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ORIGINAL ARTICLE

Torsion and bending loads on a ski-touring boot shell during uphill and downhill skiing

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Abstract

Ski touring is an established winter activity that has experienced a recent increase in popularity. Differently to alpine skiing, skier gains altitude without lifts, thus equipment weight must be minimized. Nevertheless, structural properties of the equipment, such as ski boots, must be adequate to withstand skiing loads. Several studies provided data on flexural stiffness of alpine ski boots in bench and field tests. The present study focused on the torsional properties of ski-touring boots. Indeed, touring bindings design implies a higher torque transmission to the front piece which induces a torsional load throughout the shell. To conduct the study, we prepared a ski-touring boot with strain gage bridges, and we performed bench tests to determine the stiffness of the boot and the bridge sensitivity. We also positioned and calibrated strain gage bridges to measure bending load in the shell and axial load in the ski/walk lever placed between shell and cuff of the boot. Then, we conducted a field test measuring the loads during a ski-touring trip including ascent and descent. Bench tests evidenced linearity of the torsion sensor, and a variation of stiffness depending on dummy leg absence/presence and boot buckle setting. Field tests showed torque ranges of 17 Nm in climbing and of 27 Nm in skiing. Bending moment range on the boot shell was of 150 and 228 Nm, respectively. Maximum force on the ski/walk mechanism reached 570 N. Results could be useful to test ski-touring boot performances and to optimize their design.

Keywords Ski touring · Ski boot · Shell · Lever · Winter sports

1 Introduction

Ski-touring is an established winter/spring activity in mountain regions, and its pool of practisers has increased over recent years. The sport has various disciplines ranging from race to freeride with different requirements in equipment performances. Optimizing the weight of this equipment is crucial since the user must gain altitude with their own thrust. Despite the need for light equipment, the boot must be structurally adequate for safe and enjoyable skiing. A key parameter in the structural performance of a boot is its stiffness, which must be sufficiently high to help the skier drive the skis during turning.

Authors have studied flexural stiffness of ski boots for alpine skiing, evidencing its key role in injury risk [1]. Flexural stiffness of the boot is often expressed in terms of a flexibility index. Its definition could vary among different manufacturers, and the measured value is influenced by factors such as the prosthetic/human leg fitted in the boot and buckle closure [1–3], which, in turn, has an influence on ski boot ergonomics [4]. Besides the setting of the boot, the material properties are also intrinsically and strongly influencing its stiffness. Indeed, since ski boots are made of plastics, visco-elasticity and temperature are key factors contributing to the material modulus, thus influencing the boot stiffness [5, 6].

The torsional stiffness of ski boots, on the other hand, is less studied. A study on cross-country ski boots identified the torsional stiffness as a possible parameter for mass optimization [7]. Another study was conducted to evaluate the effect of metal plates screwed to the bottom

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of the sole on the torsional stiffness of the boot. The research evidenced the effect of different dummy feet (of the type of dummy foot) used to calibrate the sensor devices to measure torsional stiffness and of the buckle closure on the resulting torsional stiffness [8]. On this regard, companies have studied the boot sole behavior with the intention of increasing its stiffness therefore contributing to the overall ski-binding-boot torsional stiffness that comes into play during the early stages of the turn, from edge change to full conduction when the shovel catches the snow and initiates the carving process [8].

A proper knowledge of service loads acting on the ski boot is therefore useful to optimize its design and increase performance/weight ratio. Moreover, design practises such as the implementation of a finite element model need proper boundary conditions to be meaningful and could benefit from the physical feedback of local sensors (e.g., strain gages) to be validated. Indeed, service loads during skiing can be derived from loadcells positioned at the binding interface with the toe/heel pieces, or monitored with other wearable technologies such as pressure insoles [9–11]: but instrumenting the boot itself is an alternative solution that can be valid after appropriate calibration for the specific boot under investigation.

The present work aimed to (i) evaluate torsional stiffness of a commercial ski-touring boot, (ii) develop a sensorized boot suitable for in field application and (iii) collect loads acting on the ski boot during a typical ski-touring session. This combined approach was inspired by a previous study on ski boot flexural stiffness [3]. To do so, two gage bridges were positioned on the bottom of the shell of a ski-touring boot to evaluate torsion, and bending. A further strain gage bridge was positioned to measure cuff/shell loads at the ski/walk lever.

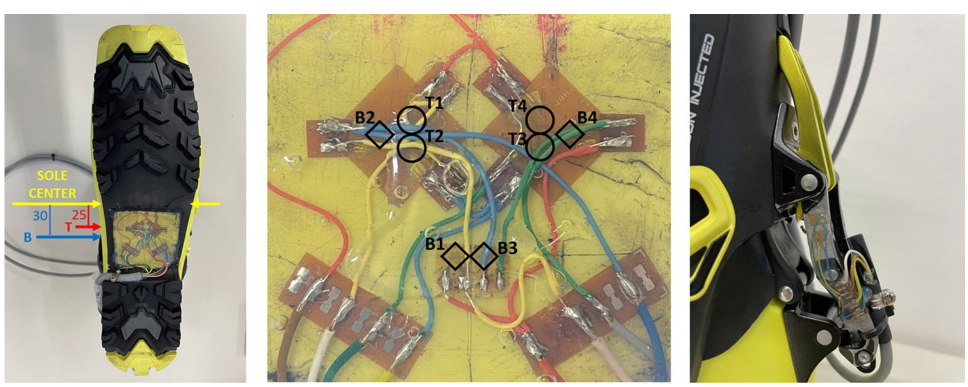
2 Materials and methods

2.1 Ski boot preparation

A pair of Zero G Tour Pro ski-touring boot (Tecnica, Italy), size 26.5 MP and mass of 1.32 kg/boot, were the object of the test. The left boot was prepared with the installation of three full Wheatstone bridges with strain gages. Two channels were installed on the bottom of the Grilamid® shell to sense torsion about the ski longitudinal axis and bending loads on the sagittal plane of the boot. A further bridge was positioned in the ski/walk mechanism to measure the axial load acting on the component.

To position the bridges under the shell, the rubber outsole was removed, and the surface was cleaned from glue residuals. Then, two strain gage rosette 1-RY18-10/120 (HBM, Germany) were glued symmetrically to the boot, aligned to the midpoint of the ski boot. Two further axial strain gages 1-LY18-0.6/120 (HBM, Germany) were positioned close to the rosettes, in a slightly backward position. To obtain the torsion and bending, the four 45° gages of the two rosettes were connected in a full bridge, and named T1, T2, T3 and T4. The bending channel was obtained by connecting the other two transverse gages of the rosette B2 and B4 together with the two longitudinal strain gages, named B1, B3. To instrument the ski/walk mechanism the external portion of the lever was cleaned from paint and four gages were positioned to sense longitudinal axial and transverse strain after completion of a full bridge. Detail of the strain gage positioning and bridge connections are shown in Fig. 1.

After the application of the strain bridge sensors, two shielded cables were soldered to the Wheatstone bridges and tightly secured to the boot. Finally, bridges were covered with SG250 silicone coating (HBM, Germany) for impact protection and water/snow impermeability: in total the added mass to the boot was about 0.1 kg.



a b c

Fig. 1 **a** Bottom of the shell instrumented with two strain gages bridges and covered with silicone for the outdoor test; **b** detail of the two full Wheatstone bridges of torsion (T1–T4) and bending (B1–B4); **c** ski/walk mechanism with strain gages and connection base

2.2 Ski boot calibration and bench tests

The calibration procedure of the three measurements channels was different based on the available machines and loading conditions. In each test, voltage data of the three sensors were acquired with SoMat eDAQlite data logger (HBM, Germany) at 100 Hz. Tests were conducted indoors at room temperature (25 °C).

The ski/walk mechanism was calibrated when removed from the boot, using a set of calibrated weights and a load cell (full scale: 1 kN). The loadcell was fixed to a frame, then the upper part of the mechanism above the sensing portion was suspended using a Kevlar cable. Progressive weights up to 370 N were attached to another cable tied to the lower end of the mechanism. A straight line was fitted to the data, and the sensitivity was defined as its slope. Ski/walk force was set positive when in tension, that occurs when the mechanism is in "ski" position (connecting shell and cuff in the back of the boot) and the skier leans forward on the cuff. Figure 2c shows the calibration procedure.

Shell bending calibration was performed by fixing the boot to two surrogates of the heel and toe piece of ski-touring bindings, manufactured by welding steel plates, and threading custom shaped bolts to replicate toe and heel piece pins. A Kevlar rope was placed over the midpoint of the ski boot shell and a set of known weights was applied for calibration, obtaining a three-point bending. To be representative of the usage, a prosthetic leg was fitted in the boot. This dummy leg was made of silicone rubber on the dimensions of an elite male skier's right shank and foot (size 26.5 MP), with a steel linkage replicating the skeletal structures (see Figure S1 in online supplementary materials). Tests were repeated both with and without the dummy leg. A straight line was fitted to the data, and its slope was extrapolated as the bridge sensitivity. The bending moment was set positive when stretching the bottom of the shell, as in Fig. 2b.

To calibrate the torsion bridge, the above described grip of the toe piece was combined with a heel piece surrogate made of two steel plates which clamped the rear of the boot like in an alpine binding. These grips were mounted on a torsional servo hydraulic machine (MFL System) to apply a rotation to the ski boot tip, while recording the torque on the boot heel with the integrated 400 Nm load cell. The ski boot was positioned in the machine and a static ramp up to ± 5 degrees was applied for calibration. Machine angular and torque sensors signals were acquired synchronously with the strain gage sensors of torsion and bending. Machine with the boot mounted for the test is showed in Fig. 2a.

Torsional tests were conducted in different configurations: (i) without the dummy leg and ski boot with open buckles; (ii) with dummy leg and ski boot with open buckles; (iii) with dummy leg and tightest closure of buckles. These configurations were tested to evaluate the effect of boot closure on bridge sensitivity and torsional stiffness. To obtain sensitivity, bridge voltage was linearly fitted with torque data, and the inverse of the slope was defined as the calibration constant. Similarly, torsional stiffness was computed as the slope of the best fitting line between torque and angle.

2.3 Field test

In-field test took place in Val di Zoldo (BL, Italy) on 26th May 2021. The route chosen for the test followed the first half of a classic ski-touring trail *Forca Rossa*, which is graded BS in Blacherè scale. Snow conditions, "firn", were typical for the late spring season. Outside air temperature was of 10 ° C and the weather was sunny.

To conduct the test, an experienced amateur skier skier (age: 26, weight: 70 kg, height: 175 cm) wore the pair of instrumented boots. The route described above was familiar to the skier. The participant signed an informed consent, and the test was approved by the institutional review board. To conduct the test, the participant connected the ski boot to a pair of Dynafit FT 6.0 skis (Dynafit, Italy), through Dynafit TLT Vertical ST (Dynafit, Italy) ski-touring bindings.

To acquire data, we fitted our datalogger in a compact backpack together with a 12 V lithium battery, adding about 5 kg to the participant's mass. Data of the three

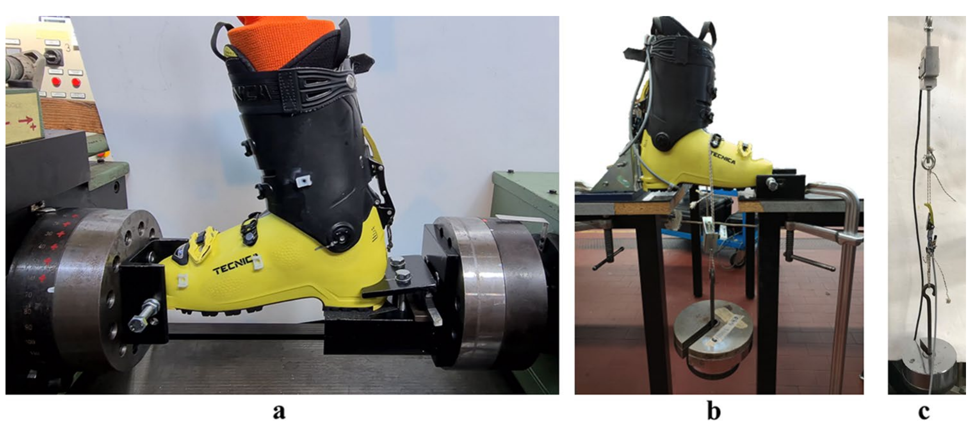


Fig. 2 **a** Servo hydraulic machine used to calibrate the torsion bridge and to evaluate the effect of prosthetic leg and buckle closure; **b** bending bridge calibration procedure; **c** ski/walk lever calibration

measurements channel were zeroed five minutes after the participant wore the ski boot to allow for fitting and thermal stability. During the test runs, data were sampled at 500 Hz. A GoPro Hero8 (GoPro, USA, 1080p at 60 fps) was fixed to the front of the left ski to view the participant and allow an easier interpretation of acquired data. The field test location and the participant prepared with the data acquisition system are shown in Fig. 3.

During the uphill phase, the participant was asked to perform a straight uphill climb, as well as right and left traverses with inversions. The participant walked at a self-selected speed for about 40 min, gaining 400 m of altitude. Each downhill skiing was performed in one go in the late morning: the participant started with some tight slaloms and ended the course with wider slaloms (Fig. 4d). The buckle closure was set equal to the indoor calibration test (Fig. 4a, b, c).

In-field test data were low pass filtered with a zero phase Butterworth lowpass filter (4th order, cut off frequency: 5 Hz). Cleaned data was analyzed to obtain the mean value, the maximum value and the minimum value reached during each phase. Moreover, by using Peak/Valley algorithms we identified and averaged each local maxima (Peaks) and minima (Valleys) of the signals during the test.

3 Results

3.1 Calibration and bench test

Calibration results of the bridges are reported in Table 1.

The tests conducted on the torsion machine evidenced a different torsional stiffness of 5.34, 6.43, 9.89 Nm/deg depending on whether the boot was empty or fitted with the prosthetic leg, and whether the boot was open or fully closed (Fig. 5). Similar differences were true for calibration constants of Table 1.

3.2 Field test

Results of the field test are reported in Table 2. Time history of load data are shown in Fig. 6. From these data, parameters such as range, mean and peak values could be extracted. Moreover, the sign of the torque could indicate the turning direction, and smoothness of the curve either skiing technique or snow type (icy, soft, etc.). Torsion bridge showed that when skiing downhill, torsion torque had a range of 27 Nm, centered around the zero value. In ascent phases the torque values were below 17 Nm, and there are differences in the mean value between left and right traverses. Bending bridge data showed similar behavior, with range up to 228

Fig. 3 **a** Uphill/downhill path of the test; **b** skier prepared with instrumented boot and data acquisition system

Fig. 4 Performed actions: **a** straight climb; **b** left traverse; **c** right traverse; **d** narrow and wide slaloms turns

Table 1 Bridge calibration results

Channel	Applied load [Nm] [N]	Output at maximum load [mV/V]	Calibration Constant [Nm/mV/V] [N/mV/V]	Linearity (R^2)
Torsion, empty	29.4	4.2	7.400	0.82
Torsion, dummy leg (open)	37.3	4.1	9.277	0.88
*Torsion, dummy leg (max closure)	55.4	5.0	11.772	0.91
*Bending	28.2	0.37	72.52	0.63
*Lever	370	0.6	2125.88	0.98

*Indicates constants used to retrieve loads during in field tests

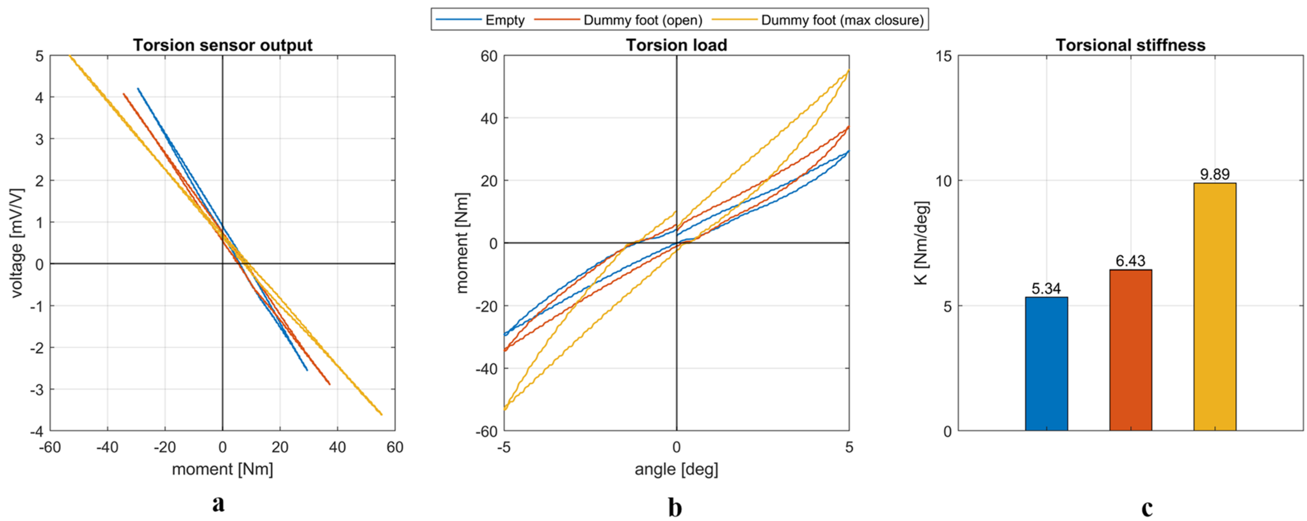


Fig. 5 **a** Electrical output of the torsion bridge during torsion test; **b** torsional response of the ski boot in different configurations; **c** calculated torsional stiffness

Nm in descend phase. Ski/walk lever showed a maximum of 570 N in tensile load and of -245 N of compression.

4 Discussion

Aims of the work were to (i) determine the torsional stiffness of a commercial ski-touring boot, (ii) develop a set of laboratory calibrated strain gage sensors suitable for in field application and (iii) collect loads during a typical ski-touring session. We conducted the experiments on a commercial, high-end, ski-touring boot. The tests aimed to measure loads acting in torsion and flexion of the shell and on the ski/walk mechanism after strain gage bridges application and laboratory calibrations, in conditions corresponding to field usage.

Particular attention was given to torsion behavior since the geometry of ski-touring bindings induces a higher torsion between the front and rear pieces, with the former contributing the most to the torque transmission to the ski. Thus, torsional stiffness of the ski boot is supposed to be more involved in providing control to the skier during skiing.

As shown by calibration results, tests repeated in different configurations and buckle closure conditions confirmed the need to conduct calibrations and stiffness characterization with a representative dummy leg and buckle closure. Indeed, stiffness of the boot was influenced by these two factors. Also bridge sensitivity was modified by these factors, suggesting a different load distribution when the dummy leg was placed inside the boot as well as when all buckles were closed. This evidence should be accounted for when modeling the boot in finite element analysis.

In-field tests allowed to determine torque and moment ranges in uphill and downhill phases. Torque ranges were similar between different subphases of uphill climbing and increased in downhill skiing up to almost twice the uphill values, reaching ranges of 17 and 27 Nm for uphill and downhill, respectively. Similar increases were true also for bending loads with ranges of 146 and 228 Nm respectively. Torque load curves were almost centered on zero indicating symmetrical behavior of the ski boot on the longitudinal axis. Bending moment curves instead were almost entirely

Table 2 Loads recorded during each phase

		Uphill			Downhill	
		Straight ascent	Left traverse	Right traverse	Wide slaloms	Narrow slaloms
Torque [Nm]	Mean	0.41	1	–1.93	1.36	–0.52
	Max	10.43	12.07	7.33	17.78	14.71
	Min	–4.61	–4.5	–8.56	–7.61	–12.53
	Range	15.04	16.57	15.89	25.39	27.25
	Peaks (std)	7.45 (1.47)	7.75 (1.89)	4.45 (1.04)	14.32 (3.80)	11.03 (2.12)
	Valleys (std)	–4.20 (0.33)	–3.55 (0.48)	–6.19 (1.46)	–6.23 (1.20)	–11.51 (0.61)
Bending moment [Nm]	Mean	30.66	25.67	42.89	71.62	93.95
	Max	96.06	73.14	141.1	209.48	208.02
	Min	–24.84	–28.4	–4.79	–18.51	11.27
	Range	120.9	101.5	145.9	228.0	196.7
	Peaks (std)	78.48 (10.08)	63.59 (7.70)	102.86 (15.13)	179.58 (42.28)	167.49 (21.52)
	Valleys (std)	–8.72 (7.97)	–8.20 (7.54)	0.37 (3.81)	–5.52 (18.38)	35.90 (15.28)
Ski/Walk axial force [N]	Mean	–	–	–	–13.42	–16.78
	Max	–	–	–	569.28	322.79
	Min	–	–	–	–245.25	–149.78
	Range	–	–	–	814.53	472.57
	Peaks (std)	–	–	–	273.54 (151.66)	92.74 (89.58)
	Valleys (std)	–	–	–	–90.45 (87.05)	–74.39 (34.56)

positive (i.e., with the shell curvature facing the ski) as the weight of the skier flexes the boot during turns.

About the rear lever sensor, ski/walk data showed peaks up to 570 N of tension, with lower values in compression (-245 N). This load could help understanding the posture of the skier during the activity. Given these results, we can identify both forward and backward leaning actions by looking if the ski/walk lever acts in tension and compression, respectively. The former was more intense in modulus but of short duration, where the latter were smaller but longer in duration and more periodical. This could suggest that peaks values obtained in forward leaning were linked with some instability of the skier after a wrong maneuver, while leaning backward during the turns was more linked with the specific skiing technique of the participant involved. However, behavior of the ski/walk lever is somewhat unclear from the collected data. This could be because the locking mechanism has a double point of action, and we were able to apply strain gages only on one of the two links composing the mechanism (see Fig. 1).

A test campaign involving more participants of possibly professional or elite skill level should be conducted to validate results and compare different skill levels and techniques on several routes. Moreover, as snow conditions in ski touring can vary, more tests should be repeated with softer (powder) or harder (icy) snow to evaluate its influences on loading. Another factor that should be taken in consideration for future test is the effect of temperature on the ski boot properties and on the applied sensors. Field test should be repeated in colder conditions, as well as calibration of the ski boot.

About the comparison with bench test data, field recorded torque was within the 100 Nm range applied in the calibration stage. We can also conclude that torsional angle of the boot was well below 5 degrees, as applied in calibration. However, in the field torque range was still higher than results for alpine skiing [8], obtained on different ski boots and with professional athletes. Values reported in the present study could be instead more useful to design and analyze ski-touring boots.

Further analysis should be conducted to compare torque transmitted to this ski-touring boot with standard alpine ski bindings to analyze differences. Given the different binding mechanism of the heel piece we would expect torque on the boot shell to be influenced by these binding conditions; on the other hand, the alpine ski stiffer construction with plates will have an influence as well on the torque loading the boot shell. More data coming from further sensors such as pressure insoles and pressure pads on the front and rear sides of the cuff could be helpful to better understand internal loading actions. Moreover, a set of tests combining the present instrumented ski-touring boot with dynamometric bindings [12] could give precious information on the load sharing between the boot and ski during skiing in different configurations and conditions.

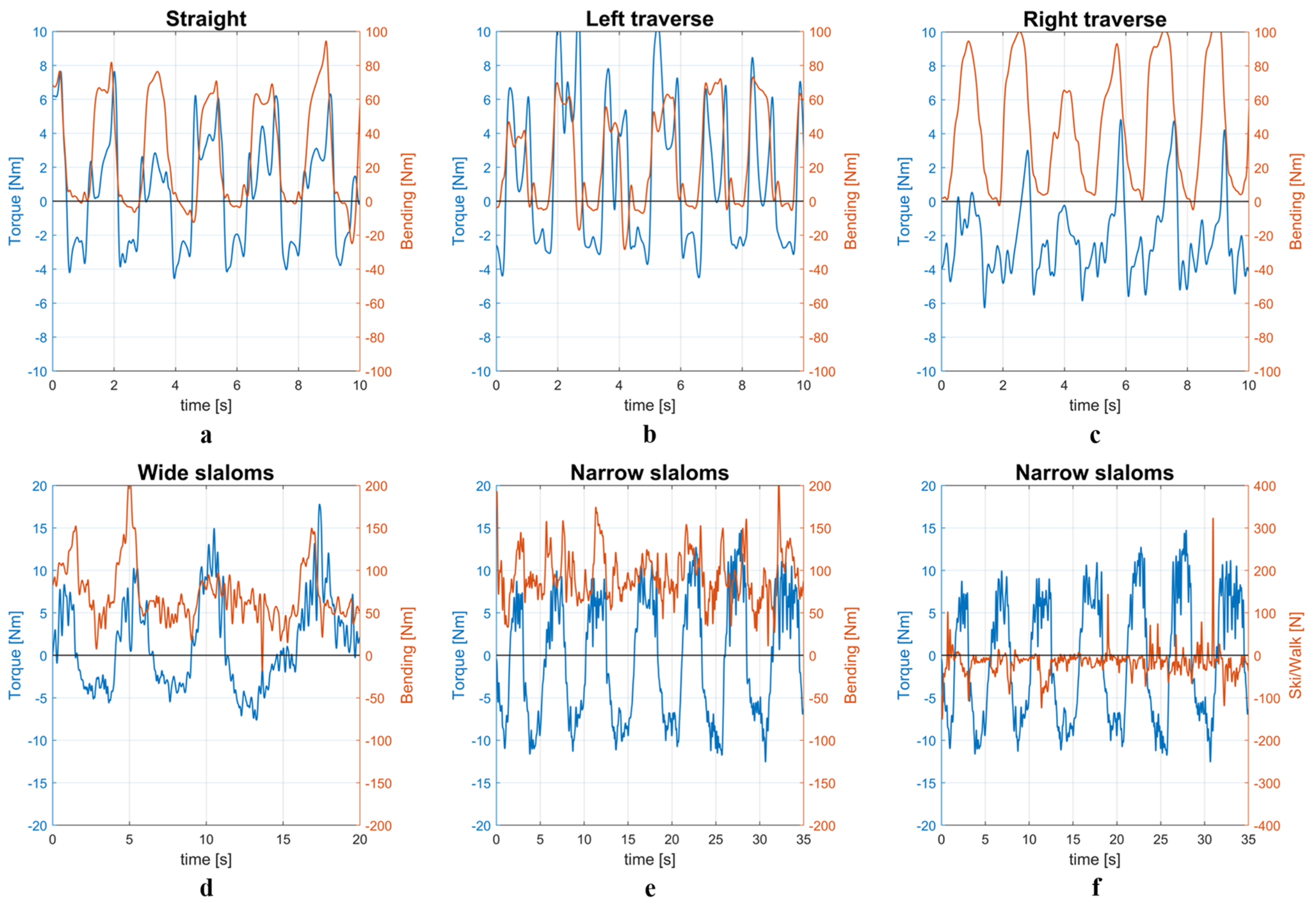


Fig. 6 Ski boot torque and bending during **a** straight ascent; **b** left traverse; **c** right traverse; **d** wide slalom; **e** narrow slalom. Leverage load and torque load comparison in narrow slaloms **f**

5 Conclusions

This preliminary set of tests was helpful to understand the loads acting on a ski-touring boot shell during use. The study evidenced the dependency of torsional stiffness of ski-touring boot on buckle closure and presence/absence of a dummy leg. Another outcome of the study is also a sensor to measure the torque on the shell during field test by using strain gages. Field tests showed torque ranges of 17 Nm in climbing and of 27 Nm in skiing. Besides torsion, also bending moment on the boot shell was recorded, resulting in a 150 and 228 Nm range for uphill and downhill, respectively. These results could be interesting to manufacturers who are interested in knowledge of ski boot loads to optimize their design.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s12283-023-00412-w.

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Data availability statement Research data can be shared by the Corresponding Author on request after an email describing the purpose of the data analysis.

Declarations

Conflict of interest The authors declare no conflict of interest.

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