Three-Dimensional Knee Joint Loading in Alpine Skiing: A Comparison Between a Carved and a Skidded Turn

Miriam Klous,1,2 Erich Müller,2 and Hermann Schwameder2
1College of Charleston, South Carolina; 2University of Salzburg

Limited data exists on knee biomechanics in alpine ski turns despite the high rate of injuries associated with this maneuver. The purpose of the current study was to compare knee joint loading between a carved and a skidded ski turn and between the inner and outer leg. Kinetic data were collected using Kistler mobile force plates. Kinematic data were collected with five synchronized, panning, tilting, and zooming cameras. Inertial properties of the segments were calculated using an extended version of the Yeadon model. Knee joint forces and moments were calculated using inverse dynamics analysis. The obtained results indicate that knee joint loading in carving is not consistently greater than knee joint loading in skidding. In addition, knee joint loading at the outer leg is not always greater than at the inner leg. Differentiation is required between forces and moments, the direction of the forces and moments, and the phase of the turn that is considered. Even though the authors believe that the analyzed turns are representative, results have to be interpreted with caution due to the small sample size.

Keywords: winter sports, motion analysis, inverse dynamics

Accident statistics of recreational skiing showed that 40–64% of all injuries occurred at the lower extremities, predominately at the knee (31%), and that in recent years the severity of the injuries has increased (Klous, 2007; Hörterer, 2005; Langran & Selvaraj, 2004). The introduction of the carving ski and more specifically the carved turn technique has been suggested as contributing to the increase in the severity of knee injuries. The higher velocity and the smaller turn radius of carved turns would account for an increase of lower extremity joint loading (Raschner et al., 1997; Hörterer, 2005). Furthermore, Urabe et al. (2002) observed a larger number of injuries at the outer leg. The outer leg might experience higher forces and moments due to its function as steering leg in skiing.

In skiing two different turning techniques can be distinguished: carving and skidding. In a carved turn, the orientation vector of the ski is in line with the current direction of the ski velocity vector, while it is not in a skidded turn. Previous studies showed changes in kinetics and kinematics due to the carving ski (Lüthi et al., 2005; Greenwald et al. 1997) and the turning technique (Raschner et al., 2001; Brodie et al., 2008; Yoneyama et al. 2000). The question is what the consequences of these kinematic and kinetic changes due to turning technique are on knee joint loading. As a first step, it is of special interest to observe forces and moments of force in a normal carved and skidded ski turn where no injuries occur.

Several biomechanical studies estimated joint loading in turning (Maxwell & Hull, 1989; Quinn & Mote, 1992) and on landing maneuvers after a jump (Read & Herzog, 1992; Nachbauer et al., 1996), but none in full 3D and with sufficient accuracy due to the complexity of collecting 3D kinematic data accurately (Quinn & Mote, 1992). Recently, this deficit has been eliminated as we developed a novel method to collect accurate 3D kinematic data (Klous et al., 2010). The comprehensive accuracy examination of the kinematic setup, the kinematic data collection, and analysis led to photogrammetric errors of 11, 9, and 13 mm in x-, y-, and z-direction, respectively. The maximum error caused by skin movement artifacts was 39 mm. Together with the collected 3D kinetic data, the kinematic data served as input for inverse dynamics analysis to determine lower extremity joint loading in full 3D with sufficient accuracy. The goal of the current study was to compare knee joint loading (a) between inner and outer leg in a carved turn and (b) between a carved and a skidded turn, performed with a carving ski in a real life situation. Presumably, the forces and moments at the knee joint were higher at the outer leg due to its function as steering leg in skiing.
Furthermore, based on biomechanical principles in skiing (Howe, 2001) and the experience and opinions of ski coaches and experts, it was expected that knee joint loading was higher in carved than in skidded turns due to higher possible speed and smaller turning radii in the carved turning technique.

**Methods**

**Subjects and Equipment**

Three male skilled subjects (height: 174 ± 5.6 cm, weight: 75 ± 3.5 kg) skied on an all-round carver (length: 170 cm, side cut: 34 mm, ski radius: 17 m). Subjects were wearing their own ski boots. All subjects gave their informed consent.

**Measuring Device**

*Kinematic Setup.* A description of the kinematic setup can be found in Klous et al. (2010). Briefly, the course was set on a 21° inclined slope with five gates. Snow was compact without the use of chemical substances or icing. Data were collected around the third gate from edge change to the next (Figure 1, thick line). Kinematic data were collected with five synchronized panning, tilting, and zooming cameras (Panasonic F15, 50 Hz). Figure 1 shows the course definition (left panel) and the camera setup (right panel).

To describe the 3D movement of the skier a reference point system was set up on the hill. The positions of the reference points, the camera tripods, and the positions of the gates were measured using a theodolite. The kinematic setup allowed only one skiing trajectory for both turning techniques. Hence, the radii of the carved and skidded turn were similar, but the velocity of the turns varied. Approximately 100 markers were attached to a tight fitting black-white stretch-suit on the pelvis, legs, ski boots, and skies. This procedure was necessary to have at least three markers per segment in sight of two cameras during the entire run, which was required to perform 3D kinematic analysis (Robertson et al., 2004).

*Kinetic Setup.* A detailed description of the kinetic setup can be found in Stricker et al. (2009). Briefly, a mobile force plate system (Kistler, CH, 200 Hz) consisting of 4 six-component dynamometers was used to collect kinetic data. Two dynamometers were mounted on each ski under the toe and heel part of the binding. The standing height was 8 cm (from the snow to the bottom of the ski boot). Four cables connected the dynamometers to the charging amplifiers in a backpack worn by the subject. The complete measuring device provided an additional weight of approximately 7 kg. The measurement error of the dynamometers was 0.3% for 3D forces (F > 292 N) and ranged from 4.0% to 8.3% for 3D torques. The deviation of the calculated point of force application from its reference was 1.4 and 8.8 mm in medio-lateral and antero-posterior direction, respectively (Stricker et al., 2009). Temperature had little impact on the measurement accuracy of the dynamometers.

**Experiment**

Before the experiment three test runs were performed for warm-up and adjustment of measurement devices. Data were collected for a carved and a skidded left turn. For each technique data of three runs were collected in which the technique was correctly performed and the skier was clearly visible in all videos. Correct performance of the turning technique was controlled by visual inspection.

![Figure 1](image-url) — Course definition (left) and camera setup (right) including gates (@), cameras (CXXX), and the part of the turn that is analyzed (in between the thick lines).
Subjects performed quiet stance trials parallel and orthogonal to the fall line before the experiment to allow definition of local coordinate systems (LCSs) for each segment. The kinetic measuring device was reset before the subject stepped into the bindings. After finishing the run, the skier performed a jump filmed by at least one camera to enable synchronization of the kinematic and kinetic measuring devices in the data analysis. To control for possible drift behaviors of the kinetic system, a second reset of the kinetic measuring device was performed after the run.

**Data Analysis**

Synchronization of kinetic data of the left and right leg and offset correction was performed. In addition, kinetic and kinematic data were synchronized. Details about the kinematic data analysis are described in Klous et al. (2010). Briefly, for each video frame all visible markers were manually digitized using SIMI Motion (Version 7.0, Build 242). 3D marker coordinates were calculated from two successive cameras (i.e., C1 and C2, C2 and C3, C4 and C5 in Figure 1). Interpolation and filtering of the data and the calculation of the position and orientation of the segments was performed with software developed in Matlab (Version 6.5). The transformation from global to local coordinate system and vice versa, hence the orientation of the segments, was calculated using Cardan angles with the xyz-rotation sequence (Nigg & Herzog, 2007; Zatsiorsky, 1998). Joint center positions were calculated using the SCoRE method (Ehrig et al., 2006).

The geometric model of Yeadon (1990) was applied to calculate the inertial properties of the lower extremities. In this model (parts of) body segments are modeled as stadium solids. A stadium solid is bounded by two parallel stadia, where a stadium is defined as a rectangle with a certain width and depth with adjoining semicircles with a certain circle radius at each end of its width (Yeadon, 1990). In the current study, the human body model was extended by adding ski boots. These adjustments led to a geometric model with 20 stadium solids for the human body and 10 stadium solids for the inside and outside ski boot. The parts of the boot below the ankle were attached to the foot segment and the parts above the ankle were added to the shank segment. To calculate the inertial parameters of the segments, density values from Dempster (1955) were taken according to Yeadon (1990). The experimentally determined densities for the inside and outside ski boot were 280 kg/m³ and 1400 kg/m³, respectively.

Inverse dynamics analysis was applied to calculate net joint forces and moments (net joint loading) from edge changing to the subsequent one. Kinetic and kinematic data were time normalized to an arbitrarily chosen 201 data points before entering into the inverse dynamic analysis. The global position of the center of mass (COMₐ) as well as the orientation of each of the segments were filtered using a 4th-order zero-phase Butterworth low-pass filter with a cutoff frequency of 2 Hz. Translational and angular accelerations for each segment were calculated by numerical differentiation of the time-displacement/orientation data of each segment by using the midpoint rule.

Net joint forces were normalized to body weight (BW) and net joint moments were normalized to body mass. The net forces and net moments at the knee joint represented the net forces and net moments transferred from the shank to the thigh and expressed in the LCS of the thigh. For comparison with previous studies, net knee joint forces and net knee joint moments were also calculated in the LCS of the shank. The LCS was defined with the y-axis in anterior-posterior direction (positive y-axis anterior), and the z-axis along the length of the segment (positive z-axis proximal). Regarding the x-axis in medio-lateral direction, the positive x-axis changed depending on the leg, i.e., the positive x-axis pointed lateral for the right leg, and medial for the left leg. In a left turn, as in the given study, the right leg is the outer leg and the left leg is the inner leg. In addition, positive moments around the y-axis and z-axis are pointing in opposite anatomical directions for the inner and outer leg (Figure 2).

Note that these net joint forces and net joint moments were the external forces and moments the skier is exposed to in alpine skiing. They are a measure of the combined effects of muscles, tendons, and ligaments acting across

![Figure 2 — Definition of the local coordinate system (LCS) at the thigh of the inner (left) and outer (right) leg](image-url)
Joint forces and moments of force due to muscle action can exceed the externally created forces and moments substantially. For convenience, throughout the remaining paper net joint loading, normalized net (joint) forces, and normalized net (joint) moments of force will be referred to as joint loading, joint forces, and joint moments, respectively.

Due to the complexity of the experimental setup and the related difficulty to collect accurate data, only a small number of runs were available for data analysis. In the following, one representative carved and one representative skidded turn of the same subject is presented comparatively. Data were divided in three phases of equal duration. These phases correspond approximately to the functional aspects of the turn: Initiation phase, steering phase 1 and steering phase 2 (Müller, 1991; Raschner et al., 2001).

To objectively distinguish between a carved and skidded turn a skidding angle \( \beta \) was calculated describing the skidding component in a turn. The angle \( \beta \) was defined as the angle between the orientation vector (line from the front to the rear binding piece of the ski) and the velocity vector of the ankle of the skier’s leg. Hence, the smaller the angle \( \beta \) the less skidding was performed during the turn (Müller et al., 2008). In the current study, one average skidding angle was calculated for each technique by averaging the position of the front binding piece of both skies, the position of the rear binding piece of both skies and averaging the ankle joint position of the left and right leg. Since high frequencies kinematic movements were not expected, position data were filtered with a 5 Hz low-pass 4th-order, zero-lag Butterworth filter before calculating the skidding angle (Wagner, 2006).

**Results**

**Turning Technique**

The proper performance of the turning techniques were verified by calculating the skidding angle \( \beta \) (Figure 3). The average angle for the carved turn was 6.1° (± 3.2°) and 15.5° (± 10.5°) for the skidded turn. Note that the two turning techniques were performed with similar turning radii of approximately 10 m, but different velocities. The average velocity was 13.9 m/s in the carved turn and 10.4 m/s in the skidded turn. The maximum velocities for the carved and skidded turn were 16.5 m/s and 11.9 m/s, respectively.

**Joint Loading: Carving vs. Skidding**

Time profiles of the medio-lateral forces, anterior-posterior forces, and longitudinal forces at the knee joint for the outer leg in carving and skidding are shown in Figure 4. Anterior-posterior forces and forces along the longitudinal axis of the knee joint showed similar patterns in both carved and skidded turns. The forces increased until approximately 60% of the turning phase and then decreased. In a skidded turn the forces increased to approximately 1.5–2 times BW, whereas in a carved turn these forces exceeded 2 times BW. Medio-lateral forces showed different patterns for carving and skidding. In skidding forces increased between 25–50% of the turning phase and to a lesser extend in the last 30% of the turn. In the carved turn the larger increase was observed between 50 and 75% of the turn, and a smaller increase in the first 25% of the turn. Table 1 shows average magnitudes of the forces in all three directions of the three phases. Average forces in anterior-posterior and longitudinal direction were slightly higher in carving than in skidding in the first

<table>
<thead>
<tr>
<th>Phase</th>
<th>( F_{med/lat} / F_{BW} ) (SD)</th>
<th>( F_{ant/pos} / F_{BW} ) (SD)</th>
<th>( F_{long} / F_{BW} ) (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Carving</td>
<td>Skidding</td>
<td>Carving</td>
</tr>
<tr>
<td>1</td>
<td>0.5 (0.2)</td>
<td>0.6 (0.6)</td>
<td>0.7 (0.4)</td>
</tr>
<tr>
<td>2</td>
<td>0.5 (0.4)</td>
<td>0.6 (0.5)</td>
<td>1.1 (0.4)</td>
</tr>
<tr>
<td>3</td>
<td>0.3 (0.2)</td>
<td>0.3 (0.3)</td>
<td>0.4 (0.3)</td>
</tr>
</tbody>
</table>
two phases. In phase 3 and in the medio-lateral direction differences were very small.

Figure 5 shows time profiles of the moments about all three axes at the knee joint for the outer leg in carving and skidding. During the turn, predominantly a flexion moment, abduction moment, and internal rotation moment acted at the knee joint in both carving and skidding. Time profiles for flexion-extension moments were similar for carving and skidding, but seemed time shifted for the carved turn, with smaller flexion moments and larger extension moments. Also the time profile of the abduction-adduction moment showed similarities between carving and skidding, but with the skidded turn being shifted particularly in the second and third phase. Table 2 shows average values and standard deviations for all three phases for the carved and skidded turn.

Table 2  Average net knee joint flexion/extension moments ($M_{\text{flex/ext}}$), net adduction/abduction moments ($M_{\text{add/ab}}$), and net internal/external rotation moments ($M_{\text{int/ext}}$) and standard deviations at the outer leg in carving and skidding for each of the three phases

<table>
<thead>
<tr>
<th>Phase</th>
<th>$M_{\text{flex/ext}}$ / m (SD) (N·m/kg)</th>
<th>$M_{\text{add/ab}}$ / m (SD) (N·m/kg)</th>
<th>$M_{\text{int/ext}}$ / m (SD) (N·m/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Carving</td>
<td>Skidding</td>
<td>Carving</td>
</tr>
<tr>
<td>1</td>
<td>1.1 (2.0)</td>
<td>2.5 (1.6)</td>
<td>-1.0 (1.1)</td>
</tr>
<tr>
<td>2</td>
<td>0.8 (1.4)</td>
<td>0.3 (1.3)</td>
<td>-1.6 (1.4)</td>
</tr>
<tr>
<td>3</td>
<td>-0.4 (1.5)</td>
<td>0.6 (1.2)</td>
<td>-0.8 (0.7)</td>
</tr>
</tbody>
</table>

Figure 4 — Time profiles of the net medial/lateral knee joint forces (left), net anterior/posterior knee joint forces (middle), and net knee joint forces along the longitudinal axis (right) for the outer leg in carving (black) and skidding (gray).

Figure 5 — Time profiles of the net flexion/extension moments (left), net adduction/abduction moments (middle), and net internal/external rotation moments (right) in the knee joint for the outer leg in carving (black) and skidding (gray).
Overall, higher moments were observed in skidding than in carving. In addition, larger fluctuations in skidding in all phases in the internal-external rotation moment and in the abduction-adduction moment in the first and third phase were observed.

Joint Loading: Inner vs. Outer Leg in Carving

A comparison between knee joint loading at the inner and outer leg is only shown for a carved turn, since similar time profiles and magnitudes were observed for a carved and skidded turn. Figure 6 shows the time profiles of the knee joint forces of the inner and outer leg.

At the knee joints of both the outer and inner leg a force acted in anterior, vertically upward, and lateral direction. These knee joint forces were much lower at the inner leg than at the outer leg. The forces in anterior and lateral direction showed more fluctuations at the inner leg. Table 3 shows that the average values for all three force directions for all three phases were larger at the outer than at the inner leg.

The time profiles of the moments were rather different for the knee joint at the inner and outer leg (Figure 7).

A flexion moment between 0 N·m/kg and 2 N·m/kg acted at the knee joint of the inner leg, whereas the moment at the knee of the outer leg varied between flexion and extension throughout the turn which is reflected by the large standard deviation (Table 4). At the knee joint of the outer leg an abduction moment acted during most of the turn with values up to 6 N·m/kg, and at the knee joint of the inner leg first a lower abduction moment acted that changed to a small adduction moment in the third phase. The internal-external rotation moment shows opposite patterns for the inner and outer leg. The outer leg started with an external rotation moment and ended with an internal rotation moment, whereas the inner leg started with an internal rotation moment up till the third phase of the turn where it changed to an external rotation moment. In addition, the inner leg showed greater fluctuations. Average values (Table 4) showed larger flexion-extension moments at the inner leg for all three phases of the turn, but the opposite was shown for the abduction-adduction moments. The average internal-external rotation moment was larger at the inner leg in the first phase of the turn, but smaller in the second and third phase.

Table 3  Average net knee joint forces in medial-lateral direction ($F_{\text{med/lat}}/F_{\text{BW}}$), anterior-posterior direction ($F_{\text{ant/pos}}/F_{\text{BW}}$), and along the longitudinal axis ($F_{\text{long}}/F_{\text{BW}}$) and standard deviations at the outer and inner leg in a carved turn for each of the three phases

<table>
<thead>
<tr>
<th>Phase</th>
<th>$F_{\text{med/lat}}/F_{\text{BW}}$ (SD)</th>
<th>$F_{\text{ant/pos}}/F_{\text{BW}}$ (SD)</th>
<th>$F_{\text{long}}/F_{\text{BW}}$ (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Outer leg</td>
<td>Inner leg</td>
<td>Outer leg</td>
</tr>
<tr>
<td>1</td>
<td>0.5 (0.2)</td>
<td>–0.3 (0.3)</td>
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Comparison Between a Carved and a Skidded Turn in Alpine Skiing

Discussion

This is the first study to use high accuracy kinetic and kinematic methods to calculate knee joint loading during real-life turning in alpine skiing. Although it is a single case study it provides valuable information on the magnitude and timing of biomechanical variables that can be used to direct future studies. The current study compared knee joint loading in a carved and a skidded turn, both performed on a carving ski. Ski coaches and experts suggested that knee joint loading is larger at the outer leg in carving than in skidding. Furthermore, based on biomechanical principles in skiing (Howe, 2001), the larger speed in a carved turn combined with a similar turning radius would cause larger forces and moments at the knee joint due to the larger centrifugal force. However, these unequivocal results were not observed. Secondly, it was expected that knee joint loading was higher at the outer leg in carving than in skidding. Furthermore, based on biomechanical principles in skiing (Howe, 2001), the larger speed in a carved turn combined with a similar turning radius would cause larger forces and moments at the knee joint due to the larger centrifugal force. However, these unequivocal results were not observed. Secondly, it was expected that knee joint loading was higher at the outer leg than at the inner leg. Our data demonstrated that for all forces and moments knee joint loading was higher at the outer leg, except the flexion-extension moment that showed larger average values for the inner leg as well as the internal-external rotation moment in the first phase of the turn.

Results showed that also in the carved turn skidding components were observed. However, throughout the turn, the skidded turn showed a higher skidding angle. Results were in agreement with Müller et al. (2008) and Wagner (2006) who reported average skidding angles for the carving technique of 4.1° and 17.8° for the skidding technique. The maximum average angle of 35.5° in skidding was higher than the maximum values of 25° angle reported in the previous studies. Knünz et al. (2000) reported angles of 1–2° at the outer leg and 7–8° for the inner leg in a (purely) carved turn. Overall it can be concluded that in the current study the two analyzed turns were typical carved and skidded turns.

The higher forces at the outer leg of a carved turn in longitudinal and anterior-posterior direction particularly in the first and second part of the turn can be explained by the higher forces that were required to keep the skis on their edges. In the third part of the turn, skis were prepared for edge changing in both carved and skidded turns. The greater abduction and internal rotation moment, and the reduced force in anterior-posterior and longitudinal direction at the outer leg in skidding between 25% and 50% of the turn were consistent with the larger skidding angle observed in the same period of the turn.

**Table 4** Average net knee joint flexion/extension moments ($M_{\text{flex/ext}}$), net adduction/abduction moments ($M_{\text{add/ab}}$), and net internal/external rotation moments ($M_{\text{int/ext}}$) and standard deviations in the outer and inner leg in a carved turn for each of the three phases

<table>
<thead>
<tr>
<th>Phase</th>
<th>$M_{\text{flex-ext}} / m$ (SD) ($N\cdot m/\text{kg}$)</th>
<th>$M_{\text{add-ab}} / m$ (SD) ($N\cdot m/\text{kg}$)</th>
<th>$M_{\text{int-ext}} / m$ (SD) ($N\cdot m/\text{kg}$)</th>
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<tr>
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<tr>
<td>3</td>
<td>–0.4 (1.5)</td>
<td>1.2 (0.8)</td>
<td>–0.8 (0.7)</td>
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**Figure 7** — Time profiles of the net flexion-extension moments (left), net adduction/abduction moments (middle), and net internal/external rotation moments (right) in the knee joint for the outer leg (black) and inner leg (gray) in a carved turn.
A similar pattern was observed at approximately 75% of the turn. However, the joint forces and moments showed substantial fluctuations that did not always appear to be systematic or related to the turn phase. These fluctuations could be a consequence of the unevenness of the slope and the related vibrations of the skis. Brodie (2008) also mentioned similar rapid fluctuations.

Several previous studies investigated ground reaction forces and kinematics of the lower extremities in alpine skiing (Brodie et al. 2008; Raschner et al. 1997, Yoneyama et al. 2000, Nachbauer et al. 1999). Only four studies calculated knee joint loading while turning (Quinn & Mote, 1992; Maxwell & Hull, 1989; Schindelwig et al. 1999, 2000). However, these previous studies calculated knee joint forces and moments in the LCS of the shank. For comparison with the named studies average and peak forces and moments over the entire turn from the current study were also calculated in the LCS of the shank applying the rotation sequence described in the Methods section. The results are presented in Table 5 and Table 6 (2nd and 3rd column).

Schindelwig et al. (1999, 2000) reported a higher peak internal/external rotation moment in a skidded turn as was also observed in the current study. The higher peak flexion/extension moment in carving and the higher peak abduction/adduction moment in skidding described by Schindelwig and colleagues were not observed in the current study (see last two columns in Table 6). Comparing the results of the current study with Schindelwig et al. (1999, 2000) in absolute values is not possible, since in the latter study the data were not normalized to the subject’s body weight. However, when assuming a body weight of 100 kg of the skier, absolute peak values were clearly lower in the study of Schindelwig and colleagues than in the current study.

Maxwell and Hull (1989) measured forces and moments at the right leg using a 6 df dynamometer and calculated the average load in a left and a right turn for all three subjects. An average value over these subjects was calculated and compared with the average values of the entire turn for carving and skidding in the current study; all components calculated in the LCS of the shank (Table 5).

Average forces and moments at the inner leg were similar between a skidded turn calculated in the current study and the study of Maxwell and Hull (1989). For the knee joint at the outer leg, forces along the longitudinal axis, abduction moments, and internal rotation moments were clearly higher in the current study in both carving and skidding. Also flexion-extension forces and the extension moments in skidding were clearly higher in the current study than in Maxwell and Hull (1989), whereas the flexion-extension moment in Maxwell and Hull (1989) was higher than in the carved turn in the current study.

Table 6 shows the peak knee joint forces and moments at the outer leg calculated in the LCS of the shank, for the current study and for the study of Quinn and Mote (1992). Quinn and Mote (1992) measured forces and moments at the left leg in skiing for six subjects. Peak forces and moments, appearing in left or right turn, were calculated by taking averages of the data for five samples. An average peak value over these six subjects was calculated.

The same trend as for average values was observed for peak forces. Peak forces and moments at the knee joint calculated in the current study were clearly higher than in the study of Quinn & Mote (1992).

The different results observed for the current study and the study of Quinn & Mote (1992) and Maxwell & Hull (1989) can be explained by the different methods for kinetic and kinematic data collection. The current study used a motion capture system to collect kinematic data, 6 df dynamometers containing piezoelectric sensors to collect kinetic data, and knee joint loading was calculated by applying 3D inverse dynamics analysis with subject specific segmental inertia parameters. In both previous studies the 6 df dynamometers to collect kinetic data contained strain gauges load cells and kinematic data.

<table>
<thead>
<tr>
<th>Table 5 Average knee joint forces and moments in carving and skidding for each component for the current study and Maxwell and Hull (1989). These forces and moments are calculated in the local coordinate system of the shank. Note that in the current study, average net knee joint loading and standard deviations were calculated from one carved and one skidded turn, whereas the presented average knee joint loading and standard deviations from Maxwell and Hull (1989) were calculated by taking the average of 3 subjects.</th>
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<tbody>
<tr>
<td>Component</td>
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<td></td>
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<tr>
<td>F̄med/lat / F̄BW</td>
</tr>
<tr>
<td>F̄antispos / F̄BW</td>
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<tr>
<td>F̄long / F̄BW</td>
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<tr>
<td>M̄flex/ext / m (N·m/kg)</td>
</tr>
<tr>
<td>M̄med / m (N·m/kg)</td>
</tr>
<tr>
<td>M̄lateral / m (N·m/kg)</td>
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</table>
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were collected using potentiometers. While calculating knee joint loading, moments of inertia and mass of the body segments, and thereby the accelerations of the body segments, were not accounted for. Furthermore, the higher forces and moments in a carved turn might be a consequence of the higher velocity of the skier in the current study. In addition, in the current study a carving ski was used, whereas the previous two studies used a traditional ski.

Due to the complexity of the experimental setup only one carved and one skidded turn reached the required accuracy to calculate 3D joint loading using inverse dynamics. Comparison of videos and data of ground reaction forces with remaining data showed that the analyzed turns were representative. However, results should be interpreted with care due to the small sample size ($n=1$). The kinematic setup allowed the carved and skidded turn to be skied with similar radii but different velocities. Even though the velocity in the carved turn was higher, the applied forces and moments at the knee joint were not consistently greater. Hence, the results were in contrast with the suggestion that the higher joint loading in a carved turn is caused by the higher velocities that can be reached. Supposing that velocity and turn radius could be similar for both turning techniques, a higher velocity in skidded turns might have increased the forces and moments at the knee joint even more. Hence, the joint loading characteristics of the outer and inner leg observed in the current study might be a result of the load distribution between inner and outer leg and/or a result of the individual skiing technique.

**Acknowledgments**

We thank the ski company Atomic for providing the test equipment. We appreciate the helpful discussions with Dr. Josef Kröll.

**References**


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**Table 6** Peak knee joint forces and moments in carving and skidding for each component for the current study and Quinn & Mote (1992). These forces and moments are calculated in the local coordinate system of the shank. Note that in the current study, net peak forces and net peak moments of force were calculated from one carved and one skidded turn, whereas the presented peak net knee joint loading from Quinn & Mote (1992) were calculated by taking the average of 6 subjects.

<table>
<thead>
<tr>
<th></th>
<th>Quinn &amp; Mote (1992)</th>
<th>Current Study—</th>
<th>Current Study—</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Skidded</td>
<td>Carved</td>
<td></td>
</tr>
<tr>
<td>$F_{\text{med-lat}} / F_{\text{BW}}$</td>
<td>$-0.30$ (0.05)</td>
<td>$-1.83$</td>
<td>$0.98$</td>
</tr>
<tr>
<td>$F_{\text{ant-post}} / F_{\text{BW}}$</td>
<td>$1.26$ (0.22)</td>
<td>$1.66$</td>
<td>$1.22$</td>
</tr>
<tr>
<td>$F_{\text{lous}} / F_{\text{bw}}$</td>
<td>$-2.09$ (0.24)</td>
<td>$-1.99$</td>
<td>$-3.38$</td>
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<tr>
<td>$M_{\text{flex/ext}} / m (\text{N·m/kg})$</td>
<td>$-2.82$ (0.95)</td>
<td>$-8.35$</td>
<td>$-4.07$</td>
</tr>
<tr>
<td>$M_{\text{abdo}} / m (\text{N·m/kg})$</td>
<td>$1.56$ (0.26)</td>
<td>$5.70$</td>
<td>$5.75$</td>
</tr>
<tr>
<td>$M_{\text{adduct}} / m (\text{N·m/kg})$</td>
<td>$0.71$ (0.21)</td>
<td>$6.85$</td>
<td>$2.75$</td>
</tr>
</tbody>
</table>


