The Velocity and Energy Profiles of Elite Cross-Country Skiers Executing Downhill Turns With Different Radii

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This study examined the influence of turn radius on velocity and energy profiles when skidding and step turning during more and less effective downhill turns while cross-country skiing. Thirteen elite female cross-country skiers performed single turns with a 9- or 12-m radius using the skidding technique and a 12- or 15-m radius with step turning. Mechanical parameters were monitored using a real-time kinematic Global Navigation Satellite System and video analysis. Step turning was more effective during all phases of a turn, leading to higher velocities than skidding (P < .05). With both techniques, a greater radius was associated with higher velocity (P < .05), but the quality of turning, as assessed on the basis of energy characteristics, was the same. More effective skidding turns involved more pronounced deceleration early in the turn and maintenance of higher velocity thereafter, while more effective step turning involved lower energy dissipation during the latter half of the turn. In conclusion, the single-turn analysis employed here reveals differences in the various techniques chosen by elite cross-country skiers when executing downhill turns of varying radii and can be used to assess the quality of such turns.

Keywords: cross-country skiing, energy dissipation, female, mechanics, Global Navigation Satellite System

Olympic cross-country-skiing races involve uphill, flat, and downhill sections evenly distributed across the distance. Most research to date has focused on performance-limiting factors on uphill and flat terrain, where skiers demonstrate the most pronounced differences in elapsed time. At the same time, the exit velocity from and energy expended in downhill sections may exert an important influence on performance. In addition, the outcome of several races has been decided in challenging downhill turns. For example, during the 15-km pursuit race in the 2010 Olympics in Vancouver, Marit Bjørgen passed Justina Kowalczyk in the last downhill turn to win the gold medal.

Sandbakk et al demonstrated that in sprint cross-country-skiing performance a demanding downhill turn was strongly correlated to overall performance. In an experimental giant-slalom setup, Bucher Sandbakk et al examined downhill turns involving primarily snow plowing, skidding, and step turning in detail. Snow plowing is characterized by a reverse V-formation of the skis with gliding on the inside edges; skidding involves parallel skis at an angle to the direction of movement with gliding on the edge; in step turning an outward skating motion requires leg work ranging from stepping to active push-off. Bucher Sandbakk et al found that faster skiers used less snow plowing, exhibited shorter but more effective skidding (ie, more rapid deceleration), and used the step-turn technique more extensively in their downhill turns. Thus, in the 2010 Olympics Bjørgen chose a longer radius and could start step turning earlier in the turn, whereas Kowalczyk employed a narrower radius, skidded to a greater extent, and consequently slowed down. This aspect of skiing will be especially important in the forthcoming 2014 Sochi Olympics, where the races include challenging downhill turns.

Downhill turns during cross-country skiing are most often single turns performed under a wide variety of conditions. In alpine skiing, good performance in a single turn requires minimization of the time spent in combination with acceleration to achieve as high an exit velocity as possible. In this context a specialized parameter based on the principle of energy (ΔEmech/Vin, determined as the change in mechanical energy normalized with respect to entrance velocity) has been developed as a measure of the quality of a single turn. This parameter is more satisfactory than simply the time that elapses from when a skier is at the initial and final positions of a turn.

To optimize these factors, skiers must use gravity and propulsive forces effectively. Our previous investigation revealed that maintenance of high velocity is more important than achieving the shortest trajectory and that higher velocity is linked to an earlier transition to the step-turn technique. However, in cross-country-ski races
downhill turns are performed with different radii, where optimal performance may require different techniques. Comparison of the effectiveness of the skidding and step-turn techniques throughout turns of various radii should provide a more in-depth mechanistic understanding of the optimal strategies.

Accordingly, in the current investigation we examined the influence of turn radius on the velocity profile and energy expenditure associated with skidding and step turning during more and less effective downhill cross-country-skiing turns.

**Methods**

**Subjects**
Ten Norwegian and 3 Swiss elite female cross-country skiers, including 3 members of national teams and competitors in international championships (age 20 ± 3 y, body height 168 ± 5 cm, body mass 60 ± 6 kg; mean ± SD), volunteered. All procedures were preapproved by the regional ethics committee of Umeå, Sweden, and all subjects were fully informed about the study before providing their written consent to participate.

**Overall Design**
Downhill courses involving single turns with a radius of 9, 12, or 15 m were employed (Figure 1). During pilot testing, all subjects skied all 3 courses using the skidding and step-turn techniques; however, they could not step turn with the 9-m radius without losing balance or skidding or skid with the 15-m radius without stopping. Consequently, the 9-m turn was performed with skidding only, the 12-m turn with both skidding and step turning, and the 15-m turn with step turning only. Mechanical parameters were monitored by a 20-Hz real-time kinematic Global Navigation Satellite System (GNSS), and step frequency was determined from camcorder films.

**Experimental Setup**
Each skier performed all trials with standard skating cross-country-ski racing equipment. To minimize differences in gliding, all of the skis had an identical stone-grind and were prepared with the same fluorinated wax by a professional technician. The course had an almost constant gradient of 7.3° and the run-in was 31.5 m. In pilot trials the average run-in velocity (determined with photocells, TC-Timer, Brower Timing Systems, Draper, UT, USA) was 7.4 m/s, and experimental trials that deviated by more than 0.3 m/s from this value were excluded and repeated. The gates were arranged so the skier entered at an angle of 30° and exited at 60° relative to the fall line (Figure 1). Weather conditions were stable, with light wind, an air temperature of +1°C to 3°C, snow temperature of 0°C, and relative humidity of 92% to 96%. The slope was groomed by machine and salted before the experimental runs.

**Instrumentation**
The rover and reference stations for the GNSS system both consisted of Leica GX1230 GG 72-channel, dual-frequency L1/L2 receivers; Leica AX1202 GG survey antennas; and Leica GFU14 Satellite 3AS radio modems (Leica Geosystems AG, Heerbrugg, Switzerland). The rover’s receiver, modem, and antenna were placed in a small backpack (21.2 × 16.6 × 7.9 cm, 1.64 kg) worn by the athlete, with the antenna carefully positioned at the level of the upper thoracic spine (T2–T4). The handling and accuracy of these devices are described in greater detail elsewhere.4,5

All test runs were performed between 11 AM and 2 PM, when satellite availability was highest, with 9 to 15 satellites being visible above the 15° azimuth during all measurements, resulting in a geometric dilution of precision (GDOP) of 1.5 to 3.7. Before each run, position error, satellite availability, and GDOP were assessed. A single rapid vertical squat by the skier before run-in allowed synchronization of the GNSS system with the Panasonic video camera (NV-GS 280).

**Data Processing**
The skier’s trajectory and the positions of the reference poles (determined by GNSS) were used to evaluate time, velocity, and energy dissipation. The point-by-point trajectory was analyzed in a 3-dimensional Cartesian coordinate system and smoothed using a 2-way Kalman filter with boundary conditions, so that each point could be determined within the error retrieved from the GNSS measurements. Vertical body movement was eliminated by orthogonal projection onto the surface of the slope.6

![Figure 1 — Schematic illustration of the experimental downhill courses. The radius was 9, 12, or 15 m. Open circles placed between the start and finish of the turn define the course.](image-url)
The single turn time was computed as described by Supej and Holmberg.\(^6\) At the start and finish lines, virtual vertical planes were constructed (Figure 1).

The length of the trajectory was the sum of the linear displacements between all consecutive pairs of measurement. The velocity at each point of the turn, including the entrance\((v_{in})\) and exit velocities\((v_{out})\), were calculated by cubic-spline interpolation. Differential specific mechanical energy\((\Delta e_{mech}/v_{in})\), that is, the change in mechanical energy divided by the difference in altitude and mass of the skier, was calculated for each point of the turn as described elsewhere.\(^6\) Thereafter, these parameters were calculated for each percentage of the turn cycle (0–100%) using cubic-spline interpolation. The difference in mechanical energy from the beginning to the end of a turn was calculated and normalized to the entrance velocity\((\Delta e_{mech}/v_{in})\).\(^3\) All calculations were performed in Office Excel 2007 (Microsoft Corp, Redmond, WA, USA) or Matlab 2007a (MathWorks, Natick, MA, USA).

### Video Analysis

To analyze the step frequency associated with step turning and to relate this frequency and various movements to mechanical parameters, the PAL video recordings were first transformed to a 50-Hz format employing a field-to-frame procedure. Analysis of technique was achieved with the Dartfish ProSuite 4.5 program (DartFish Ltd, Fribourg, Switzerland).

As classified by Bucher Sandbakk et al.,\(^2\) step turning was initiated by lifting the inner ski or extending the outer leg for push-off and skidding by an unloading movement designed to maintain the skis parallel, as indicated by a distinct lowering of the body (Figure 2). An expert panel consisting of 3 cross-country- and alpine-skiing researchers determined visually whether turns were performed with the appropriate technique, and unsuccessful turns were repeated. In addition, all turns were rechecked through video analysis by the same researchers. The step time during step turning was the time between each liftoff of the inner or outer ski, with 1 cycle containing 2 steps. Frequency was calculated as the reciprocal of cycle time.

### Laboratory Evaluations

The anthropometric and physical characteristics of the skiers were assessed in the laboratory on a separate day. Body mass (without equipment) was measured on a force plate (Kistler 9286AA, Kistler Instrument Corp, Winterthur, Switzerland), and body height, with a calibrated stadiometer (Holtain Ltd, Crosswell, UK). None of the participants reported any major preference for their right or left side during turning.

### Statistical Analyses

All data were shown to be normally distributed by a Shapiro–Wilks test and are presented as mean ± standard deviation (SD). Interindividual differences in the mechanical parameters between the 3 turns of different radii and 2 techniques were analyzed using multiple\(t\) tests for dependent correlations. Statistical significance was defined as an \(\alpha\) value of \(\leq .05\). All statistical tests were performed with SPSS 17.0 software (SPSS Inc, Chicago, IL, USA).

### Results

The elapsed times were as follows: the 12-m turn when step turning < 15-m step turning < 12-m skidding < 9-m skidding \((P < .05\) for all pairwise comparisons). In contrast, \(v_{in}\) was similar for all of the turns (Table 1).

With the turn radius of 12 m, the mean turn velocity, \(v_{out}\), and \(\Delta e_{mech}/v_{in}\) were all higher when using step turning in comparison with skidding (both \(P < .05\); Table 1). Specifically, with step turning, the velocity remained constant during the first half of the turn and increased during the second half, due to the more distinct leg push-offs and resulting higher \(\Delta e_{mech}\) (Figures 3[b] and 4[b]). With skidding, the velocity was reduced during the first half of the turn and remained constant thereafter (Figure 3[a]), in association with a low \(\Delta e_{mech}\) during the first half followed by reduced energy dissipation and higher \(\Delta e_{mech}\) during the second (Figure 4[a]).

When skidding during the 12-m turn, the mean velocity and \(v_{out}\) were higher than with the 9-m radius \((P < .05\) in both cases; Table 1), with no significant difference in \(\Delta e_{mech}/v_{in}\). When skidding with a 9-m radius, the velocity fell during approximately 70% of the turn, before becoming relatively constant with an increase in \(\Delta e_{mech}\) (Figures 3[a] and 4[a]). When skidding at the 12-m radius, the skiers lost velocity during the first half of the turn, followed by enhanced \(\Delta e_{mech}\) and maintenance of a constant velocity higher than during the 9-m turn (Figures 3[c] and 4[c]).

With step turning, the mean velocity and \(v_{out}\) were both higher with the 15-m than the 12-m radius \((P < .05\) in both cases; Table 1), with no difference in \(\Delta e_{mech}/v_{in}\). The velocity increased at an earlier stage (after approximately 20% of the turn) during step turning when compared with skidding (both \(P < .05\); Table 1).

The step frequency was higher for step turning \((1.34 ± 0.15\) steps/s) than for skidding \((1.28 ± 0.13\) steps/s). A distinctive lowering of the body was noted with step turning, consistent with a high \(\Delta e_{mech}\) (Figures 3[b] and 4[b]). With skidding, the body remained in a more flexed position with a low \(\Delta e_{mech}\) (Figures 3[a] and 4[a]). Specific lowering of the body was initiated at the start of the turn and maintained throughout, with a higher \(\Delta e_{mech}\) (Figures 3[c] and 4[c]).

With step turning, the skiers maintained the skis parallel for the entire turn, with the appropriate leg movement for push-off and skidding by an unloading movement. With skidding, the skiers either maintained the skis parallel during the whole turn or were unable to maintain a parallel position throughout the turn, with less distinct leg movement for push-off and skidding by an unloading movement (Figures 3–4).

### Figure 2

Schematic illustration of the 2 cross-country turning techniques employed: (a) skidding and (b) step turning.
Table 1  The Velocity, Energy Characteristics, and Kinematics of 13 Elite Female Cross-Country Skiers Performing Downhill Turns of 3 Different Radii Using the Skidding or Step-Turn Technique, Mean ± SD

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Skidding Turn Radius</th>
<th>Step-Turn Turn Radius</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>9 m</td>
<td>12 m</td>
<td>12 m</td>
</tr>
<tr>
<td>Trajectory (m)</td>
<td>16.5 ± 0.2†</td>
<td>21.0 ± 0.1*</td>
<td>21.0 ± 0.2*</td>
</tr>
<tr>
<td>Time (s)</td>
<td>2.61 ± 0.08†</td>
<td>3.19 ± 0.12*†</td>
<td>2.75 ± 0.11*</td>
</tr>
<tr>
<td>Entrance velocity</td>
<td>7.58 ± 0.18</td>
<td>7.41 ± 0.15</td>
<td>7.51 ± 0.23</td>
</tr>
<tr>
<td>Exit velocity</td>
<td>5.56 ± 0.29†</td>
<td>6.40 ± 0.37*†</td>
<td>8.05 ± 0.36*</td>
</tr>
<tr>
<td>Mean velocity</td>
<td>6.32 ± 0.18†</td>
<td>6.61 ± 0.19*†</td>
<td>7.63 ± 0.27*</td>
</tr>
<tr>
<td>$\Delta e_{\text{mech}}/v_{in}$</td>
<td>−3.46 ± 0.34†</td>
<td>−3.43 ± 0.31†</td>
<td>−1.98 ± 0.28*</td>
</tr>
<tr>
<td>Step frequency</td>
<td>0.56 ± 0.04</td>
<td>0.57 ± 0.07</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: $\Delta e_{\text{mech}}$, the difference in mechanical energy from the beginning to the end of a turn.
*Significantly different from skidding with a 9-m radius. †Significantly different from step turning with a 12-m radius.

Figure 3 — Absolute skiing velocity at different stages of cross-country turns with different radii and involving different techniques:
(a) 12 m and skidding, (b) 12 m and step turning, (c) 9 m and skidding, and (d) 15 m and step turning. The straight lines depict the mean values, and the gray areas, standard deviations.
20% of the turn) in the former than in the latter case (Figures 3[b] and 3[d]), reflecting more effective push-off steps (as indicated by the higher $\text{diff}(e_{\text{mech}})$; Figures 4[b] and 4[d]).

Application of $\Delta e_{\text{mech}}/v_{\text{in}}$ as the criterion for quality revealed that when skidding, effective turns were generally performed with slightly more deceleration early in the turn, followed by maintenance of a relatively high velocity from an earlier time point in the turn and an increase in $\text{diff}(e_{\text{mech}})$ (Figures 4[a] and 4[c]). With step turning, effective turns involved more pronounced leg push-offs during the last half of the turns, where higher positive peak values of $\text{diff}(e_{\text{mech}}/v_{\text{in}})$ were observed (Figures 4[b] and 4[d]).

The step frequency during step turning was similar with the 12-m and 15-m radii, whereas in both cases the outer step was approximately 50% longer than the inner (0.34 ± 0.05 vs 0.21 ± 0.04 s, $P < .05$ in both cases). There was no significant correlation between step frequency and velocity or energy characteristics when step turning at 12-m radius. However, with the 15-m radius the step frequency tended to be higher at lower values of $\Delta e_{\text{mech}}/v_{\text{in}}$ ($P = .08$).

**Discussion**

The major findings of this characterization of the patterns of velocity and energy expenditure by elite cross-country skiers performing single downhill turns of varying radius using the skidding and step-turning techniques were as follows: During all phases of a turn with a 12-m radius, the step-turning technique was more effective than skidding; with both techniques, a greater radius led to higher velocity, with no change in the quality of turning as assessed on the basis of energy characteristics ($\Delta e_{\text{mech}}/v_{\text{in}}$); and more effective skidding turns were associated with more pronounced deceleration early in the turn and maintenance of higher velocity during the latter part, whereas effective step turning involved more effective leg push-offs during the last half of the turn.

Our current comparisons reveal that with a 12-m radius, step turning was associated with lower energy dissipation than skidding during all phases of the turn. This should also be true under other conditions where skiers can perform step turning properly, since this technique appears to produce less resistance and lower
energy dissipation than skidding, during which the skis are edged and angled. This conclusion is supported by previous findings that reduction of ski–snow friction improves the effectiveness of turning techniques.\textsuperscript{2, 7} In addition, the propulsive forces generated by the repetitive leg push-off at medium to high frequency during step turning are absent from alpine-skiing turns, where velocity is increased almost exclusively by utilization of potential energy.\textsuperscript{6}

When skidding, the shorter radius was associated with longer absolute and relative phases of deceleration and a lower exit velocity, indicating that deceleration is required to counteract the forces acting on the skier when changing direction under these conditions. However, the quality of skidding turns (as indicated by Δ\textit{e}_{\text{mech}}/v_{\text{in}}) was the same at the different radii because the difference in altitude per turn (potential energy expended) was also lower with shorter radii.

The same was observed with step turning—different patterns of velocity and energy expenditure were employed at the different radii, with no change in Δ\textit{e}_{\text{mech}}/v_{\text{in}}. In addition, with the longest radius the increase in velocity was initiated earlier in the turn and the push-off propulsion was more pronounced. With both techniques, the disadvantage of a larger turn radius is the longer distance skied and possible resulting enhancement in energy dissipation, although nonetheless with a higher exit velocity. Overall, this study indicates that different choices of trajectory and technique are needed to achieve optimal performance in downhill turns of different radii.

When skidding at a given radius, more effective turns were characterized by more pronounced deceleration early in the turn and maintenance of higher velocity during the latter part. This finding indicates that the direction can be changed more effectively during the early phase and that there is less ski–snow friction later during the turn, in line with previous results concerning alpine skiing.\textsuperscript{6} The importance of short and effective skidding is also consistent with our previous report that when choosing their own turning techniques, faster skiers initially used short and effective phases of skidding and were able to initiate step turning earlier and at higher velocities.\textsuperscript{2}

Furthermore, effective step turning was characterized by more distinct push-offs that reduced energy dissipation during the latter phase of the turn. Moreover, with a 15-m radius more rapid step frequency tended to be associated with the quality of the turn (i.e., higher Δ\textit{e}_{\text{mech}}/v_{\text{in}}). This combination probably requires explosive leg power and dynamic balance, and training strategies designed to improve these aspects of skiing should be examined further. There was no relationship between step frequency (which varied relatively little between skiers) and the quality of skiing during the turn with a 12-m radius. However, the 15-m radius allowed greater variation in the step frequency and thereby also enhanced the possibility to increase velocity by elevating this frequency.

In summary, the current characterization of velocity and energy profiles provides a deeper understanding of the mechanics associated with optimal strategies for negotiation of downhill turns of different radii by elite cross-country skiers.

### Practical Applications

The single-turn analysis employed here can be applied to characterize differences between downhill turns performed by different elite cross-country skiers. Indeed, the RTK GNSS technology, with its high accuracy and sampling frequency, can be used to analyze activities on varying terrain in connection with a variety of outdoor sports. These mechanical analyses, including video feedback, can help coaches and athletes identify areas for individual development.

On the basis of our current and previous findings,\textsuperscript{2} certain guidelines for effective downhill turns during cross-country skiing can be formulated:

- Whenever possible, skiers should prioritize high turning velocity over a short turning radius, with the overall goal of exiting at as great a velocity as possible.
- Skidding, which is required for slowing down when entering downhill turns at a velocity that is too high, should be used for as short a time as possible, with rapid deceleration.
- The accelerating step-turn technique should be initiated as early as possible during a turn and thereafter maintained for the remainder of the turn.

Clearly, strategies for effective performance of cross-country-skiing turns with different radii, entrance velocities, inlines, and snow conditions must be developed on an individual basis and, moreover, should be a major focus of daily training.

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