Ski Boots: Biomechanical Issues Regarding Skiing Safety and Performance

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In a state-of-the-art paper on skiing performance and on skiing safety, aspects of ski boot design are discussed. The influence of ski boots on the skier-boot-binding-ski system is described, and suggestions are made about improving ski boots regarding better skiing performance, less inadvertent binding releases, and less lower extremity equipment related injuries. The design of the boot sole and the boot shaft with its influence on binding release values is particularly described. Furthermore, in the forward lean the shaft stiffness of modern ski boots and their pressure distribution is very important for good skiing performance and reduction of injuries of the ankle joint and the tibia. The built-in forward lean and the stiffness to the rear can be related to the acting forces in the anterior cruciate ligament, and first approximations to reduce the risk of these injuries are given.

Development of Ski Boots

The design of ski boots has changed dramatically during the past 20 years. In the early 1960s, leather boots with shoelaces were common. Then special buckles were developed and the material changed from soft leather, to stiff leather reinforced by plastic, to modern plastics. Simultaneously, the sole was designed to be more like a machine element for the boot/binding/ski system, and the boot shaft became higher and stiffer. As a result of these biomechanical changes in the boot, new skiing techniques such as jet swings became possible and were widely adapted. One of the biggest promotors of these techniques in the late 1960s was Jean-Claude Killy.

Besides the advantage that new skiing techniques are possible, modern ski boots also cause severe problems. They are accused of increasing the risk of complicated knee injuries (Figuera, Llobet, Bulo, Morgenstem, & Merino, 1985; Karpf, 1977) as well as being the cause of poor skiing techniques among today’s skiers (Hauser & Schaff, 1987; Hörterer & Karpf, 1983). Also, all internationally

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used binding setting tables (American Society for Testing and Materials, 1981; Schweizer Beratungsstelle für Unfallverhütung, 1982; Deutsches Institut für Normung, 1984; Internationaler Arbeitskreis Sicherheit beim Skilauf, 1979) do not consider shaft stiffness and height of ski boots when determining setting values for the heel (Asang & Hauser, 1982).

We have conducted a number of biomechanical studies (Asang & Hauser, 1982; Hauser, 1981; Hauser, Asang, & Müller, 1985; Hauser, Asang, & Schaff, 1985; Hauser & Schaff, 1987; Schaff, Kirsch, Hauser, & Mehnert, 1986; Schattner, Asang, Hauser, & Velho, 1985; Schattner, Hauser, & Asang, 1985) during the past 5 years to describe and define properties of ski boots relating to these problems of function and safety. The purpose of this study is to discuss the influence of ski boot construction on skiing safety and performance.

**Boot Sole**

The characteristics of the materials at the boot/binding interface should not interfere with the function of the binding. This problem is not solved by stating requirements and test procedures on the coefficient of friction of the boot sole as currently described in DIN-specifications (DIN 7880 [1984]). The complete boot/binding system function must be taken instead into consideration. Therefore, the release forces of safety bindings (Figures 1 and 2) with different ski boot soles in various circumstances have been tested (Asang & Hauser, 1982).

Several different types of ski boots, which are representative of those on the market, have been combined with different types of bindings. The boot/binding systems have been released under standard dry conditions at 20°C, as is customary in sport shops (DIN 32923 [1984]) and in a variety of other environmental conditions.

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**Figure 1** — Measure axis of the boot/system.
Figure 2 — Reaction forces of the boot/binding system.

- $F_{sh}$ force at the toe, parallel to the plane of the top of the ski, perpendicular to the longitudinal axis of the boot sole.
- $F_{sv}$ force, acting at the toe, perpendicular to the plane of the top of the ski.
- $F_{sl}$ force, acting along the longitudinal axis of the boot sole, toward the toe.
- $F_{ah}$ force, acting at the heel, parallel to the plane of the top of the ski, perpendicular to the longitudinal axis of the boot sole.
- $F_{av}$ force, acting at the heel, perpendicular to the plane of the top of the ski.
- $F_{al}$ force, acting along the longitudinal axis of the ski toward the heel.
- $F_{bn}$ force, acting perpendicular to the top of the ski, downward, at the area of the ball of the foot.

Conditions. Figure 3 shows the results with a typical binding system. The DIN reference test sole (DIN 7881 [1982]) has a very low coefficient of friction. It shows fairly consistent results during all experimental conditions. However, other boot soles, especially materials like thermoplastic rubber, show great deviations in their actual release value compared to the reference test sole. In adults, deviations up to 40% were observed (Figure 3), and in children up to 100% (Asang & Hauser, 1982).

Additionally, the tested boot/binding systems were covered with powder snow for 20 min to simulate an extreme skiing environment. The observed release values were very similar to test condition 1 in Figure 3 (Asang & Hauser, 1982). Test condition 1 shows the greatest difference in the release values with respect to the test with a dry sole (d). Therefore, in the laboratory it is sufficient to measure the difference of the release values between a dry and a lubricated sole for testing the expected deviation during skiing.

The IAS specifications “ski boots for adults” (No. 150 [1980] and “ski boots for children” (No. 151 [1980]) are based on these results (Asang & Hauser, 1982). They recommend that the test bindings used should be representative of those on the market and their function should be dependent on the boot sole characteristics. To protect the skier from typical skiing injuries and inadvertent
release caused by torsion, the following requirements are stated: Results of the measurements with a dry sole must not exceed those obtained with a lubricated boot sole by more than 20%. If boot soles do not fulfill the requirements of the IAS specifications, the release value set in sport shops may vary greatly during skiing, as shown in Figure 3. Despite a correct setting in the sport shop, inadvertent release and lower extremity equipment-related injuries may occur with these boot soles. Only boot soles with a reaction similar to the DIN test sole show no great deviations in the release values with modern bindings under various environmental conditions and can improve skiing safety.
Boot Shaft—Forward Lean

Desired Shaft Functions

Ski instruction plans worldwide call for a sufficient dorsal flexion range at the ankle joint for a good skiing technique. The desired angle measured relative to the vertical axis (Figure 7) should be in the range from $0^\circ - 5^\circ$ to about $35^\circ$. A backward lean of the lower leg is not necessary for normal skiing techniques. A forward lean of distinctly more than $35^\circ$ can be hazardous to the ankle joint since dorsal flexion of the ankle joint is limited at an angle of about $45^\circ$. Thus the range between $0^\circ - 5^\circ$ and $35^\circ$ allows for optimal safe movements in skiing; however, the average ski boots on the market do not allow for these movements (Schaff & Hauser, 1986). The stiffness of the boot shaft in the forward direction seems much too high especially for children, youths, and in ski boots for women.

Therefore, the forward movements necessary for the steering (Figure 4) of swings cannot be performed correctly. If skiers are urged to "go down," they do not bend their ankle joint. They only bend their knees and the hip joints and move to a position where skiing is not very controllable (Figure 5). These improper movements are caused by poorly designed ski boot shafts.

What are the reasons for insufficient flexion of the ankle joint? We ascertain that there are mainly two. First, the weight of the skier and the resulting moments in the ankle joint by "going down" and bending the ankle, knee, and hip joints are often lower than the stiffness of the boot shaft. The stiffness of the

Figure 4 — Desired movement of the ankle joint according to ski instruction plans.
boot is defined by the moment necessary to reach a certain angle of the shaft (Figure 5). Therefore, especially learners and all-around skiers, in which quasistatic movements are the rule, have problems with sufficient movement of the ankle joint. In speedy, aggressive skiers, dynamic aspects must be taken into account: According to the high speed and the radius of swings, a corresponding inertial force can be added to the force resulting from the body weight. Therefore these skiers can achieve sufficient flexion of the ankle joint even with stiffer ski boots (Schattner et al., 1985).

The second reason for the insufficient movement of many skiers in the ankle joint is that they feel pain because of the high pressure resulting in front of the shaft in modern ski boots. For this reason, extensive studies have been carried out measuring the pressure distribution inside modern ski boots.

**Pressure Distribution Measurement in Modern Ski Boots**

There are different principles for pressure measurements. Some are based on an optical principle, while others use strain gauges or even inductive and piezoelectrical systems with a crystal as the pressure transducer for sensing pressure. Nearly all of them can only be used for measurements on flat, ground-installed platforms. Although some in-shoe measurements have been performed with the piezoelectrical system, we chose the capacitive principle. This seemed to be the
optimal basis for the development of thin and highly flexible mats in different shapes to be placed inside the shoe.

*Development of Special Measuring Mats.* Based on various prototypes, we developed a set of four different mats for measuring between the boot shaft in the front of the lower leg as well as for determining the pressure distribution underneath the foot (Hauser et al., 1985; Schaff, Hauser, Schattner, & Kulot, in press). The measuring mat is connected to special lightweight electronic equipment for processing, storing, or sending data by telemetry, allowing measurements to be made either in the laboratory or on the slopes. Additionally by using single sensors, problematic areas of interest (e.g., over the instep) can be analyzed. A symbolic diagram of the electronics used is given in Figure 6. We used different types of mats. The results given in this paper have been accomplished with a standardized mat with eight separate sensors. The position of the mat is shown in Figure 7.

*Types of Dorsal Flexion of the Ankle Joint.* Dorsal flexion of the ankle joint can be achieved by either knee flexion or by simply leaning forward. The latter leads to an atypical skiing position, only relevant in skier falls. In this position the activity of the musculus gastrocnemius is high (Figure 8). Although the pressure distribution on the lower leg is not greatly influenced by the different positions, it causes great variations of the upward acting force at the heel ($F_{AV}$). The fact that the knees are bent and that EMG activity is low or nonexistent suggests that there is little activity in the gastrocnemius. The measurements in the laboratory were done under quasistatic conditions.

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**Figure 6** — Symbolic diagram of the capacitive pressure measuring system.
Positioning of 8-point measuring mat. Definition of the angle measured to the vertical axis,

\[ \delta = \frac{sM_y}{sa} \]

Results of Pressure Distribution Measurements. Remarkable differences in the pressure distribution could be seen between different boot constructions. Various rear entry boots have higher values near the boot top and lower values over the instep (Figure 9), while traditional boots show the highest value over the instep and a decrease of pressure at the boot top (Figure 10). Maximum pressure peaks of up to 28 N/cm² over the instep can be observed in traditional boots.
Figure 8 — Forward position without bending the knees. High upward acting force at the heel ($F_{av}$).

The maximum for rear entry boots was only 14 N/cm². The reaction force at the heel ($F_{AV}$) is influenced by this. Rear entry boots (Figure 9) have significantly higher $F_{AV}$ values for the same flexion angle than conventional boots (Figure 10) because high pressure values are resulting at sensors 4, 5, and 6 (Figure 7). The long lever arm of the resulting forces leads to high moments $M_y$ and therefore to high $F_{AV}$-values.

Pressure values and distribution were only minimally influenced by the size of the boot. For model G (rear entry), maximum pressure was located 15 cm above the ankle joint in both sizes with values of 18 N/cm² and 20 N/cm², respectively (Figure 11). Only one model using a spring for adjusting the stiffness of
Figure 9 — Pressure distribution in rear entry boots. Three different types of boots (different lines) have been tested with the same subject. In Figures 9–12, curve fitting was done according to spline functions $f(x)$ of the type,

$$P_i(x) = a_i(x-x_i)^3 + b_i(x-x_i)^2 + c_i(x-x_i) + d_i$$

Figure 10 — Pressure distribution in conventional boots. Three different types of boots (different lines) have been tested with the same subject.
the shaft had distinctly different maximum values for both sizes (11 N/cm², 18 N/cm²). These results show that most boots are not different for men and women in the pressure distribution, and this is also true for the resulting moments $M_y$ despite the different weight proportions according to gender.

The influence of temperature on pressure distribution was demonstrated at 0°C and 21°C. For a flexion angle of 35°, models using distorsion of plastic for adjusting the shaft stiffness led to over 80% higher pressure value at the freezing point (Figure 12). Only spring dampened models are less influenced by temperature. The movability of the ankle joint in the same boot is therefore, in most boots, completely different in typical situations: trying them in sport shops at 20°C, on the slopes in January at $-15°C$, or during summer skiing at $+10°C$.

**Pain Tolerance.** In another study, we found that the pain tolerance of men and women is different in reference to the area in front of the lower leg. The average tolerance in men lies in the region of 31 N/cm², and the average in women is about 23 N/cm². The difference is significant on a 95% level. The variation is very high. We have found in women a pain tolerance from 14 N/cm² up to 32 N/cm², and for men from 21 N/cm² up to 42 N/cm² (Ruckdeschl, 1987). High values over 30 N/cm² can be seen in our pressure measurements in average ski boots at room temperature. Therefore, on slopes where boots get stiffer, many skiers can only come to the desired forward lean if they go beyond their individual pain tolerance. In leisure sport activities this cannot be expected. This is another reason for the poor skiing techniques seen on the slopes described above.

**Pressure Caused by Increased Forward Lean.** The various absolute values and locations of the pressure maxima in the different ski boots allow for the analysis of biomechanical relations in the frontal fall in a more complex way. Models
of injury, in which only the upper part of the shaft acts as the main support for the lower leg in a frontal fall, and which connect all leverage forces or moments exclusively to the height of the shaft, are certainly not sufficient for describing the true relations in shoes with maximal pressure values close to the ankle joints. Menke (1985), however, refers exclusively to the upper area of the shaft as the primary support in his studies. The applicability of rear entry models (high pressure toward the top of the shaft) may be justified and be sufficient in many cases, but the pressure relations in conventional ski boots (higher pressure in the lower part of the shaft) must be incorporated into a mathematical model when describing the biomechanical stress in a frontal fall.

In comparison to rear entry boots, the influence of the shaft construction on the pressure course is clearly displayed in conventional boots. The differences in the position of the pressure maxima are not only important in judging a possible flexion load on the bone, but they also decidedly influence the skiing characteristics of a boot. Thus, a higher moment can be obtained in a rear entry model with localized, relatively smaller pressure loads than in the conventional buckle boot. The same pressure sensation, in comparison to a conventional boot, means a transfer of higher moments in a rear entry boot. The experiences of skiers using rear entry boots for the first time could confirm these considerations: They usually have great difficulties in steering their skis at first. However, the force $F_{AV}$ leading to the release of the heel element is also increased by the greater moment transfer at lesser forward lean angles in rear entry boots. This can lead to inadvertent releases of the heel element in bindings, which are correctly adjusted according to the present setting tables. Thus, in the future adjustment of the heel element, consideration of the influence of boot construction may be necessary, especially in high-shafted rear entry models (Figure 13).
Shaft Stiffness and Prevention of Injuries. The human ankle joint can move to the maximum angle in a dorsal flexion of about 45°. While skiing, high moments in this joint can occur and soft boot shafts cannot protect the ankle joint from the dangerous end position. The protective function of the ski boot shaft for the ankle joint can be obtained by releasing the heel element in these critical situations. The boot/binding system should prevent more than 45° of dorsal flexion from occurring. Before reaching this angle, $F_{AV}$ generated by the boot shaft has to reach a sufficiently high level for releasing the heel element. To protect the tibia, the pressure distribution should show no spikes and also no sharp-edged pivot points.

Boot Shaft Construction and Skiing Safety

Dorsal flexion of the ankle joint must be possible up to an angle of 35°. The determination of the optimal stiffness of the boot shaft should therefore take into account the following: (a) the skier’s weight (responsible for the resulting quasi-static moments), (b) his/her skiing performance (responsible for the additionally resulting moments caused by the inertial forces), and (c) his/her individual pain tolerance at the lower leg.

As a first approximation we would suggest the following classification:

- Weight (male/female): Subaverage Average Above average
- Skiing performance: Learner Allaround Speedy
- Pain tolerance: Maximum pressure should not exceed the pain tolerance of 10% of men or women.
To meet these proposed requirements, the manufacturer has many options in design. In particular, a smooth pressure distribution with maximum values near the top of the boot will help to fulfill these requirements. With such a pressure distribution, the pain tolerance will not be reached and the shaft stiffness can be designed according to the proposed weight/sex and skiing performance classification. The inflexibility should be relatively greater in experienced skiers than in learners (Schattner et al., 1985). In future studies we will try to define the stiffness more exactly according to our classification. Today we can say, for a beginning skier it must be possible to reach the 35° angle of the ankle joint by quasistatic movement. No inertial force should be necessary to get the boot shaft in this position. For an experienced skier the stiffness of the boot should be higher: his/her weight and the inertial force (e.g., resulting from a speed of about 15 m/s and a swing with a radius of about 20 m) should lead to the angle of 35°. Furthermore, the lower leg should always have contact to the front of the boot shaft. A slackness especially at low angles (5°-20°) should be avoided.

The binding setting must correspond to the resulting $F_{AV}$ at an angle of 35°. It should be at least 30% higher than the resulting $F_{AV}$-value. If the binding is set to the range of the resulting $F_{AV}$, inadvertent releases will occur. Today, tolerances in binding setting lie in a range of 20%. Thus the setting should be at least 30% above the $F_{AV}$ resulting from the shaft stiffness at 35°. Dorsal flexion over 45° must be avoided by releasing the binding. Thus $F_{AV}$ resulting from the boot shaft construction must be at least 60% higher than the resulting $F_{AV}$ at an angle of 35°. If the binding is set 30% above the $F_{AV}$ at an angle of 35°, we must have enough safety margin to protect the ankle joint. If we accept the tolerance of 20%, again we should obtain at least approximately 60%. The influence of temperature to the shaft's stiffness must not exceed 20%, from room temperature to 0°C.

**Pressure Distribution Under the Foot**

We also measured the pressure distribution under the foot (Kulot, 1987). The influence on the compression of the forefoot by adjusting the buckles of a conventional boot could easily be demonstrated (see Figure 14). There was an increase of almost 100 N for the total force in comparison to the open boot. The forefoot stress in rear entry boots with one buckle is only minimally influenced by adjusting the buckle. The forefoot stress during flexion in the ankle joint in different boots is influenced by the adjusted buckle and it changes if the boot fits properly or not. These results give only a glimpse of what is happening underneath the foot sole in different ski boots. We think that further investigations in this direction will distinctly help to improve the comfort in ski boots and offer suggestions to an orthopedic design of the foot bed.

**Knee Injuries and Boot Shafts**

During the last 10 years knee injuries have become the most frequent ones in ski injury statistics (Johnson, Feagin, Brown, Ettlinger, & Pope, 1983). This seems to correlate with the growing height and stiffness of modern boot shafts. There are several indications, however, that this is not the cause for all kinds of knee injuries. In a current experimental prospective study (Hauser, in press), lower
extremity equipment-related (LEER-) injuries (Johnson, Ettlinger, Campbell, & Pope, 1980) have been reduced by a correct binding setting. The decrease in the experimental group with the correct binding setting was 3.5-fold regarding lower extremity equipment-related injuries. Today they are mainly knee injuries, compared to the control group, where most of the skiers had incorrect binding settings. Furthermore, the moment of torsion $M_z$, which is mainly responsible for injuries of the medial collateral ligament, depends not on the height and stiffness of the boot shaft but on the fixing of the foot in the boot. Therefore, the increasing height of modern boots can hardly be responsible for the increase of medial collateral ligament injuries.

In another study it has been shown (Hauser & Gläser, 1985) that the risk of knee injuries, when classified by gender, has been changed during the past 4 years (Figure 15). This seems to coincide with new setting tables used since the winter season 1981/82 in some parts of Europe (Hauser, 1982; Hauser & Schattner, 1984). These setting tables differ distinctly in the recommended setting values for men and women and lead to lower release values in women.

The pattern of knee injuries has also changed during the last 4 years (Figure 16). Medical collateral ligament injuries have decreased, while anterior cruciate ligament injuries and unhappy triads have increased dramatically. Anterior cruciate ligament injuries and unhappy triads are seen especially in male speedy skiers. We state the following hypothesis: The risk of knee injuries is not directly the effect of current boot construction, but a result of today’s high-speed skiing and the properties and function of modern ski equipment. Medial collateral ligament injuries can be reduced by correct binding setting of the toe piece and ski boots with boot soles having low friction coefficients like the standard test sole.
Figure 15 — Influence of gender on knee injuries.

Risk: risk index = \[
\frac{\text{percentage of a specific attribute (gender) in injured skiers}}{\text{percentage of a specific attribute (gender) in uninjured skiers (control group)}}
\]

Figure 16 — Change in the pattern of knee injuries in the last 4 years.
(see section under ‘‘Boot Sole’’). Avoiding backward positions, as seen in Figure 5, reduces the risk of anterior cruciate ligament injuries, the risk of falls and therefore various injuries, including those of the medial collateral ligament.

The isolated injury of the anterior cruciate ligament occurs particularly if the skier comes to the extreme backward position (Figure 5). The built-in forward lean and the height of the rear of today’s boots can lead to extremely high forces in the anterior cruciate ligament. If the rear of the boot could give way for a short time without a complete release, the peaks of the force acting in the anterior cruciate ligament could be reduced and some of these injuries could be avoided. Also if the built-in forward lean of today’s boots is reduced to about 5° and the flexion of the ankle joint is possible over the desired range (see section under ‘‘Desired Shaft Functions’’), skiing in a backward position will be avoided, and in extreme situations the forces acting in the anterior cruciate ligament will be reduced.

**Conclusion**

Modern ski boots could be improved by attention to the following design factors:

- Boot soles acting optimally with today’s bindings;
- Boot shaft-forward lean: Function and safety must be controlled by pressure distribution measurement and related to the individual skier’s weight and skiing ability. Shaft stiffness should not be influenced by temperature;
- Slackness between boot shaft and lower leg should be avoided;
- Binding setting must correspond to the acting $F_{AV}$ value, which is mainly influenced by the shaft stiffness;
- Boot shaft-backward lean: Reduced built-in forward lean and a controlled giving way of the rear.

We think that these requirements and correct binding settings will lead to comfortable skiing, allow skiing techniques according to ski instruction plans, reduce the risk in knee injuries, protect the tibia and the ankle joint, and diminish the risk of inadvertent release.

**References**


