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ORIGINAL ARTICLE

The effect of boot stiffness on field and laboratory flexural behavior of alpine ski boots

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Abstract The aim of this work was to study the effect of boot stiffness on the field and laboratory flexural behavior of alpine ski boots. Ski boots have a direct influence on performance, safety, and comfort of alpine skiers. Despite their technological evolution during a number of years, the parameters used in the evaluation of boot stiffness are not yet standardized and still require a shared engineering approach to achieve common quantitative definitions to be used either in boot classification or in boot selection for the different users. This work reports the boot flexion angles between shell and cuff and between cuff and tibia, collected during slalom tests on three boots with different nominal Flex Index. The laboratory data collected on the same boots under conventional cyclic bending tests are reported and compared with the field data for the development of a new test method more representative of the field behavior. As a result, clear definitions of Flex Index and of boot stiffness are introduced: boot stiffness had a clear effect on both the field and the laboratory flexural behavior of boots.

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1 Introduction

Ski boots are fundamental pieces of equipment in alpine skiing. Their function is not only to protect the foot/ankle/tibia complex from the environmental and mechanical loadings, but also to ensure the correct and efficient load transmission to the skis through the bindings while enabling the skier to reach the desired skiing posture in the case of downhill, turning, jumping or stopping maneuvers.

Over the years, boots have developed from the first low profile leather boots with strings to the modern high spoiler plastic boots with buckles. This evolution helped lead to a reduction in the incidence of ankle and tibial fractures of the early years [1, 2], but increased the incidence of knee injuries, particularly of ACL ruptures [3, 4]. This supports the evidence that ski boots have a key importance in skiing safety, mostly in combination with modern bindings release mechanisms and settings [5]. A lot of work has been carried out in the past and in more recent times towards the field acquisition of loads acting on the ski binding system [6–13]: the main focus of this research was the definition of proper safety binding release settings, the understanding of the skiing mechanics and of the biomechanics of lower leg joints.

Skiing biomechanics has been extensively studied over the past years [6–8, 10, 11, 26, 29], and knowledge of external loads acting at the binding and the internal loads resolved at the ankle and knee joints has improved, following the evolution of ski biomechanics introduced by the carving skis. A detailed description of the ankle kinematics and kinetics inside a boot of given mechanical properties is however still missing, particularly in terms of clear definition of the set of angular quantities needed to express the foot and tibial posture while wearing the ski with respect to the barefoot standing position of a skier.

When considering alpine ski boots, there is also a certain lack of standard test methods regarding the stiffness engineering properties of the boot: existing standards focus on the standardization of the boot sole or on adjustment and inspection of the ski/binding/boot system [14, 15].

An accurate study on the effect of ski boot settings on tibiofemoral abduction and rotation during standing and simulated skiing was recently proposed using an indoor laboratory approach, focusing mostly on the effects of the boot construction and adjustment angles on the knee misalignments [16]. Accurate measurements of the field boot kinematics, similar to what has been proposed for the snowboard boots [17], have not yet been carried out. In particular, the spatial linkage successfully used in snowboarding [17], despite its accuracy, has several limitations in the case of application to alpine skiing, mainly related to the robustness of the system: in contrast to snowboarding, where the two boots are strapped to the board and are separated from each other, in alpine skiing the two boots can easily impact each other or receive strong impacts from the slalom poles. This limitation of the spatial linkage for the ski boot applications emphasizes the need for the adoption of noninvasive, robust, possibly wireless systems for angle sensors applied to the boots.

The development of carving skis [10, 11] changed load distributions at the joints with respect to the previous conventional skiing in such a way that, from a biomechanical point of view, new attention should be given to the ski boots and to their functionality with respect to performance and safety issues. Some researches carried out by different boot manufacturers have highlighted that great advantages in performance can be achieved by developing innovative solutions inside the boot [18, 19]. In these cases, innovative interventions focused mainly on the ski boot sole orientation or stiffening rather than on the overall flexural behavior of the ski boot. In addition to that, particular care has been given by manufacturers to the comfort properties of ski boots [20] and to their proper selection for the different users characteristics such as foot size, gender, mass, age, anthropometry, and skill level. It can be expected that a correct selection of the boot with a more subject-specific approach will not only improve the general development of the ski industry, but also reduce the injury rate with a consequent improvement of safety.

When considering technical specifications of ski boots, most manufacturers report only the “Flex Index” that is associated with the boot stiffness in forward flexion. Despite its popularity between common practitioners and its common use as marketing expression, its definition has not been standardized, so that a common engineering test method to assess it, such as in ISO Standard, has not been established.

Different boot manufacturers and independent test laboratories have developed internal standard tests methods to quantify the Flex Index. From the technical point of view, usually the boot sole is applied to an adjustable fixture, a prosthetic leg simulating the shank–foot complex of the skier is inserted into the boot, and a loading arm is rigidly connected to the prosthetic leg to flex the boot cyclically. The loading arm can be moved by a servocontrolled rotational motor with the axis parallel to the boot ankle hinge, or a linear actuator can be connected almost perpendicular to the prosthetic leg that can translate it by extension or retraction movements [21]. The test control mode can also vary, 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).

In addition to this, the nature and behavior of materials involved in the construction of modern ski boots need to be considered. In fact, the polymeric materials used in ski boots are visco-elastic, with a strong influence of strain levels, loading path and strain rate [22–24]. A typical Moment–Angle or Moment–Deflection curve can show highly nonlinear behavior both in forward and rearward bending, together with large hysteresis loops [21]. Test procedures that have different max/min values of the loading cycles will lead to different loading paths of the materials that will not be comparable: however, when using consistently the same test procedure within a test laboratory, comparative evaluations of different boots are possible, provided that clear engineering definitions of stiffness parameters extracted from the recorded curves will be introduced. Particular care needs to be taken in the definition of the test extreme values and the testing frequency, as these two parameters will influence the peak values of the strain and the strain rate: in fact, inappropriate choices of these parameters during cycling can cause reversible and irreversible softening of the ski boot material, as well as changes in the internal temperature due to the hysteresis that, in turn, will influence mechanical response.

The environment temperature and humidity during the test shall be controlled as they have great influence in the behavior of ski boot materials [22–24]: this has to be accomplished using climatic chambers that enclose the testing devices and conditioning the ski boot for several hours in the climatic chamber before the test.

From what has been reported, it should be clear how Flex Index depends on the test method and how values from different manufacturers are not easily comparable. The extreme values of the test cycle, the test frequency, temperature, and humidity of the test chamber, the orientation of the bending axis with respect to the boot sole depend on the available test machine: the level and order of closure of the buckles, the shape and behavior of the prosthetic leg depend on the manufacturer's experience. All these factors can have an influence on the results of a flexion test on the same ski boot: only after a strict application of a precise test protocol covering specifications for all these factors and repeatable curves can be expected for the same piece of equipment. The standardization should also address the curve analysis in such a way that the Moment–Angle data points are used to workout one or more values (such as the Flex Index) that characterize the flexural behavior of the ski boot.

It is worth mentioning the fact that the Flex Index has become, over the years, a parameter used also in the marketing of ski boots to express the "performance" of the ski boot and to justify the market segmentation based on the price levels; it is not uncommon that the Flex Index that is communicated to the dealers or the market may not match to the engineering parameter that can be measured in a test laboratory by a standard test and analysis procedure. Therefore, the Flex Index associated to a commercial product as communicated by the manufactures will be indicated in the following paper as "nominal Flex Index" (nFI).

Based on academics and boot manufacturer involved in the present study, the engineering effective Flex Index (eFI) is defined as the value of the bending moment (expressed in Nm) about the boot hinge applied to a specific prosthetic leg to obtain a forward leaning angle of 10° from the neutral position (i.e., the natural leg posture with closed buckles and no bending moment applied). This definition of Flex Index corresponds to its original introduction in the ski boot industry and implies the use of a test machine able to flex the ski boot with a loading arm hinged at the ski boot ankle and actuated under angle control in a climatic chamber.

As mentioned earlier, the Moment–Angle curves show highly nonlinear behavior both in forward and rearward bending, together with large hysteresis loops, so that the forward bending loading branch of the loop is different from the unloading rearward bending branch [21].

From an engineering point of view, the use of a single number as the Flex Index (even when consistently measured at 10° in a standard defined test cycle) is not sufficient to describe completely the stiffness behavior of the boot. In fact, the same value of bending moment at 10° can be reached with a linear slope or with a nonlinear stiffening portion of the curve: from a user point of view, the stiffening of the curve in forward is associated with the "progression" of the boot, that is appreciated particularly in free-ride and free-style boots. On the other hand, the boot behavior should be quantified also in rearward bending, with a "rearward Flex Index" that is at present never mentioned but that can be correlated with the risk of "boot induced drawer" and, in the past, justified the comparison of some boots with a "rearward release" system. A complete engineering characterization of the ski boot flexural behavior should, therefore, overcome these limitations and should permit the quantifications of the boot stiffness (intended as the local slope of the Moment–Angle curve) at different points along the forward/rearward bending to quantify the intensity of the stiffening.

The conventional test procedure currently used at the boot manufacturer laboratories involved in this study consists in the cyclic application of flexion angles of $+10°$ (forward) and $-10°$ (rearward) from the neutral position of the boot, while recording the bending moment and the flexion angle; the same boot manufacturer was interested in understanding how this established procedure (that will be indicated Current Test in what follows) was representative of the real usage of the ski boots. In fact, when assessing a standard test method to quantify the boot flexural stiffness, it is fundamental to reproduce the real field usage conditions of the boots to ensure that the range of deflections/moments applied in the laboratory setup are representative. Very few data on the field flexural behavior of ski boots are available from literature, in comparison with experience developed for snowboard boots [17].

Based on the former considerations, from a general point of view, a standard procedure for quantifying the boot flexural stiffness is needed for correctly classifying the boots, clearly expressing the boot stiffness to the dealers and customers, and helping the users in the choice of the most suitable boots. Following this rationale, the aims of the present work were: (i) to collect field data regarding the boot flexion angles on three boots with different nFI, (ii) to collect laboratory data on the same boots under conventional cyclic bending tests, and (iii) to compare field and laboratory data to discuss the validity of the Current Test method.

2 Materials

2.1 Ski boots

Three boots manufactured by the same boot manufacturer were selected for the study (Fig. 1). The boots were chosen from different market segments and with different nFI, mass and neutral angle values as reported in Table 1. The neutral angle is ideally the angle to which the tibia of a skier is set with respect to a line perpendicular to the boot sole, without any muscular (dorsi/plantar flexion) or ground reaction load (with the boot laying on the floor). Its measure is conventional and related to the adopted reference systems: in this case, the boot neutral angles were based on what can be measured in the Walkmeter® testing machine (described below). Given a tibial prosthesis and a certain buckle closure setting, the loading arm angle is at a zero value when perpendicular to the boot sole: the neutral angle indicates the angle between a line perpendicular to the boot sole and the loading arm, in the laboratory testing machine when a zero bending moment is applied. Usual values of this angle vary from 15° to 30° (forward), usually increasing from beginner towards racer applications.

2.2 Subject

A healthy male racing skier (26 years old, 70 kg and 1.75 m), free from recent injuries or pain to the lower limbs, volunteered for the study. When performing racing trials, he normally used boots with a nFI equal to 150; when skiing as a ski instructor or for recreation, he normally used boots with a nFI equal to 130. He was requested to read and sign an informed consent form about the tests.

2.3 Instrumentation

Kinematic data were recorded by means of biplanar electrogoniometers (Biometrics, UK) presenting a nominal accuracy of ±2°, able to measure Flexion and Abduction angles, depending on the plane of application to the moving body segments around each joint. Cross sensitivities lower than ±3° were measured during bench validation tests of the sensors after full ranges of ±90° on each plane. However, in the present work, only flexion angles will be presented.

Two electrogoniometers were used to measure the right boot flexural behavior during field and laboratory tests in a sagittal plane: the shell to cuff angle φSC and the cuff to tibia angle φCT were in fact the dependent variables of the study (Fig. 2). Their values were set to zero at the boot neutral position, both in the testing machine and in the field tests: in this case, the zero value was taken with worn boot, closed buckles, and boot lifted from the ground. In this way, the angles measured during skiing were assumed to be angles relative to the neutral position.

The relative flexion angle φSC between shell and cuff was measured by a first Biometrics goniometer placed around the boot hinge, with the distal unit fixed to the medial surface of the shell and the proximal unit fixed to the medial surface of the cuff (Fig. 2). The medial surface of the boot was chosen due to the absence of buckles, despite the risk of damage coming from a boot-ski contact during skiing. Particular care was taken in leaving the spring that connects the two units free from obstacles

Fig. 1 The three boots involved in the study, with indication of the boot/leg terminology. **a** Boot #1, nominal Flex Index 150. **b** Boot #2, nominal Flex Index 100. **c** Boot #3, nominal Flex Index 70

Table 1 Description of the three tested ski boots

No.	Size (EU)	Mass (kg)	No. buckles	Neutral angle (°)	Nominal Flex Index
Boot # 1	42	2.75	4	30.4	150
Boot # 2	42	2.5	4	26.1	100
Boot # 3	42	2.0	4	23.9	70

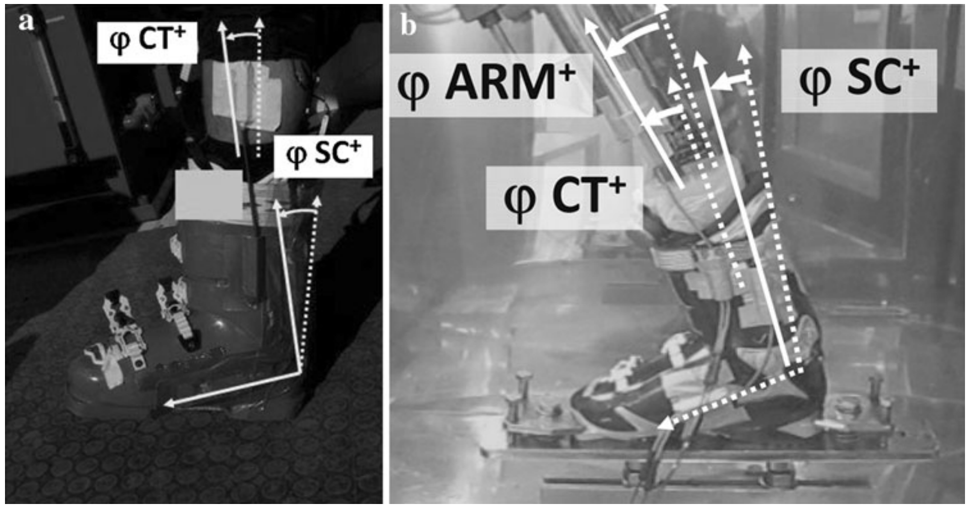

Fig. 2 Description of the angles adopted in the study with indication of the *positive sign*. *Dotted lines* correspond to the neutral angle position. **a** Field tests and **b** laboratory tests

during the boot flexion, as well as in applying a waterproof cover to avoid snow and water contact to sensors and connectors.

The relative flexion angle φCT between cuff and tibia was measured by a second Biometrics goniometer placed at the top of the cuff, with the distal unit fixed to the medial surface of the cuff and the proximal unit fixed to the medial face of the tibial bone, at the proximal portion of the leg external to the boot (Fig. 2). Particular care was taken in placing the units in such a way as to give the interconnecting spring the maximum possibility of elongation, as required by the sensor's manufacturers.

Two more electrogoniometers were applied by double-sided adhesive tape to the two legs' lateral surfaces to collect the flexion–extension angles of the right and left knees of the subject during field tests. The two knee angles, denominated φKR and φKL, respectively, for the right and left knee, were expressed in degrees (°) and were set to a zero value in a fully extended position: therefore, flexing the knees would result in an increasing knee angle.

Electro-goniometric data were synchronously recorded (1 kHz) using a portable data logger with 16 channels (PDA-PocketEMG, BTS Bioengineering, Italy, 0.3 kg mass) that was placed on the chest of the skier during the field tests.

2.4 Test machine

A Walkmeter® test machine (commercially available from Giuliani Tecnologie Srl, Torino, IT) was used for the laboratory tests. The machine has a climatic chamber containing an adjustable fixture for the boot sole and a loading arm rotating about an axis parallel to the boot ankle hinge (Fig. 3). The boot was tested with a standardized prosthetic leg–foot assembly, made of two steel tubes simulating the tibia and the foot bones, connected by a cardan joint at the ankles and surrounded by a silicone mould, based on a real subject cast with foot size 42. Regarding the prosthetic leg, the calf height from the foot sole was 290 mm, the circumference at the upper calf extremity was 365 mm, the malleolus width was 80 mm, the foot breadth was 80 mm, and the foot length was 275 mm [25].

During the tests, the loading arm can be controlled in displacement mode after setting the forward and backward flexion angles to be reached, relative to the neutral angle. The frequency of the test can also be set at the minimum value of 7 cycles/min or the maximum value of 25 cycles/min. The machine has a sensor measuring the angle between the loading arm and the boot sole φARM (°) that can be zeroed at the neutral position as required by the boot construction, and a torque cell measuring the bending moment M (Nm) needed to flex the boot, around the boot hinge. The machine is able to apply a triangular waveform to the loading arm angle, so that a constant angular velocity is maintained by the machine controller while the arm moves from the preset minimum to the maximum value of the angle and vice versa.

3 Methods

Two independent variables were considered: the boot type and the test type. The boot type was explored choosing three different boots of very different "nominal Flex Index". The test type was changed after planning a field test session and a laboratory test session with the conventional test procedure φARM = −10°/+10°.

The dependent variables of the study were the shell to cuff angle φSC and the cuff to tibia angle φCT of the boot, together with their first time derivative.

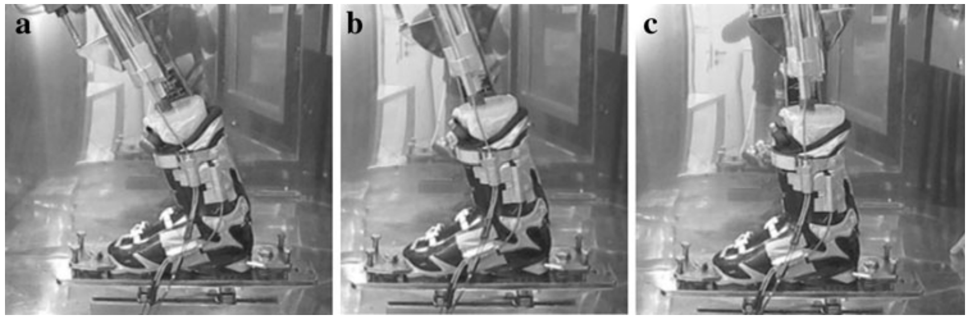

Fig. 3 Three positions of the loading arm during the laboratory current tests. **a** Forward +10°, **b** neutral angle and **c** rearward −10°

3.1 Field testing protocol

The field tests were performed on a spring sunny day at the Monti-Zardini slope (Faloria resort, Cortina D'Ampezzo, Italy). The slope, presenting an average inclination of 25°, is oriented towards north and ensures the consistency of the snow properties throughout the day, until the early afternoon. The slope was chosen to minimize the effect of uncontrolled variables such as the snow hardness on the boot flexion tests: the average air temperature was around 5 °C.

Two portions of the slope were used during the tests: the pole slalom in the upper part, and the free slalom in the lower part. The pole slalom was prepared by placing 16 short poles on the snow at a longitudinal distance of 10 m and a lateral distance of 4 m: two couples of poles marked the beginning and the end of the slalom.

After performing a familiarization pre-run, the subject was asked to perform two valid runs for each pair of boots. The electrogoniometer unit positions were marked by paint on each pair of boots to ensure the exact repositioning for the successive laboratory test session. In addition to that, the buckles and strap positions used by the skier for the different boots were recorded to be repeated in the laboratory test sessions.

Each run was composed by the following detailed protocol. Lift the boot from the ground to measure the neutral angle (in order to exclude any undesired bending moment about the ankle hinge coming from the ground reaction forces), connect to the bindings, perform a static maximal rearward leaning for 5 s, perform a static maximal forward leaning for 5 s, mark the start of the pole slalom with three voluntary quick boot flexions, perform the pole slalom until the final gate, mark the start of the free slalom with three voluntary quick boot flexions, perform the free slalom at self selected speed and turning radius, mark the end of the free slalom with three voluntary quick boot flexions, make a full stop, disconnect the boot from the bindings, lift the boot from the ground to measure the neutral angle.

3.2 Laboratory testing protocol

The three boots subsequently underwent the laboratory tests in the Walkmeter® machine: the two electrogoniometers were reapplied to the shell and the cuff of each boot with the proximal and distal units as marked during the field tests.

The instrumented boots were applied to the test prosthesis and closed with the same buckle positions as recorded in the field tests: the upper strap positions were also recorded and repeated from the field tests.

During the laboratory tests, the cuff to tibia electrogoniometer used in the field had its proximal unit repositioned on the loading arm, corresponding to the tibial portion of the prosthetic lower leg (Fig. 3), to simulate as much closely as possible the cuff to tibia connection used in the field tests.

Tests were performed at room temperature (20 °C) and at the field test temperature (5 °C) and relative humidity (40 %) on each boot using the conventional procedure adopted by the manufacturer in its Current Test procedure: a cyclic oscillation of the loading arm with the angle φARM varying between −10° and +10° from the neutral angle, at a frequency of 7 cycles/min (4.6°/s), while recording the bending moment M and the boot flexural angles φSC and φCT.

To evaluate the effect of test speed, this conventional flexural test was also performed at 25 cycles/min (16.6°/s).

Finally, following the outcomes of the study and the comparison between field test data and Current Test results, a New Test procedure was introduced by cycling the loading arm angle φARM between −5° and +15° from the neutral angle, at a frequency of 7 cycles/min (4.6°/s) and at a temperature of 5 °C. The New Test (φARM = −5°/+15°) Moment/Angle curves were recorded on the same three boots without electrogoniometers and compared to the curves obtained on the instrumented boots with the Current Test setup φARM = −10°/+10°.

3.3 Data analysis

A set of customized protocols was developed for data analysis using SMART Analyzer (BTS Bioengineering, Italy) and Matlab (The MathWorks Inc., USA).

All data coming from the field tests were filtered with a fourth-order low pass Butterworth filter (cut-off frequency of 5 Hz). Flexion–extension angle of the right knee was then used to define turn cycles following the definition given by Berg et al. [26]. Each turn cycle was defined as two consequent values of maximum knee flexion; 0° was considered full knee extension.

All filtered data coming from the field tests were analyzed to evaluate the maximum, minimum, and range (range = maximum − minimum) values of the shell to cuff angle and the cuff to tibia angle, relative to the neutral position taken as zero. Positive values were associated to forward bending, negative to rearward leaning.

Three field test conditions were analyzed: the two skiing conditions of pole slalom and free slalom, together with the static testing recorded during the maximal forward or rearward voluntary bending of the boots. For each skiing conditions, two runs were repeated, and their average values were reported in the results (Table 2).

When skiing, the cyclic nature of the slalom enabled the turning cycles to be recognized, separated and analyzed as shown in Figs. 4 and 5. Within the pole slalom, six subsequent cycles were considered to be indicated by seven consecutive high peaks of the right knee flexion angles. Similarly, within the free slalom, three subsequent cycles were considered to be indicated by four consecutive high peaks of the right knee flexion angles. Within each cycle, the maximum, minimum, and range values were evaluated and subsequently averaged over the 6 cycles of the pole slalom or the 3 cycles of the free slalom to give values for comparison with the laboratory tests. The same approach was adopted with the laboratory test data over a total of 5 cycles.

The flexing ratio RF = φCT/φSC was introduced to express the ratio between the excursion of the tibia relative to the cuff and the excursion of the cuff relative to the shell: values much larger than 1 express a larger deformability of the liner, the upper tongue or the leg soft tissues with respect to the cuff to shell hinge movement.

The angular velocities at electrogoniometers were obtained from the filtered data after numerical derivation.

An interesting analysis was possible after assuming the additive property of the two measured angles φSC and φCT, and estimating the angle φST* between shell and tibia, (symbol * expresses the fact that it is an estimated value) defined as:

$$\varphi\,\mathrm{ST}* = \varphi\,\mathrm{SC} + \varphi\,\mathrm{CT} \quad (1)$$

The amount of error implied with this assumption was evaluated during the laboratory tests with the Current Test procedure, when the applied range of the loading arm $\Delta\varphi$ ARM = 20° (taken as reference angle) was compared with the corresponding range of the estimated shell–tibia angle $\Delta\varphi$ ST*. The possibility of estimating a correction factor based on this comparison would enable the φST* field values to be corrected to give indications for the more appropriate laboratory angle test range.

Finally, after the collection of cyclic test data, the Moment/Angle curves for the different boots and tests conditions were available for the evaluation of the comparative flexural parameters.

An eFI was calculated from the Current Test cyclic curves as the bending moment M value corresponding to a flexion angle of φARM = +10° from the neutral angle during the forward bending (Eq. 2):

$$\mathrm{eFI} = M_{\mathrm{FW}}(\varphi\mathrm{ARM} = +10^\circ) \quad (2)$$

The Boot Stiffness was the new parameter introduced using the New Test cyclic curves to characterize the boot flexural properties along its Moment/Angle curve. Being defined as the local slope of the Moment/Angle curves, its value depends on the instantaneous angle position adopted for its evaluation and on which branch of the Moment/Angle curve (forward or backward) it is based on. This quantity is applicable to any given Moment/Angle curve, of any range and maximum or minimum values, as it is based on the local derivative of the Forward Flexion branch (apex FW) or the Backward Flexion branch (BW apex). Its formulation refers to a specific angle (the subscript) that can be positive or negative, but needs to be relative to the neutral position.

A Forward Stiffness $K^{\mathrm{FW}}_{5^\circ}$ was introduced as the stiffness at 5° from neutral angle in forward bending (Eq. 3):

$$K^{\mathrm{FW}}_{5^\circ} = \frac{\mathrm{d}M^{\mathrm{FW}}(\varphi\mathrm{ARM} = 5^\circ)}{\mathrm{d}\varphi\mathrm{ARM}} = (\mathrm{Nm}/^\circ) \quad (3)$$

By evaluating the ski boot stiffness at two angles of the forward branch, for instance $K^{\mathrm{FW}}_{5^\circ}$ and $K^{\mathrm{FW}}_{10^\circ}$, it is possible to evaluate the degree of stiffening that is occurring over a certain angle interval: a value if the ratio between $K^{\mathrm{FW}}_{10^\circ}$ and $K^{\mathrm{FW}}_{5^\circ}$ much greater than one will highlight a pronounced stiffening effect.

4 Results

4.1 Field tests

The field tests enabled to collect the maximum/minimum/range values of two skiing conditions and of the static extreme tests performed with three different boots, as collected in Table 2.

From a general point of view, the repeatability of the tester during the pole and the free slaloms can be appreciated after comparing the two runs' values: the range values of the φCT angle (the angle with largest range) did not differ more than 4.6°. In addition to that, the sign of the two measured angles was predominantly positive, with minimum recorded rearward flexion values of φSC = −1.2° and φCT = −7.8°, obtained with Boot #3 during

Table 2 Results of the field tests on the three boots

	Type	Run	Knee angles			Boot flexion angles									
			Right knee			Shell–cuff (measured)			Cuff–tibia (measured)			Δ*φ*CT/Δ*φ*SC	Shell–tibia (*estimated)		
			*φ*KR (°)			*φ*SC (°)			*φ*CT (°)			RF	*φ*ST* (°)		
			Max	Min	Δ	Max	Min	Δ	Max	Min	Δ		Max	Min	Δ
Boot # 1 (nFI 150)	Pole	1	83.4	16.2	67.2	6.8	0.8	6.0	13.9	−6.1	20.1	–	**20.7**	**−5.4**	**26.1**
	Slalom	2	76.0	12.2	63.8	6.6	0.9	5.7	14.6	−3.1	17.7	–	**21.1**	**−2.2**	**23.3**
		Mean	79.7	14.2	65.5	6.7	0.8	5.8	14.3	−4.6	18.9	3.2	**20.9**	**−3.8**	**24.7**
	Free	1	88.4	24.7	63.8	6.0	0.7	5.3	14.8	−1.6	16.4	–	**20.8**	**−0.9**	**21.7**
	Slalom	2	83.4	19.3	64.1	6.4	1.1	5.3	13.7	−4.0	17.6	–	**20.1**	**−2.9**	**23.0**
		Mean	85.9	22.0	64.0	6.2	0.9	5.3	14.3	−2.8	17.0	3.2	**20.5**	**−1.9**	**22.4**
	Static		88.4	−2.0	90.5	8.2	−4.6	12.8	17.9	−17.8	35.8	2.8	**26.1**	**−22.5**	**48.6**
Boot # 2 (nFI 100)	Pole	1	78.2	12.2	66.0	9.2	−1.7	10.9	17.2	−9.6	26.8	–	**26.4**	**−11.3**	**37.7**
	Slalom	2	68.0	7.3	60.7	9.2	−0.2	9.4	18.4	−3.8	22.2	–	**27.6**	**−3.9**	**31.5**
		Mean	73.1	9.7	63.3	9.2	−0.9	10.1	17.8	−6.7	24.5	2.4	**27.0**	**−7.6**	**34.6**
	Free	1	73.8	20.9	52.9	10.2	2.0	8.3	17.5	−2.0	19.5	–	**27.8**	**0.0**	**27.8**
	Slalom	2	65.1	14.7	50.4	9.8	1.9	7.9	18.3	−0.9	19.2	–	**28.1**	**1.0**	**27.1**
		Mean	69.5	17.8	51.6	10.0	1.9	8.1	17.9	−1.4	19.4	2.4	**27.9**	**0.5**	**27.5**
	Static		78.2	−4.1	82.3	12.7	−5.9	18.5	22.5	−23.2	45.6	2.5	**35.1**	**−29.0**	**64.1**
	Pole	1	68.0	7.3	60.7	9.2	−0.2	9.4	18.4	−3.8	22.2	–	**27.6**	**−3.9**	**31.5**
	Slalom	2	60.6	2.6	58.0	11.1	−2.2	13.3	11.5	−11.9	23.4	–	**22.5**	**−14.2**	**36.7**
Boot # 3 (nFI 70)		Mean	64.3	5.0	59.3	10.1	−1.2	11.3	14.9	−7.8	22.8	2.0	**25.1**	**−9.1**	**34.1**
	Free	1	65.1	14.7	50.4	9.8	1.9	7.9	18.3	−0.9	19.2	–	**28.1**	**1.0**	**27.1**
	Slalom	2	63.7	13.4	50.3	11.9	0.4	11.5	12.7	−5.0	17.7	–	**24.6**	**−4.5**	**29.1**
		Mean	64.4	14.1	50.3	10.9	1.2	9.7	15.5	−2.9	18.4	1.9	**26.4**	**−1.8**	**28.1**
	Static		68.9	−7.2	76.1	15.4	−7.8	23.3	16.9	−21.4	38.3	1.6	**32.4**	**−29.2**	**61.6**

Bold values indicate the mean values of the two runs used for the discussion of results

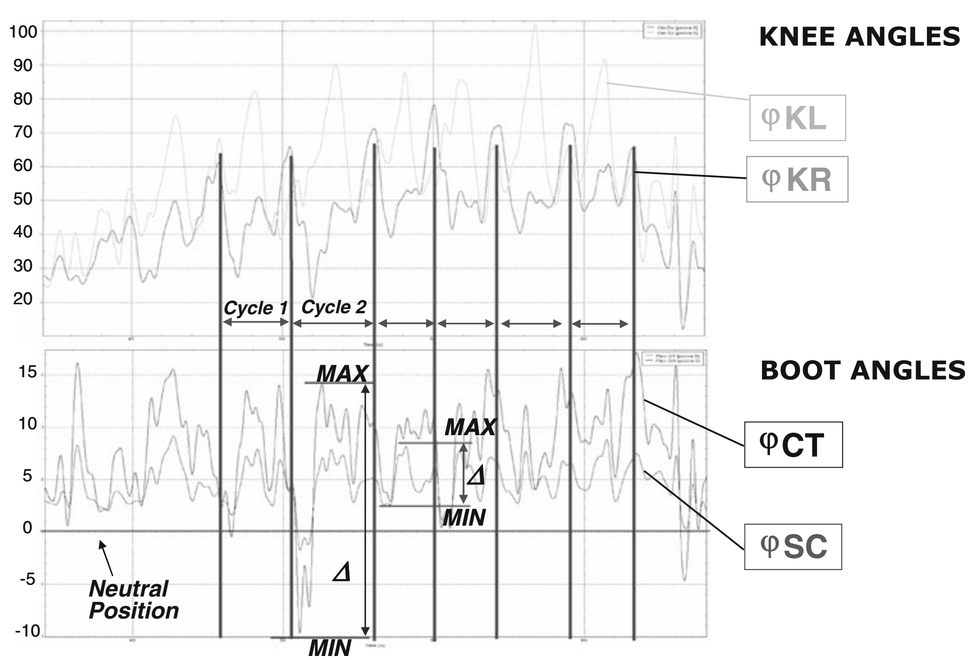

Fig. 4 Example of pole slalom tests outputs with indication of six turn cycles and of max/min/range values of the measured boot angles

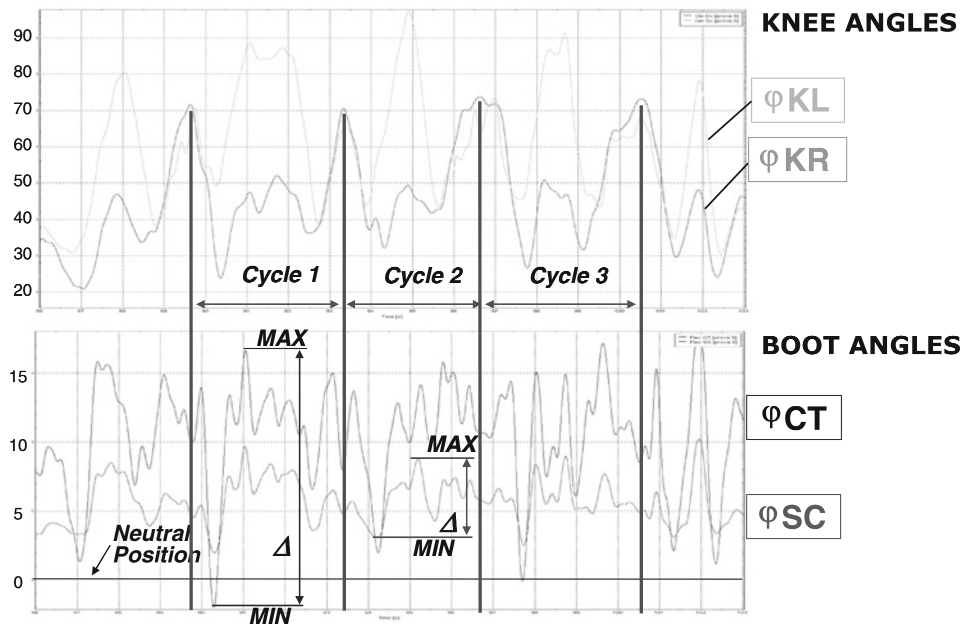

Fig. 5 Example of free slalom tests outputs with indication of three turn cycles and of max/min/range values of the measured boot angles

pole slalom: this was considered to be the indication of a generally correct forward leaning posture of the tester throughout the tests. Finally, the variability of the right knee angle range between the two runs was generally between 5 and 10 %, thus confirming the comparability among the different runs, despite the intrinsic variability of the skiing action on the slope surface roughness: these results should be confirmed by test sessions involving a greater number of repeated runs.

Results of Table 2 show how the largest amount of flexion takes place between the cuff and the tibia: the flexing ratio RF (ratio between $\Delta\varphi$CT and $\Delta\varphi$SC) results have values larger than 3 for Boot #1, around 2.4 for Boots #2 and around 2.0 for Boot #3.

Boot #1, namely a racing boot with the nFI as high as 150, showed, as expected, the lowest values of φSC ranges both during pole (5.8°) and free (5.3°) slaloms tests.

Boot #2, namely an amateur boot with a nFI equal to 100, showed φSC range values similar to those recorded for Boot #3, namely an intermediate level boot, having the lowest nFI equal to 70.

The range values recorded during pole slalom for the two angles, φSC and φCT, were consistently larger that those obtained during free slalom, and the differences were more evident for softer Boots #2 and #3.

A further set of results from the field tests were the angular velocities at the different joints (knee, shell–cuff, cuff–tibia): the angular velocities' curves were obtained after numerical differentiation of the filtered signals collected in the two skiing conditions for the three different boots. The mean values of the positive and negative angular velocities recorded over the analyzed cycles of the two runs were evaluated at the knee (positive in flexion) and the boot angles (positive when forward leaning) (Table 3).

The highest value of ωKR = 352°/s was recorded at the right knee in extension for Boot #1 in pole slalom, against a maximum knee flexion velocity of 171°/s recorded for Boot #3 in pole slalom: free slalom showed consistently lower values than pole slalom for all the angular velocities. The knee flexion velocity increased with decreasing boot stiffness (from Boot #1 to Boots #2 and #3): on the contrary, extension velocity decreased with decreasing boot stiffness.

The highest angular velocity at the boot was recorded at the cuff–tibia joint for Boot #2 in flexion (+117°/s) and extension (−145°/s) during pole slalom: the highest angular velocity at the shell–cuff joint were recorded for Boot #3 in flexion (+56°/s) and extension (−58°/s) again during pole slalom. No systematic variation of angular velocities with the boot stiffness emerged from values measured at the boot joints.

Static tests gave the largest maximum, minimum, and range values of the boot angles: usually static values resulted to have a range double than the pole slalom range, representing really extreme values never reached in normal skiing conditions by an expert skier (Table 2).

4.2 Laboratory tests

The laboratory tests results gave the possibility of comparing the boot flexion angles recorded in the field at the shell–cuff joint (φSC) and the cuff–tibia joint (φCT) with the same joint angles obtained on the test machine after the

Table 3 Angular velocity data recorded during the field tests on the three boots

Boot	Type	Run	Angular velocity (°/s)							
			Knee		Boot					
			ωKR (measured)		ωSC (measured)		ωCT (measured)		ωST* (estimated)	
			Flex	Ext	Fwd	Rwd	Fwd	Rwd	Fwd	Rwd
Boot # 1	Pole	Mean	140	**−352**	26	−32	76	−122	*102*	*−154*
	Free	Mean	105	−160	21	−25	56	−72	*77*	*−98*
Boot # 2	Pole	Mean	156	−287	41	−48	**117**	**−145**	***158***	***−192***
	Free	Mean	107	−140	34	−35	73	−91	*107*	*−126*
Boot # 3	Pole	Mean	**171**	−294	**56**	**−58**	82	−102	*138*	*−160*
	Free	Mean	109	−143	37	−39	57	−73	*94*	*−112*

Bold indicates the values of highest magnitude of each column

Italic highlights the values that were not measured but estimated

imposition of a fixed tibia (loading arm) excursion $\Delta\varphi$ARM = 20°, from −10° to +10° around the neutral position (Table 4).

For each boot, the maximum/minimum/range values of φSC and φCT were obtained at two angular speeds; all boots underwent the cyclic tests not only at room temperature (20 °C), but also at the same temperature recorded in the field tests (5 °C).

The test condition common to the field and the laboratory tests is the low temperature testing at 5 °C: the attention shall, therefore, be placed initially on those test results for direct comparison with the field results. On the other hand, results from laboratory tests performed at room temperature of 20 °C may be representative of the boots behavior in the retails or rental shops, where initial subjective evaluations are carried out by users at room temperature. As the lowest angular speed of 4.6°/s was the typical test frequency adopted in the manufacturer laboratory, these values were considered for further comparison with historical data on other boots.

The first result from laboratory tests performed with the φARM = −10°/+ 10° setup at 5 °C temperature is that the Flexing Ratio RF is close to 1 for Boot #1 (1.23) and almost equal to 2 for Boots #2 (1.93) and #3 (1.71). Secondly, the range of flexion obtained for angle φSC on Boot #1 is higher than those recorded for Boots #2 and #3: this is opposite to what resulted from the field tests. The range of φSC for Boot #1 (at 5 °C) is about double the maximum range recorded in the field tests at 5 °C (Table 2): the laboratory test range results are not directly comparable with the field tests for Boot #1, and there is no evident trend with the nFI. Furthermore, all boots show large negative minimum values of both φSC and φCT, mostly of greater modulus than their positive maximum values.

The temperature decrease (from 20 to 5 °C) had opposite effects for the shell and the cuff, as the ranges of the shell–cuff angle φSC decrease with decreasing temperature by at least 10 %, whereas the ranges of the cuff–tibia angle φCT increase by at least 12 % (Table 4).

A negligible effect can be associated with the increase of angular velocity from 4.6°/s to 16.6°/s for both three boots at all the temperatures.

An interesting comparison is between the calculated values of φST* and the loading arm angle applied by the machine φARM (range = 20°): after adding the range of φSC and the range of φCT, the total values φST* are consistently higher than the applied range of 20°, with errors not exceeding 24 %.

The direct comparison of field (pole slalom, 5 °C) and Current Test laboratory results (5 °C, 4.6°/s) is clear in Fig. 6, where the boot flexion angles at the two joints are presented as histograms: the field test results are clearly shifted towards the positive direction (forward flexion) by an estimated average amount of 5°. This result inspired the introduction of the New Test method with $-5° \le \varphi$ARM $\le +15°$.

With respect to the recorded peak bending moments associated with the Current laboratory tests (Table 4), the extreme values corresponding to φARM = −10° and φARM = +10° were the highest for Boot #1, as expected, given its highest nFI; unexpectedly, the moments recorded for Boot #3 were not so different from those obtained for Boot #2, having a nFI 30 % higher than Boot #3.

The Moment/Angle curves obtained after the Current Test $-10° \le \varphi$ARM $\le +10°$ and those recorded with the New Test $-5° \le \varphi$ARM $\le +15°$ were compared in Fig. 7: the nonlinear behavior of the three boots is more evident in the New Test method. The nFI, the eFI calculated from Fig. 7a and the boot stiffness K_5^{FW} calculated from the curves shown in Fig. 7b at 5° flexion are collected for final comparison in Table 5.

From the limited amount of available data collected during the work, the following trends have emerged, although a much greater testing matrix is needed to confirm these:

Table 4 Results of the laboratory tests on the three boots for the current test setup φARM = −10°/+10°

	Temp (°C)	Test speed (°/s)	Flexion angles										Peak bending moments	
			Shell–cuff (measured)			Cuff–tibia (measured)			$\Delta\varphi$CT/ $\Delta\varphi$SC	Shell–tibia (*estimated)			φARM = +10°	φARM = −10°
			φSC (°)			φCT (°)			RF	φST* (°)			*M* (Nm)	
			Max	Min	Δ	Max	Min	Δ		Max	Min	Δ	Max	Min
Boot # 1 (nFI 150)	20	4.6	6.4	−6.6	13.0	5.6	−6.2	11.8	0.91	**12.0**	**−12.8**	**24.8**	150	−167
	20	16.6	6.9	−5.6	12.5	4.8	−6.6	11.4	0.92	**11.7**	**−12.2**	**23.9**	142	−161
	5	4.6	5.5	−5.6	11.1	6.5	−7.2	13.7	1.23	**12.0**	**−12.8**	**24.9**	175	−176
	5	16.6	5.9	−4.8	10.7	5.6	−7.7	13.3	1.24	**11.5**	**−12.4**	**23.9**	165	−170
Boot # 2 (nFI 100)	20	4.6	4.7	−5.6	10.3	6.6	−7.2	13.9	1.35	**11.3**	**−12.8**	**24.1**	118	−129
	20	16.6	5.2	−4.8	10.0	6.1	−7.3	13.4	1.35	**11.2**	**−12.1**	**23.4**	113	−125
	5	4.6	3.4	−4.7	8.1	7.7	−7.8	15.6	1.93	**11.1**	**−12.5**	**23.6**	128	−117
	5	16.6	3.5	−4.7	8.2	8.0	−8.0	15.9	1.94	**11.5**	**−12.7**	**24.2**	128	−113
Boot # 3 (nFI 70)	20	4.6	4.9	−4.4	9.3	5.2	−7.3	12.5	1.34	**10.1**	**−11.7**	**21.8**	113	−153
	20	16.6	5.4	−3.8	9.2	5.2	−7.6	12.8	1.40	**10.6**	**−11.4**	**22.0**	116	−156
	5	4.6	4.4	−4.3	8.8	7.1	−7.9	15.0	1.71	**11.5**	**−12.2**	**23.8**	121	−127
	5	16.6	4.1	−4.2	8.3	6.3	−9.1	15.4	1.85	**10.3**	**−13.3**	**23.6**	125	−120

Bold highlights the values that were not measured but estimated

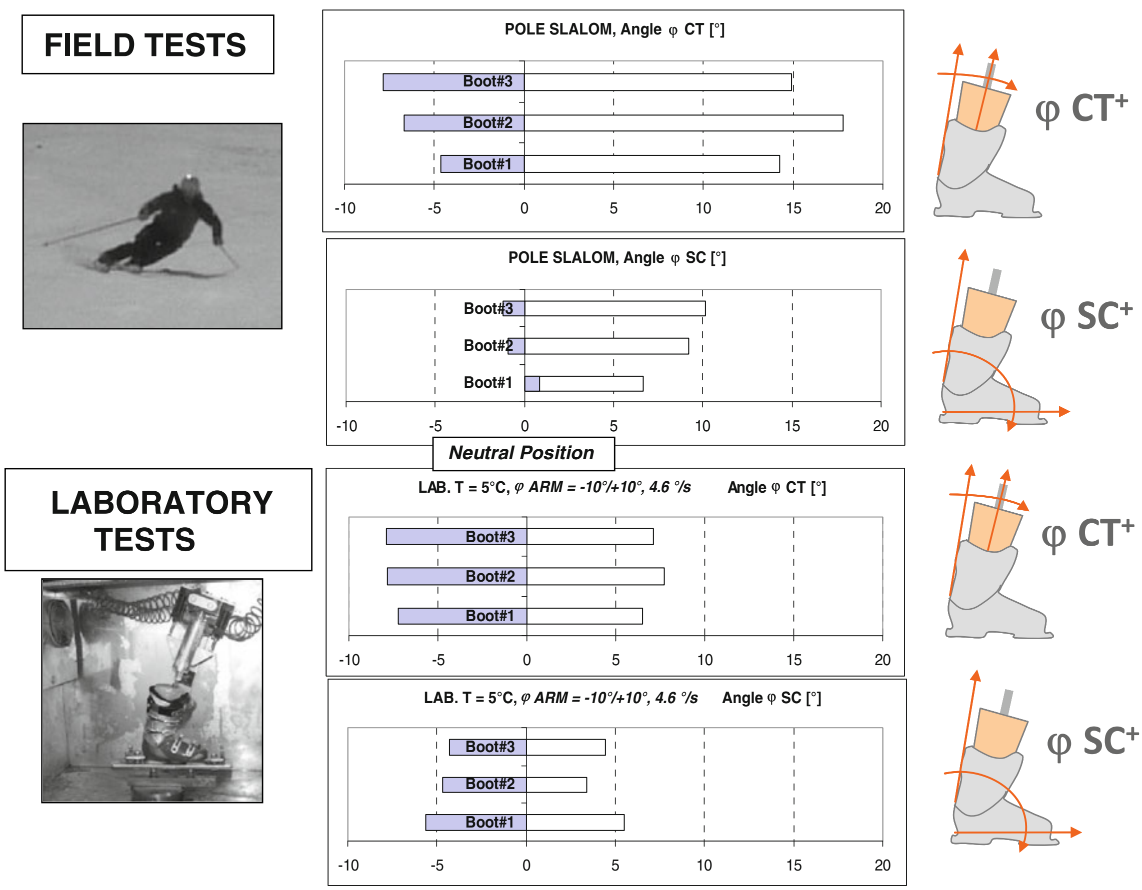

Fig. 6 Comparison of the three boots in the pole slalom tests and in the laboratory current tests (−10°/+10°)

R1: the maximal forward and rearward excursions of the cuff relative to the shell of a ski boot recorded with an expert amateur skiing on spring snow were recorded as $+0.8° \leq \varphi SC \leq +6.7°$ on a racing boot (stiffness $K_5^{FW} \approx 15$ Nm/°) and of $-1.2° \leq \varphi SC \leq +10.9°$ on a soft boot (stiffness $K_5^{FW} \approx 10$ Nm/°).

R2: given an overall tibia flexion with respect to the boot sole, the amount of flexion due to the shell to cuff motion as recorded in the field tests (expert amateur skiing on spring snow) is about 25 % in a stiff boot ($K_5^{FW} \approx 15$ Nm/°) and about 33 % in a soft boot ($K_5^{FW} \approx 10$ Nm/°). Things can change very much in a test lab environment depending on the construction of the test prosthesis, the temperature of the test and the closure of the buckles.

R3: the maximal and minimal flexion angles to be applied to a prosthetic tibia by the loading arm that better reproduces the boot field behavior in terms of minimum/maximum values of the boot angles can be expressed as $-5° \leq \varphi ARM \leq +15°$, based on the available present data: this holds true for the machine running under displacement control.

R4: the angular velocities encountered during expert skiing on spring snow were higher for the softer boots, but no clear trend with stiffness or nFI: the highest values recorded at the shell–cuff joint were +56°/s (FW), −58°/s (RW) (Boot #3), highest values recorded at the cuff–tibia joint were +117°/s (FW), −145°/s (RW) (Boot #2). Based on these results and the assumption of the additive property of the shell–cuff and cuff–tibia angles, the loading arm ideally should be able to reach FW angular velocities as high as 160°/s and RW velocities as high as 180°/s. However, as from the laboratory test performed so far, the influence of the test speed was negligible within the tested angular speed range (limited by the test machine performances).

5 Discussion

The present study was designed to give a contribution to the knowledge of the flexural behavior of ski boots during field tests, in relation with the boot stiffness properties that

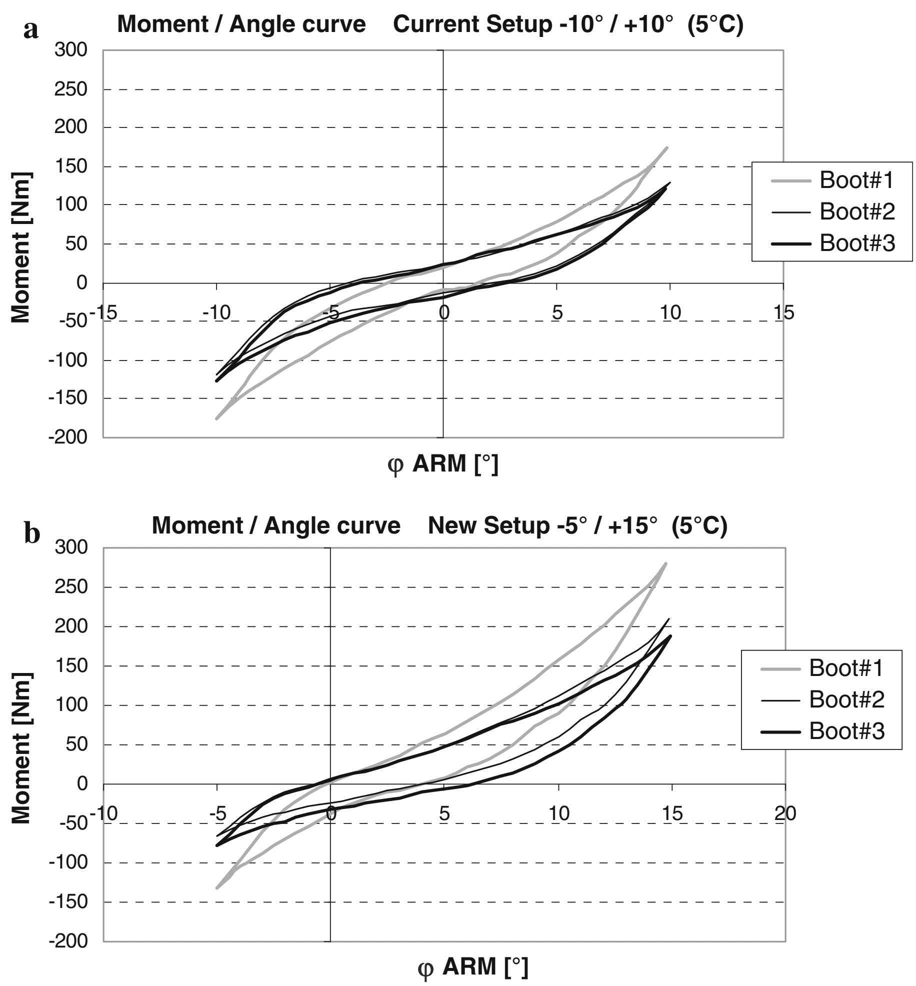

Fig. 7 Comparison of the three boots moment/angle laboratory curves. **a** Current test setup, φARM = −10°/+10°. **b** New test setup, φARM = −5°/+15°

Table 5 Comparison of the stiffness parameters for the three boots

No.	Neutral angle (°)	Nominal Flex Index (Nm)	Effective Flex Index (Nm)	Stiffness K_5^{FW} (Nm/°)
Boot # 1	30.4	150	175	14.7
Boot # 2	26.1	100	128	11.3
Boot # 3	23.9	70	121	10.2

can be evaluated in a laboratory test setup. The aims of the work were addressed by different field and laboratory test activities: the corresponding research conclusions will be formulated after having stated the limitations of the study and having discussed the results.

The first limitation of the study can be found in the fact that it is a single subject study, with respect to field skiing data: the choice of a single racer skier can be justified by the need of involving a skier familiar not only with touristic boots, but also with very stiff racing boots and pole slalom. Practical reasons such as the need to adapt the racing boots to the subject feet anthropometry, the best matching between the laboratory prosthetic lower leg and the subject lower leg as well as the time/costs related to a wider sample of racing skiers were taken into account. Further tests should involve a larger number of testers, possibly with classified skill levels within the touristic market segment, enabled to test ski boots of stiffness ranging from −40 % to +40 % of the stiffness currently used.

A second limitation can be associated to testing under single snow conditions: also in this case, the effect of different snow surfaces and ambient temperature could have been explored with a longer study throughout the skiing season.

The limited number of boots tested can be seen as a further limitation of the study: given the need of keeping the most stable conditions of the snow and the track throughout the day of testing, a larger number of boots would not have been sustainable, considering the time needed for the application of sensors to the ski boots and the skier. However, the three boots were initially indicated by the manufacturer as representative boots from different market segments, spanning different values of the nFI.

In addition, the focus on the sagittal behavior of the boot can be considered as a limitation of the work, if compared to literature reports from indoor studies [16] or snowboard studies [17]. The ab-adduction deflections at the shell–cuff or cuff–tibia joints, as well as some torsional relative motions between the tibia and the cuff could have been analyzed during the study. However, the biometric biplanar sensors used were not considered to be sufficiently accurate to measure such small angular displacements. This is the reason why the data collected on the second plane of the biometric sensors were not considered in the study: Biometric® torsion sensors were also not available at the time of the study.

Finally, the major limitation of which the authors are aware is the lack of an instrumented device to perform the buckle and strap closure in a controlled manner, both in the field and in the laboratory test conditions. In fact, a common experience of expert skiers is that a change in a single buckle hook position can be felt as a change in the boot flexural behavior; in addition, the manufacturer's laboratory experience is that the buckle closure conditions shall be very much standardized to give repeatable results. This limitation was faced by following strictly a standard procedure for the closure of the buckles.

Despite the fact that these limitations could be addressed in future developments of the research, on the basis of the available results several considerations can be developed in order to draw some conclusions.

The differences between the three boots in terms of range of flexion at the two observed joints (SC and CT) can be associated to the differences in the boot shape, materials, thicknesses and constructions, but the three boots were characterized as "assemblies". The stiffest boot, Boot #1, showed lowest flexions at the boot hinge while demanding higher flexions at the cuff–tibia joint: the flexing ratio RF reached a maximum value equal to 3.2 on this boot during field tests, but dropped to a value equal to 1.2 during laboratory tests. This behavior differed from the two other boots, which gave RF values close to 2 in the field and the lab tests. This would be consistent with the absence of thick deformable liners, in the case of racing boots, so that a large flexural deformation is still correlated with the skier's calf soft tissues as they are compressed into the cuff. The decrease of RF in laboratory tests performed with a much stiffer silicone mould reduces this compression effect as the deflection on the boot hinge increased. An important observation resulting from these tests is that the hardness of the artificial leg plays a major role in influencing the stiffness results. Comparable stiffness parameters will be achieved by similar test setups shared by different manufacturers provided that the artificial legs used in different laboratories present the same dimensions, shape, and hardness. The harder the artificial leg outer material, the larger the difference between the human leg behavior and the laboratory: it is also reasonable to expect that the stiffness of the anterior face of the artificial leg should differ from the posterior surface, like the human shank where the calf muscles are much softer that the anterior margin of the tibia.

Secondly, the nFI commercially associated with the three boots involved in the study was not directly correlated to the boot flexural stiffness properties that could be evaluated by studying the engineering Moment–Angle angle curves during a flexing cyclic test (Fig. 7; Table 5). This is confirmed by the almost equivalent results obtained by Boots #2 and #3 in the field (Table 2) and laboratory tests (Table 4), despite a nFI for Boot #3 claimed to be 30 % lower than Boot #2. The analysis of bending moments associated with the boots laboratory tests further confirms this, showing eFI values for Boot #3 similar to Boot #2 (Table 5). A more extensive laboratory evaluation of ski boots with very different nFI would be needed to evaluate the degree of correlation between nFI and eFI over a range of commercial products, from different brands.

The new stiffness parameter K_5^{FW} was introduced by the boot manufacturer to better represent the complex nonlinear behavior of boots rather than a single stiffness value as the Flex Index: referring to Fig. 7b, the stiffness can be evaluated at different values of the forward flexion angle φARM, thus expressing the amount of stiffening of the boot with progressing flexion. In fact, following the outcomes of the present work, the manufacturer defined the progression of a boot as the ratio between $K_{10^\circ}^{\mathrm{FW}}$ and $K_{5^\circ}^{\mathrm{FW}}$, and values greater than one express a large stiffening effect [28]. Moreover, other stiffness parameters can be introduced in analogy to K_5^{FW} to express the backward stiffness of the boots in the case of an extreme backward flexion, that has been correlated to the ACL injury mechanism known as "Boot Induced Drawer" [2, 5, 27]. From a perspective point of view, this approach can open several lines of research, either in the correlation between customers' subjective evaluations and engineering parameters, or in the complete specification of such engineering parameters based on consistent and widely agreed methods for the test conduction and the consequent data analysis.

An important result outcome from the work, as perceived by the manufacturer involved in this study, was the fact that its Current Test procedure based on a $-10°/+10°$ excursion of the loading arm was not correct for a proper boot characterization, as shown by the comparison with collected field data in Fig. 6. In fact, the exaggerated negative values recorded during the φARM $= -10°/+10°$ tests for the two angles φSC and φCT could be corrected after a shift of the testing protocol of 5° on the positive direction, therefore giving preference to a New Test performed between φARM $= -5°/+15°$: evidence of this was found in Fig. 6 in terms of comparison between the maximum/minimum ratio values of both φSC and φCT angles. This lead to a more realistic testing of the boot: starting from a possible rearward unbalanced position (as recorded in the field tests), moving across the neutral angle towards the highest forward leaning angle. By recording the Moment–Angle curve, information about the slope of the curve, its linearity within the range and its degree of stiffening at the extreme positions can be observed and quantified (Fig. 7). This approach was undertaken by the manufacturer and is at present being implemented for all its boot production and communication [28].

After comparing the angular velocities ωCT* estimated at the shell–tibia joint measured in the field (Table 3) with the maximum values recorded in the quickest test (arm angular velocity of 16.6°/s), the laboratory maximum angular velocity of the arm resulted to be smaller than the field pole recorded velocities ωCT* for about a factor of 10: this involves that the test bench (Walkmeter®), as it is designed and controlled now, is not able to reproduce the material properties dependency on strain rate that the real boot can experience in the field. Therefore, the stiffness properties that can be evaluated on a test bench working at such small angular velocities are mostly conventional evaluations of the overall behavior of the boots. From the results of the present tests, the influence of the test speed on the maximum/minimum values of the bending moments at the cycle extremes was negligible within the tested angular speed range (between 4.6°/s and 16.6°/s): more tests are needed to explore the effect of test speeds reaching the peak values of 160°/s in flexion and 190°/s in extension, provided that a suitable test machine is available, to state which value of the angular velocity shall be prescribed in a standard test method.

An interesting analysis of the available results regards the comparison between the estimated shell–tibia angles φST* and the loading arm angles φARM, as it can be evident for the reanalysis of data of Table 4: all three boots show (at 5 °C and 4.6°/s) a range of φST* close to 24°, for a given arm range of 20° as controlled by the loading arm. The laboratory tests thus confirmed the additive property between the two joint angles as a method to estimate the φARM angle with a possible conservative error of +24 %. On the other hand, the field range values of φST* resulting from the snow test (Table 2), reduced by a 24 %, give a general confirmation to the laboratory test range of 20°, particularly for Boot #1, whereas Boot #2 and #3 would be corresponding to a slightly higher range of about 25°. These observations, together with the comparison of field and laboratory results as presented in Fig. 6, oriented the manufacturer to the introduction of the New Test φARM $= -5°/+15°$ [28].

In addition to that, some considerations regard the peak values of estimated φST* in the field tests: from the combined analysis of Tables 1 and 2, it can be noticed that the sum of the neutral angle and the maximum forward angle φST* for the three boots in poles slalom gives consistently a value around 52° forward flexion for the three boots: this means that, despite the great difference among the boots, the same skier tends to reach the same tibia–shell postural angle when performing the same slalom in the same snow conditions. Given the strong differences in boot stiffness between at least Boot #1 and Boots #2 and #3, this means that the pole slalom was performed with the tester applying different bending moments to the boot, higher for Boot #1 than for Boot #2 and #3, to reach the same lower leg posture. A combined acquisition of kinematic and kinetic data would be needed to evaluate whether skiers achieve their posture under force or displacement control, in analogy with some researches recently developed for mogul skiing [29] also to the alpine skiing. Correspondingly, it would be clear if it is more correct to perform boot flexural stiffness tests under controlled extreme moment values or under controlled extreme flexion angle values.

6 Conclusions

Three pairs of ski boots presenting different nominal "Flex Index" were selected for the study: Biometrics electrogoniometers were placed on the boots, one between shell and cuff, the second between cuff and tibia and one on the skier's knee. A racing ski athlete, wearing a portable data logger, executed two repeated runs on spring snow with each ski boot performing pole slalom turns and free slalom turns. The maximal forward and rearward excursions of the cuff relative to the shell were determined to be $+0.8° \leq \varphi\text{SC} \leq +6.7°$ on a racing boot (stiffness $K_5^{FW} \approx 15$ Nm/°) and $-1.2° \leq \varphi\text{SC} \leq +10.9°$ on a soft boot (stiffness $K_5^{FW} \approx 10$ Nm/°). Furthermore, given an overall tibia flexion with respect to the boot sole, the amount of flexion due to the shell to cuff motion in the field tests was about the 24 % in a stiff boot ($K_5^{FW} \approx 15$ Nm/°) and about 33 % in a soft boot ($K_5^{FW} \approx 10$ Nm/°).

The same instrumented boots underwent a laboratory test session performed in a climate chambers at 20 and 5 °C: a loading arm, cyclically flexing between −10° and +10° from the neutral axis, acted on a silicon foot prosthesis inside the boot, while recording the bending moment, the arm angle, and the angle at the boot joints. In this case, the amount of flexion due to the shell to cuff motion is about the 50 % in a stiff boot ($K_5^{FW} \approx 15$ Nm/°) and again about the 34 % in a soft boot ($K_5^{FW} \approx 10$ Nm/°). Results indicated that the −10°/ +10° Current Test setup gave unrealistic negative values of the boot flexion: a better replication of field behavior was assumed to be obtained with a New Test setup where $-5° \leq \varphi\text{ARM} \leq +15°$. In addition, angular velocities encountered during expert skiing on snow, higher for the softer boots, resulted about ten times higher than the maximum angular velocities applied by the machine at its maximum frequency. The influence of the test speed was negligible within the tested angular speed range, a stronger effect of test temperature was detected on the three tested boots. Clear definitions of Flex Index (Nm) and of boot stiffness (Nm/°) as agreed with the boot manufacturer involved in the study were introduced to quantify the flexural behavior of boots and their classification, as well as to guide the users in the boot comparison and selection process.

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