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ScienceDirect

Procedia Engineering 72 (2014) 630 – 635

Procedia Engineering

www.elsevier.com/locate/procedia

The 2014 conference of the International Sports Engineering Association

The effect of buckle closure and temperature on the in-vivo flexibility of ski-boots: a pilot study

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Abstract

Stiffness properties of ski-boots in forward/backward flexion are fundamental in characterizing their level of performance considering that they have to transmit control loads from the skier to the skis. Despite their importance, the mechanical characterization of the ski-boots still lacks of a standardized laboratory method. Ski-boot behavior can be influenced by several factors in addition to their construction, such as buckles level of closure and environmental temperature.

The aim of the present work was to measure the "in-vivo" bending moment and the shell/tibia angle at two temperature conditions and two levels of buckles closure. A force plate, a portable dynamometric ski plate and two biplanar electrogoniometers allowed measuring the above mentioned parameters during simulated forward flexions as well as during real skiing on the slope of an expert skier. This allowed producing synchronous data of ski-boot hinge bending moment and of shell/tibia angle during skiing sessions that were not yet available in the literature.

Results concerning the relationship between ankle bending moment and shell/tibia angle didn't show a correspondence between simulated flexions and real skiing: these findings will require further investigations to lead to possible standard laboratory test procedures simulating the real skiing.

Selection and peer-review under responsibility of the Centre for Sports Engineering Research, Sheffield Hallam University

"Keywords: ski-boots;flexibility;buckle closure;temperature"

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Selection and peer-review under responsibility of the Centre for Sports Engineering Research, Sheffield Hallam University
doi:10.1016/j.proeng.2014.06.108

1. Introduction

Ski-boots are one of the most important pieces of equipment in skiing for the following two factors: (i) they protect the tibia and the foot from the solicitations occurring during skiing on the slope; (ii) they transfer to the skis the loads applied by the skier's body allowing the ski to carve into the snow and to obtain the desired trajectory.

Considering the importance of the boots, different investigations have been conducted in the last years regarding their effect on skiing safety (Senner et al. (1996), Bohm & Senner (2008)), their structural behaviour (Corazza & Cobelli (2005), Petrone et al. (2008)) and the methods to quantify their thermal comfort (Fauland et al. (2011), Hofer et al. (2013)). A recent work (Petrone et al.(2013)) focused on the introduction of engineering parameters regarding the quantification of the ski-boot flexural properties, after field data collection of kinematic data such as the flexion angles between the tibia and the boot elements. There is however a lack of kinetic field data referred to the boot, as most of the available field data are reported with respect to a ski reference system.

From an engineering point of view, the mechanical properties of a boot are usually communicated by the manufacturers with the Flex Index which would be intended to represent the boot flexibility in forward flexion, given a repeatable test procedure. Because an international standard test (ISO) procedure has not been introduced yet, the collection of experimental data is still useful to define and propose meaningful standard test methods (Petrone et al.(2013)). Aim of the present pilot study was to collect the in-vivo flexural behavior of ski boots in term of the ankle bending moment and the tibia/shell flexion angle while introducing the effect of the environmental temperature and the level of buckle closure. The collected data could be useful to optimize standard test procedures allowing a better characterization of the mechanical and dynamical properties of the boots.

2. Materials and Methods

2.1. Instrumentations

Concerning the skiing simulation, bending moment about the ankle joint was measured fixing the right ski on a Kistler force platform sampling at 500Hz. A portable dynamometric plate (Petrone et al. (2008)) was also placed between the right ski and the binding. This setup allowed to compare the output data of the force platform with the dynamometric plate data to verify their comparability in term of bending moment. Therefore two biplanar electrogoniometers were applied on the boot to measure the shell-cuff (φSC) and the cuff-tibia (φCT) angles (Petrone et al.(2013)). Goniometers and dynamometric plate on the right ski were synchronously recorded by means of a PDA (BTS Bioengineering, 0.3 kg mass) at 1kHz . A pair of HEAD Edge ski-boots (nominal Flex Index 80) was used by the tester: the ski-boots presented four buckles and a strap (Fig. 1b).


(a) (b) (c)

Fig. 1. (a) Particular of the right ski with the dynamometric plate fixed on the Kistler force platform (side view); (b) Placement of the two goniometers on the right boot and the tibia. (c) Set up for the simulated forward flexion runs on force platform at ambient temperature.

2.2. Test protocol

An expert skier (85 kg mass, 1.90 m height) was involved in this pilot study. The session took place on June 2013 in the Stubai glacier (AT) at an environmental temperature of 4°C. The first step was the placement of the goniometers on the skier right boot and tibia (Fig 1b). Then the instrumented ski was fixed on the force platform (Fig 1a) in indoor conditions (20°C). The left ski was placed on a wood support in order to have both the skis at the same height from the ground allowing a realistic simulation of forward flexions. The skier was asked to perform immediately after his preparation a maximal forward flexion followed by a maximal backward flexion. Then he simulated the action of skiing performing five consecutive mild forward flexions followed by five consecutive deep forward flexions. The sequence described above was repeated twice with two defined levels of buckle closure: soft and strong. The buckle closure was controlled by the position of the buckle hook on the buckle rail: strong closure was the closure preferred by the skier, soft closure was obtained by releasing the two upper buckles by two teethes each.

After the skiing simulation on the force platform, the skier performed four runs of real skiing on the slope: two with soft buckle closure and two with strong buckle closure. For each run the slope was divided into two parts: in the first the skier performed a slalom among 16 short poles and in the second one he performed repetitive free carving without poles. Immediately after skiing on the slope the subject repeated again the skiing simulation with the right ski fixed on the force platform with the same two levels of buckle closure, soft and strong.

The first session on the force platform was performed immediately after the skier preparation in a room with a constant temperature of about 20°C, so in a “warm” condition The second session was performed outside, after skiing on the slope, so in a “cold” condition, at ambient temperature of 4°C. Therefore the effect of the temperature as well as of the buckle closure on the boot flexibility was investigated in the present study.

2.3. Data analysis

A set of customized protocols were developed for data analysis using SMART Analyzer (BTS Bioengineering, Italy). The ankle bending moment M_A was calculated as the moment of the Resultant Ground Reaction Force with respect to the hinge of the boot between the cuff and the shell. All data collected on the slope were filtered with a fourth order low pass Butterworth filter (cut-off frequency of 2 Hz). Following the method proposed by Petrone et al. (2013), the angle between tibia and shell (φST) was estimated as the arithmetic sum of the two measured angles φSC and φCT. The right boot was initially lifted from the ground to measure its neutral angle that was then taken as zero. Positive values of angle and moment were associated to forward bending, negative to backward bending.

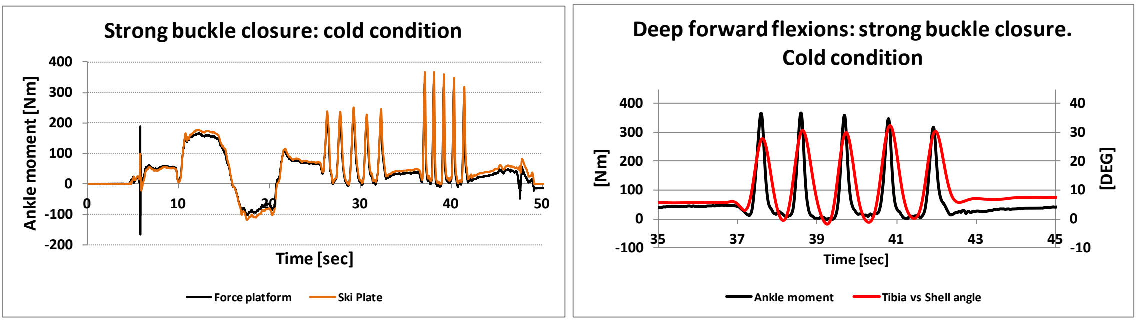
The ankle bending moment and the φST angle were compared at the two different levels of buckle closure and at the two different temperatures.

3. Results

From the comparison of the ankle bending moment calculated with the Kistler force platform and the moment recorded with the portable dynamometric ski plate (Fig. 2a), a very good correlation was found confirming that the two instrumentations gave comparable results and that the portable dynamometric ski plate was suitable for collecting data in the field. The curves show how the tester was out of the bindings during the first 5 sec, stepped into the bindings, performed maximal forward flexion (11-15 sec) and maximal rearward flexion (16-20 sec), then completed the two series of mild and deep simulated flexions.

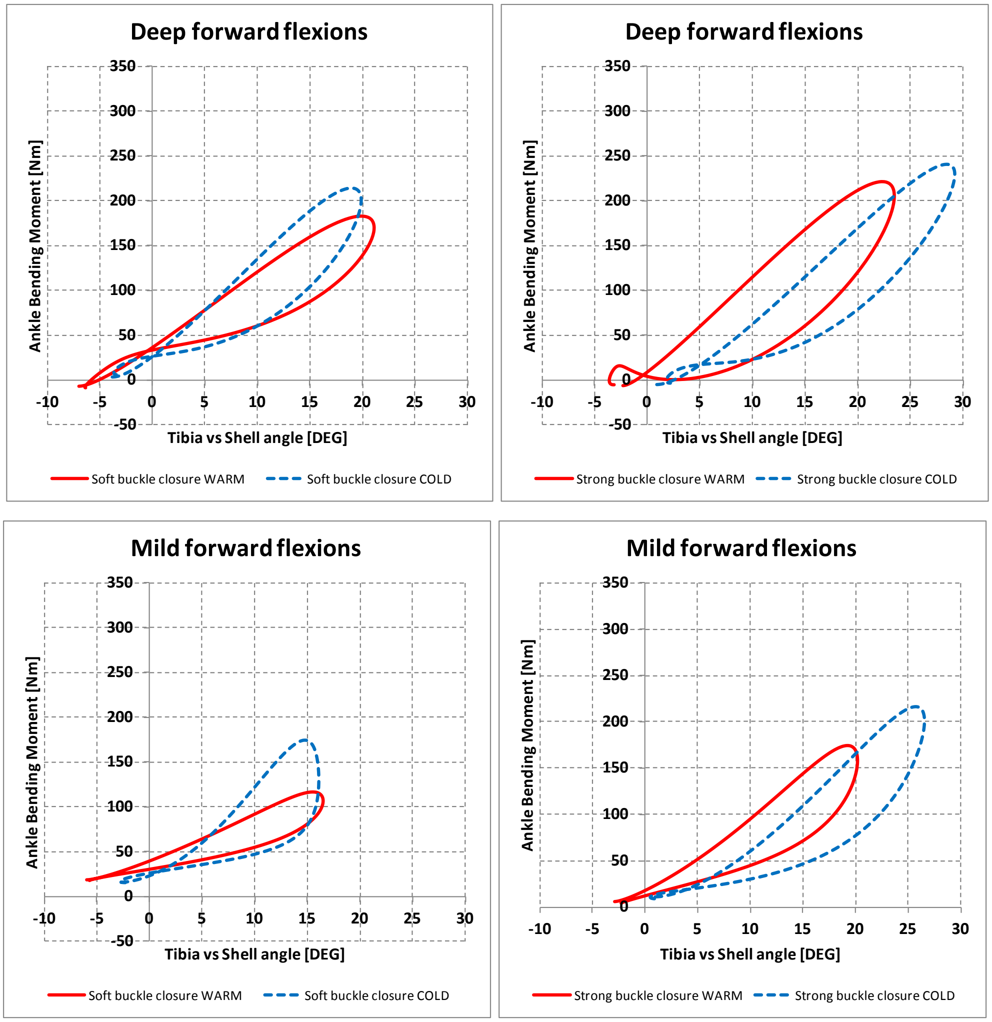
A detailed view of the ankle bending moment and the φST angle curves during simulated deep flexions is reported in Figure 2b. Forward flexions from the neutral angle induced positive bending moment: forward φST angle peaks and bending moment peaks result to be almost synchronous, whereas the angle curves show a certain degree of delayed decrease that is also indicated by the hysteresis in the moment-angle curves (Fig. 3).

The effect of environmental temperature and buckle closure during simulated skiing on a force platform is reported in the cross plots of Fig. 3. Each curve represents the mean curve among 5 flexion cycles.



(a) (b)

Fig. 2. (a) Superposition of the ankle moment data output from the Kistler force platform and the dynamometric ski plate; (b) curves of the ankle bending moment and the φST angle in five deep simulated forward flexions performed on the platform.



(a) (b) (c) (d)

Fig 3. Effect of environmental temperature and buckle closure represented by cross plots between φST angle and ankle bending moment (mean curves out of 5 cycles): deep forward flexions (a) and (b); mild forward flexions (c) and (d).

The main hysteresis loops showed in the first quadrant starting from the origin are deployed clockwise: this corresponds to the evidence that the angle first increases almost synchronously with the moment, but subsequently the angle stays longer around the peak value while the moment rapidly decreases. This behavior has already been justified with the nonlinear and viscoelastic behavior of the soft tissues in the tibia, the liners foam and the plastic of cuff and shell (Petrone et al.(2013)), together with the friction between moving parts. A tendency to a right shift of about 5° of the loops obtained in the cold conditions and strong closure is evident: it has to be noticed that between the two simulated flexion tests performed on the platform, warm and cold, a skiing session was carried out by the tester. Ankle bending moment M_A and angle φST values during skiing on the slopes are reported in Fig. 4 for all the different conditions: level of buckle closure (Strong and Soft) and type of tracks (slalom among short poles and free carving).

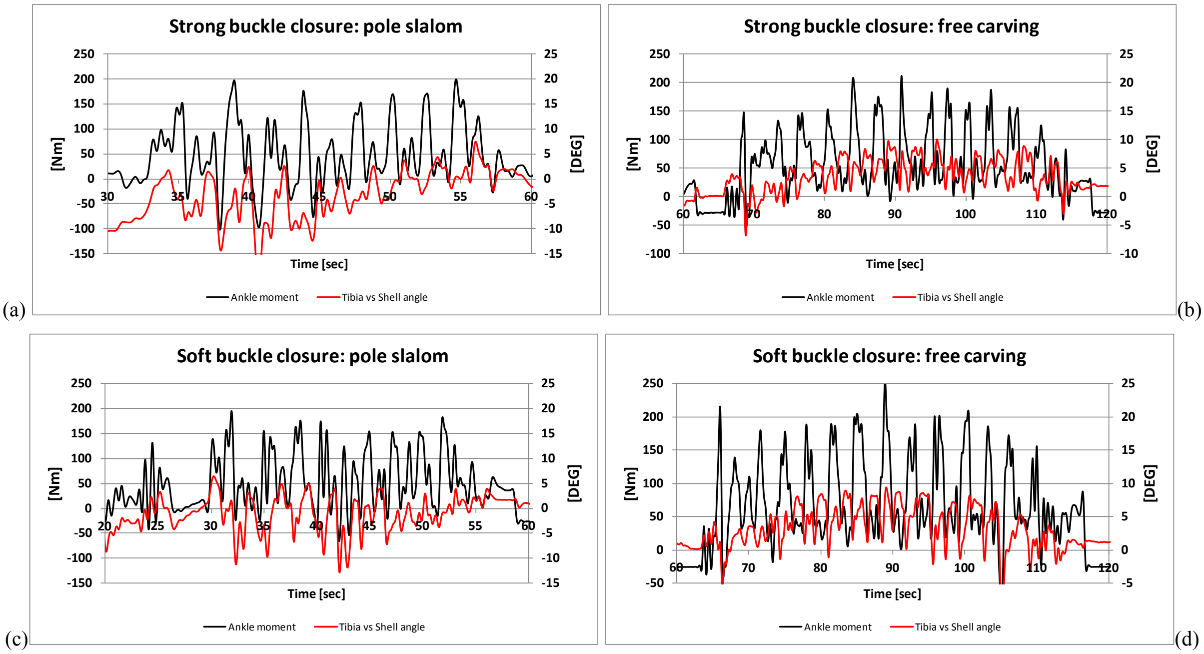


Fig. 4. Results of field tests. (a),(b) strong closure pole and free slaloms; (c),(d) soft closure pole and free slaloms.

From the field collected data, the attempt of the tester in performing repeatable turns can be appreciated, mostly in the free slalom portions, where the angle values are more consistently positive. Forward peak values of the ankle moment M_A (not greater than 250 Nm) are in agreement with the simulated flexion peak moments (Fig. 3) in deep flexion. Skiing technique seems more repeatable in free slalom: video analysis confirmed that the peaks correspond to the left turns when the right ski is external. However, from the comparison of Fig. 1.b and Fig. 4.b, the tendency to synchronicity between M_A moment peaks and φST angle peaks experienced in simulated flexion seems not to occur in real skiing, where the major peaks of the φST angle occur almost counter phase with M_A major peaks.

4. Discussion and Conclusions

The aim of the present work was to study the effect of the environmental temperature and of two different buckle closures on the in-vivo flexural behavior of the boots. The fact that data were collected on a single day at mild temperature (4°C), from a single subject using a single type of ski-boots is the major limitation of the work.

Nevertheless, the tests in the field allowed collecting important values of the ankle moment M_A that can orient future tests and can be used in the development of representative laboratory tests.

The inclusion of in-vivo simulated forward flexions in the research is due to the hypothesis that these actions may be representative of what a skier does in the slope while carving with his own skis. In this sense, it was expected that the presence of the vertical ground reaction force acting on the boot sole, the non-constant value of the angular velocity of the φST angle and the presence of a human tibia make the data obtained from the in-vivo procedure more realistic with respect to laboratory test where a prosthetic tibia and foot is used, the angular velocity is small and the flexing action is obtained by a pure moment M_A applied about the ankle hinge. Despite this, there is a general similarity between the rounded hysteresis loops recorded "in-vivo" on the force platforms and the hysteresis loop shape recorded "in-vitro" on a flexing test machine (Petrone et al.(2013)).

On the contrary, the fact that major peaks of the φST angle occur almost counter phase with M_A major peaks during real skiing (Fig. 4) opens the need of further detailed analysis of the mechanical behavior of ski-boots during external (maximum) and internal (minimum) turns. Unexpectedly, at low values of forward flexion angle the bending moment was high, at high values of forward flexion angle the bending moment value was low.

Graphs presented in Fig. 3 show that the backward flexions of the skier were less marked when a strong buckle closure was adopted, both in the deep and the mild flexions, while forward flexions were more pronounced again in the strong buckle closure condition. We can speculate that the range in the forward flexion with a soft buckle closure was reduced because the skier felt less confident and less supported by the boot structure.

In the cold condition an overall shift of the hysteresis loop was detected with strong buckle closure while not significant changes were detected with the soft closure. This can be interpreted as the inability of the boot in the strong-closure cold conditions to return back from its flexed position. However, if comparing the "warm" Vs "cold" raising branches of the loops in the strong closure conditions, the two branches seem to have the same slope, which is the same Stiffness (Petrone et al.(2013)): this is again an unexpected result considering that the cold temperature should have stiffened the boots. On the contrary, the effect of temperature in the change of slope of the loops (Stiffness) is evident in the soft closure conditions, in conjunction with the ski-boot liner contribution.

The work results indicate the need for a further deeper analysis of the mechanics of the ski-boot both in field test sessions and in laboratory tests, to converge towards a meaningful definition of standard test methods and engineering quantitative parameters.

Acknowledgements

The work was conducted within the Interreg IV project "Pro-Fit-Boot", Nr. 6602-27.

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