Muscle Activity Patterns of Elite Downhill Ski Racers During Landing

Peter Schaff, Lars Nordsletten, and Arne Kristian Aune

The purpose of this study was to examine motion and muscle activity in downhill skiing in order to estimate muscular involvement during the landing phase and its potential effect on ACL injury. Specially developed 8-channel portable electromyography registration was conducted during three jumps on the Russi jump of the 1994 Olympic downhill slope, and six control jumps were carried out in the laboratory. The results reveal that the skier adapts to the expected loading of the knee, possibly by using a learned motor control pattern. It is still not clear, however, how important muscular adaptation to expected forces is. The complex functional EMG pattern that skiers use while landing indicates that ACL rupture caused during a backward fall in downhill skiing might be due to a combination of the boot-top-induced anterior shear, the force generated in the ACL by forceful knee hyperflexion supported by the high bending moment generated by a stiff spoiler, and the possible absence of a significant protecting hamstrings force during maximum loading.

Although the overall injury rate in alpine skiing has decreased over the past 20 years, severe knee sprains, usually involving the anterior cruciate ligament (ACL), have increased greatly (Johnson, Ettlinger, & Sheaqly, 1993). This is particularly true of downhill skiing by top athletes. One of the mechanisms that lead to isolated ACL injuries is a flat landing after a jump that may also cause the downhill skier to fall backward (Figure 1).

Johnson and Ettlinger (1987) suggested that the tail of the ski catches the snow as the skier is off balance toward the back (“big bump, flat landing syndrome”). This causes the ski and the boot to rapidly accelerate forward, pushing the tibia forward due to the stiff spoiler and tearing the ACL (Schaff & Hauser, 1990). Ekeland and Thoresen (1987) suggested that the vigorous, weighted knee hyperflexion may cause the ACL to rupture. Some authors suggest that active quadriceps contraction causes a dangerous anterior drawer syndrome and may rupture the ACL (Feagin et al., 1987; Figueras, 1987; McConkey, 1986, 1987). However, biomechanical studies do not support the idea of a quadriceps-induced anterior drawer leading to ACL rupture (Aune, Nordsletten, & Ekeland, 1994; Chiang & Mote, 1993). The role of the antagonist, the hamstrings, is also to protect against an anterior drawer and consequent overloading and rupture of the ACL (Aune et al., 1994; Aune, Nordsletten, Skjeldal, Madsen, & Ekeland, in press; Yasuda & Sasaki, 1987).

Peter Schaff is with BASiS Institute for Biomechanical Analysis in Sports, Ridlerstr. 31/ TÜV, 80339 Munich, Germany. Lars Nordsletten and Arne Kristian Aune are with the Institute for Surgical Research, University of Oslo, Oslo N-0027, Norway.
To estimate the role of the agonist and antagonist with respect to ACL strain, it is necessary to know their activity during real-life, dynamic conditions on the slope in a potential injury situation. Knowledge of the motion pattern, accessible through video analysis, has to be accompanied by knowledge of possible inner moments generated through muscle activity.

The goal of this study was to develop a portable electromyography (EMG) system for use in downhill skiing, to determine the activity of knee joint muscles when a skier lands after a jump, and to analyze the performed motion pattern.

Method

The study was conducted at the “Russi jump” during Olympic downhill training at Kvitfjell, Lillehammer. After a rather flat section of the course, the skier takes off at about 80 km/hr,
jumps 30–50 m, and lands on a 50° slope. Three runs by 2 skiers were examined. The skiers gave their consent to participate in the study.

A portable, 8-channel EMG system (BASiS/Paromed System), custom-made for use under extreme conditions on the downhill slope, was used. Surface EMG recordings were taken from four bilateral locations: m. gastrocnemius, m. biceps femoris, m. rectus femoris, and m. vastus lateralis.

The skin was shaved and prepared with sandpaper. Bipolar, adhesive silver/silver chloride electrodes were placed uniformly over each muscle along the muscle belly. A reference electrode was placed over the hip. The electrodes preamplified the signals directly onto the skin to minimize disturbances from cable movements. The signal was secondarily amplified through an intensifier carried on the back and then stored on a chipcard in a storage unit carried around the waist. A 9.6-V battery provided the system with energy. The weight of the portable system was 600 g, and it was carried under the racing suit (Figure 2). The skiers performed the whole course as if in competition situation.

The EMG apparatus and a high-speed shuttered video camera (1/1,000 s) were started simultaneously using a pulse code modulation remote control device as the skier approached the Russi jump. The EMG recordings were sampled at a frequency of 300 Hz, and the synchronous video recordings were conducted at 50 Hz. To compare the test to a typical everyday situation, 6 subjects performed an 85-cm jump from a table to the floor in the laboratory using the same EMG and video equipment as on the slope. The aim was to study the EMG patterns that can be considered as standard motor behavior patterns aggrivated during human evolution.

The subjects were between 25 and 35 years old, with an average height of 177 cm and weight of 75 kg. They performed the jumps wearing ski boots. The subjects were told to make a controlled landing. They practiced several times, could assess their height, and were allowed to look down at their expected landing position.

The EMG results were processed using AD-Graph version 2.1 software (BASiS Institute, Munich) to make it possible to arrange the EMG samples and the video image synchronously by visual interpretation. This was particularly helpful for discriminating the different actions during the Russi jump (Figure 3). The video image was digitized and analyzed with Peak Performance System (Peak Performance, Denver, CO).
When significant software (Penn State, PA) for a level of $d < 0.05$ was considered significant. If the mean was not significantly different from the relaxed muscle, the relaxed muscle. To evaluate any differences between muscle activity were defined as the point where the EMG signal reached $3$ standard deviations above the mean, the EMG signal was converted into milliseconds. Single subject and individual EMG amplitudes measured and converted into milliseconds. The EMG activity for the raw EMG. Detailed patterns of muscle activity.

Figure 3 — Typical EMG pattern of knee flexors and extensors as synchronised to the video.
Figure 4 — Filtering used for EMG analysis.

Results

The 8-channel EMG with video overlay technique showed increased activity of flexors and extensors at takeoff and a short time of inactivity during the flight phase (Figure 4). The knee flexors (lateral gastrocnemius and biceps femoris) were recruited before touchdown and approximately 60 ms earlier than the extensors (vastus lateralis and rectus femoris). Peak activity of extensors and flexors was reached simultaneously at the instant of landing.
The knee flexion angle at the instant of landing was 37° (31°–40°) (Figure 5). A movement of stabilization lasting about 200 ms could be defined after the instant of landing. This movement was characterized by the skier resisting a sit-back position and reestablishing the knee-flexed, downhill position. As the landing was stabilized, extensor activity persisted as eccentric work during increasing knee flexion, and there was a corresponding flexor relaxation (Figure 6).

The control jumps from the 85-cm table in the laboratory showed a similar recruitment order and timing. The biceps femoris was recruited before floor contact and significantly earlier than the rectus femoris, with a mean delay of 63 ± 18 ms ($p = .001$). The gastrocnemius was recruited 96 ± 16 ms earlier ($p = .001$) than the rectus femoris. The data are provided in Table 1.

Due to the EMG signal and the corresponding video analysis, 4 different phases could be defined: take-off phase (A), flight phase (F), landing phase (L), and stabilization phase (S). A typical EMG pattern showing the different phases is seen in Figure 7.

**Discussion**

The test did not provide any direct information about the muscle force, but muscle activity and recruitment pattern could be clearly established. The skiers were examined not when sustaining a backward fall but rather in an activity leading to a possible trauma situation, as demonstrated later during the Olympics when a skier sustained an ACL injury from a backward fall in the Russi jump. Therefore, the results of this study may be regarded only as a basis for the estimation of active muscle forces during a backward fall after jumping.
Voluntary movements such as the downhill jump and landing are learned and require practice. Once learned, such a complicated movement can be used to form a motor program (Fuchs, Anderson, Binder, & Fetz, 1989). Then, the complex task of intercepting the landing energy with a typical muscle recruitment pattern engaging the kinetic chain of muscular cocontraction can be accomplished: The hamstrings, as hip extensors, contract before landing to stabilize the hip flexor moment from the upper body weight at landing.
Table 1  Time Difference (in ms) Between Muscle Activity of Flexor and Extensor Muscles of the Knee With Respect to the Instant of Landing After a Jump

<table>
<thead>
<tr>
<th>Subject</th>
<th>Time difference of activity</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M. biceps femoris vs. m. rectus femoris</td>
<td>M. gastrocnemius vs. m. rectus femoris</td>
</tr>
<tr>
<td>A</td>
<td>40</td>
<td>70</td>
</tr>
<tr>
<td>B</td>
<td>85</td>
<td>110</td>
</tr>
<tr>
<td>C</td>
<td>70</td>
<td>100</td>
</tr>
<tr>
<td>D</td>
<td>70</td>
<td>100</td>
</tr>
<tr>
<td>E</td>
<td>70</td>
<td>85</td>
</tr>
<tr>
<td>F</td>
<td>40</td>
<td>110</td>
</tr>
<tr>
<td>Average</td>
<td>62.5</td>
<td>95.8</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>18.3</td>
<td>15.6</td>
</tr>
</tbody>
</table>

Note. Paired t-test was significant at $t = -4.32, p = .0075$.

Figure 7 — Rectified raw EMG display of Subject A. Gastrocnemius and biceps femoris are shown on top, and vastus lateralis and medialis are listed in the lower two rows. Different phases can be defined (according to the text).
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(Fuchs et al., 1989). The gastrocsoleus contracts to stabilize the ankle and has a secondary effect of stabilizing the knee joint (Hsu, Perry, Gronley, & Hislop, 1993). The increasing knee flexion moment in the stabilization phase recruits an eccentric quadriceps contraction and a hamstrings relaxation. If the skier falls backward at this moment, it is an unforeseen movement to be managed by the learned motor task. The hamstrings have already reduced activity, and a protective reflex from the strained ACL to the hamstrings is perhaps too slow to reengage activity.

Although during landing the shear force is minor and therefore not much affected by the stiff back spoiler, at the moment of initial stabilization an increasing shear force is generated by the stiff spoiler. This is known through experiments performed on a dummy by Senner, Schaff, and Hauser (1996). Senner et al. used an artificial skier to simulate the backward fall movement, neglecting the muscle patterns but directly measuring the bending moment and generated forces with an instrumented artificial leg with strain gauge transducers. The dummy was also used in numerous applications in the 1970s and early 1980s to evaluate ski binding constructions (Senner et al., 1996).

At the instant of spoiler contact during the backward fall, the shear force from the boot top pushing the tibia forward may reach the in vitro failure load of the ACL, and the addition of an increasing tension threatening the ACL by knee hyperflexion (Wascher, Markolf, Shapiro, & Finerman, 1993) may be enough to rupture it.

The EMG and video recordings provided reproducible results and were suitable for evaluation of muscle activity and the simultaneous video motion analysis on the slope. Even under extreme conditions, like -20 °C, it was possible to collect clear signals. The electronics were well tolerated by the skiers. Storage of the EMG samples on a portable chipcard eliminated the noise that frequently accompanies telemetry and created a very lightweight unit.

Biomechanical studies indicate that the quadriceps are not able to prevent an anterior shear force ACL injury (Aune et al., 1994; Chiang & Mote, 1993; Howell, 1990). Several studies have revealed an anterior displacement of the tibia during quadriceps force at the terminal degrees of knee extension with a peak at 30° (Hirokawa, Solomonow, Lu, Lou, & D’Ambrosia, 1992; Howell, 1990; Yasuda & Sasaki, 1987) and with a corresponding increase in ACL strain (Arms et al., 1984; Beynnon, Howe, Pope, Johnson, & Fleming, 1992; Renstrom, Arms, Stanwyck, Johnson, & Pope, 1986). This optimal knee flexion for a quadriceps-induced anterior tibial translation was measured at the instant of landing. However, at this moment the protective knee flexors were already maximally activated. Additionally, the maximum anterior shear force induced by a maximum quadriceps contraction at 30° is minimal (less than 89 N) (Chiang & Mote, 1993; Howell, 1990). As knee flexion increases above 60° (as from the backward fall), the quadriceps shear force reverses, translating the tibia posteriorly (Daniel & Stone, 1990; Draganich, Andriacchi, & Andersson, 1987; Howell, 1990; Hirokawa et al., 1992); this loads not the ACL but the posterior cruciate ligament (Figure 8).

First results from a retrospective video analysis during actual backward falls show that movement patterns associated with ACL injury are also carried out by athletes with no injury (Schaff, 1995). However, the study reveals also that the backward position is mainly involved in the ACL injuries of top skiers and that the actual fall probably is not the cause of the rupture. This indicates the importance of obtaining EMG and force measurements with 2-D and 3-D video analyses. Knowledge of the motion and muscle activity patterns in critical situations can serve as a basis for training programs to engrain protection patterns into the athlete’s motor learning program. So far this direct link to active injury prevention has not been examined, but it may be an important approach.
Barone, Senner, Schaff, and Rosemeyer (1996) reported an imbalance between flexor and extensor muscle when a skier falls backward against a stiff back spoiler of the boot. Although the study was conducted in a laboratory, the results indicate that ski boot design might influence muscle patterns. Haus, Halata, and Refior (1992) showed that besides providing stabilization, the ACL also fulfills a sensory, proprioceptive function. A protective reflex of the knee flexor m. biceps was reported by Grüber, Wolter, and Lierse (1986) and Solomonov et al. (1987). At this time we do not know exactly whether the backward fall is influenced by such a reflex or whether the backward fall affects the proprioceptive functions. For this reason it is necessary to examine the EMG situation on the slope under real conditions in more detail. Lab experiments must be accompanied by field studies.

Skiing equipment and its relationship to injury are already being considered. Schaff and Hauser (1993) measured the forces generated during a backward fall at the boot top as an indirect indicator for knee loading; they demonstrated that a stiff back spoiler generated up to 6 times higher maximum forces at the boot top compared to a soft spoiler. The role of the backward spoiler in ACL injury therefore cannot be neglected, even if one is only considering mechanical aspects. Future designs should address this problem with a built-in “give way” mechanism, allowing the skier to have more joint movement. This might also stimulate proprioceptive feedback in time to stabilize the knee again. More investigation in this field is necessary before such a boot is introduced in competitive sports as a method for ACL injury prevention. The current study is intended as a first step toward a better understanding of the backward fall with respect to ACL rupture.

Findings in the literature and the complex functional EMG pattern demonstrated in this study indicate that ACL rupture during a backward fall in downhill skiing might be due to a combination of three factors: (a) the boot-top-induced anterior shear, (b) force
generated in the ACL by forceful knee hyperflexion supported by the high bending moment generated by a stiff spoiler, and (c) the possible absence of a significant protecting hamstrings force during maximum loading. The relative levels of joint protection offered by the flexors cannot be described with the present study and need further investigation. The role of the hamstrings and quadriceps in ACL injury in skiing is therefore still not understood but is important in understanding ACL injury in skiing.

References


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