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Analysis of the structural behavior of an innovative reinforced ski boot

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Abstract

The effect on the boot structural behavior of a stiffening aluminum bootboard has been investigated by laboratory and field tests. Stiffness tests on the boot with the bootboard screwed to the shell (state ON) showed a 20 % increase with respect to the unscrewed state (OFF). Lateral stiffness tests conducted on a servohydraulic test bench together with motion capture techniques did not show significant increases due to the bootboard. Strain gauges applied to the bootboard for measuring torsion and bending moments in the field confirmed the intervention of the bootboard torsional stiffness at the edge changes during slalom turns.

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1. Introduction

The ski boot is a very special piece of footwear that has been evolving since the early development of skiing. The different functions of the ski-boot can be stated as (i) transmitting control loads to the ski, (ii) enabling a quick connection and a safety release of boots from bindings, (iii) protecting the foot-ankle-shank complex from injuries due to overloads during falls and (iv) maintaining the foot pressure, thermal and humidity optimal conditions.

The effort of manufacturers is towards the maximization of all performance and comfort parameters of ski-boots with mass and cost reduction. A crucial role in the field of performance is played by the boot stiffness parameters as they influence the ability of quick transmission of control loads from the foot to the binding-plate-ski assembly.

The present work was carried out for evaluating the structural behaviour of an innovative ski-boot presenting an extruded aluminium bootboard (known also as “zeppa”) having not only a simple support function to the foot but also a reinforcing function due to the presence of four screws that can be connecting the bootboard to the shell sole. When connected (state “ON”), the overall stiffness of the boot was much higher that when not connected (“OFF”).

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The positive effect on the athlete of the new ski-boot was already studied in a previous work by means of a comparative EMG analysis of the same subject in special slaloms [1], leading to a reduction of main muscle activations when performing similar time trials.

2. Instrumentation

A pair of racing boots was equipped with a set of innovative bootboards made of an extruded aluminum profile with an additional upper layer of molded high density foam. The bootboard can be fixed to the plastic shell sole by means of four nuts inserted into the profile engaging with four screws that can be tightened (state ON) or un-tightened (state OFF) from the outside, as shown in Fig. 1.a. The bootboard will therefore be able to add a structural function to its usual function of supporting the inner boot sole.

On the lower face of the two bootboards a strain gauge rosette HBM 3-120-RY43 was placed with 0°/+45°/-45° gauge arrangement (Fig. 1.b), whereas on the upper face a longitudinal 0° strain gauge was placed in correspondence of the rosette (Fig. 1.c). The four strain gauges were connected as four single quarter bridge to a portable data logger.

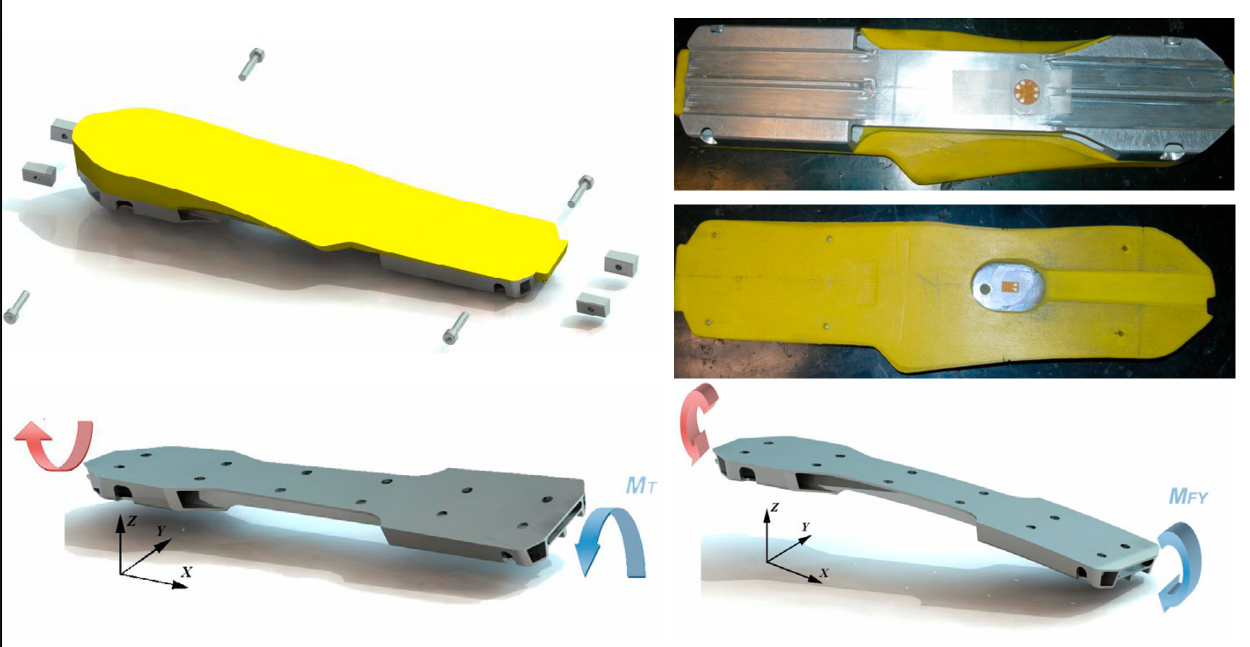

Fig.1. The instrumented bootboard used in the study. (a) Bootboard; (b) Lower face rosette (c) Upper face single strain gauge; (d) Torsional Calibration Mt. (e) Bending Calibration Mf.

The strain signal were measured by means of a Somat® 2300 Card Corder portable system, used both in the laboratory and the field tests: during the field tests on the snow, also a couple of MTI Xsens sensor was connected to the data logger to record the skis roll angles during the slaloms.

The Laboratory stiffness tests were performed by means of a test bench enabling to lock the heel of the boot and to apply a known torque by deadweights to the front sole (Fig. 2.a): the relative rotation was measured with a calibrated LVDT applied to the loading lever arm.

Cyclic tests on the boot were performed in the lateral direction by means of a servohydraulic MTS 242 cylinder under force control. The boot sole was fixed onto a Bertec force platform placed on the test bench (Fig. 2.b).

The boot deflection patterns under cyclic loading were recorded after installation in the test area of a Motion Capture system Smart BTS®, calibrated for measuring 1 m^3 volume around the boot. A set of 46 semispherical markers (6mm diameter) was placed on the boot surface to define a reticular mesh of control nodes (Fig. 2.c). This allowed a resolution of 0.1 mm in the spatial positioning of the reflective markers.

3. Methods

The strain channels on the bootboard were calibrated after application of know torsional (Fig. 1.d) and bending loads (Fig. 1.e) to the bootboard restrained as a simple beam. The direct and transverse sensitivity of each channel to the Torsion Moment Mt and the sagittal plane Bending Moment Mf were evaluated and used to estimate loads recorded in the laboratory and field testing.

The following laboratory tests on the boot in the different ON/OFF conditions were performed: (I) torsion and bending tests on the boot, after loading the sole, with the boot open or closed on a dummy silicon foot, (II) lateral and sagittal bending of the boot on a force platform in different conditions, (III) stereo photogrammetric analysis of boot deflections in the ON/OFF conditions.

The torsion tests were performed by applying an increasing value of Torque (maximum value 8 Nm) at a controlled temperature of 23°C and measuring the deflection after 1 min. of application. The test configurations were the combination of the Bootboard state (ON or OFF), the absence or presence of a silicon dummy foot (respectively ND or DF) and the state Open or Closed of the boot clips (respectively OP or CL). A test therefore will be identified by a sequence of letters such as ON_DF_CL (bootboard ON, Dummy foot inserted, clips Closed): this notation will be used also in the presentation of results. The Rear Restraint Torsional Stiffness Kt^{RR} in Nm/° was evaluated as the regression slope of Torque-Rotation diagrams in the different configurations.

The cyclic bending tests were performed after imposing a trapezoidal load history to the dummy foot shank, in the lateral plane. A reversed lateral bending moment of 72 Nm was applied to the boot sole with the boot fixed to the force platform at a frequency of 0.5 Hz. The cylinder displacement, the strains at the bootboards and the displacements of the reflective markers on the boot were synchronously recorded.

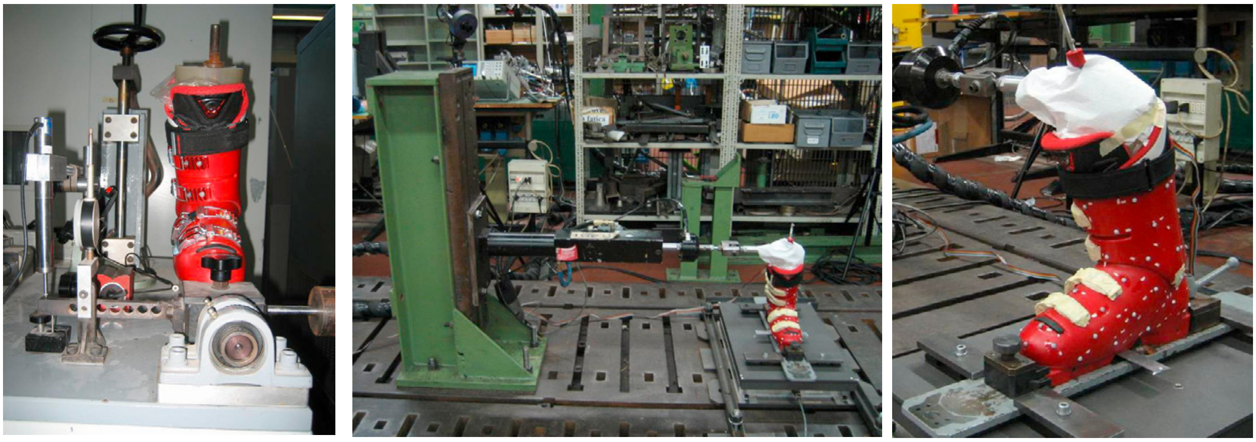

Fig.2. The Laboratory tests. (a) Torsional stiffness test setup; (b) Lateral stiffness tests setup. (c) Motion Capture setup for the collection of the boot displacement patterns during lateral bending.

The overall Lateral bending Stiffness shown by the boot at the hydraulic actuator K_{LB} in N/mm was evaluated as the regression slope of Load-Displacement diagrams recorded at the cylinder in the two configurations OFF_DF_CL and ON_DF_CL.

The motion capture acquisitions allowed to introduce a mesh of 46 nodes applied on the boot (Fig. 3.a) whose displacements were recorded during the load cycles. Local analysis of the displacement behavior of 5 linear Links at the boot shell (Fig. 3.b), plus 2 pins extending outwards from the sole arch, and of 8 structural sections defined along the boot (Fig. 3.c) were performed to evaluate the effect of the bootboard locally along the boot structure.

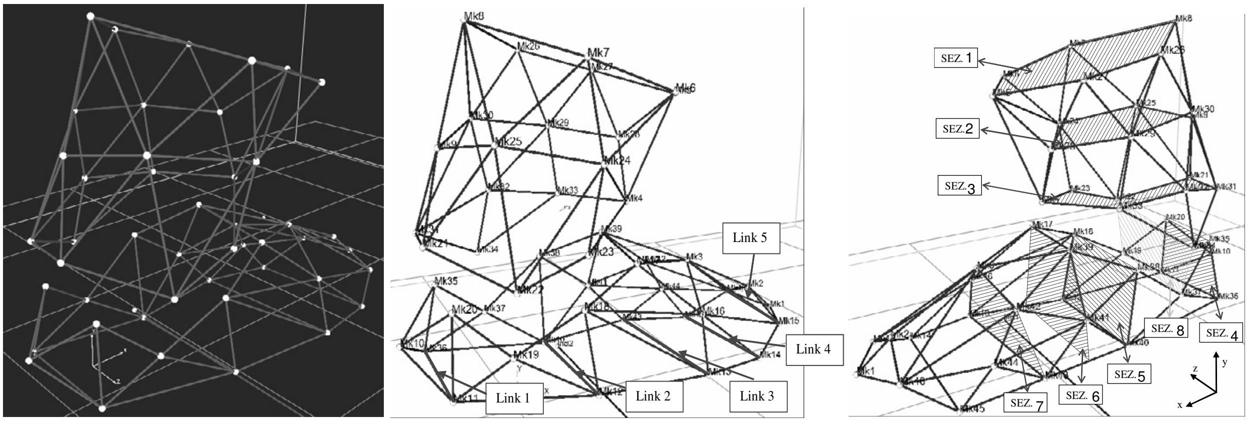

Fig.3. Displacement analysis by means of Motion Capture technique (a) Reticular mesh of 46 markers; (b) Linear Links at the boot sheel; (c) Control Sections along the Boot structure.

The Field tests were performed on icy snow by a professional ski tester with long experience in special slalom [1]. Ten short poles were placed in the snow (span 4 m, pace 12 m) along a medium slope. Two additional poles at a span of 60 m were employed to mark the free slalom area. The skier performed at least two courses for each type of boot (OFF & ON) starting with the slalom between the short poles and concluding with the 60 m free slalom.

4. Results

The results of torsion tests (type I) on the boot in the different configurations are reported in Fig. 4.a as Kt^{RR}. The test configurations most representative of the real skiing conditions are those with the dummy foot and the clips closed. Columns with bold borders correspond to the state ON of the bootboard: the last two grey shaded columns show that the bootboard in the state ON implies an increment of the 20.6% of Kt^{RR} Torsional Stiffness. The two independent effects of introducing the Dummy Foot and of closing the boot clips can be as well quantified from the stiffness values reported in Fig. 4.a.

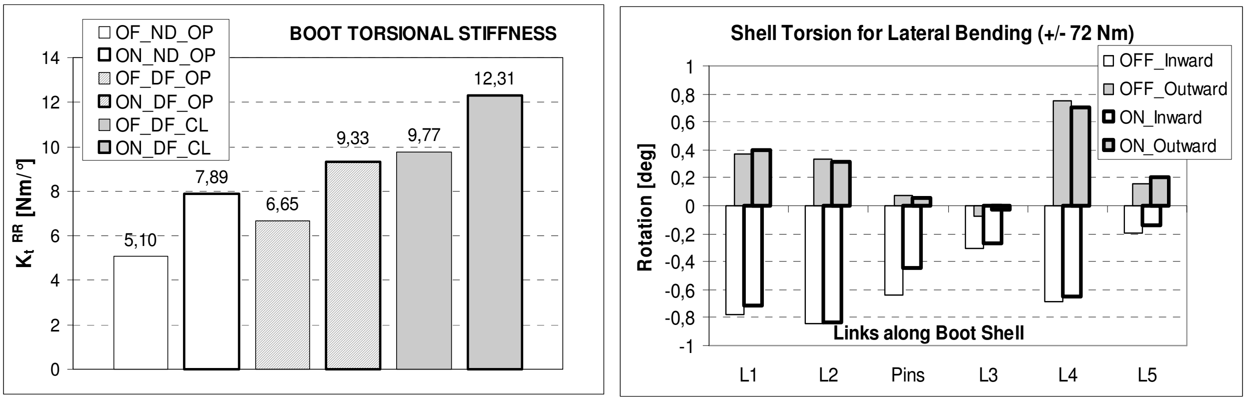

Fig. 4. (a) Results of Torsion Stiffness tests; (b) Results of motion capture local stiffness analysis on the boot shell.

In terms of Lateral Bending tests (type II) the effect of the bootboard introduction was not evident: the bootboard ON changed the overall lateral stiffness measured at the cylinder from K_{LB} (OFF) = 15.624 N/mm to K_{LB} (ON) = 15.961 N/mm, equivalent to only a +2.1% increase.

The local analysis of the boot displacement pattern during cyclic tests showed a complex behavior of the shell under lateral bending loads: as documented in Fig. 4.b, the links from 1 to 5 at the boot shell showed an asymmetric behavior when the boot was loaded symmetrically by Outward (positive) or Inward (negative) Lateral bending moments of 72 Nm. The rotation of the links from the heel (L1) to the tip (L5), including two additional pins that were stuck to the sole arch between L2 and L3, were expressing the shell Torsional behavior: as it can be appreciated from the analysis of Fig. 4.b, the shell showed a stiffer behavior under Outward Lateral bending, that corresponds to an internal ski turn.

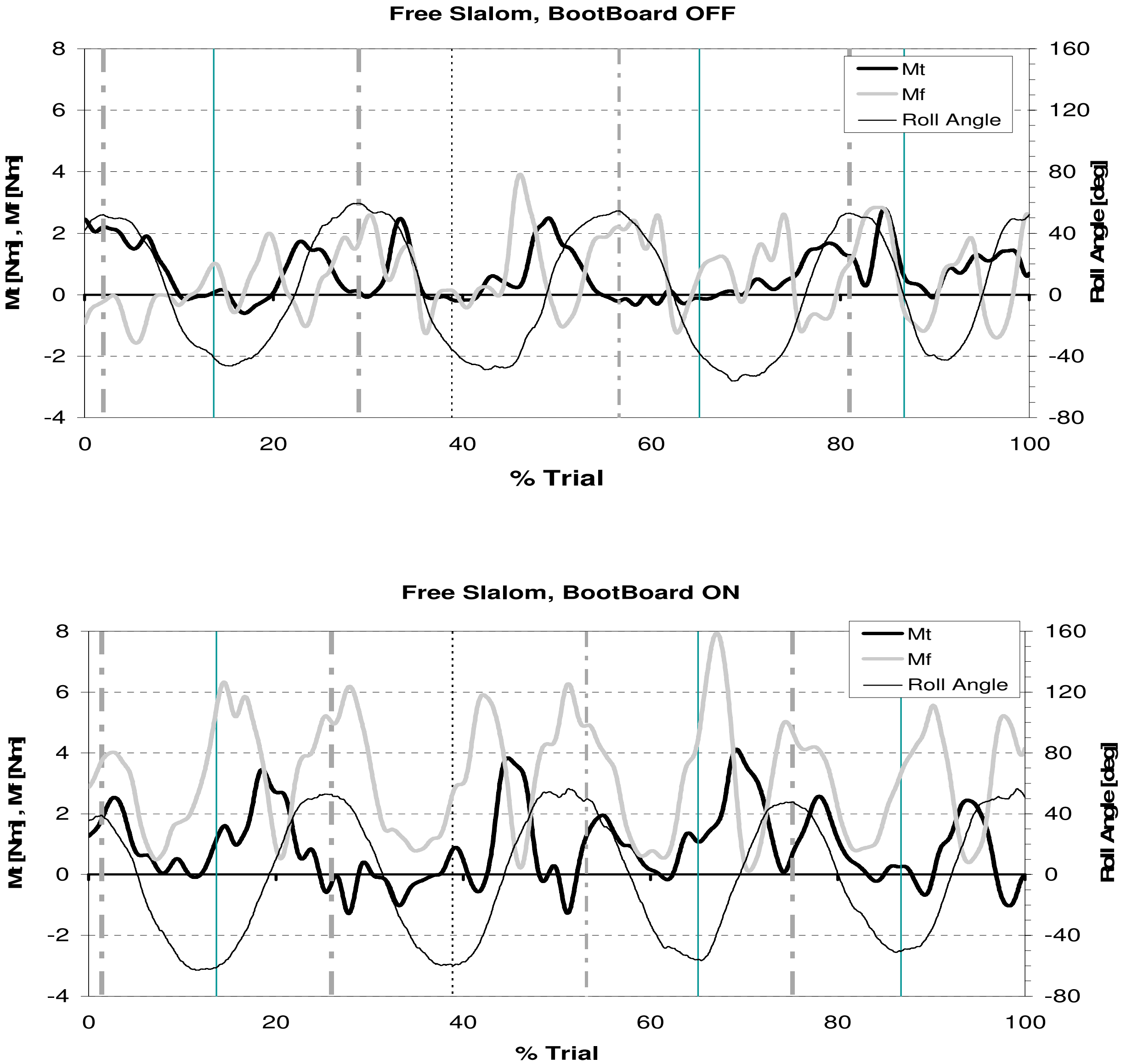

Fig. 5 . (a) Torsion and Bending moments at the Bootboard in the OFF state. (b) Torsion and Bending moments at the Bootboard in the ON state.

Field data results for the right ski-boot are presented in Fig. 5. The two free slalom skiing trials are presented in the two conditions of bootboard OFF and ON. The torsion moment Mt and bending moment Mf at the bootboard recorded by strain gauges are plotted synchronously to the roll angle. Maximum positive values of the roll angle correspond to internal curves of the right ski: null values of the roll angle correspond to edge changes. The bootboard is sensing torsion and flexion loads also in the OFF state: in the ON state, peak values of torsion and bending moments are almost doubled.

5. Discussion

The aim of the work was the evaluation of engineering parameters correlated to the enhanced performances that a boot reinforced with an innovative bootboard had shown in the snow tests. The increase of torsional stiffness of the boot shell was supposed to be the main reason of better skiing performances.

The stiffness tests results shown in Fig. 4.a confirmed the significant increase (20%) of Tip-Heel Torsional stiffness of the closed boot. On the other side, lateral stiffness tests gave no evidence of any global lateral stiffening, therefore inducing to consider the experienced advantage in skiing as correlated more with the contribution of the reinforced ski-boot to the overall ski-shovel torsional stiffness during transition from edge to edge rather than to its contribution to lateral stiffness during the steady curve conduction.

The application of strain gauges to the bootboard and its calibration allowed to measure the torques transmitted by the bootboard in the field and gave further confirmation to this interpretation. In fact, as it can be seen in Fig. 5.b, the peak values of the torque transmitted by the bootboard are found in correspondence of the edge transition from external to internal turn. In correspondence with the maximum roll values, both during internal or external turns, the torsion moment show minimum values, therefore suggesting that the bootboard stiffening effect is not requested when the ski is in full carving conditions. In those instants, bending contribution of the bootboard to the boot stiffness is maximized as expected, due to the peaks reached by the forces normal to the boot sole.

The application of motion capture techniques to the structural analysis of such deformable structures can be seen as a powerful advance in the functional analysis of boots: results as those of Fig. 4.b can be achieved relatively simply and give an insight into the boots deflection patterns: the trend of local twist angles along the shell can highlight areas where stiffening (or softening) is appropriate. In particular, about this boot, the highest torsional stiffness of the shell under lateral bending were shown in Outward bending, corresponding to an internal ski turn: this may be seen as unexpected given the fact that highest values of binding loads are reached during external ski turns [2]. In addition to that, the analysis of deformation of cross sections along the boot during loading cycles can give quantitative information about possible discomfort reasons at the medio/lateral malleoli. In any case, these type of measurements can act as validating tools for the numerical model of such complex structures as the ski boots are.

In terms of boot technical development, the study confirmed the correlation between high values of torsion stiffness and top slalom performances.

Acknowledgements

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