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Research article

AN INNOVATIVE SKI-BOOT: DESIGN, NUMERICAL SIMULATIONS AND TESTING

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ABSTRACT

The present work is concerned with the design of an innovative ski-boot. In order to optimize ergonomics and biomechanical behavior of the ski-boot it is important to take into account the orientation of the leg with respect to the ground. The SGS system (Stance Geometry System) developed in this work allows the skier to adjust for posture in the frontal plane by rotating the sole of the boot about the antero-posterior axis (ski-boot is then locked in the desired position before skiing). A simplified model of the effect of ski-boot deformation on skiing behavior is used to evaluate the minimal stiffness the system must have. An experimental analysis on the ski slopes was carried out to provide ski-boot deformations and loading data in different skiing conditions, to be used in numerical simulations. Finite Elements Method (FEM) simulations were performed for optimal design of the joint between ski-boot and sole. The active loads and local ski-boot deformations during small- and large-radius turns were experimentally determined and used to validate a FEM model of the ski-boot. The model was used to optimize the design for maximum stiffness and to demonstrate the efficacy of virtual design supported by proper experimental data. Mean loads up to 164% body weight were measured on the outer ski during turning. The new SGS design system allows the adjustment of lateral stance before using the ski-boot, optimizing the ski-boot stiffness through FEM analysis. Innovative aspects of this work included not only the stance geometry system ski-boot but also the setup of a virtual design environment that was validated by experimental evidence. An entire dataset describing loads during skiing has been obtained. The optimized SGS ski-boot increases intrinsic knee stability due to proper adjustment of lateral stance, guaranteeing appropriate stiffness of the ski-boot system.

KEY WORDS: Stance geometry system, stiffness, virtual design environment, FEM analysis, skiing performance.

INTRODUCTION

Skiing is a winter sport enjoyed by approximately 200 million people in the world, with an overall injury rate of approximately 3 per 1000 skier-days (Hunter, 1999). A large percentage of injuries involve the knee joint, especially in adults (Deibert et al., 1998, Schneider, 2003). Several studies on ski dynamics (Gerritsen et al., 1996; Langran et al., 2002; Sutherland and Holmes, 1996) have demonstrated the importance of a proper skiing posture for safer skiing and faster learning. Some studies also addressed directly the relation between ski-boot design and load at the knee joint (Schaff et al., 1993). More than 30% of knee injuries are caused by excessive ligament strain. Similar to knee injuries, ankle or foot injuries (~7%) are due to skiing dynamics and skiing posture. In general, since many skiers have valgus or varus leg alignment, proper skiing posture is normally achieved only when the ski-boot sole is machine milled until a good posture is obtained (as determined subjectively

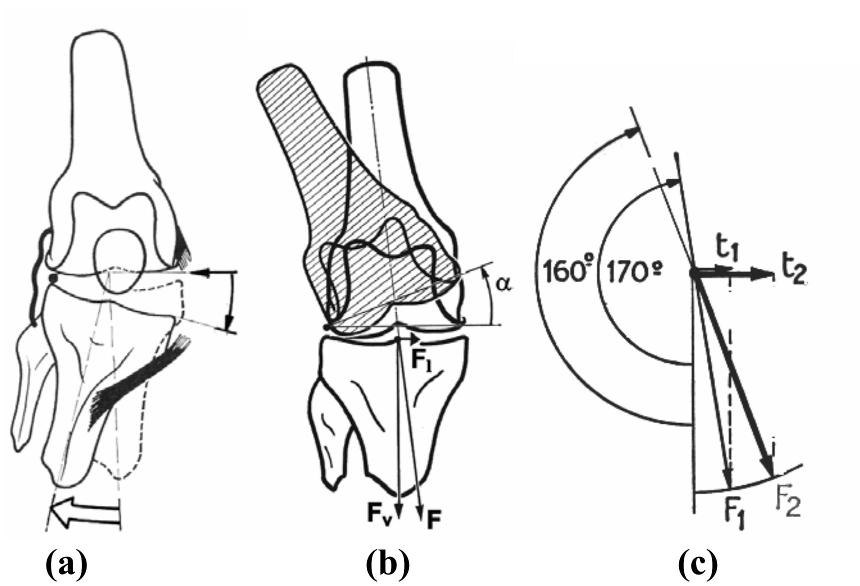


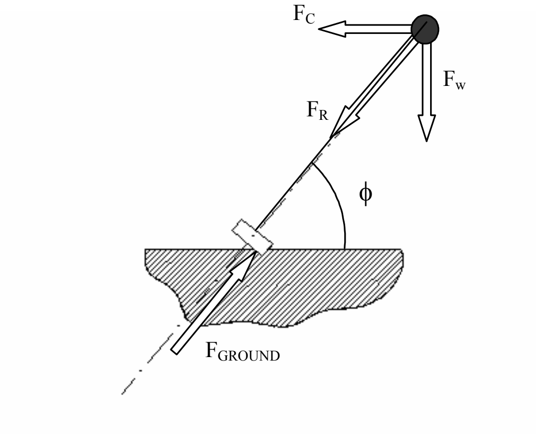
Figure 1. Varus-valgus angle and related medial collateral ligament injury (a). The force transferred from the femur to the tibia can be decomposed as shown in (b) in normal and tangential forces. In (c) F1 and F2 are forces normal to tibial plateau, t1 and t2 tangential forces. A decrease of 10° of varus-valgus angle respect to normal physiology increases tibial plateau tangential force of a factor of 2.

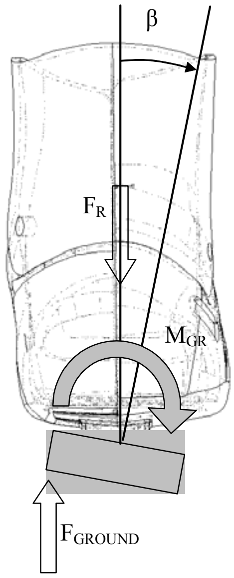
by the athlete). This procedure is obviously not feasible for the majority of skiers. Moreover, it is a cumbersome trial and error procedure. For these reasons, ski trainers have advocated the use of an adjustable stance system that is easy to set up and compatible with competition standards and rules. Furthermore, the adjustment of lateral stance is also important for beginners, since proper posture means in general easier learning. Even if no quantitative evidence is provided, qualitative response from ski schools goes in this direction. To further emphasize possible consequences of a non correct skiing posture, Figure 1a shows how the medial collateral ligament limits valgus movement of the knee. Rupture can occur more easily for example for a varus skier, as the ski-boots force the leg to orthogonality with the ground in the frontal plane. The same mechanism can occur for a valgus skier relatively to the lateral compartment. Moving far from the physiological varus-valgus angle (170°) produces an increase of tangential forces in the tibial plateau (see Figure 1b, 1c) that decreases knee stability and may lead to the rupture of other ligaments. In general the injury mechanisms for anterior cruciate ligament rupture can be (Maes et al., 2002) i) valgus movement coincidental with external rotation, ii) anterior draw caused by the shoe in backward falling and iii) the combination valgus-flexion-internal rotation, demonstrating how the varus-valgus knee stance can influence the entire knee stability. One very common injury mechanism occurring mostly to beginners is the so called "phantom foot" (Ettlinger et al., 1995). According to this injury mechanism, rupture of the ACL can occur when the skier tries to stand up after a fall or during the fall itself. The injury mechanism involves in this case coincidental valgus movement and deep flexion which causes internal rotation and anterior displacement of the tibia

Using normal ski-boots a skier with natural varus leg alignment is forced to a valgus movement in order to preserve parallelism of the ski to the ground. This phenomenon according to the "phantom foot" theory increases the risk of ACL rupture. In the opposite case, in which a valgus legs alignment skier is forced by ski-boots to a varus movement, we can say that the intrinsic geometric stability of the knee is affected.

In order to overcome the problems listed above, an innovative ski-boot is proposed, endowed with a sole that can be rotated for adjusting skier posture in the frontal plane. This system is integrated in the sole and allows the rigid lateral tilting of shell and cuff with respect to the ski plane in order to fit the skier's natural lateral stance. Once the best fit is found, the ski-boot SGS system is locked in the desired configuration.

The present work is concerned with the design of an innovative ski-boot that optimizes ergonomics and biomechanical behavior of the ski-boot by controlling the orientation of the human leg relative to the ground. A Stance Geometry System (SGS) was developed and tested both numerically and experimentally. SGS allows a proper posture of the user during skiing relative to the ski plane, as demonstrated in the following section. The design of the system follows these three strongly interdependent targets: i) design of the sole for





(a) **(b)**

Figure 2. Forces acting on the skier during turning phase (a). F_{GROUND} (ground reaction) acts eccentrically respect to the skier axis generating M_{GR} (moment) that deforms in particular the lower part of the ski-boot (b). M_{GR} (moment) acting on the ski-boot sole causes sole and sole joint deformation resulting in drift angle β that reduces the real value of the ski inclination on the ground (b).

maximum stiffness; ski-boot torsional stiffness with respect to the ski longitudinal axis in particular is very important as it deeply influences the performance of the skier during turning, ii) design of sole rotating mechanism, for skiing posture adjustment iii) reduction of foot height from the ski plane in order to reach the limit allowed in competitions.

METHODS

Simplified model to evaluate the importance of stiffness

The importance of ski-boot – sole stiffness is demonstrated with a simplified skier model. We considered forces to be in equilibrium during constant radius turning (Glenne et al., 1997). Weight, inertia forces and ground forces act on the skier. As the first two are known, the only unknown, the ground reaction force, can be solved for using equilibrium of forces hypothesis. Assuming the resultant moment equals zero, the skier's inclination can be expressed as a function of tangential velocity and trajectory curvature. The skier was modeled as an inverse pendulum with inertial and weight forces applied to the center of mass (see Figure. 2a).

Equation (1) defines the turning radius R as a function of skier speed V and ϕ representing inclination of the skier respect to the ground in the frontal plane.

$$R = \frac{V^2}{g} \cdot tg\phi \qquad (1)$$

As shown in Figure 2a F_R (sum of centrifugal and weight forces) and F_{GROUND} (ground reaction force) are not acting on the same axis thus generating a moment M_{GR} that causes a deformation of the ski-boot – sole system (Figure 2b) leading to a rotation of the ground reaction force direction. The final effect is to reduce the centripetal reaction force of the ground, causing the skier to drift to the outside of the turn (R decreases, causing the drift event). This model assumes an ideal ground with no asperities and an ideal turning situation. A passage over a bump or a hollow may generate a sudden change in the ground reaction force that may lead to a rapid change in value of the drift angle β, for the reasons above mentioned. This can affect the smoothness of the skier trajectory as well as affecting stability. For these reasons the stiffness of the ski-boot – sole system is very important and was considered one of the most important goals of the design process.

FEM model

A 3D solid model of the ski-boot was developed and simulations were performed using Finite Elements Methods (FEM). Boundary conditions were specified using loads obtained from experimental analysis and a load distribution model. The lower surface of the sole is assumed fully constrained in the regions close to the ski fixations. For the calculation of the loads the mean value of the external load within a single turning event was used. The adopted material model was linear elastic, although the boot-sole material shows some viscoelastic properties, in particular at higher temperatures. The FEM code used was pro/Mechanica, with a solid mesh of p-elements. Numerical simulation of ski-boot behavior included two main targets that cannot be achieved through experimental analysis except with a long and expensive trial and error process (Berti et al., 2001). They are i) proper design of ski-boot thickness in different regions and ii) maximization of ski-boot – joint – sole stiffness. The first requirement deals with the optimum design of a ski-boot that has to reconcile two opposing ideals: comfort and lightness on one side, suitable stiffness and deformation pattern on the other. The equilibrium point of this compromise is related to the kind of use of the ski-boot and the skier level, leaning toward stiffness for athletes. In other words a suitable stiffness and deformation pattern means that the ski-boot must be as stiff as possible going from the lower part of the boot to the ski (i.e. lower shell-joint-sole system), but, at the same time the shell and cuff must allow an adequate deformation in order to permit the skier movement in the sagittal plane, in particular ankle dorsi-flexion. For this reason a special study on shell thickness was necessary, fitting it to different regions of the boot. For the boot-sole joint, two different strategies were examined, one with the sole male and the fixation on the boot as female, and vice versa. In order to evaluate the performance of the two design solutions the sole was tested numerically in torsion and flexion. For torsion simulation, a force of 500 N was applied to the upper part of the shell, in the medio-lateral direction. This value of load force was obtained from inverse dynamics assuming a mean value for normal forces acting during tester turning and using the hypothesis of load distribution in the ski-boot as a function of strain achieved in the simulations. Mechanical properties of the material utilized in the manufacturing of ski-boots are directly influenced by temperature. For this reason the simulations were carried out by assuming environmental temperature equal to 5°C (as on the ski slopes during data acquisition), and correcting material data that were given by the supplier for 20°C. Material (typically polyurethane for the cuff) mechanical response is inversely proportional to temperature. The correction was done testing material specimens monoaxially at 0°C and 20°C and interpolating linearly to obtain the proper value for the material's Young's modulus.

Experiments

The purpose of the experimental analysis was to measure loads on the ski and deformation of the ski-boot at the same instant of time. Forces exerted by the skier on the ski were measured through 8 Kistler monoaxial piezoelectric load cells (linearity error and hysteresis both <1%), placed with the sensing axis vertical, as shown in Figure 3 and 4. Sensors were installed under the ski-boot soles and data was acquired using a 10 kHz sampling rate. Ski-boot deformations were measured in correspondence of specific points during skiing using strain gages (strain gages bandwidth = 30kHz, sampled at 10 kHz) and were compared with the deformations calculated in numerical simulations. The data acquisition interface samples at 10 kHz that is enough for the measurement of the considered event as we demonstrate in the next paragraph.

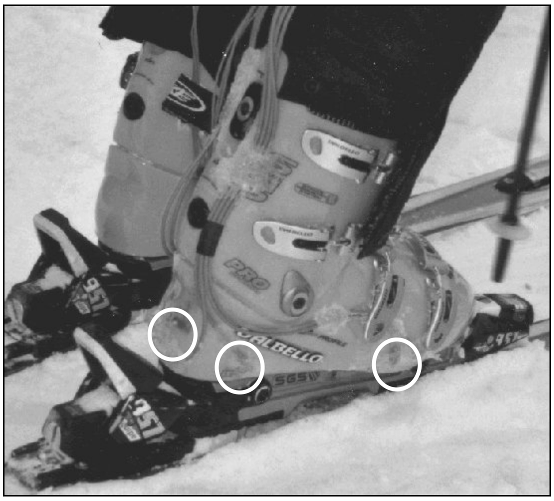


Figure 3. Ski-boots equipped with load cells and strain gages on the ski slope. Some strain gages locations are highlighted by white circles.

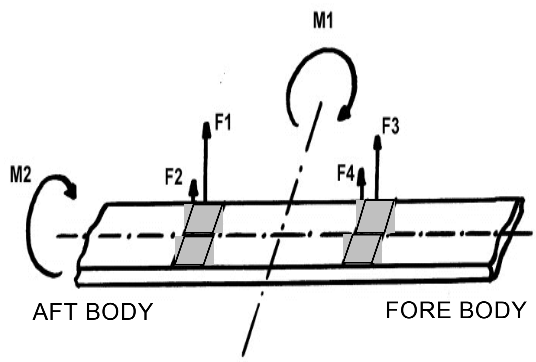


Figure 4. F_i represent load cells reaction forces that are acquired by the load cells monoaxially in the vertical direction. Only compressive loads are acquired, been considered positive. Using the 4 forces F_i it is possible to obtain momentum exerted along medio-lateral (M_1) and antero-posterior (M_2) axes. The total number of load cells used is 8, 4 for each ski.

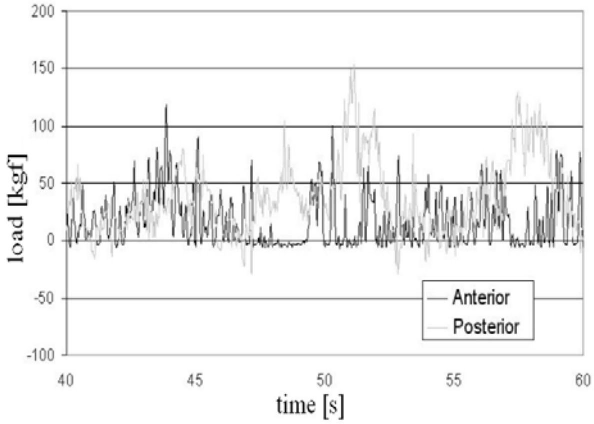
Test skiers were asked to perform a series of small radius turns and a series of large radius turns, similar to slalom and super-giant slalom events. Measurements were repeated several times (>5) on the same ski slope, with each row consisting of 3 series of turning (large radius - small radius – large radius).

RESULTS

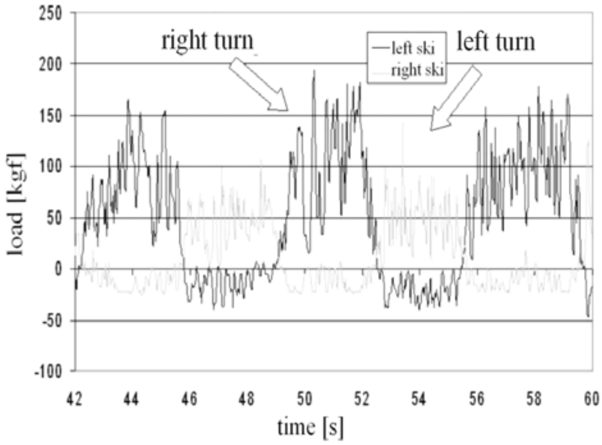
Skiing dynamics

As described, experimental data characterizing the dynamics of skiing during turning was acquired. In Figures 5a and 5b and Table 1, loads measured by load cells are reported describing the load transfer between the medial-lateral and anterior – posterior (ski fore body and after body) part of the ski. The load transfer between anterior and posterior part of the ski is more evident than medial-lateral that is also more noisy. It is clear that high frequency phenomena characterize the acquired signals due to bumps and dips on the ground. Low frequency components of the signal are relative to load transfer between two consecutive turns and are on the order of twice the body weight. For a proper ski-boot design and simulation, forces must be obtained from low-pass filtered signals. However, high frequency phenomena should not be simply rejected but rather must be interpreted and understood. They are caused by impact of the ski against ground asperities. Modeling this phenomenon allows the determination of the maximum frequency that can contain significant information on the phenomenon. If we consider a perturbation (a hump for example) being transmitted to the sole when the subject is skiing, the generated signal will have a frequency approximately equal to the ratio between the skier speed and the ski sole length. Considering extreme values of these two parameters (maximum speed of athletes and ski length equal to ski-boot length) we obtain a frequency on the order of 100 Hz that can be assumed to be the maximum possible frequency of the skiing phenomenon in the strict sense (i.e. we are not talking about impacts) defining a proper cut-off frequency of the low-pass filtering process. However the high frequency loads, considered as impact in this study, would request an extensive specific study. While acquiring load data, ski-boot deformation is also measured in correspondence to several critical points that was identified through a preliminary FEM analysis. They are close to the heel, to buckles one and two, to the anterior and to the posterior part of the shell (respectively at the level of the forefoot and of the lateral malleolus). In Figure 5c the correlation between heel region strain and the load applied on the medial region of the ski is reported.

Mean loads up to 164% body weight, corresponding to 1129 N (see table 1) were measured on the outer ski during turning.



(a)



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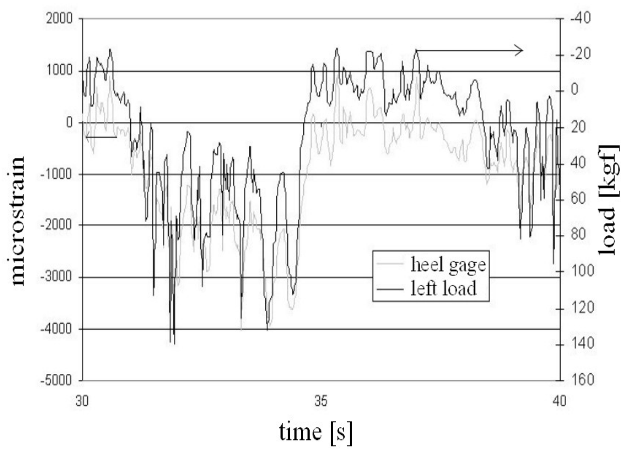


(c)

Figure 5. (a) Load signals F3 (anterior or shovel versus time) in black, and load signals F1 (posterior or heel versus time) in grey, as reported in Figure 4b, relative to the medial compartment of the same ski. **(b)** Load signals F1 (as reported in Figure 4b) for left and right ski (medial for one and lateral for the other). **(c)** Medially acting load on the left ski-boot and corresponding heel region deformation.

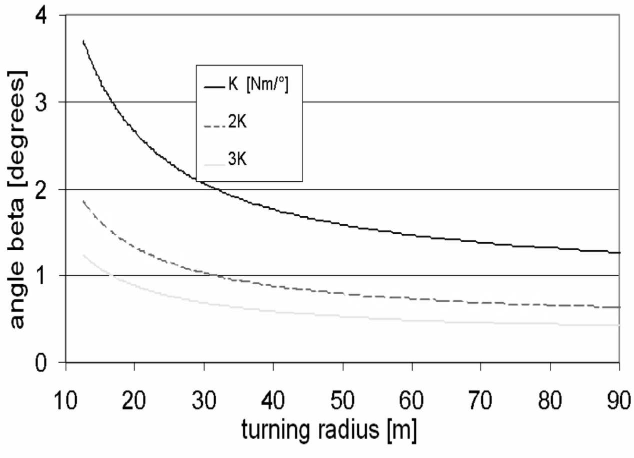
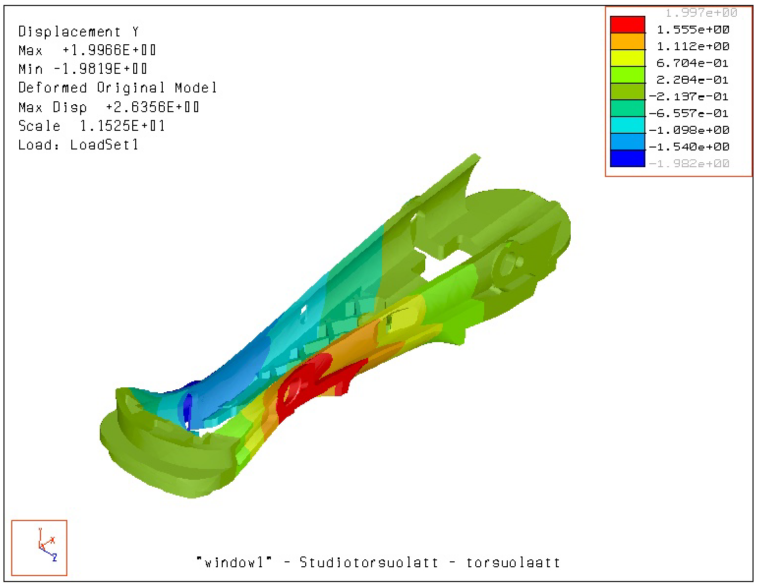


Figure 6. Torsion angle β function of turning radius (and for a given value of the skier velocity), for different stiffness values K of the ski-boot sole.

In order to understand how different stiffness of the sole can affect the turning radius and stability, the plot of Figure 6 represents the value of the drift angle β as function of the turning radius (i.e. of the applied mean load force during a turning event, with the skier velocity fixed) for three different values of sole stiffness. Values of drift angle β of some degree (>2-3°) cannot be accepted, even for a small period of time, because it results in a direct decrease of the incidence of the ski with the ground (see Figure 2a, 2b). As a consequence the skier stability and equilibrium could be seriously compromised, especially when the radius of curvature is small. An imperfect condition of the ski slope will emphasize this problem, leading to difficulties maintaining constant turning radius and optimal trajectory. The use of SGS ski-boot in



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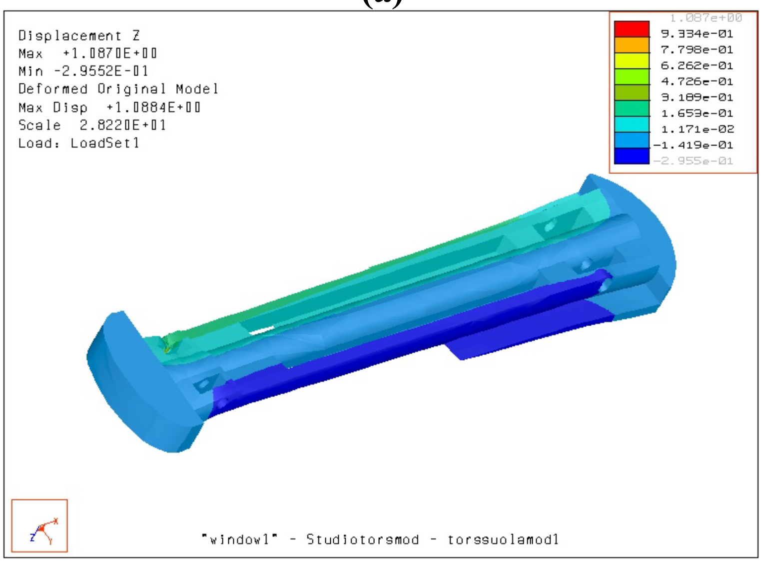


(b)

Figure 7. FEM Numerical simulation of torsional behavior of the two ski-boot sole (male **(a)** and female **(b)** fixation). The reported color scale is relevant to displacement in the medio-lateral axis, perpendicular to the ski principal axis.

competitions requires a particular focus on this aspect due to the larger loads that can be produced during races.

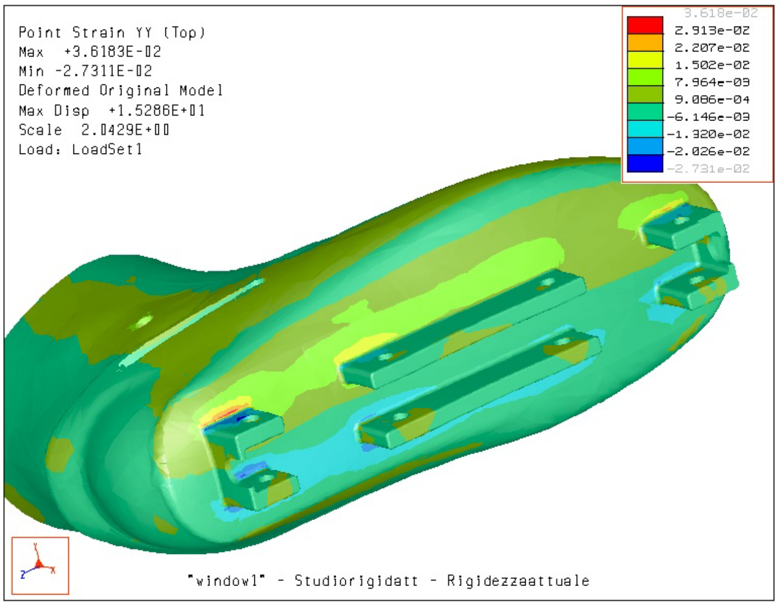
Table 1. Mean acting loads during skiing turning phase. See Figure 4.

MEAN ACTING LOADS DURING TURNING PHASE	
F3 (ant.left)	235 N
F4 (ant. right)	2 N
F1 (post.left)	755 N
F2 (post. right)	137 N
M1	-41.50 Nm
M2	19.13 Nm
Resultant vertical Force	1129 N

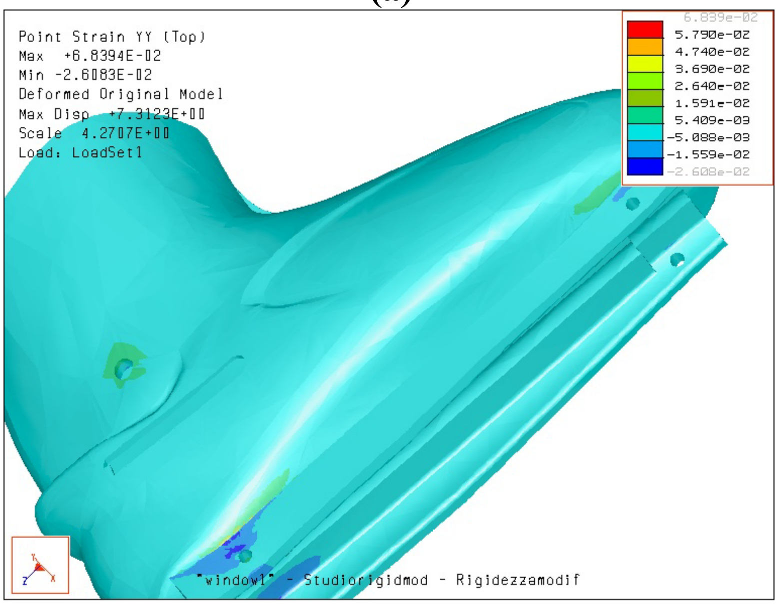
SGS: design, testing and model validation

For the ski-boot – sole joint the main problem is not material failure, but large amounts of local deformation that can affect the efficiency of the locking system and the stiffness of the overall system.

In Figure 7a, 7b, 8a and 8b the deformation in the medio-lateral direction is plotted under loads active during skier turning for both kind of boot-sole joints. The improved behavior of the male boot - female sole solution (the stiffness is incremented by a factor of two) is mainly due to the increased distance between the two rails of the locking system, as the joint flexional stiffness is proportional to the square of this distance. In order to understand how



(a)



(b)

Figure 8. FEM numerical simulation of ski-boot behavior applying external load measured in the experimental analysis. Deformation in the y direction (medio-lateral) of male joint boot **(a)** and of female joint boot **(b)**.

different stiffness of the sole can affect the turning radius and stability, the plot of Figure 6 represents the value of the drift angle β as function of the turning radius (i.e. of the applied mean load force during a turning event, the skier velocity is fixed) for three different values of sole stiffness. As explained in the method section using the simplified model, values of some degree cannot be accepted, even for a small period of time, because the skier stability and equilibrium could be seriously compromised especially when the radius of curvature is small. A non perfect condition of the ski slope will emphasize the problem, leading to big difficulties for maintaining constant turning radius and optimal trajectory.

From experimental data through some assumption it is possible to obtain resultant force and momentum acting on the ski-boot. This is used as boundary condition in FEM numerical analysis that returns as an output the deformation field in the ski-boot. In order to validate the numerical simulations, ski-boot deformations are acquired in several points during skiing by strain gages. The solution with sole as male (fixation is then female, Figure 7b) has been demonstrated to be also easier to lock when proper stance posture is found and in general better also for the assembly process, reducing the number of needed components and operations. Prototypes made by different materials have been tested, going from standard polyurethane to carbon fiber, the latter guaranteeing the best performances despite production costs.

In table 2 the experimental and model results are compared compensating for the different temperatures. The comparison is performed for the posterior shell, anterior shell, first and second buckle and heel regions. The results show good agreement, with a mean error in deformation determination of about 10% (always < 17%), as shown in table 2. In terms of strain we have a mean error of 26,2 με and standard deviation of 27,7 με. The result of the whole design process is shown in Figure 9.

To summarize, several results have been presented in this study, including:

i) development of an innovative design environment for ski-boot optimal design;
ii) quantification of loads acting during different phases of active skiing;
iii) evidence of the effects of ski-boot – ski-boot sole stiffness during skiing;
iv) biomechanical design of a more skier-fitted ski-boot, with the innovative idea of stance geometry adaptation to users anatomy; the skier can now adjust the ski-boots to his stance and lock the SGS system in the optimal position before start skiing.

Table 2. Deformation of ski-boot regions in microstrain, comparison between simulated and experimental deformations. See Figure 3a.

SKI-BOOT STRAINS IN DIFFERENT ZONES		
	experimental	**simulated**
Posterior shell	-1180 με	-1200 με
Anterior shell	149 με	174 με
Buckle 1 (superior)	300 με	340 με
Buckle 2	-172 με	-140 με
Heel	174 με	160 με

DISCUSSION

Design of ski-boot is always a trade-off between capability of the ski-boot to properly transmit forces exerted by the skier to the skis (that basically means stiffness) and comfort. While comfort is a rather subjective parameter that has not been addressed in this work - it has been investigated in (Schaff et al., 1987) -, the paper identifies a relation between stiffness and performances. The SGS system allows a better transfer of the load from the subject's body to the skis, increasing knee joint stability without affecting ankle biomechanics. Further improvement on ski-boots should go in the direction of preventing precisely identified injury mechanism e.g. the reported "phantom foot".

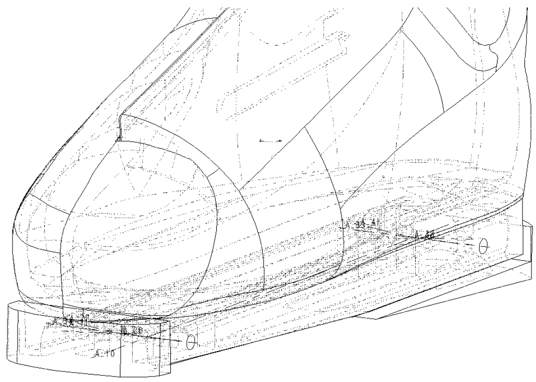


Figure 9. Perspective view of the new designed SGS ski-boot.

A proper ski-boot design and engineering can be achieved starting from real loads during skiing. The male boot - female sole guarantees a better behavior for the considered performance criterions. Even if a substantial validation of the ski-boot model was achieved, further developments of the FEM model should go in the direction of a more accurate material model that can reduce the uncertainty of numerical simulations, that is at present estimated to be around 10-15%. A consistent part of model error is thought to be due to the lack of material response data at varying temperatures and to uncertainty of the real temperature of the ski-boot during experimental data acquisition. In fact a thermal gradient is present between internal and external sides of the ski-boot, increasing nonlinear behavior. The problem could be solved acquiring inside and outside temperature and carrying out an extensive material testing plan, at different temperature and rates of straining, leading to a more accurate material model that can improve consistently FEM model reliability.

The measured deformation in the ski-boot has been found to be related with load cycles, strongly dependent on the location of the transducer. Figure 5c is an example of the correlation between heel region strain and the load applied on the medial region of the ski. This phenomenon could be due to the change in the sagittal stance during transition from left and right turning and vice versa, that is in phase with load transfer from the medial to the lateral region of the ski. This experimental data of loads acting on the ski-boot and the resulting deformations, represent a reliable basis for ski-boot design process.

The validation was achieved comparing predicted and experimental strain values in correspondence of 5 ski-boot points that are the most critical. A comparison of the whole deformation field wasn't possible because ski-boot strain was acquired only in same points. 2-dimensional strain field could be obtained through the use of strain gages matrices allowing a more precise comparison between experimental and numerical data.

CONCLUSIONS

Authors pushed forward the integration of experiments and modeling on ski-boots that will lead to a design environment in which the optimal compromise between stiffness and comfort can be reached.

The possibility of measuring accurately the skier kinematics on the ski slope, not addressed in the presented study, could represent a further step in the understanding of skiing dynamics and thus could provide even more insightful ideas for the ski-boot design process.

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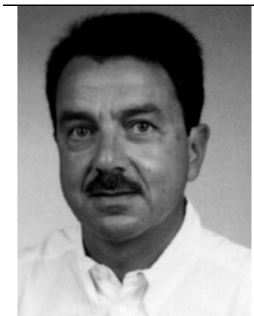

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KEY POINTS

- Load acting during different phases of active skiing have been investigated in both qualitative and quantitative ways.
- The effects of ski-boot – ski-boot sole stiffness during skiing has been investigated.
- A ski-boot stance geometry system and an innovative design environment have been developed to make skiing easier and safer.

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