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Flexural behavior of ski boots under realistic loads – The concept of an improved test method

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Abstract

The design of ski and ski touring boots should consider three key elements: performance, safety and comfort. For all three aspects, the boot's (shaft) flexural behavior is one of the crucial characteristics. Knowing the importance of this design parameter it is surprising that up to now no generally accepted standardized method exists to test and quantify the stiffness of the boot. First test methods, developed in the late eighties, used a leg prosthesis loaded with a horizontal force at the top of the shank in order to apply a bending moment to the boot hinge. Since then the basic principle has not been changed and it is widely used to quantify the dorsal and plantar flexion under slope conditions as well as the effect of buckle closure, temperature and fit of the boot. This common approach however neglects some of the important boundary conditions such as the realistic plantar pressure distribution underneath the artificial foot or the correct location and shift of the point of force application during the flexion movement. The aim of this study was to design a new test bench which overcomes some of the previous limitations thus being able to improve validity of the load simulation. The major addition to the current state is that the new test bench simulates ground reaction forces by using a pneumatic driven active leg-prosthesis generating an internal extension moment in knee and ankle. Further a linear bearing allows simultaneous displacement of the foot in the sagittal plane, simulating forward or backward shift of the center of pressure, which is typical for skiing maneuvers. The presentation will illustrate the theory behind this new concept and describe the details of its design.

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1. Introduction

With over 115 million skiers worldwide alpine skiing is the most popular snow sports activity [1]. Over the years there was a constant development in riding styles, techniques and equipment. Nowadays alpine skiing is divided in a lot of different categories and subcategories, such as freeriding, racing or freestyle skiing. Every discipline requires different skiing techniques and provides a different loading pattern for the skier. Therefore skiing industry offers a variety of special skis, bindings and boots. Whereas industry and special interest magazines regularly perform and publish ski performance tests, very few systematically derived knowledge is available on ski boots. This is surprising as ski and boot are influencing each other's mechanical behaviour and should therefore be treated as a system. More research has been conducted to analyse the ski boot's influence on safety issues and few studies have looked at comfort. This paper focuses on the boot's flexural behaviour w.r.t. dorsal flexion (forward bending, forward fall). The role of the boot's rear stiffness (plantar flexion in the ankle) under safety aspects during backward fall situations has been investigated in several other studies [2-5].

Over the last four decades, the incidence rate for lower extremity injuries has been reduced by approximately 53%. Ankle sprains and fractures as well as tibia fractures have been significantly reduced since the 1970s [6]. Simultaneously the injury rate of the ligamentous structures in the knee has tripled [7]. Since higher and stiffer ski boots were introduced at the same time, it is assumed that the stiffer boot relocates high loads from the ankle and tibia to the knee and contributes to the increase in knee injuries [6]. According to Schaff and Hauser [8] stiffer ski boots can lead to an upright or even backward lean position and to an

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increased load on the knee ligaments [9]. Particularly anterior cruciate ligament (ACL) ruptures have become more frequent [10, 11]. Kupiers et al. confirmed the correlation between boot stiffness and mechanical load on the knee for mogul skiing [12].

The performance of a ski boot is often equated with its (forward) flex index. A parameter used by nearly every manufacturer ranging from 50 (soft) up to 150 (very stiff). Despite the widespread usage there is no regulation how to measure these stiffness indices and it is up to the manufacturer to test and rate their models. Usually boots with high flex indices are used by more experienced and skilled skiers whereas for beginners softer boots are recommended. However personal preferences alter from skier to skier depending on the riding style and the main discipline. During the XXII Olympic Winter games two different boot designs were used in racing disciplines and freestyle events [13]. Significantly different flexural behavior could be found for the two models. The 3-piece design used in freestyle events offered a much more linear increase in stiffness making it more efficient in absorbing landings and bumps on the slope. Whereas the overlap boot design (racing) provides a faster power transmission from the skier to the ski. Elite mogul skiers showed an improved performance when using a boot with much more forward flex than their normal boot. They were able to keep a more centered skiing position and knee bending moments were reduced [14].

Muscular activity of the lower leg is also affected by the boots flexural behavior showing a higher activation with softer boots [15]. Coincidentally experienced skiers tend to keep a constant lower leg posture using boots with varying stiffness [16, 17]. Since a softer boot gives less resistance against external bending moments, the muscles in hip, knee and ankle need to generate more muscular power, eventually leading to faster fatigue. Furthermore boot stiffness is considered to influence learning behavior of novice skiers [18].

Comfort in ski boots is one of the main buying criteria especially for recreational skiers. Besides a proper fit, pressure distribution under the foot and at the tibia during skiing motions can be used as indicator for comfort [19]. Different pressure pattern occur during forward movement of the tibia depending on the ski boot design and foot shape.

Given this important relation between flexural behavior and safety, performance and comfort, researchers have often demanded an international standard on ski boot flexion behavior, defining requirements and appropriate testing procedures [20, 13, 21]. This missing standard is even more surprising knowing that in 1980, a guideline (IAS No. 150) established by the International Working Group on Safety in Skiing [22] defined minimum requirements in respect of the dorsiflexion behaviour of ski boots. Additionally to this guideline, several scientific papers were published in the following years which dealt with the issue of dorsiflexion and the necessary ski boot shaft hysteresis [20, 23, 24]. Shealy and Miller [24] determined the maximum voluntary dorsiflexion (mean values being 42° for both male and female, 5th percentile being 28° and 95th percentile being 56°). The following paragraph will derive design requirements for a potential standard, analyzing the few existing testing procedures and pointing out the crucial aspects for realistic testing conditions.

2. Design requirements

Walkhoff and Bauman were the first to quantify the flexural behavior of ski boots using a prosthetic leg [20]. Since then the fundamental principle has not been changed and was used in many different test setups [16, 25, 13, 26]. An artificial leg simulating the shank-foot complex is fitted into the boot and the boot is fixed to a force plate. On top of the tibia a horizontal force is applied causing the lower leg to rotate around the ankle joint. The test control mode can be varied, depending on the fact that the test cycle is defined by the extreme values of the moment acting at the boot hinge (moment control); the extreme values of the force acting on the prosthetic axis (force control); or the extreme values of the flexion angle (angle control) [16]. Typical moment-angle curves show a nonlinear behavior and large hysteresis [20]. The results can be influenced by temperature, speed of deflection, number of loading cycles and many other factors. Therefore a constant test environment and procedure is crucial to make results from different boots comparable.

To ensure a practically orientated measurement it is important to test the boot stiffness for a realistic range of motion. Petrone et al. suggested a range from -5° to +15° from the neutral position (no bending moment applied to the boot) in accordance to field measurements during carving and slalom skiing. Since the moment-deflection curves show a highly nonlinear behavior, a single flex index at maximum deflection is not sufficient to describe the flex pattern. Therefore the use of two indices for the forward flexion at +5° and +10° and one for backward flexion was proposed [16].

Only few studies [16, 20, 13, 23, 24] are comparing the flexural behavior, measured with a prosthetic leg, to real life situation with human subjects. In these studies hysteresis' shape as well as overall stiffness changed significantly. Walkhoff and Bauman [20] used a wooden leg model which gives a good explanation for the varying results due to the unnatural rigidity of the prosthetic. Petrone et al. found similar differences, however with using a softer, more realistic prosthetic. Especially the relation between the cuff-tibia angle and shell-cuff angle changed between laboratory and in-field measurements and cannot sufficiently be explained by differences in rigidity of the prosthetic. One considerable factor is the effect of buckle closure [25]. Due to the huge influence of buckle positions on the flexural behavior, a concept to quantify the tightness and fit of the boot is necessary.

Looking on the mechanical mechanism that bends the boot in the current test setup and in real life skiing, some important differences appear giving a good starting point for further improvements. First of all there is no vertical force acting on the boot-leg system. In alpine skiing, high levels of ground reaction forces (GRF) were measured for various skiing situations reaching from 1500 N up to 3000 N for professional skiers [27–29]. These forces are causing high external flexion moments on ankle-, knee- and hip-joints which need to be absorbed by the athlete and the ski boot. Therefore instead of using a horizontal force to induce a bending moment, it would be appropriate to apply a vertical force to the entire boot-leg system according to the GRF measured for various skiing situations. This vertical force is likely to change the loading pattern on the prosthesis and ski boot.

Especially the load distribution at the boot's shaft and beneath the foot sole will be influenced and considerable friction and compression effects can be expected.

Furthermore by applying a vertical force instead of a single bending moment the force application point (FAP) and the center of pressure (COP) could be altered. During a skiing turn the skier is constantly changing body posture to adept to the current situation which results in different skiing positions (e.g.: centered, forward or backward lean). As a consequence COP and FAP are shifting in anterior-posterior direction as well as in medial-lateral direction [30, 31]. The quantity of this movement depends on skiing technique, slope conditions and skiing performance [32]. Figure 1 shows characteristic tracks for the FAP and COP during a carving turn.
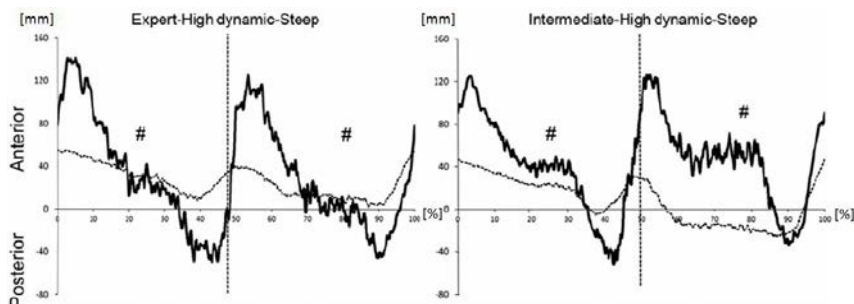

Fig. 1. Time characteristics of the FAP (thick line) and COP (thin line) in anterior-posterior direction during high dynamic carving turns [32, modified]. One complete turn consists of an outside phase (time period from 0 to 50%, leg is located toward the outside of the turn) and inside phase (time period 50 to 100 %, leg is located toward the inside of the turn).

When skiing in a forward lean position, the FAP shifts to an anterior position leading to higher horizontal forces in posterior direction (see eq. 1 and 2). This is forcing the foot to move in posterior direction inside the boot. Walkhoff et al. [20] examined the movement of the foot relative to the ski boot using x-ray. Depending on the boot design and fit of the boot a considerable movement was measured. This relative motion changes the distance between the axis of the ankle joint and the boot hinge and will also lead to a different pressure distribution at the tibia and foot sole. Although it is not yet reported, this is most likely to influence the boot's flexural behavior.

The FAP and COP movement is not only controlled by the body position of the skier as plantar flexion or dorsal extension moments at the ankle joint will also contribute to the shift of the FAP/COP. For various skiing situations, high activation levels for the m. triceps surae and m. gastrocnemius were measured [15, 33]. Hintermeister et al. argued that the skier is using the medial gastrocnemius to maintain a stable position, increase the pressure on the ski and resist vibrations. A passive prosthesis as used in most of the recent test setups cannot simulate this mechanism. Menke et al. proposed the use of prosthesis with spring elements simulating the gastrocnemius in order to apply a contraction force on the achilles tendon [34]. This construction produces an increasing plantar flexion moment with higher forward flexion of the tibia. An active prosthesis like this will be much more sufficient both to simulate the realistic pressure distribution under the foot and the natural movement of the foot inside the boot.

In summary the following points need to be considered in order to achieve a better congruence between laboratory testing and the actual flexural behavior of ski boots:

- prosthesis with realistic plasticity and dimensions
- application of vertical ground reaction forces
- alteration of the force application point
- use of an active prosthesis
- controlled buckle closure

3. Realization

The primary goal for the new test bench was to simulate the behavior of the entire boot-leg system under loading conditions similar to real time skiing. Therefore a leg model including joints, upper leg, lower leg and foot was needed. Figure 2 shows the basic concept for the new test setup. Due to the principle of actio-reactio, GRF can be applied either at the hip or at the boot. For constructional reasons the former was chosen and will be further explained.

A pneumatic drive (a) applies the GRF to the hip joint which is restricted in x-direction by a linear bearing (b). A second pneumatic drive (c) is used to simulate the m. quadriceps femoris. It is fixed to the upper leg and can rotate around the z-axis. The end of the rod is connected to a lever (d) fixed at the tibia which results in an extension moment at the "knee joint (M_{knee})" when the pneumatic cylinder produces a concentric force (F_{quad}). Due to the limited space at the lower leg, a spring element (e) is used to stabilize the ankle joint (or simulate the m. gastrocnemius). A cylindrical socket fixed to the lower leg contains a compression spring which is connected to the posterior end of the calcaneus with a steel cable (f).
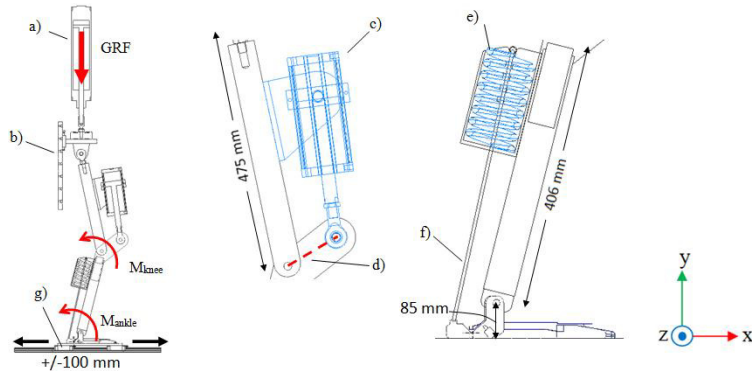
Fig. 2. Concept design of the new test bench and detailed views on the joint mechanics. a) pneumatic drive, b) linear bearing, c) pneumatic drive, d) knee lever, e) spring element, f) steel cable, g) linear positioning drive.

The boot (not illustrated) is firmly anchored to a linear position unit with a spindle drive (g). It allows a movement in x-direction which is used to alter the FAP. The following paragraph will work out the mechanical relations between the applied forces and the resulting bending moments and reaction forces. All length- and ankle parameters can be calculated from a given φ_{tibia}, Δx and length of the prosthesis elements (lower leg, upper leg, levers) and will not be further explained.

Horizontal reaction forces in point A can be calculated using the equilibrium of moments (eq. 1) for the axis of the knee joint (Fig. 3b). No further external horizontal or vertical forces are applied to the system, therefore similar forces acting in Point C (eq. 2). For a given F_{quad} the horizontal force C_h is higher in a forward lean position ($\Delta x < 0$) or in a deeper squat position (small Δy).
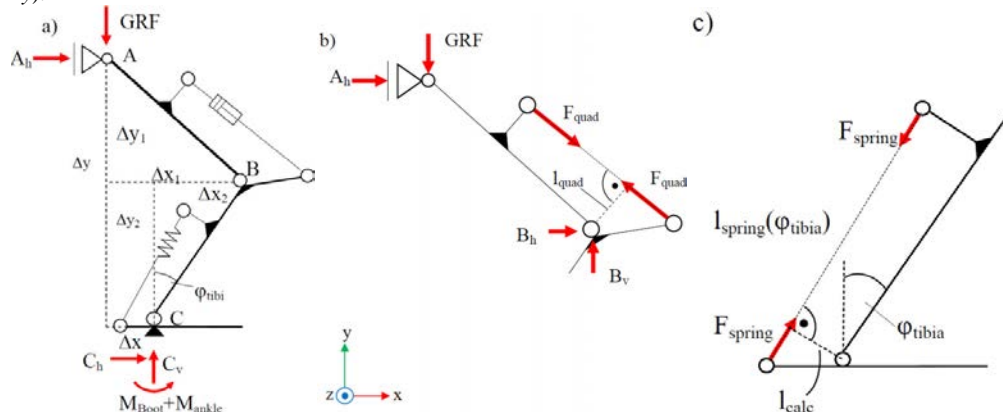

Fig. 3. Mechanical relations between the applied forces and the resulting bending moment on the boot. Acting forces GRF, F_{quad} and F_{spring} and resulting reaction forces A_h, C_h, C_v and M_{Boot} (red arrows) at the hip (A), knee (B) and ankle joint (C). Horizontal distance between hip and ankle (Δx), hip and knee (Δx_1), knee and ankle (Δx_2); vertical distance between hip and ankle (Δy), hip and knee (Δy_1), knee and ankle (Δy_2); length of the achilles spring (l_{spring}) as a function of the tibia angle (φ_{tibia}); length of the knee lever (l_{quad}) and ankle joint lever (l_{calc}).

The pneumatic drive provides a maximal contraction force of 4400 N which is equal to a maximum M_{knee} of 400 Nm. In comparison, mean knee extension moments of 1.57 Nm/kg and peak values of 5 Nm/kg were calculated for carving turns [35] which is in the same range.

$$\sum M_{A_z} \stackrel{\text{def}}{=} 0: \quad A_h = \frac{GRF * \Delta x_1 - F_{quad} * l_{quad}}{\Delta y_1} \tag{1}$$

$$\sum F_x \stackrel{\text{def}}{=} 0: \quad C_h = -A_h; \qquad \sum F_y \stackrel{\text{def}}{=} 0: \quad C_v = GRF \tag{2}$$

At a neutral tibia ankle ($\varphi_{tibia}=0°$) the spring is completely relaxed. With increasing forward flexion of the tibia, l_{spring} decreases and the spring gets compressed. The resulting concentric force (F_{ankle}) creates an extension moment (M_{ankle}, eq. 3). Klous, Müller and Schwameder [35] calculated mean and peak ankle extension moments of 1.65 Nm/kg and 4.5 Nm/kg respectively. Due to the limited space it was difficult to provide a spring or a combination of springs stiff enough to create such high moments. For that reason a compression spring with a stiffness rate (R) of 74.5 N/mm was chosen. At maximum forward flexion ($\varphi_{tibia} = 45°$) an ankle joint moment M_{ankle} of 141 Nm is reached, which lies between the mean and peak values measured in skiing.

$$M_{ankle} = \Delta l_{spring} * R * l_{calc} \qquad\qquad (3)$$

Finally the resulting bending moment acting on the boot can be calculated from an equilibrium of moments in point B (eq. 5).

$$\sum M_{B_z} \stackrel{\text{def}}{=} 0: M_{boot} = -C_h * \Delta y_2 + C_v * \Delta x_2 - M_{ankle} - M_{knee} \qquad (4)$$

A bending cycle is controlled by the parameters *GRF*, F_{quad}/M_{knee} and Δx. Their values need to be considered carefully in order to achieve a realistic loading pattern. Therefore kinetic and kinematic data was collected for various skiing situations using force plate equipped skis and an inertial measurement unit (MyoMotion, Noraxon Velamed GmbH) [36]. Time curves for these parameters can then be used to simulate an entire skiing turn and the related flexural behavior of the ski boot can be measured. In Figure 4 the simulation of a carved turn with medium turning radius is displayed. Since the boot stiffness is unknown, this is only a theoretical example with estimated values for the tibia flexion angle. Nevertheless resulting boot bending moments M_{boot} appear to be similar to the results found by Petrone et al. [16].
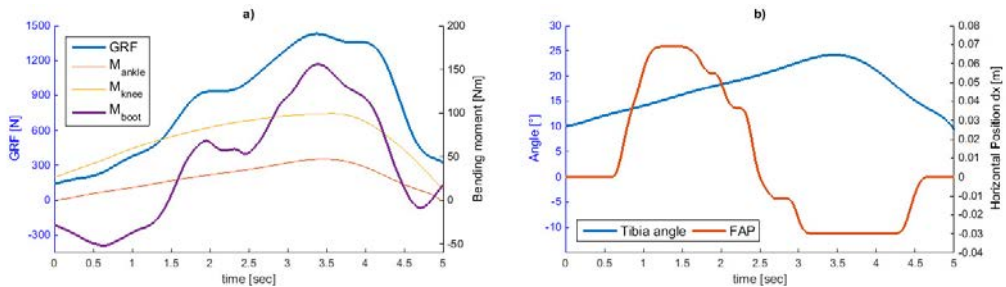

Fig. 4. Simulation of a carved turn with medium turning radius. The resulting boot bending Moment (purple) is shown for the control parameters GRF (blue), M_{ankle} (red), M_{knee} (yellow) in a) and the tibia angle (blue) and horizontal displacement of the FAP (red) in b).

Force application and horizontal movement of the boot will be slowed down due to the limited speed of the linear positioning drive. Therefore the flexural behaviour will be tested under quasi-stationary conditions.

The foot prosthesis model was originally designed and evaluated for a soccer boot test device (TrakTester, [37]). Using this foot model, realistic pressure distributions could be measured using a similar construction for the achilles tendon [38]. The ankle joint is designed to allow flexion and extension movements as well as inversion and eversion. Foot and tibia are surrounded by a silicon shell to ensure a natural rigidity. Height of the ankle and length of the lower and upper leg are designed to match the 50th percentile measured for male adults in Germany [39].

A force transducer at the hip joint will be used to measure and controll the GRF and the flexion of the leg will be measured with a conductive potentiometer placed at the ankle joint. The prosthesis will be equipped with flexible pressure mats on top of the foot and at the front and back of the tibia to measure the fit of the boot and to control the effect of buckle closure.

4. Discussion and perspective

To date the new test bench is in fabrication and for this reason experimental data is not yet available to evaluate the improvements compared to recent approaches. Nevertheless due to more realistic loads on the ski boot and the use of an active prosthesis, a more natural behavior of the foot inside the boot can be expected. Especially the application of ground reaction forces is assumed to have a major effect on the flexural behavior and to contribute to a higher congruence between laboratory and in-field tests.

The missing option to alter the FAP in medio-lateral direction can be seen as an important limitation and will be addressed in the future eventually. Due to the quasi-stationary testing procedure, dynamic forces and time depending material properties will not be considered. Altough it will be possible to simulate the forward flexion in real time with a fixed horizontal position of the ski boot. With maximal values for M_{ankle} being only one half of peak ankle moments measured in skiing, the pressure distribution at the boot sole might not be equivalent to actual skiing. Pressure distribution measurements will be necessary to analyze the divergence and its effect. The current prosthesis is designed to match the 50th percentile of male adults. Segment lengths, foot size and shape of the calf will need to be adjusted to match other target groups.

Eventually it will be possible to simulate loading pattern for different skiing situations and performance levels and analyze the boots flexural behavior. As a future perspective this data might be used to make a recommendation for appropriate target groups in order to enhance comfort, safety and performance.

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