step and ploughing techniques correlated with CMJ time to peak force and rate of force development (all  $p < 0.05$ ).

**Table 4.** Correlations for kinematics and technique distribution versus power and strength characteristics.

	JT	JH	PF	PF <sub>rel</sub>	TTP	RFD	RFD <sub>rel</sub>	ISO	ISO <sub>rel</sub>
Time	.56	-.09	-.71*	-.51	.78**	-.83**	-.75**	-.50	-.41
Velocity	-.58*	.06	.69*	.46	-.73**	.78**	.70*	.47	.38
Trajectory	.20	-.30	-.46	-.61*	.75**	-.78**	-.83**	-.67*	-.72*
TRS	.42	-.40	-.60*	-.48	.75**	-.72**	-.69*	-.43	-.37
$V_{\text{TRS}}$	-.47	.24	.56	.37	-.73**	.72**	.65*	.57	.51
% SS	-.39	.31	.65*	.56	-.72**	.75**	.72**	.43	.38
% SK	-.23	.05	-.28	-.48	-.27	.03	-.02	-.59	-.56
% P	.44	-.30	-.38	-.22	.80**	-.69*	-.65*	-.39	-.37

Jump time (JT), jump height (JH), peak force (PF), peak force normalized for body weight (PF<sub>rel</sub>), time to peak force (TTP), rate of force development (RFD), rate of force development normalized for body weight (RFD<sub>rel</sub>) were measured in a counter movement jump. Peak isometric strength (ISO), and peak isometric strength normalized for body weight (ISO<sub>rel</sub>) under a fixed bar. \*\* denotes correlations significant at the 0.01-level. \* denotes correlations significant at the 0.05-level.

## DISCUSSION

The current study characterized the main techniques utilized in cross-country skiing downhill turns among female elite skiers and examined how performances was influenced by technique distribution, mechanical parameters, and strength and power characteristics. Side-stepping, skidding and ploughing were identified as the three main techniques utilized in different phases of the turns, in which different mechanical characteristics were revealed. The fastest skiers in downhill turns preferred skidding to ploughing for deceleration and showed an earlier initiation and overall greater use of the accelerating side-stepping technique. The athletes' peak force and rate of force development in countermovement jumps in the laboratory was linked to better performance and associated with their ability to ski at a high velocity and with short trajectories throughout.

### *Characteristics of the main techniques*

The three main techniques employed by elite skiers in downhill turns in cross-country skiing here were side-stepping, skidding and ploughing. The side-stepping technique, performed by changing direction in the turn whilst rapidly changing between gliding and stepping with the skis, was typically used in the second part of the turn. Side-stepping served as an accelerating technique characterized by an average increase in velocity and with less loss in mechanical energy compared to other techniques. This can be explained by the side-step's nature of movement causing little ski-snow friction and giving the skier a good possibility to utilize gravitational acceleration and gain kinetic energy by the leg push-off. In the skidding and ploughing techniques skiers increased friction by angling and edging the skis when changing direction, and were thereby mainly used for deceleration at the beginning of the turn. Skidding was performed with high pressure on the paralleled and edged skis and ploughing with edging and angling the skis in a reverse V-formation.

The current study was, to the best of my knowledge, the first to investigate techniques in downhill turns in cross-country skiing. However, techniques employed in similar terrain have been examined in alpine skiing (Howe 2001). Overall, the current data demonstrates that cross-country skiers are more likely to use the side-stepping technique and ploughing than alpine skiers. These findings may be due to lower

racing velocities in downhill turns, as well as differences between alpine and cross-country skiing equipment. In alpine skiing, side-steps are solely applied at the very beginning of a course when velocity is low enough to obtain effective steps. This is different in cross-country skiing, whereby side-stepping is performed at distinctively lower velocities, allowing the skier more time for effective propulsion. Moreover, cross-country skiing equipment is primarily designed for flat and uphill terrain, featuring better conditions for leg push-off. However, the lack of steel edges, no or only marginal side-cut and less stable skis and boots not only make carving impossible, but also lead to less efficient deceleration and more instabilities while turning. A consequence is the distinctively higher amount of ploughing in cross-country skiing, even amongst elite athletes. The skis' orientation in ploughing technique generates a larger support area that is perpendicular below the skier's centre of mass and is therefore a safer strategy, especially in uneven terrain.

#### *Technique distribution*

The typical technique distribution for cross-country skiing downhill turns was an initial phase of deceleration, whereby skiers used both skidding and ploughing techniques, which was then followed by a phase of acceleration, executed in the side-stepping technique. However, substantial inter-subjective differences in turning strategy, depending on the skiers' performance level, were revealed. The best five subjects chose a strategy with a short phase of skidding at the beginning of their turns, followed by an early transition to and overall greater proportion of side-stepping (Figure 4a). All techniques were executed at higher average velocities in the best subjects. However, energy dissipation while skidding was larger in the fastest subjects compared to less-performing subjects. The three mid-level skiers in the current study featured the same general pattern as the best ones. However, the skidding phase was more often prefaced by a short section of ploughing and the transition to side-stepping was initiated at a later point, which led to an overall shorter phase of side-stepping (Figure 4b) at moderately lower velocities. Both deceleration and acceleration were less effective compared to the best subjects. The least performing four skiers used primarily skidding and ploughing throughout their entire turns. Additionally, these subjects featured a high amount of imbalances, most often as a consequence of too high entrance velocity to the turn or attempted initiation of side-stepping at either a too early phase of the turn or at too high velocity. Only minor parts of side stepping

were used by the least performing athletes, and their stepping propulsion was the least effective compared to the other skiers. Furthermore, consistency in technical patterns was related to performance level. Better subjects featured similar technique patterns throughout all turns, whereas less successful subjects executed a more inconsistent technique distribution and showed increasing proportions of skidding and ploughing towards the end of the course.

Overall, better skiers featured a higher total use of side-stepping and a smaller proportion of ploughing and preferred skidding to ploughing as decelerating technique. Skidding is potentially a more effective technique for deceleration compared to ploughing, as more friction can be generated due to more distinctive lowering of the body's centre of mass and thereby inducing a deeper snow penetration of the skis. A short and effective phase of skidding enables the skier an early transition, leading to an earlier initiation and consequently an overall greater proportion of the side-stepping technique. Hence, particular attention should be attached to this transition between deceleration and acceleration. An early transition and high velocity at this point were strongly related to downhill turn performance in cross-country skiing. Therefore, the key to a well-performed turn is to slow down as fast and little as possible, so that acceleration can begin at an earlier point and at higher velocity.

#### *Mechanical parameters*

The time spent in a turn is the product of velocity and the length of the trajectory. In the current study, both mean velocity and trajectory are strongly related to performance in cross-country skiing downhill turns. Consequently, both velocity and trajectory should be optimized in order to increase performance. However, the proportional impact of velocity and trajectory on downhill turn performance revealed a significantly greater impact of velocity. In alpine skiing, it is demonstrated that the most effective strategy was maintaining high velocity rather than skiing the most direct line with the shortest radius and trajectory length (Supej 2008). It is therefore suggested that improved turning performance in cross-country skiing is primarily linked to maintaining a high mean velocity.

In cross-country skiing, turns are an integrated part of an entire competition executed in varying terrain. Consequently, time in itself cannot be regarded as a satisfactory parameter in order to determine the quality of a single turn, as it only gives chronological information about when the skier was present at the initial and final position of the turn (Supej 2008; Supej et al. 2011). For example, the skier's mistakes close to the end of the turn may not affect time used for the turn considerably. However, the resulting low exit velocity would negatively influence the following section. On the other hand, high exit velocity, achieved towards the end of the section, may only have marginal impact on the measured section time, despite its potential importance on performance on the following section (Supej et al. 2011). In the current study, this challenge was met by designing a course consisting of six consecutive, highly standardized turns and mean values for each skier used for further analyses. Intersection analysis revealed no significant differences between the six turns' time, mean velocity, entrance- and exit velocity, trajectory and the transition point and its corresponding velocity. It was therefore regarded legitimate to use parameters solely based on single turns (i.e. entrance- and exit velocity, the transition point and velocity) in the calculations of the current study. However, future analysis of short intersections would need an additional parameter for its quality. A relevant approach based on the principals of energy dissipation has been introduced in alpine skiing (Supej 2008; Supej et al. 2011). Here the difference in mechanical energy from the beginning to the end of a turn, normalized for entrance velocity ( $\Delta e_{\text{mech}}/v_{\text{in}}$ ) may give a more meaningful picture of the quality of turns in cross-country skiing.  $\Delta e_{\text{mech}}/v_{\text{in}}$  is shown to be a good parameter for the quality of short intersections in alpine skiing (Supej et al. 2011), but remains examination in cross-country skiing.

#### *Strength and power characteristics associated with performance*

Peak force, time to peak force and rate of force development in a counter-movement jump were strongly associated with performance, the ability to use a high proportion of side-stepping, to ski short trajectories at high velocities and with an early transition between the decelerating and accelerating phase at high velocity. Hence, explosive leg power seems to be a discriminating factor for turning performance. Maximal isometric leg strength did not correlate to any parameters in downhill turns. Overall, it seems that peak power in more dynamic movements is more important than the ability to produce high absolute forces.



During downhill turns at short trajectories with high velocities, high centripetal forces are acting on the skier. In order to maintain an adequate technique and overcome these forces, high maximal leg strength and power is mandatory. This has earlier been shown in alpine skiing, where the skiers demonstrate extremely high maximal leg strength, particularly at relatively slow contraction velocity (White and Johnson 1993; Berg and Eiken 1999). In cross-country skiing, which is performed at distinctively lower racing velocities and with different equipment than in alpine skiing, the requirements of explosive power seem more important. This conclusion is supported by the findings of Stöggl et al. (2011), which show that the impact of strength and power characteristics on performance in specific techniques is linked to the similarities in movement characteristics.

In the current study, a strong link between explosive leg power and the use of the side-stepping technique is shown. The ability to initiate side-stepping at an early point in the turn, and at high velocity, was strongly related to the ability for fast force production. As earlier demonstrated in the G3 skating technique straightforward, the push-off duration in the skating steps can be maintained even when velocity increases, by altering the ski orientation angle as regards the forward direction (Sandbakk et al. 2011a; Stöggl et al. 2011). When exceeding the limits for what can be compensated by altered ski angle, the skiers have to increase cycle rate in their steps. When the skiers cannot maintain the cycle rate required to change direction, they will be forced to skidding. Consequently, a skier is challenged to the limits in technique-specific power and agility in a downhill turn.

The current study supports the assumption that is possible to increase kinetic energy due to muscle work. The high use of the side-stepping technique in the examined downhill turns allows the skiers to apply accelerating forces and thereby increase velocity considerably by an effective leg push-off. This is in contradiction to the largely accepted assumption in alpine skiing, where acceleration in turns is mainly a result of the utilization of potential energy, while the contribution of muscle work is negligible (Supej 2008). Moreover, different grades of effectiveness in side-stepping were observed among the skiers. The fastest skiers were able to accelerate even at high velocities when side-stepping and also featured better explosive power

characteristics. They featured less energy dissipation ( $\Delta e_{\text{mech}}/v_{\text{in}}$ ) while side-stepping compared to slower skiers, and were even able to increase mechanical energy (i.e. a positive value for  $\Delta e_{\text{mech}}/v_{\text{in}}$ ) in some of their side-stepping sections. Furthermore, faster skiers obtained high peaks in  $\text{diff}(e_{\text{mech}})$  in their side-steps even at high velocity, while slower skiers only performed effective side-steps at low velocities. The fact that the fastest skiers also showed better explosive power characteristics indicates that this factor contributed to their ability to add energy when side-stepping at high velocity. This is supported by relationships between muscle power and the ability to produce propulsion when maximal sprinting at velocity higher than employed in the current study (Stöggl et al. 2011). If we assume that muscle power leads to better ability to accelerate during the important last part of a turn, skiers should aim to improve both their specific power abilities and turning technique.

## **CONCLUSION**

The current study revealed that a typical strategy in downhill turns in cross-country skiing consists of an initial decelerating phase, whereby skiers used skidding and/or ploughing techniques, followed by an accelerating phase executed in the side-stepping technique. The faster skiers used less ploughing and performed short and effective skidding in the decelerating phase, and initiated the side-stepping technique earlier in the turn and at higher velocity. These technical patterns lead to higher velocities at shorter trajectories throughout the turn. The ability to overcome the arising centripetal forces and obtain an effective leg push-off when side-stepping at high velocity was linked to high absolute peak leg power. Overall, the optimal technical strategies in downhill turns are depending on the nature of a turn and the skier's physical and mental abilities. However, the general principles revealed in this study and their association with physical characteristics are also applicable to other conditions. As a practical consequence, these parameters should be optimized in order to improve performance in cross-country skiing turns.

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