Measuring Pressure in Different Layers of the Ski Boot to Estimate Skiing Movements

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Abstract: A pressure sensing measurement ski boot or sock would allow to estimate body positions, skiing manoeuvres, and external loads on the foot. This information may be used for research, in consumer products or for intelligent safety systems like a mechatronic ski binding. To investigate the optimal placement of pressure sensors with respect to the foot and the number of sensors needed to detect six pre-defined loading conditions, three pressure sensor systems were developed measuring the pressure in three respective layers: between foot and sock, sock and liner, liner and shell. The prototypes were evaluated in a laboratory test. The participant performed a series of six simulated ski manoeuvres each held for 5 seconds. In this pilot test the system sock / liner shows the best overall performance due to pressure curves in the mid-range of the sensor characteristics. Though, with an optimized sensor design a measurement boot with sensors between inner boot and shell may be possible, which would increase the robustness of the system needed for a future customer product. As a result of this study, a recommendation for sensor positions for the determination of the loading conditions in alpine skiing is given.

1 INTRODUCTION

Tracking skiing loads is normally done with specially developed equipment. An optimal sensor system would not only allow to measure forces, but also to calculate the resulting torques at the binding, the force application points and the centre of gravity. This information also allows to make assumptions about the body position (for example a possible backward-lean) and resulting loads at the knee (e.g. valgus/varus due to a high side-load on the ski).

The use of standard laboratory dynamometers is not applicable, as the system must be carried by the skier or attached to the skiing equipment.

Several custom-made systems were developed for recording the forces and moments acting on the ski. Most systems are based on strain gauge sensors for measuring the forces between the ski and the ski binding or between the ski binding and the ski boot. In many systems, forces and moments are recorded separately for the front and back component of the ski binding (Schwameder et al. 2001; Falda-Buscaiot et al. 2017; Saito et al. 2015; Stricker et al. 2010). This is advantageous if the force transmission through the two binding components is investigated, but susceptible for provoking and recording coercive forces in the ski-boot-binding-complex, as the system is statically overdetermined, thus limiting interpretability of the results. Other systems use only one sensing component (Kiefmann et al. 2006), thus measuring the absolute skiing loads.

Such "measurement bindings" can give highly accurate information about the forces, moments, and the centre of vertical force application along the longitudinal axis of the ski. On the other hand, these bindings are unhandy to use, as they are stiff, large, and heavy. Moreover, they are unique and of a complexity that does not allow widespread use in skiing as a consumer product.

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One option to reduce weight and size is to reduce the degrees of freedom measured by the system. However, force sensor systems measuring only the vertical force are still heavy and, due to the measurement principle, need to be very stiff. For example the system by Wimmer and Holzner (1997) had a total weight of 990 g.

An alternative to force measurement is the measurement of pressure. With a known measurement surface and pressure distribution, the acting forces and moments can theoretically be calculated. Pressure sensors are cheaper and can be very thin and therefore minimize a possible restriction of the athlete by the system itself. A flexible design of pressure sensors is possible and allows the integration inside a ski boot. Various systems of different sensor types (resistive, capacitive, hydro cells) have been used in research and are also available as commercial products.

Drawbacks of pressure sensors are the limitation on unidirectional measurements and the reduced measurement frequency compared to force sensors (depending on the measuring principle and the number of sensors used, but usually lower than 250 Hz). Moreover, further limitations are a difficult calibration when inside the boot (for example due to shoe buckles and changing position of the foot inside the boot), and the difficult determination of the force application points (only possible for forces inside the sensing area). As with all sensor systems, a compromise between spatial resolution, time resolution, measurement accuracy, robustness and usability must be found for the intended use.

Nevertheless, pressure insoles were successfully used in skiing research for various reasons. Krueger et al. (2006) determined the edging angle and the ground reaction force with a 24 sensor insole. Raschner et al. (2001) used insoles with 99 capacitive sensors to compare carving turns to (at that time) traditional turns. Spitzenpfeil et al. (2006) tracked mechanical loads in alpine ski racing and derived implications for safety and material considerations and Lafontaine et al. (1998) conducted a study with PEDAR pressure measuring soles (Novel, Munich, Germany) with professional Ski instructors. The maximum and average vertical forces, the maximum pressure, the pressure distribution, and the trajectory of the pressure point was calculated for different turns. In their congress abstract, Brodie et al. (2008) propose, that pressure insoles can provide insight into possible stance alteration to reduce knee torques or aid preventive programs. An interesting work was presented by Holleczek et al. (2010) who used self-made pressure sensors (Holleczek et al. 2009) and artificial intelligence to detect snowboard turns. Falda-Buscaiot et al. (2017) studied the influence of slope angle, foot position, and turn phase on the plantar pressure distribution.

Stricker et al. (2010) compared forces calculated with data from pressure measurement soles with forces recorded by 3D dynamometers. The compressive force measured by the soles were on average between 21 % (outer ski) and 54 % (inner ski) lower than that measured by the 3D dynamometers. The authors attribute this to the different positions of the measuring systems, as well as to the fact that part of the force is absorbed in the boot shaft. However, a high degree of similarity between the force-time curves of the pressure measuring pads and the dynamometers was found.

A sophisticated pressure sensing system was presented by Schaff et al. (1997), who used a measurement sock with 64 sensors attached beneath the foot, as well as around the lower leg, the instep and medially and laterally at the foot.

The use of pressure sensors, not only in the plantar region of the foot, but also in the shaft, can add valuable information and enable the estimation of all force and moment components acting on the foot. A system working on pressure sensors is preferable to a system based on force sensors because it would be easier to integrate in the existing equipment and would be a lot cheaper. Especially an integration into the outer shell of the ski boot would be relatively easy

Table 1: Advantages and disadvantages of resistive and capacitive pressure sensors.

Resistive	**Capacitive**
+ simple sensor design	+ not sensitive to temperature and humidity
+ simple data logger design	- complex data logger design
+ large measurement range	- sensor thickness
+ fast reaction time	
- non-linear	
- sensitive to temperature and humidity	
o records maximal pressure acting on the sensor	*o records mean pressure acting on the sensor*

to manufacture and may have advantages to an integration in the soft boot or sock with respect to manufacturing and sensor robustness. On the other hand, the pressure amplitude certainly is diluted through the different material layers from the foot to the outer shell.

For the development of sensors for measuring the pressure distribution in a ski boot either capacitive or resistive sensors are applicable.

The two technologies each have advantages and disadvantages (Table 1) and the decision for a technology depends on the application and the resulting requirements. The most important requirements for pressure sensors as well as their practical application are summarized by Razak et al. (2012) and mainly concern hysteresis, linearity, temperature sensitivity, and the pressure range of the sensor. In addition, the two pressure measurement methods differ fundamentally with respect to the measurement results. While resistive sensors measure the peak pressure of the entire sensor surface, the result of the capacitive measurement is the average pressure over the sensor surface (Ashruf 2002).

Main aim of this study was to find the (1) number of sensors and the (2) location of those sensors on the foot needed to optimally estimate load states, and to determine the (3) pressure differences between a placement of sensors in the three layers between foot / sock, sock / liner, and liner / shell.

2 METHODS

For this study self-made prototype systems were developed to measure pressure distribution in the ski boot. In total three systems for the right foot were built:

- PTBoot: Pressure sensors attached to the plastic shell of the boot, between the shell and the inner soft boot.
- PTSock: Pressure sensors attached to the inside of the soft boot, between the soft boot and the ski sock.
- PTFoot: Pressure sensors directly attached to the foot.

This allowed to investigate the best location for the sensors around the leg and test the loss of pressure amplitude from one (material) layer to the next.

In a laboratory study, simulated skiing movements were recorded simultaneously with all three systems. Based on the results, a recommendation of a reduced number of sensors is given. Fewer sensors allow higher measurement frequencies and reduce complexity of a to-be commercial measurement boot and the required microcontrollers.

For the easy structure of the sensor and the logging module, a resistive solution was chosen. The two types of self-made sensors have a circular design with a sensitive area of 30 mm in diameter and a surface of 707 mm² (Figure 1) for a larger sensor and 20 mm in diameter and a surface of 314 mm² for the smaller sensor. The sensors consist of a flexible carrier foil of 25 µm thickness with 18 µm thick copper tracks printed on it. The tracks form two interlocking combs. The two conductive tracks are wired for the connection to the data logger and a reference conductor. Velostat® (electrically conductive foil due to a carbon black impregnation, 3M, Maplewood, United States) was used as pressure sensitive conductive material. Three layers, each 0.1 mm thick, were placed on the conductive side of the foil. All layers were fixed and isolated by laminating them with conventional laminating film. A voltage divider circuit with a 100 Ω reference conductor was used to record the sensor signal (see equation (2)).

Figure 1: Schema of the pressure sensor (left) and steps of manufacturing: middle left: foils with conductive tracks; middle right: wired sensor foils; right: finished sensor with pressure sensitive conductive material layer over the foils with the conductive tracks and protective, non-conductive foils laminated on both sides of the sensor.

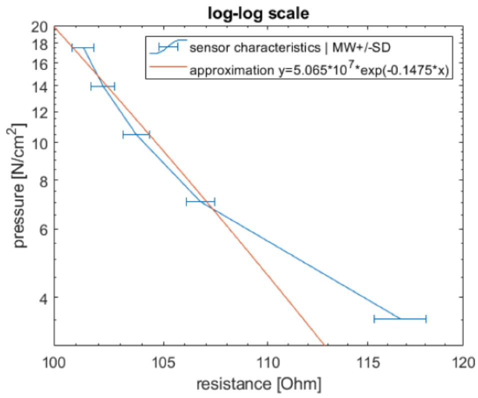

Figure 2: Sensor characteristic of the large sensor type derived of 5 of the self-made pressure sensors.

$$y = ae^{-bx} \tag{1}$$

The sensor characteristics were determined (Figure 2) by applying defined loads on the sensors. An approximation curve was calculated using equation (1) with the curve fitting tool of Matlab 2020a (MathWorks, Natick, Massachusetts, USA).with y being the pressure seen by the sensor, x being the electrical resistance of the sensor, and the parameters $a = 5.065 * 10^7$, and $b = 0{,}1475$ for the large sensor type, having a corelation of $R^2 = 0.9527$ between pressure und electrical resistance. Due to the small number of the smaller sensors the sensor characteristics for each of the small sensors was determined individually and is given in Table 2.

Table 2: Parameters for the sensor characteristic approximation for the four small sensors used. Parameters refer to equation (1).

Sensor	***a***	***b***	***R²***
PTSock 6	125.1	0.01671	0.9286
PTSock 10	115.8	0.008495	0.9588
PTFoot 6	95.98	0.001639	0.9743
PTFoot10	370.5	0.0364	0.9775

The placement of the sensors was determined based on preliminary tests and considerations with regard to an optimal detection of following loads acting on the foot, which are for-/backward leaning (My) / rotation torque (Mz) /edging loads (Mx / Fy) / vertical ground reaction force (Fz).

For all three prototypes 17 sensors were distributed around the foot and lower leg (see Figure 3). Four sensors are placed on, both, the medial and lateral side of the foot, five sensors were placed in the plantar region, two sensors at the tibia shaft, one sensor at the heel and one sensor above the instep. For PTSock and PTFoot the sensors in the toe region no. 6 and 10, have a smaller diameter of 20 mm, due to space limitations.

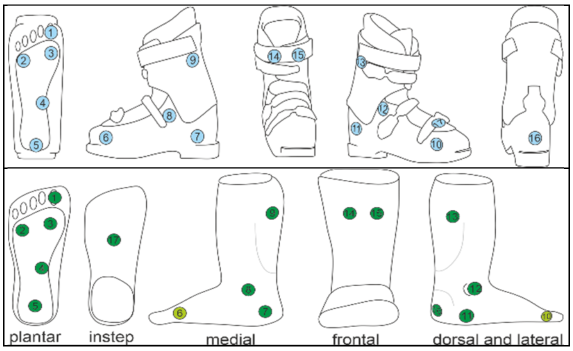

Figure 3: First line: Placement of the 17 pressure sensors of ski boot prototype 'PTBoot' (placed on the inner side of the hard shell of the boot). All sensors have a diameter of 30 mm. Second line: Placement of 17 pressure sensors in the sock prototype 'PTSock' and the placement of the sensors directly on the skin of the foot 'PTFoot'. Sensors 6, and 10 are of a smaller diameter (20 mm). All other sensors have a diameter of 30 mm.

A myRio-1900 (National Instruments, Austin, Texas, USA) was used for A/D conversion, processing, and logging. To allow the logging of all sensors, multiplexers (MUX, CD74HC4051E, Texas Instruments, Dallas, Texas, USA) were used with reference conductors ($R_{Reference} = 100\Omega$). The sensors were supplied with $U_0 = 5V$. The resistance of each sensor R_{Sensor} is calculated using equation (2), were U_{Sensor} is the measured signal in Volt.

$$R_{sensor} = \frac{U_{Sensor} * R_{Reference}}{U_0 - U_{Sensor}} \tag{2}$$

A LabView 2015 (National Instruments, Austin, Texas, USA) program was running on the myRio. Measurement frequency was set to 10 Hz (limited by the number of sensors and the hardware, e.g., switching time of the MUX). Data was saved on an USB-stick plugged into the myRio-modul.

All three pressure sensing prototypes (Figure 4) were used simultaneously. The setting of the data collection is stationary. One participant is simulating ski-typical body postures by shifting body weight and using muscle activation.

Simulated postures are backward-leaning, forward-leaning, left curve (inner edge of the measurement boot), right curve (outer edge of the measurement boot), internal rotation, and external rotation. Each position was held for 5 seconds.

The pressure values were calculated using equations (1) and (2) with the respective equation parameters of the above-mentioned sensor characteristics. All calculations were performed using Matlab.

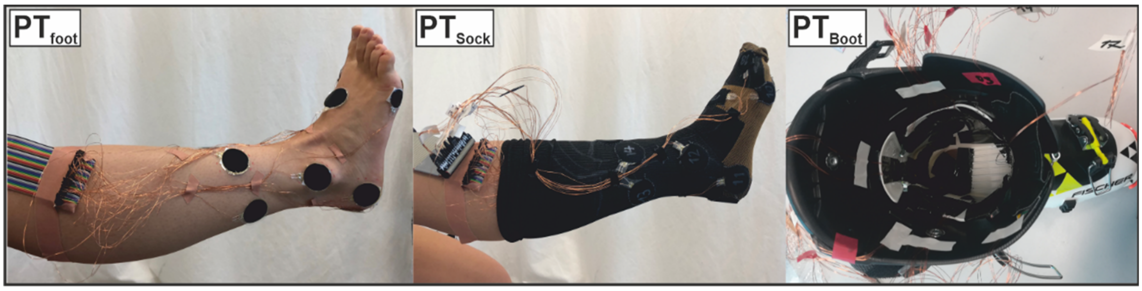

Figure 4: The three sensor prototypes and the test set up with the participant wearing all prototypes.

3 RESULTS

The comparison of the respective values of each sensor of the different prototypes at the same position indicate a qualitative similarity between the pressure curves with a loss of amplitude from PTFoot to PTSock to PTBoot (Figure). The loss is not the same for each sensor position. The pressure recorded by PTBoot is low with values smaller than 0.125 N/cm² for most of the sensors and not exceeding 10 N/cm² in any sensor. The pressure range for PTFoot and PTSock is mainly between 0 and 40 N/cm². Higher values are reached by PTFoot sensor 2 (positioned under the outside edge of the ball of the foot), which reaches 68 N/cm² and PTFoot sensor 6 (positioned at the medial side of the ball of the foot), which reaches a maximum of 83.4 N/cm².

Both sensors under the ball of the foot (sensor 2 and 3) show highest pressure values in the plantar region and have a distinguishable resolution of the measured manoeuvres in all three systems. The sensor positioned under the heel (sensor 5) hardly measures any pressure for PTBoot but higher values (about 10 N/cm²) for PTFoot and PTSock. The sensors under the big toe (Sensor 1) of PTFoot and PTSock show only small pressure responses to the six skiing manoeuvres, with highest values for the time spans of the transition from one manoeuvre to another. The same sensor of PTBoot shows nearly no signal. The different skiing manoeuvres are not prominently expressed in the sensor data under the arch of the foot (sensor 4), which recorded small pressures over the total measurement. At the medial and lateral side, the higher positioned sensors 8 and 12 of PTBoot show higher pressures than the lower positioned sensors 6, 7 (medial) and 10, 11 (lateral) of PTBoot. The same sensors of PTSock and PTFoot give more pronounced values than the sensors of PTBoot, but some signals of sensors 6, 7, and 12 show an abnormal behaviour (see discussion). Even though, the sensors at the calf (9 and 13) show high pressures for PTFoot and PTSock, only low values are recorded by PTBoot. At the tibia (sensors 14 and 15), the sensors of all three prototypes are sensitive to the six skiing manoeuvres. Sensor 16 (backside of heel) and 17 (instep) record high pressure and allow to distinguish the skiing manoeuvres for PTFoot and PTSock but record only low values for PTBoot.

4 DISCUSSION

In this study, PTBoot measured only very small pressure values and the loss of amplitude from PTFoot to PTBoot is large. Therefore, sensors for a to-be measuring boot or sock need to be designed very specifically with respect to resolution and sensitivity and probably different sensor designs are needed for different sensor positions in the boot. It may be advisable to design the shell shape in such a way that the liner transfers a large part of the force to the shell on defined surface areas on which the sensors are placed.

In general, the sock prototype produced the best results compared to both other prototypes. This prototype generates sensor values in the middle range of the sensor characteristics for almost all sensors and thus seems best suited for this application. Therefore, an integration of such a pressure measurement system in the sock or the liner would be more expedient than the integration between the hard-shell and the liner. On the other hand, with respect to robustness and easy manufacturing, a pressure sensing boot is preferable to a pressure sensing sock.

The qualitative determination of specific skiing manoeuvres with a pressure measurement system in the ski boot is possible. Based on the results of the investigations with the three prototypes it is possible to reduce the number of pressure sensors needed. A recommendation of sensor positions based on qualitative judgments is given in Table 3. The sensors which show the most significant change in pressure for the specific movements are highlighted in bold letters.

To detect a forward or backward leaning body position the tibia shaft may be better suited than a position at the calf or the plantar region. The sensors at the calf are not only influenced by the leaning position, but also by muscle activation. The sensors in the plantar region may be non-optimal as they may give misleading information in some situations. For example, the sensors under the ball of the foot may be unloaded even though the skier is leaning forward. In such a case, the skier presses the tibia in the boot and pulls the toes up to increase this pressure on the tibia by increasing the pressure on the heel.

The exact selection of a sensor position at the outer sides of the foot may heavily influence the quality of results in detecting turns or rotation movements. One issue to consider is the very individual geometry of the foot, another reason is the

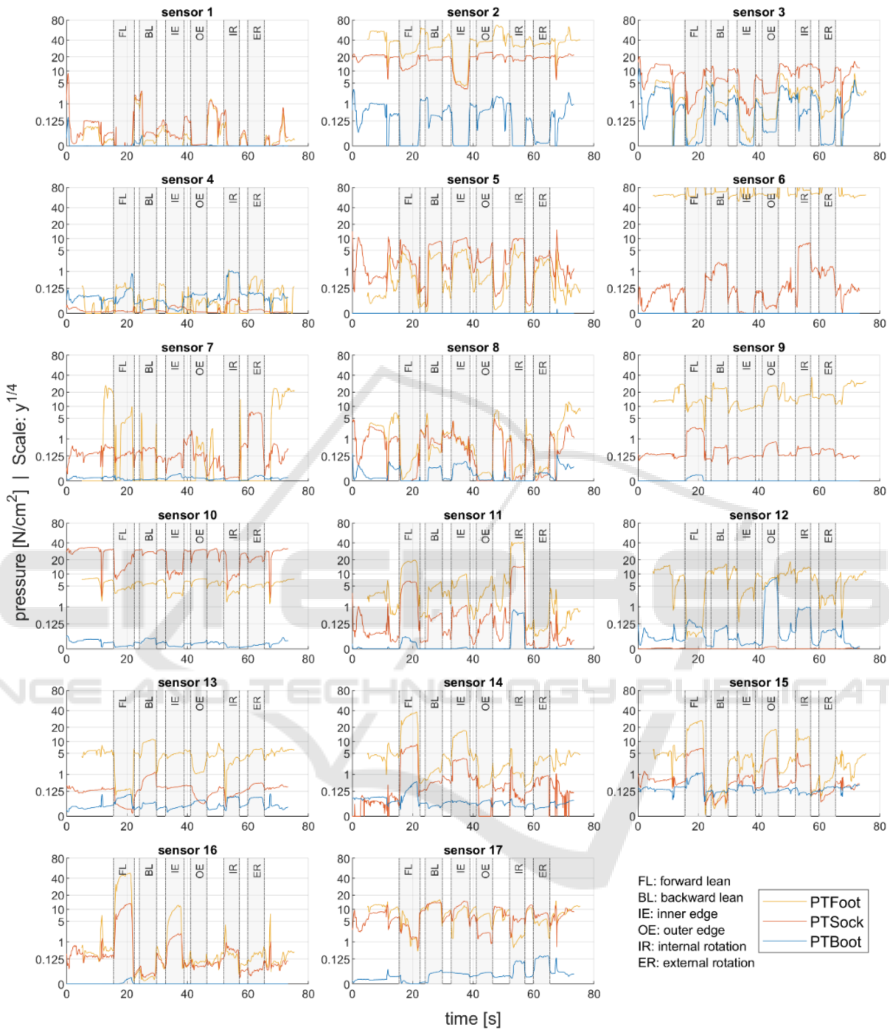

Figure 5: Comparison of the pressure sensor values of the three prototypes. The six skiing positions are indicated by the grey areas and a respective annotation.

Table 3: Recommendation of the placement of pressure sensors to determine skiing manoeuvres based on the results with the three prototypes.

Detection of	***Sensor***	***Sensor position***
Forward / backward lean	(2), (3), 9, 13, **14**, **15**, 16, 17	(ball of foot), calf, **tibia shaft**, heel, instep
Left / right curve	8, 9 / 12, 13	Upper part of the lateral and medial side of the foot, near the bend of the foot and the calf.
Internal / external rotation	6, **11** / 7, **10**	Lower part of the lateral and medial side of the foot.

clamping of the foot in the boot, which varies for different skiing positions and manoeuvres but also as a result of deliberate force production to control the ski.

If exact pressure values or loads should be determined (in contrast to the estimation of body position only), a great challenge will be the calibration of the sensors. A commonly used procedure for plantar pressure measurements is that the persons foot is in the boot or shoe and the person lifts the foot for a static and unloaded recording which is then used to ‘zero’ the sensors. In the following these values of the static recording are subtracted from the later recorded values to determine the loads acting on the foot. This procedure is not possible in the prototypes used in this study. Even though the lifting of the foot unloads the sensors placed under the foot, the sensors positioned in other regions are loaded. Moreover, a tight setting of the buckles of the ski boot can produce high pressure values which even may bring the sensors to a saturation.

The above given recommendation may only hold for the detections of isolated and very specific movements and will probably not be applicable if multiple movement patterns occur simultaneously. A possible solution approach to this could be the use of artificial intelligence with a well-trained neuronal network. As attractive as such a solution is, the training of such a network would need sufficient real-life data which also has to be labelled labour-intensively.

Due to the design of the study, no high dynamics are apparent, and the loads and pressures measured with the prototypes are relatively low with most sensors measuring values below 5 to 10 N/cm² and only singular sensors reaching values of 20 to 40 N/mm². Up to ~ 6.4 N/cm² the pressure is underestimated, due to the sensor characteristics shown in Figure 2. Still, the values are small compared to maximal (only plantar) pressure values reported in on-slope skiing of 28 to 38 N/cm² (Lafontaine et al. 1998).

As only the local maximal pressure of each resistive sensor at each time is recorded, the system is prone to large errors due to wrinkles in the sock, a small hard object pressing on the sensor (for example a stiff seam of the sock or inner boot or a bone of the foot), or a bending of the sensor. This may also be a reason for the, significantly, higher pressure signals of single sensors of PTFoot compared to the other prototypes (for example sensors 2, 3, 5, 6, 12). Therefore, the use of capacitive sensors would be advantageous, as local pressure peaks at the sensor surface are filtered and a mean pressure of the sensor surface is measured. But capacitive sensor designs are more complicated and need specific experience.

The self-designed sensors used in this study are non-linear and the approximation is not ideal. This may lead to large errors in the calculation of pressure values especially for very small and very high sensor values. This is a result of various aspects of the sensor design and, therefore, could be addressed in multiple ways. For example, by replacing the Velostat® layers by a carbon black silicon compound, potential contact loss between the Velostat® layers themselves and between Velostat® and the printed circuit board material may be prevented. This contact loss results in higher electrical resistance and thus lower pressure values.

5 CONCLUSION

This work shows the relevance of certain sensor positions for detecting the simulated load states. Two groups of sensors should be emphasized here: the anterior shaft sensors (Sensors 14 and 15) for determining a forward/backward lean, and the sensors on the lower part of the lateral and medial side of the foot for determining an internal/external rotation.

In general, the sensor design must be specifically made for the respective position and the corresponding pressure value range. Here the sock prototype shows the most balanced sensor values for the different sensor positions. To tackle the various challenges with respect to an optimal sensor design (for example, measurement range, saturation, and sensor size), field data will be needed to allow more insights.

Injuries of the knee in alpine skiing often result from a backward leaning position (Freudiger and Friedrich 2000). Therefore, the implementation of a measurement boot recording external loads and body positions in an adaptive safety system (for example a future mechatronic ski binding) may allow to detect risky situations and react accordingly. A combination of force sensors measuring torques around the vertical axis and pressure sensors used to predict forward and backward lean and torques in the sagittal plane might be a possible compromise.

Artificial Intelligence may allow to cope with the high complexity due to imperfect defined sensor characteristics. A neuronal network with a small number of pressure sensors at defined positions could be trained with ground reaction forces (My, Mz, Fy, Fz) recorded by a measurement binding. With sufficient training data, the neuronal network will predict the skiing loads using the pressure sensor data. This has been successfully done for a snowboard binding by Holleczek et al. (2010).

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