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On Bending Characteristics of Skis in Use

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Abstract

Measuring ski deflection while skiing allows the characterization of essential aspects of the complex interplay between the skier's performance and the interaction of the ski with the snow. This provides an opportunity to optimize skis with regard to skiers' skills and athletic ability, thus improving skiing performance. To establish an analysis system, we developed, characterized and tested a system capable of measuring ski deflection while skiing. Using competition-type slalom skis, we applied 30 strain gauge sensors - 15 on each ski. The strain gauges sampled data at 65 Hz and the readings were translated into deflection estimates. This was done by validating the system using a specialized bending machine equipped with a laser sensor system to accurately track the changes in ski shape with increasing applied force. We sampled strain gauge data while the bending apparatus deformed the ski. The RMS error of our ski-shape estimates relative to laser-measured data was 11mm. In on slope tests, the center of mass (CoM) position and speed of a skier were acquired using a highly accurate differential Global Navigation Satellite System (dGNSS) at 50 Hz and a pendulum model. From this data we estimated the CoM turn radii of carved turns. During the ski tests, the bending radii along the ski over time were obtained from strain gauge data and analyzed for each carved turn. We observed smaller radii relative to the path radii at the tip of a ski. We further analyzed the correlation between ski turn radius from deflection measurements and the CoM turn radius. The RMS error between radii calculated from deflection measurements and CoM radii obtained with a high resolution dGNSS was on average 1.26m, with the smallest error being 0.78m. We tested our system on a hard-snow slope and a soft-snow slope. Our system has manageable technological complexity and is potentially suitable as a training tool or for use in ski-fitting for skiers of various skill levels.

Keywords: Ski; Sensor System; GPS; Bending Sensors; Field Test; Prototype.

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1. Introduction

With the advent of parabolic skis, it has become possible for recreational and competitive skiers to perform carved turns, i.e. to change their direction on snow with reduced sideways slide. In carved turns, the side-cut and the deflection of a ski together define the radius of a turn (Federolf et al. 2010). The side-cut is a fixed property of a ski and gives the ski a geometrical turn radius. For competition, the International Skiing Federation (FIS) regulates the geometrical side-cut and length of skis. Length and side-cut differ between disciplines and between genders (Kröll et al. 2013). The radius becomes smaller with increasing deflection. Deflection increases with increasing force exerted on the ski (Federolf et al. 2010). Thus, to perform a carved turn of a given radius with a ski of a given side-cut, a stiffer ski (less deflection) is necessary when ski loading increases. As it is the goal of competitive alpine skiing to ski given radii at the highest possible speeds, athletes need stiff skis that have the appropriate bending characteristics to tolerate more than 3 times the skier's body weight (equivalent to approx. 3000N exerted force) in Giant Slalom (Gilgien et al. 2014). For non-athletes these skis would be difficult to use, as non-athletes can not generate enough force to deflect the ski and hence attain the desired turn radius.

In alpine countries skiing is a popular sport and is practiced by approximately 55% of Europe's population (BMWFI (undisclosed authors) 2010). There are many different ski brands selling various ski models aiming to satisfy the preferences and skill levels of a wide range of consumers. Yet the question of which ski (model) to choose is often addressed only superficially. The parameters commonly used for finding the right ski are body height and weight, athlete-reported and skill level. With this study we wanted to alleviate this black-box approach by providing objective tools for ski selection for individual skiers. When does a ski suit a specific skier? In a simplified view, one might claim that a skier needs to have the technical skills and the physical strength to exploit the possibilitie*s* of a given ski model. An athlete with given capabilities is able to exert a certain amount of force on the ski. By analyzing the curvatures of the ski during skiing it might be possible to assess athlete–gear fits and enhance the selection of a suitable ski for a given skier. A competitive athlete needs a stiffer ski to handle the ski loading forces imposed by the skier. A recreational skier needs an inherently softer and/or shorter ski to successfully perform turns. Skis suitable for recreational skiers have, however, obvious drawbacks such as reduced stability at increased speed.

In this work, we present the first step towards a ski/athlete analysis system with a proof-of-concept implementation. Our system comprises a combination of multiple strain gauges reversibly attached to the skis and a high-accuracy dGNSS worn by the skier during skiing. With this system we can relate measured ski radii to CoM turn radii and speed. Our vision is the creation of a device with the same sensing power as the system prototype presented in this paper, but which is smaller and more comfortable to use.

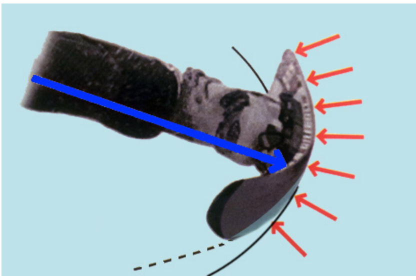

Figure. 1. Deflection of a Ski during a carved turn.

2. Related Work

The athlete's mechanics while skiing can be assessed with a range of sensor modalities. Full body skier kinematics have been assessed using video-based photogrammetric systems (Reid 2010;Spörri et al. 2012), combinations of dGNSS and inertial measurement units attached to the segments (Supej 2010;Brodie et al. 2008), inertial measurement units and ultrasound distance sensors to reconstruct segment movements (Vlasic et al. 2007), and dGNSS in combination with pendulum models (Supej et al. 2012;Gilgien et al. 2013). Ski loading has been assessed using force plates mounted between ski and binding pressure insoles in the ski boots (Nakazato et al. 2011), or ski loading is derived from CoM kinematics (Lüthi et al. 2004;Gilgien et al. 2013). To sense bending and torsion of skis, multiple strain gauges can be rigidly attached to the skis (Fauve et al. 2007) or optical fibers can be incorporated in the ski (Vogel et al. 2013). Field data based simulation models have been created to better understand the contact pressure at the contact area between the ski and snow (Heinrich et al. 2010;Federolf et al. 2010) and the contact pressure during ski runs has been measured in field studies (Scott et al. 2007).

3. The System

The resistance resulting from compression of snow increases with increasing ski penetration depth (Federolf et al. 2010). Snow is compressed by a sliding ski until the resistance is equal to the force produced by the skier and transferred to his skis. The deformation of the snow is mainly plastic, which means the trace left behind by a skier accurately reflects the skied path (in the case of an optimal carving technique). The snow's behavior under load can be characterized in two phases. In phase I, the loading phase, the snow is touched by the tip of the ski and is compressed as the ski glides. Behind the binding, snow is not compressed and the remainder of the ski glides in the previously carved path (Federolf et al. 2010;Reid 2010). Phase II is the de-loading phase, where the loading of the ski decreases and we do not expect further alterations to the snow. In other words, by measuring the curvature of a ski after the loading phase, we can infer the carved path. Hence, we needed to measure the deflection in the back part of ski to infer the skied path radius.

3.1. Center of Mass Position

Ground truth for the CoM path was provided by a differential global navigation satellite system (dGNSS) and a pendulum model (Gilgien et al. 2013). The dGNSS consisted of an antenna fixed on a skier's helmet, a datalogger carried in a backpack and a stationary GNSS base station for differential measurements. The system recorded the skier's trajectory at 50Hz. In postprocessing the skier's CoM trajectory was calculated using the dGNSS trajectory, a pendulum model and the snow surface. The snow surface was captured by static dGNSS and reconstructed by triangulation and smoothing (Gilgien et al. 2013). The system's accuracy was validated against an independent reference system. In a previous study, CoM-position error was found to be 0.09m ±0.12m and CoM-velocity error 0.08m/s ±0.19m/s (Gilgien et al. 2012).

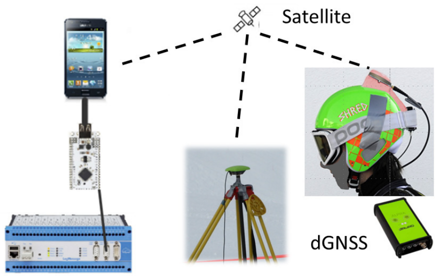

Figure 2: Data Synchronization.

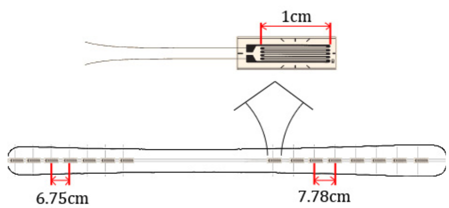

Figure 3: Placement of the strain gauges on a ski

3.2. Bending Measurements

The bending radius differs between any two points along a ski and multiple sensor points (gauges) are required for an estimation of the overall shape of a ski. As shown in Figure 3, strain gauges were glued to the front and the back part of the ski, omitting the area around the binding system due to limited space. However, our laboratory tests have shown that a least-squares fit of the curvature in this area is a decent approximation of reality. The strain gauges used in our system were 1cm long and we attached 15 to each of the skis. The electrical resistance of the gauges alters as a reaction to physical strain. Our deformation-estimation system therefore consisted of a power source and a logging device with 30 analog-to-digital (ADC) inputs connected to the strain gauges. Using simple circuitry, we connected the gauges to the power source and to the logger. The logger sampled the voltage at the ADC inputs and stored the raw data onto an SD card. One ADC input of the logging device was connected to the battery and concurrently sampled the voltage to all the strain-gauge inputs. The deflection ε of a strain gauge is calculated as follows:

$$\varepsilon = \frac{\Delta U_b}{U_{batt}} \cdot \frac{4}{k} \qquad \Delta U_b = U_{loaded} - U_{unloaded} \tag{1}$$

Equation (1) shows that the strain can be calculated using the difference between a measured voltage (in loaded conditions) and the relaxed state, divided by the supply (battery) voltage (the constant *k* depends on the model of the strain gauge and is provided by the manufacturer). Hence, the logger needed to also keep track of the supply voltage to enable us to reconstruct the bending of the strain gauges.

3.3. Connecting the Modules

The bending sub-system was not connected to the dGNSS and we needed a third module for synchronization. Exact temporal alignment between dGNSS data and the deflection measurements was required for any further analysis. An Android smartphone on which we had installed a custom application controlled a hardware module (IOIO board). The hardware module was physically connected to a synchronization port on the data logger. The Android app exposed two controls to the user: a start and a stop button. The start button triggered a pin on the IOIO board which was recorded on the logger device. In the background the application recorded the GPS time received by the satellites. Since the dGNSS also recorded GPS time we could synchronize, with high accuracy, the data from the data logger and the dGNSS data.

4. Evaluation

4.1. Bending-Module Validation

The bending estimation system was characterized and calibrated using a calibrated ski-bending machine equipped with a laser-measuring system. The accuracy of the laser system was 0.5mm. The ski was bent and its shape measured using forces ranging from 40N to 360N. At the same time, our system sampled the deflection of all strain gauges.

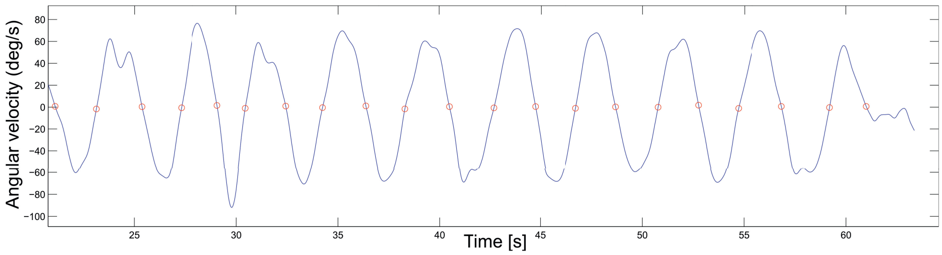

Figure 4: CoM angular velocity and turn transition points (red dots).

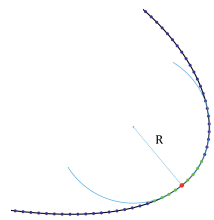

Figure 5: CoM Radius

4.2. Real-World Data Acquisition

After characterizing the bending module we tested the system in a real-world setting. The system was assessed on a slope usually used for competition training, located at Jakobshorn in Davos, Switzerland. The right part of the slope was hard, i.e. it was injected with water. On the left side of the training hill a softer, typical public skiing surface was prepared without water injection. We tested the system over 10 runs, with 5 runs on each snow type and different sampling frequencies for the bending module.

4.3. Offline Path and Deflection reconstruction

The speed and position of the CoM were calculated in a post-processing step from raw dGNSS data (which tracks only the skier's head), the snow surface and a pendulum model (Gilgien et al. 2013). The CoM turn radii during the turns were calculated using a sliding window approach with a window size of 9 CoM points as can be seen in Figure 5. Additionally, the readings from all strain gauges were collected and for each time step the shape of the ski and the instantaneous ski radius was calculated. The data post-processing chain also tracked the battery voltage in order to avoid any bias in further calculations. We detected the turn transitions from the position data by calculating the angular velocity component. Whenever this portion changed sign, a turn transition was occurring (Fig. 4).

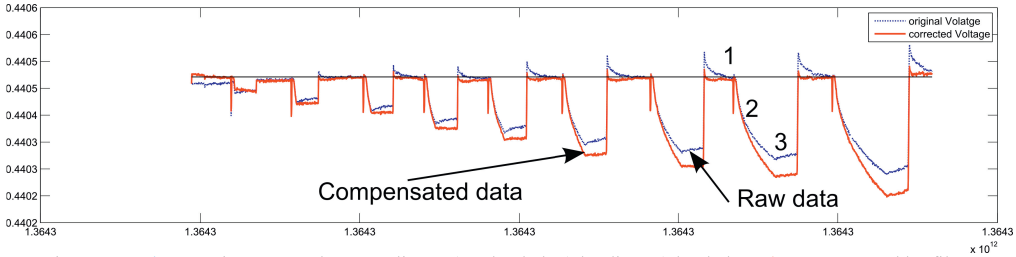

Figure 6: Blue: Strain gauge voltage readings: 1) unloaded, 2) loading, 3) loaded. Red: Compensated by filter.

5. Results

5.1. Bending-Module Validation

During calibration we were confronted with the familiar hysteresis affecting strain gauges in combination with our measurement setup. In the test setup we used a computer-controlled arm that applied a defined force to the ski for a defined amount of time. We noticed that in an unloaded phase (Figure 6: 1) following a loaded phase, and also in a novel loaded phase (Figure 6: 3) there was a significant change noticeable in the deflection readings of the strain gauges even though there was no mechanical force added or removed by the machine. To cope with this problem we needed to post-process the gauge data. We tested filters such as Kalman, but a simpler model was selected due to its low computational complexity and good results:

$$T_{k+1}(U_b) = T_k + \alpha \cdot \Delta U_b - \beta \cdot T_k \tag{2}$$

In our model, we maintained a state variable, T_k, that depended on its prior state and the voltage difference between two consecutive samples. The model parameters α and β were determined using non-linear optimization. We corrected the voltage readings with the following equation (δ=1/k is an empirical constant depending on the gauge type):

$$\widetilde{U}_k = U_{k-1} \cdot (1 + \delta \cdot (T_k - T_{k-1})) \tag{3}$$

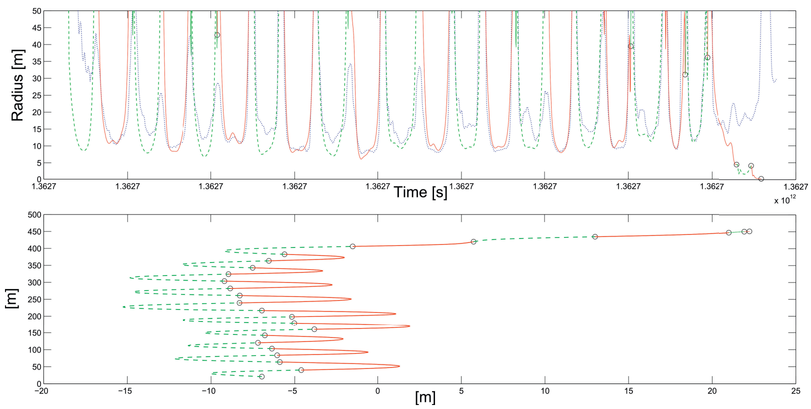

Figure 7: Data from a Test Run.

5.2. Deploying the System and Analyzing the Data

The real-world data acquisition was mostly successful, but in three runs the system did not work as expected. In one run the dGNSS module was not started, while in two other runs the supply voltage was not logged correctly and hence we could not reliably estimate the bending of the ski. Figure 7 shows the data from one test run. The lower part shows the CoM data visualization with left-turns marked in red and right-turns marked in green. The upper part of the figure illustrates the CoM turn radius during left and right turns (red and green) and shows the estimated ski turn radius from the bending subsystem of the right ski (blue). As can be seen, the estimated deflection matched well on left turns (red vs. blue), and the matches were less accurate on right turns where the right ski was the inner ski. Our analysis therefore focused solely on the outer ski: during right turns the left ski, during left turns, the right ski (see Scott (2007)). Each run consisted of approximately 9 turns on each side. The best accuracy was achieved on soft snow. The mean RMS difference between outer ski radius and CoM turn radius was 1.20m, with a best run average RMS of 0.78m and and overall average RMS of below 2.3m.

6. Conclusions and Outlook

In this work we presented a mobile, removable sensor system for ski deflection measurements and ski radius estimation on the slope. We presented the hardware and algorithmic components of our prototype system and showed that, valuable data can be acquired. The accuracy of turn radius estimation opens the doors for a future ski and athlete-estimation system targeted to enhance the choice of ski models for a given skier.

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