# METHODOLOGICAL CHALLENGES FOR BIOMECHANICAL APPOACHES IN WINTER SPORTS

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Many research questions related to performance or to injury prevention require biomechanical approaches and study plans that provide the best achievable compromise between internal and external validity. This is especially true for winter sport activities like skiing or snowboarding which cannot adequately be reproduced under laboratory conditions. The keynote presentation will illustrate how these methodological challenges have been addressed to answer three research questions related to injury prevention and the development of safety gear in winter sports:
(1) the loading of the hip joint at different skiing manoeuvers (to answer the question if skiing is recommendable sport for people with hip replacement),
(2) the effectiveness of wrist guards for the prevention of wrist or lower arm fractures in snowboarding
(3) the development of algorithms for mechatronic ski bindings with the target to reduce the unchanged high rate of knee injuries.

**KEY WORDS:** sport equipment, alpine skiing, snowboarding, injury prevention, methods

**BACKGROUND:** Even though there is no doubt that winter sports is contributing to wellbeing and health, its inherent risks cannot be overseen: the injury rate per 1000 skier days is between 1.9 and 3.5 (Bianchi & Brügger, 2015) and with approx. 325 million skier days worldwide (Vanat, 2015) we count for a total of 617,000 to 1.14 million snow sport injuries. Therefore every endeavour has to be made to improve protection and prevention. From the variety of prevention measures, i.e. better physical preparation or campaign work, our focus is on technological measures that may have the potential to increase snow sport safety. The keynote will report of three related research and development tasks, which were selected to illustrate the variety of methods necessary to deal with the underlying questions. The reason why we have chosen to focus on methods (and not on a single study's result) is the possible transfer of our approaches to other, similar difficult fields in sports biomechanics. The difficulties for researchers in winter sports are not only the challenging environmental conditions under which the sport is taking place. Even more problems arise from the fact, that skiing or snowboarding manoeuvers need an extreme large observation space and cannot be satisfactory reproduced under laboratory conditions (the external forces and the perceived snow-ski interaction are too different in artificial environments). Further, skiers and snowboarders need to protect themselves from the cold and potential falls by wearing ski suits. Both circumstances - the large observation space and wearing voluminous apparel – make it almost impossible to use the classical marker-based optical systems as key method to determine 3D-kimematics (infrared systems can anyway not be used in the brightness of snow). But also kinetics is extremely difficult to determine: Fixing the boot to a gliding element which is much longer than the foot, itself allows the transmission of two additional load components (forward-backward lean moment and the edging moment). This results in very different locations of the point of force application compared to walking, running and many other sports. Further, the magnitude of external forces can be very high, 2000 N in ski racing are rather common. Last but not least, there are a multitude of boundary conditions, which make data collections tedious – between the test runs, the subjects have to use the chair lift to get back to the starting point, communication between the stuff members is difficult due to the distance, data transmission via low energy radio (like Bluetooth or ANT) is not working due to the large observation space and very often other skiers and snowboarders on the slope interfere with our subjects. It is therefore no exaggeration to say that if research in skiing can be done successfully, it can also be applied to any other difficult sports environments.

The three research and development questions or development tasks which will be presented are:

1. The loading of the hip joint for different skiing manoeuvers.
2. The effectiveness of wrist guards for the prevention of wrist or lower arm fractures in snowboarding.
3. The development of algorithms for mechatronic ski bindings with the target to reduce the risk to suffer knee injuries.

Each one of these three research projects comprises of a variety of methods. For the determination of the hip joint loads, full body motion capturing on the snow, combined with differential GPS and ground reaction force measurements delivered the input for an inverse model. In our wrist guard study simulated falls in the lab provided the input data for a multi-body and finite element model to simulate stress and strain of both os radius and os ulna with and without wrist guard. To develop the mechatronic binding and to systematically investigate its potential to reduce loads to the anterior cruciate ligament, an artificial knee joint with full muscle control has been realized. The keynote will give the method overview and the results derived for each of these three projects.

## LOADING OF THE HIP JOINT FOR DIFFERENT SKIING MANOEUVERS

**INTRODUCTION:** There is an increasing number of total hip replacements in OECD countries, Pabinger & Geissler (2014) account for 200-280 per 100.000 population in USA, Switzerland and Germany. The majority of patients regain full mobility and formerly active people like to go back into sports. For the reason of rehabilitation intending to increase the persons' muscular protection capacity and to support the healing process, even formerly inactive people should be motivated to sport activities. In the consequence after total hip replacements, orthopaedic surgeons often have to answer the question which sport they would recommend and if skiing belongs to the recommendable ones. Skiing may create rather high loads acting on the leg, not only due to centripedal forces but also because of excitations of vibrations from the slope. Sometimes there might be even impacts in case of falls or collisions. As this could result in significant loading of the hip joint compared to daily activities, our case study intends to quantify the hip joint reaction forces – looking at first at different type of skiing manoeuvers.

Figure 1: Instrumented skier with dynamometers, goniometer, DGPS and inertia sensors.

**METHOD:** One male expert skier (50y) being former member of Germany's ski instructors demo team with bilateral total hip endoprosthesis performed a total of 17 runs demonstrating (1) short turn, (2) skidded- and (3) carved medium turns, (4) plough turns, (5) skating steps and (6) straight plough (Fig. 1).
A custom built, fully decoupled 6-component dynamometer (Kiefmann, Krinninger, Lindemann, Senner & Spitzenpfeil, 2006) was used to collect the loads between ski and ski boot. With these data the point of force application can be determined. Segment kinematics was obtained using 17 commercial MARG (Magnetic Angular Rate and Gravity) units (moven®, Xsens Technologies, Netherlands). Additionally a mechanical goniometer was applied to measure the tibia flexion angle relative to the ski. Differential GPS (Leica

Geosystems AG, Switzerland) with a spatial resolution of 1 cm horizontal and 2 cm vertical was used to track a reference point on the skier during the entire run (approx.. 600 m). Additionally in one run, the EMG of eight muscles was collected bilaterally after having sampled the data during regular gait (for later normalizing). The hip joint reaction loads were calculated using inverse dynamics.

**RESULTS:** With 125% body weight (BW) the maximum hip joint reaction forces for carved short turn were highest compared to the other manoeuvers, but the difference to drifted turns was lower than expected (i.e. drifted medium turn 115%). Plough turn in flat terrain resulted in 80% BW and even though there are no centripedal forces present during skating steps, the hip joint reaction force reached peak values of those of short turn in moderate steep terrain. It is very likely due to our skier's high skill level and his perfectly centralized position that the resulting maximum hip joint reaction forces have similar magnitude as those from daily activities, like walking and climbing stairs. (Bergmann, Deuretzbacher, Heller, Graichen, Rohlmann, Strauss & Duda, 2001).

**DISCUSSION:** Since our subject was an excellent skier, we expect reaction forces to be distributed less symmetrically and imbalanced with less skilled skiers or persons with unilateral hip endo-prosthesis. Our study did not consider the contribution of the muscles to hip joint contact forces, which are known to be very high: Bergmann, Deuretzbacher, Heller, Graichen, Rohlmann, Strauss & Duda (2001) determined peak HJ contact force for walking with 238% BW and stair climbing with 251% BW and Rooney & Derrick (2013) reported 790% to 880% BW for running.

## PREVENTION EFFECT OF WRIST GUARDS FOR SNOWBOARDING

**INTRODUCTION:** Among all snowboarding injuries, the upper extremities comprise the body region most frequently reported injured. The risk of wrist injuries is higher in snowboarding than in alpine skiing (Kim, Endres & Johnson, 2012). According to Idzikowski, Janes & Abbott (2000) 96% of wrist injuries are induced by falls. Experienced athletes tend to have fewer wrist injuries than beginners; 72% of all wrist injuries occur within the first 7 days of learning to snowboard (Hagel, Goulet & Platt, 2004). Based on a literature review, backward falls result in twice as many fractures as forward falls (i.e. Deady & Salonen, 2010). A backward fall with outstretched upper extremity joints was found as the worst case scenario (Lehner, Geyer & Michel, 2014. In their white paper on the efficacy of wrist protectors, Michel, Schmitt and Greenwald (2013) list several studies which confirm the reduction of wrist injuries due to the use of protectors [i.e. Kim & Lee, 2011; MacDermid, 2008). In consequence their application is recommended - however, it remains unclear which specific wrist protector design or protective component provides the best protection. Currently there are no national and international standards available which define minimum requirements and describe appropriate test procedures for snowboarding wrist protectors. In order to systematically investigate how design- and material factors influence the wrist guards' protection capacity, we developed computer models and performed simulations of backward falls, particularly looking at the biggest target groups, children and adolescents.

**METHOD:** In the first step a scalable multi-segment model of the human body with detailed 3D model of the upper extremity was developed using multibody simulation (MBS) software (SIMPACK AG, Gilching, Germany). The exact surface models of the arm, hand and finger bones and the solid portions of the radius and ulna had been created based on computed tomography (CT) data. Second a total of 20 different CAD models of wrist protection devices were designed in CATIA (Dassault Systèmes, Vélizy-Villacoublay, France) and "fixed" to the model of the lower arm and wrist joint. The fixations of the dorsal and palmar splints (in real-life fixed to the forearm with Velcro® fastener) are modelled with four spring-damper elements, located on the circumference of the CAD surface of the forearm.

The number of modelled hook-and-pile fasteners was varied; one was used for the short splints and two for the medium and long splints. In the third step backward falls with outstretched elbow joint and an 80° retroversion of the shoulder joint were simulated for the anthropometry of male 9 year old children, 13-14 year old adolescents and young adults with 20 years of age. The outputs of these simulations were the resulting wrist joint contact forces for the different wrist protectors as well as for the unprotected case. In the last step a detailed analysis of the loading forces on the forearm bones was conducted with finite element analysis (FEA) (ANSYS Inc., USA). We used FEA models of the os radius and os ulna (Fig. 2), taking into account that bone strength changes with age and gender.

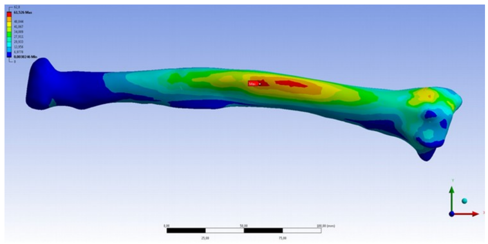

Figure 2: FEA of the stress distribution in the radius of the adult wearing the medium length dorsal protector

The major change is in the epiphyseal plate, the hyaline cartilage plate in the metaphysis at each end of the long bones, present in children and adolescents. In adults, when growth has stopped, the plate is replaced by an epiphyseal line.

**RESULTS:** Our bending results showed that the short splint versions provided insufficient protection, but protection increased with the longer versions (Fig. 3). The dorsal splint and the sandwich splint showed a slightly decreased wrist angle at impact compared to the palmar splint. This protective effect was slightly enhanced by padding, but there was no significant difference between the 10-mm and the 5-mm padding thicknesses.

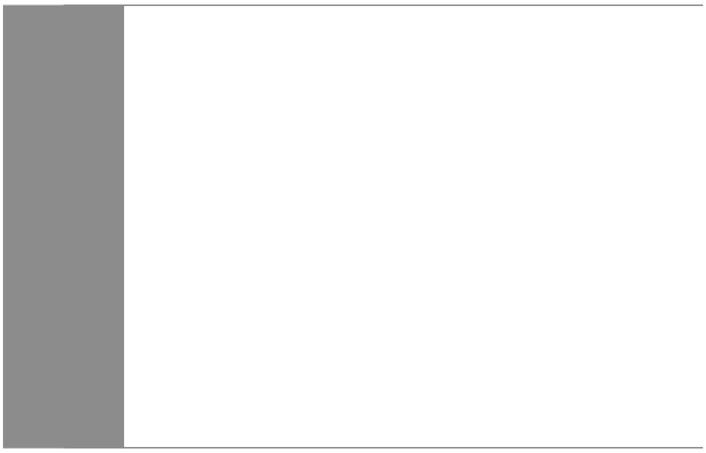

Figure 3: Relative reductions (%) in wrist extension when different protector versions were used, compared to the reference model without a protector (0.0).

For the adults in the unprotected condition, the maximum shear stress occurred at the palmar radius, just above the joint space. With protectors, one maximum was located above the styloid process of the radius, and with increasing shear stress, a second maximum was observed in the shaft.

For the adolescent and child models, the long dorsal protector reduced the maximum shear stress at the hyaline cartilage plate significantly, for the 9-year-old by 54% (compared to unprotected situation).

**CONCLUSION:** This study identified the wrist joint extension and the resulting bone stress for different age groups with and without the use of different type of wrist protection for backward falls. It provides the basis for design requirements and testing procedures of such devices thus making the formulation of ISO standards possible. The detailed description of this investigation is submitted for publication (Lehner, Michel, Brügger & Senner, 2015)

## TOWARDS THE DEVELOPMENT OF MECHATONIC SKI BINDINGS

**INTRODUCTION:** Even though the incidence of knee injuries has declined since the mid-nineties with the introduction of the carving skis (Johnson, Ettlinger & Shealy, 2009), the proportion of knee injuries remains very high compared to the total incidence of injuries. The

knee is the most commonly injured body part in downhill skiing (Bambach, Kelm & Hopp, 2008; Ruedl, Webhofer, Linortner, Schranz, Fink, Patterson et al., 2011). Considering the figures given above on the total numbers of skier days in the world and using the injury rate of anterior cruciate ligaments (ACL) injuries being reported by Laporte, Binet & Constans (2000) with 3125 MDBI (mean days between injuries), we have to deal with a total of more than 100.000 ruptured ACL ligaments every year. It is not questioned among scientists: knee injuries continue to be the central topic for prevention in downhill skiing.
This situation provokes the question, why the ski bindings are not able to avoid injury prone loads to the knee and why their release levels have not been lowered. The answer is that since the early eighties, ski release bindings have not been changed in their basic design. They were developed to protect the tibia bone and as the tibia fracture rate in alpine skiing is very low (below 5% of all injuries) they seem to do a good job. Shealy, Ettlinger & Johnson (2005) have applied the principles of signal detection theory to the problem of "no release" and "inadvertent release" to their impressive database with over 6 million skier days and 17,000 injuries. From this study they drew the conclusion *"…that the balance between the two failure modes appears to be near the optional point what concerns midshaft tibia fractures and the risk of inadvertent releases with subsequent injuries*" (Shealy et al., 2005, p.11). The author has conducted an extensive literature review on technical measures to reduce the risk of knee injuries in skiing (Senner, Michel, Lehner & Brügger, 2013; Senner, Lehner, Nusser & Michel, 2014). One of the major results of this review is the statement, that ski bindings are needed with release values set or lowered dependent on (i) gender, (ii) age, (iii) skiing speed, (iv) knee angle, (v) knee angular velocity, (vi) muscle condition of major knee flexors and (vii) of the hamstrings. This, however, can only be realized switching to mechatronic binding concepts.
Although patents of mechatronic binding concepts have already been submitted in the early eighties, no commercial solution has ever been appeared on the market since. The main reason is that the algorithm that controls such kind of mechatronic binding needs a comprehensive understanding of the complex interaction between the aforementioned parameters with respect to loading the different structures of the knee.
The target of our research is to get this necessary insight and – on longer term – develop and evaluate a function prototype of such kind of a mechatronic binding.

**METHOD:** An artificial lower leg, including a sophisticated physical model of an instrumented knee, has been constructed, manufactured and combined with a load simulation device. This device allows the application of any combination of external forces and moments typical for skiing and for injury prone situations. With this apparatus we can systematically manipulate the boundary conditions and varying the values of input parameters, i.e. muscle tension. The presentation will illustrate all details of that surrogate and give some of the results from its validation and sensitivity studies.

**CONCLUSION:** The three research projects illustrate the wide variability of methods ranging from field studies to the use of physical and mathematical models to answer open questions in the field of safety in alpine skiing and snowboarding. It is obvious, that the principles of these approaches can be transferred to other sports with similar difficult boundary conditions.

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