

# ***Experimental Test Setups and Simulations in Skiing Mechanics***

*by*

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# ***Experimental Mechanical Test Setups and Simulations in Skiing***

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## **Abstract**

Product testing and development are essential parts in sports and for the athletes in their quest to reach the podium. Manufacturers of sports equipment often use basic test methods which do not test the equipment in a sports specific way. Much of the equipment used by world-class athletes is chosen based only on subjective tests and the athletes' feelings. One short term aim was therefore to develop test methods for objective tests of sports equipment that also tested the equipment in a sports specific way. Another aim was to integrate mechanics and simulations to enhance the understanding of the test results. The more long term aims are to contribute to increased theoretical knowledge regarding test methods for sports equipment and to contribute to the development of test methods to create new and better sports equipment. Experimental tests combined with simulations can give valuable information to improve the performance and safety of sports equipment. Three studies dealt with the issue of objective yet sport specific test methods for sports equipment. The main methodological advancement is the modification of established test methods together with conventional mechanics calculations. New test devices and methodologies are proposed for alpine ski helmets and cross-country ski poles. Suggestions are given for improved test setups as well as theoretical simulation are introduced for glide tests of skis. The results show how sport specific test methodologies together with theoretical calculations can improve the objectiveness and relevance when testing sports equipment. However, the collected and used data require high precision to obtain high accuracy in the simulations. High data accuracy can be an issue in field measurements but also due to manufacturers not disclosing key material data. Still, the used methods and calculations in this thesis produce relevant and reliable results which can be implemented to accurate evaluations of different sports equipment. Even though it has not been a first priority aim in this work, the results from the alpine helmet study have been used by helmet manufacturers to design new helmets with increased safety properties. This further show how an objective and sport specific test approach together with theoretical simulation can improve sports equipment and in the longer perspective, also the athletes' performances.

**Descriptors:** sports equipment, test methods, sports mechanics, alpine skiing, cross-country skiing, poles, helmets, glide, performance



## **Preface**

This thesis studies the possibilities to increase the objectivity in the testing procedures of sports equipment based on experimental approaches accompanied by mechanics simulations. The first part gives a concise background, description of methods, results, conclusions and ideas for further work. The second part of the thesis consists of the following three papers:

**Paper 1.** Swarén, M., Holmberg, H.-C. and Eriksson, A.

“Repeated low impacts in alpine ski helmets”

Published in Sports Technology, 2012. 6(1): p. 43-52

**Paper 2.** Swarén, M., Therell, M., Eriksson, A., Holmberg, H.-C.

“Testing methods for objective evaluation of cross-country ski poles”

Published in Sports Engineering, 2013 16(4): p. 255-264

**Paper 3.** Swarén, M., Karlöf L., Holmberg, H.-C., Eriksson, A.

“Validation of test setup to evaluate glide performance in skis”

Submitted to Sports Technology in January 2014

For all papers Swarén (MS) has been responsible for the experimental setup, after dialogue with supervisors and co-authors. MS has also been the main responsible for performing the experiments. Manuscripts have been written by MS with input from Eriksson and Holmberg. The work has, in addition to journal manuscripts, been presented at two conferences.



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# **Part I**

## **Overview and Summary**



## Chapter 1. Introduction

Biomechanics is frequently used to study human movements and has been defined as the study of the movement of living things using the science of mechanics [1, 2]. Biomechanical studies are often used to improve sports performance and equipment as well as to increase the understanding of injury mechanisms. Elite sports push the human body to its maximal capacity and athletes must commit to total dedication and training discipline to reach the podium in the Olympics or the World Championships. For example, world class cross-country skiers train between 700-800 hours per year and international elite rowers around 1100 hours per year [3-5]. However, it is not only the number of training hours that is important to become an elite athlete; food as well as rest are both highly significant to performance. Overall, elite sport is today a full time job where everything has to be planned, carried out, analyzed and optimized. Hence, every detail is important and so also the equipment.

Objective mechanical and biomechanical test methods are needed to support athletes in their quest to perform at their peak capacity. This is especially important in sports like skiing, pole-vaulting, speed-skating, golf or cycling where the equipment plays an essential role, affecting the athlete's performance and hence the end result. Furthermore, objective test methods of sports equipment provide reliable and repeatable data to manufacturers to use when designing new products. Objective tests of sports equipment need to be robustly designed but test the equipment in ways as similar to reality as possible. This thesis deals with these aspects with emphasis on the methodology rather than individual results.

### 1.1. Objective tests of sports equipment

Elite athletes always strive to increase their performance to reach the top of the podium. Different reoccurring tests, e.g.  $VO_2$ , strength and lactate thresholds are often used to monitor and assess training and performance. These tests provide objective data which describe the physiological status of the athlete. Based on the received data the athlete and coach can plan and optimize the training, preparations and the tapering for an upcoming race or season. Sports activity requires specific equipment and even though thousands of hours are spent on optimizing sports equipment for elite athletes, the selection process is still in many cases based on subjective feelings.

Competitive alpine- and cross-country skiing are today well-developed athletic activities. Athletes are well-trained and the equipment is well developed with respect to both materials and geometric forms. Margins between athletes are measured in 1/100 s. which calls for further development of the athletic techniques, but also of the equipment.

### 1.2. Background

Sports biomechanics is a broad field which is used for various human motion analyses to increase the understanding of different movements, injuries, performances as well as product development and optimization. For a given athlete and exercise, equipment can play an important role for optimizing the performance by e.g. reducing the rate of fatigue or by minimizing energy losses. Today, objective test methods for sports equipment are predominantly used for evaluating the equipment's effects on the athlete's performance. Examples of this can be found in most sports, e.g. for clothing, bikes, shoes, vaulting poles, ice-hockey sticks or golf clubs [6-12]. Sperlich and Holmberg [13] investigated the physiological effects of different racing suits in cross-country skiing and found that a newly developed suit with better ventilation capacity, compared to an older one, decreased the athletes' core temperatures, lowered the oxygen uptake, minute ventilation and heart rate during an incremental intensity test on roller skis. In addition, engineering and mechanics play a central role in sports performance and also from a biomechanical point of view, as equipment often affects the athlete's movements, technique and performance. For example, Worobets et al. [8] investigated the influence of shaft stiffness on potential energy and puck speed in ice-hockey. They found that the stiffness influences puck speed during wrist shots and that more flexible sticks could store the most

energy, resulting in higher puck speed. However, how the ice-hockey player loads the stick has as much influence on puck speed as the design and properties of the stick. Another example of how mechanics can influence sports performance is the development of the klapskate in speed skating [14, 15]. The klapskate has a hinge mechanism underneath the ball of the foot instead of a rigid connection as in conventional skates. The hinge mechanism allows the foot to plantarflex during the end push off, while the whole blade still glides on the ice [15, 16]. This enhances the effectiveness of the plantarflexion which increases the work per stroke, mean power output and gross efficiency compared to conventional skates [15, 17]. Still, the here mentioned studies investigate and validate mechanical parameters by measuring how the athletes are affected by the equipment, and whether the results are better or worse compared to a baseline situation. This is highly relevant as the equipment will be used by different athletes and the aim is to increase the performance. However, the human factor is always present in such a test setup, which decreases the repeatability as every test will be different. The lack of objective evaluation methods for sports equipment is substantial. There are, however, papers where new objective test methods and simulations are presented. For instance, Bäckström et al. [18] developed a device to objectively measure essential characteristics of cross-country skis. Their device measures the span curve and pressure distribution for any selected load on the ski. The results from these measurements can be used to pair together skis with the same mechanical characteristics, and also to categorize and select skis for different weather and track conditions.

### 1.3. Sports applications

The target groups of athletes and manufacturers are both depending on the equipment to succeed in their occupations. Hence, from a scientific point of view, both groups strive for the best possible performance, but within their individual branches of occupation.

The three studies in this thesis each have their own applications. The helmet study, Paper 1, is the one where the mechanical methodology was chosen based on actual impact observations from alpine skiing as well as on established standardized test methods for alpine helmets. Paper 2 deals with objective test methods for cross-country ski poles, and develops an objective and sport specific test method to compare and categorize cross-country ski poles. This is perhaps most important for manufacturers who want to compare pole models and/or control the production quality. Still, an objective test value for comparison purposes can be beneficial to customers as well as elite athletes who want to get an objective value on certain pole characteristics. Paper 3 is more mechanics orientated as it uses the law of energy transformation. However, the field of application, friction between ski and snow, is highly relevant in all ski-sports and in future biomechanical studies where the friction coefficient needs to be considered.

#### 1.3.1. Helmets

Alpine skiing involves a risk of injury and head injuries are common among alpine skiers [19-22]. Numerous studies report a reduced risk of head injuries with helmet use, which makes the alpine ski helmet an essential piece of safety equipment [19, 23-25]. Helmets, including alpine ski helmets, typically consist of a shock absorbing core, most commonly made of Expanded polystyrene (EPS) or Expanded polypropylene (EPP) with an outer shell of Polycarbonate (PC) or/and Acrylonitrile-butadiene-styrene (ABS) [26]. The International ski federation (FIS) rules say that it is mandatory to use an approved ski helmet in all competition events. An FIS approved ski helmet must have a smooth surface, have a shell and padding that cover the head and ears, with an exception for the slalom event where soft ear padding is permitted [27]. Accepted helmets shall have been CE marked and be in line with appropriate standards such as CEE 1077, US 2040, ASTM F2040, SNELL S98 or RS 98 etc. [27]. In addition, for the alpine speed events (giant slalom, super G and downhill), approved helmets must fulfill the requirements of both ASTM 2040 and EN 1077 and have a maximum deceleration (equal to or) lower than 230 g during an impact test following the norm EN 1077 Class A. The speed events helmet must also pass an additional specific test under the EN 1077 test

procedure but with an increased impact velocity of 6.8 m/s [28]. The increased impact velocity for the speed event helmets is enhancing the similarity between test and an actual crash situation in skiing. However, the test procedure only includes a straight falling helmet with a linear impact, which seldom occurs in a crash. Gennarelli [29] reported that the most frequent brain injuries from motor vehicle accidents are due to rotational acceleration. New helmet designs and test methods to minimize rotational acceleration are being developed, especially in activities where the head hits a surface, like in alpine skiing, which enhances the tangential forces [30-32]. This development reduces the gap between the test setup and the real crash situation. However, alpine ski helmets are not only exposed to one major impact during their lifespan, but also to minor low energy impacts from different types of collisions caused by normal handling and smaller tumbles. In alpine ski racing, where the skiers often aim to ski as short a line as possible, the helmets are exposed to repetitive impacts from hitting the gates. In giant slalom the helmet is particularly exposed to violence, due to the trajectory of the skier relative to the gate. Observations made by ski-coaches, race-skiers and manufacturers report co-occurrence breakage of race helmets due to the repetitive impacts from the gates. The front and temple regions are the most exposed areas and also where the shell and core fracture. Thus, helmets need to withstand the violence caused by hitting gates without losing their protective capacities.

### 1.3.2. *Cross-country ski poles*

Cross-country ski poles consist of a handle with a wrist strap, a shaft and a ski-basket with a metallic tip. The ski-basket generates support in the snow while the metallic tip creates grip on icy and hard ski-tracks or on roads when roller skiing. The shafts were originally constructed of solid wood, later bamboo, which remained the standard shaft material until the 1970s when shafts made of aluminium or fibreglass arrived [33]. Modern racing poles are constructed of carbon fibres in an epoxy resin, a design which generates high shaft strength with minimum weight, but also rather a high level of flexibility. Cross-country skiers normally use pole lengths of 83 – 85 % of body height in classical skiing and 90 % of body height in the skating technique. Nilsson and co-workers [34] investigated the influence of pole length on ground reaction forces and propulsive impulse and found that longer poles significantly increase propulsive force and impulse, due to a longer thrust phase. In addition, Hansen & Losnegard [35] reported 0.11 s shorter sprint time with 7.5 cm longer poles than the self-selected pole length during an 80 m all-out double poling trial on snow. Hence, longer poles could be beneficial in certain situations where the highest possible propulsive pole force and maximal skiing velocity are essential. However, longer poles combined with higher peak forces and the more explosive poling techniques, described by numerous authors [36-39], generate higher demands on the poles regarding shaft strength, rigidity, durability and power transfer. In addition, Stöggel & Karlöf [40] found that the bending behavior of cross-country ski poles affects skiers' abilities to ski at high velocities and that higher performance skiers should use poles with more homogeneous bending behavior. It is therefore surprising that in contrast to the amount of time and resources invested in ski testing, cross-country ski poles are tested and selected based upon the perception of the shaft during skiing.

### 1.3.3. *Glide testing for skis*

It can be hypothesized that in all skiing events (with a minor exception for the need for grip in classical style cross-country skiing) the lowest possible friction between ski and snow is desirable. Ski bases are normally made of ultra high molecular polyethylene (UHMWPE) which has a surface that easily can be manipulated and optimized for maximal glide capacity. Lots of time and resources are invested in ski optimization through the use of different base structures and waxes. Today's waxing chemicals are highly sophisticated, as are the micro-machining techniques for the under-surfaces of the skis. Numerous studies [41-47] have investigated different parameters that directly or indirectly affect the ski-snow friction in order to increase the understanding of optimizing the glide in cross-country skis. With the obvious objective to choose a surface with the lowest possible friction coefficient, the testing and verification methods are, however, not developed far beyond a general

comparison of feelings. Today's comparison of the best possible surface properties for the expected race conditions are based on a direct comparison between different skis, waxes and base structures in a glide-track close to the arena. This method is practical to use out in the field but is sensitive to variation of the initial velocity, air resistance and the body masses of the skiers. In addition, photocells are sometimes used to measure the time between two selected points, to give more objective and comparable data. However, this setup only provides information regarding time used to glide a certain distance. This distance is often about 100 m, where the test-skiers normally starts from standing still and hence includes an acceleration phase as well as a gliding phase with higher velocity. Therefore, the test only gives a rough mean glide velocity value which could differ significantly compared to a racing situation. Breitschädel et al. [48] used inertial measurements units (IMU), attached to cross-country skis, to measure the acceleration during glide tests to attain continuous and accurate glide characteristics. The results could be used to roughly differ between skis ( $\Delta\mu \sim 0.01$ ), where  $\Delta\mu$  is the difference in friction coefficient, but did not have the desired accuracy to distinguish between the best skis ( $\Delta\mu \sim 0.001$ ), due to drift and noise in the IMU units [48]. Still, such a system could, if accurate, together with mathematical modeling of the friction coefficient give a more objective analysis of how the friction coefficient differs for various skis, grinds and waxes vary with skiing velocity. This insight is beneficial, when preparing skis for optimal performance and also for reducing time spent testing.

#### **1.4. Aim and scope**

The overall aim of this work was to enable objective test methods for sports equipment to enable repetitive and sport specific test results. A further aim was to simulate and compare the obtained test result with theoretical calculations.

##### *Paper 1, Helmet testing*

The main objective was to develop an objective test method for alpine ski helmets which could be used to evaluate the effects of repetitive impacts that arise when race skiers hit the gates. The test method should simulate similar impact patterns as in the field and allow the user to test and evaluate different helmet designs to increase the level of safety in alpine ski helmets. The methodology and relevance in this paper were primarily related to slalom and giant slalom as the impact velocity of the gate in the test setup corresponded most closely to those events.

##### *Paper 2, Objective test method for cross-country ski poles*

The objective was to develop a quantitative and reproducible methodology to establish mechanical properties of slender tapered CFRP shafts. The methodological development in this paper was primarily related to cross-country ski poles with associating loading cases. Also, an objective was to compare and validate the measured results with theoretical methods which commonly are used in mechanics. The work was aimed to result in theoretically grounded indices of cross-country ski poles which could be used for comparison purposes.

##### *Paper 3, Evaluation of test setup for glide evaluation of skis*

The aim of this study was to investigate various test setups for analyzing the glide properties of different cross-country skis and to analyze the friction coefficients for different ski pairs by using theoretical calculations. Also to further increase the accuracy of the methodologies that are commonly used for glide evaluation in cross-country skiing. A qualitative measure for the dependence of friction on velocity was a particular aim. In addition, the work included measurements of the test slope which were described as a function allowing usage of the law of energy transformation to calculate the theoretical friction coefficients during the acceleration phase of the glide tests.

### **1.5. Outline of the thesis**

The methods used in the three different papers are described in Chapter 2. Since the methods used are different in each paper they are presented with reference to their respective applications. Chapter 3 presents some main results which also are discussed. In Chapter 4, the main conclusions from the papers are found. The three papers, which this thesis is based on, are presented in the second part of the thesis.



## Chapter 2. Methods

All three papers approach a relevant problem from an applied perspective and from a view on how the equipment is used. This question formulation has been identified by input from users, manufacturers as well as from scientific papers. The method description will attend each paper separately as each paper has its own applied question formulation. The full descriptions of the methods of the three studies are given in the three appended papers in Part II of this thesis.

### Paper 1

#### *The design of test device*

A special test device was developed which was made from aluminium profiles to which an electrical motor with pertained gearbox was attached, Fig. 1. A driveshaft transferred the rotational movement from the gearbox to two asymmetrically mounted rods where a shortened slalom pole,  $l = 0.98$  m, was attached to the second rod via a short driveshaft, Fig. 1. The asymmetrically mounted rods created a sling-like motion which increased the rotational velocity of the slalom pole in the sector where it impacted the helmets. The test helmets ( $n = 12$ ) were off-the-shelf competition helmets, POC Scull Comp (POC Sweden AB, Saltsjöbaden, Sweden), size large. All helmets had the same design except from used core material, where six helmets had a core of EPS, and the other six helmets had a core of EPP. The helmets were divided into two groups, EPS and EPP ( $n = 6 + 6$ ), depending on the used core material. Beside the disparity in core material, both designs consisted of an inner liner of pneumatic honeycomb pads made of polyurethane and an outer shell of PC/ABS. The helmets were firmly fitted, using adhesive tape, to a headform which was monitored with a triaxial accelerometer, mounted at the headform's center of gravity.

The headform was positioned so the rotating pole impacted the helmet 0.035 m to the left of the helmet's centerline and the impact velocity was set to 13.3 m/s.

The two helmet designs (EPS and EPP) were tested randomly in an indoor environment. For reference purposes, one test series of 23 impacts was performed without any helmet on the headform.



Figure 1. To the left, the test device and the used test setup where the rotating pole impacted the helmet on the left side of the centerline. To the right, a close-up on the drive chain with the motor in bottom right corner and with the attached gearbox which drives the two drive shafts that are connected with asymmetrical mounted rods.

#### *Study design*

Acceleration data were collected at 10 kHz, for each axis, for 10 consecutive impacts. Five different data series were collected for each helmet, named R0, R200, R400, R600, R800 and R1000. The R0 series consists of impacts 1-10 whereas the R200, R400, R600, R800 and R1000 consist of impacts 190-200, 390-400, 590-600, 790-800 and 990-1000, respectively. The resulting acceleration acting on the headform's center of gravity was calculated from the collected acceleration data. Mean resulting

acceleration, mean peak resulting acceleration and standard deviation ( $\pm$ SD) for every sample series was calculated for test series EPS and EPP. Time to peak acceleration was calculated for all ten impacts in every series and presented as mean values  $\pm$ SD. A Head Injury Criterion (HIC) was calculated using:

$$HIC = \left[ (t_2 - t_1)^{-1} \int_{t_1}^{t_2} a(t) dt \right]^{2.5} (t_2 - t_1) \quad (1)$$

where  $a$  is the resultant head acceleration,  $t_1$  and  $t_2$  are any two points in time, with a fixed interval, but chosen to give the maximum HIC during the impact [49]. HIC was calculated for each impact using a 15 ms time interval, unfavorably placed.

One-Way ANOVA for repeated measures was used to analyze HIC and acceleration differences between the two helmet designs for each sample series, as well as for the two groups, using group mean values. The probability level accepted for statistical significance was set to  $P < 0.05$ .

## Paper 2

### *The design of the test device*

A specially designed test device was used for measuring the bending behavior of seven different cross-country ski poles that were commonly used in the cross-country ski World Cup 2011/2012. The pole length for each pole was measured from the bottom of the ski-basket to the entry of the strap in the handle and three poles for each length (145 cm, 155 cm, 165 cm and 170 cm) and model were tested.

The test device was designed to bend the poles in a similar way as during skiing, by applying the load via the handle strap. The load was applied by a sled, connected to the handle strap and sliding on two horizontally placed aluminium beams. The sled applied the load via a nut on the threaded rod (M10x1.5) which was operated by a handheld drilling machine at a constant speed of 800 rpm. The pitch of the threaded rod was 1.5 mm per thread which results in a linear velocity of 1.2 m/s at 800 rpm. Also, the sled could be connected to a wire that was led through a system of pulleys, where a 10 kg weight could be dropped in order to create a rapid eccentric axial impact load on the pole shaft.

The ski-basket at the end of the shaft was mounted to a load cell with the tip in a “cup” that allowed for unrestricted rotation within the required range of motion. Only brand-specific ski-baskets with a centrally placed tip were used. Shaft bending was measured using a laser distance meter mounted on a sled attached to two horizontal aluminium beams above the pole. The sled with the laser distance meter could be moved along the entire length of the test device and a linear encoder was attached to the laser unit to position the laser along the pole. Two guide pins were positioned on each side of the pole shaft to direct the bending direction of the shaft upwards, directly underneath the laser distance meter. All data collection was performed at 100 Hz.

### *Study design*

Three different tests were performed for each pole length and model; i) a maximal loading test was performed by increasing the load until no more force could be transferred by the shaft and only buckling-like bending occurred. The load was controlled via the nut on the threaded rod and the drilling machine. ii) a deflection test where each shaft was pre-loaded with 10 N as a baseline. The load was thereafter increased to 100 N and then with an increment of 100 N until the next level could not be reached due to breakage. iii) an impact test where a 10 kg weight, attached to the movable sled by an UHMWPE-rope, was dropped from a height of 25 cm. Each pole was tested three times. The dropped weight landed on an oil damper which lengthened the impact and reduced the force. The same measuring setup was used as that for the load test with the exception of the laser distance meter which was placed in the middle of the poles. The mean and standard deviation of the

impact forces were calculated for each pole model and length. Peak force from the falling weight on a rigid interface was  $955 \pm 10$  N ( $n=20$ ).

#### Data processing

As a theoretical reference, a mean pole  $B$ -value (flexural rigidity) was calculated for each pole. The  $B$ -value represents the effective bending stiffness of a beam section. It is possible to calculate the  $B$ -value by regarding the attached pole to be pinned at both ends by inserting Euler's expression (Eq. 2) for the critical force  $F_C$  in Eq. 4 where  $I$  (Eq. 3) is the second moment of inertia for a homogeneous hollow circular section and  $EI$  is replaced by  $B$ . The length  $L$  in Eq. 2 represents the length of the pole,  $d_o$  and  $d_i$  in Eq. 3 are the outer and inner diameters of the shaft respectively. Equation 4 gives the midpoint deflection  $\delta_{mid}$  from an end moment  $Fe$  on a simply supported bent beam of constant sectional properties.

$$F_C = \pi^2 \frac{EI}{L^2} \quad (2)$$

$$I = \frac{\pi(d_o^4 - d_i^4)}{64} \quad (3)$$

$$\delta_{mid} = \frac{0.0625FeL^2}{B(1 - \frac{F}{F_C})} \quad (4)$$

An expression for  $B$  could be achieved after inserting Eq. 2 and extracting  $B$  in Eq. 4, also refining Eq. 4 by using the maximal displacement of the shaft in the same loading situation, which gives a slightly different coefficient. In Eq. 5,  $F$  is the load on the shaft,  $e$  is the offset distance for the load from the centre of the shaft and  $\delta_{max}$  is the maximum measured deflection for the shaft along its length for a given axial load  $F$ .

$$B = \frac{0.0642FeL^2}{\delta_{max}} + \frac{FL^2}{\pi^2} \quad (5)$$

The constants of 0.0625 and 0.0642 can be derived from the standard equation for calculation of the deflection of a beam, simply supported at the ends, with an acting moment at one end, Eq. (6a-b) [50]:

$$\delta_{mid} = \frac{ML^2}{16EI} \quad (6a)$$

$$\delta_{max} = \frac{ML^2}{9\sqrt{3}EI} \quad (6b)$$

High deflections occurred for  $F > 200$  which decreases the accuracy for calculations based on buckling instability.  $F = 200$  N was the load where minimum deflection occurred, but still with deflection differences between the 145 cm and 170 cm shafts and was hence the load used in the flexural rigidity calculations with corresponding deflections values ( $\delta$ ) used, measured in the deflection test, and  $e = 0.017$  m.

The Southwell plot [51] was used to validate the maximal loading test with an established method to calculate the critical buckling load. The mean deflection value  $w$  for every load for each shaft model and length at various loads  $P$  were plotted as the value of  $w/P$  on the vertical axis versus  $w$  on the horizontal axis. The inverse slope of the Southwell plot gives the buckling failure load ( $P_C$ ) for this eccentrically compressed shaft as the load when deflections go towards infinity.

To verify the calculated theoretical buckling loads from the Southwell plots and the measured maximal static force, one FEM analysis was performed for one 155 cm shaft. The outer diameter was 15.8 mm at the top of the shaft, with a tapered shape at the tip; the final outer diameter of the thickness of the material was 0.8 mm. As a reference model, another shaft was modelled with constant outer- and inner diameters of 15.8 mm and 14.2 mm respectively. The shafts were modelled and analyzed in SolidWorks 2010 (Dassault Systèmes, Waltham, MA, USA) using aluminium

1060 with an E-modulus of 69 GPa as material due to the unavailable information regarding the representative E-modulus of the material in the carbon-fibre shafts.

The shockwave propagation velocity for a general shaft model was used for investigating if the impact test could be analyzed in a quasi-static manner or if the impact could cause a dynamic buckling scenario. Calculating the shockwave propagation velocity was done by:

$$c_p = \sqrt{(E\rho^{-1})} \quad (7)$$

where  $E$  is the estimated E-modulus for the CFRP used in the shaft and  $\rho$  is the density of the shaft,  $1638 \text{ kgm}^{-3}$ . An E-modulus of 200 GPa was used as no correct value for a carbon fibre reinforced polymer (CRFP) shaft was available due to manufacturers not disclosing key material data. The E-modulus in the longitudinal direction for CRFP materials is according to the literature somewhere between 145 -220 GPa [52]. The shockwave propagation time to move along the length of a pole was calculated by:

$$t = l/c_p \quad (8)$$

where  $l$  is the pole length.

### Paper 3

#### *The design of the test setup*

Two different pairs of skate skis were glide tested inside a ski-tunnel (Torsby, Sweden). Temperatures conditions inside the tunnel were constant with an air temperature of  $-4.0^\circ\text{C}$  and a snow temperature of  $-1.1^\circ\text{C}$ . Relative air humidity was steady at 82%. The test track consisted of a 51.38 m long slope with a vertical drop of 3.78 m. The slope was followed by a flatter glide-section of 50.36 m with a vertical drop of 0.56 m, Fig 1. All distance and vertical measurements were performed with a levelling instrument, a wooden ruler and a 50 m tape-measure, placed in the outside ski-track.

Two different pairs of skis were prepared by a professional ski-waxer with 11 years of experience working for the Swedish national cross-country team. One pair of skis, Fisher RCS Carbonlite Skate, was waxed with 100% flour carbons for maximal glide and high performance (HP). The other pair of skis, Madshus Nanosonic Carbon Skate RS (LP), was deliberately less well waxed, using a standard paraffin, Swix LF-7. Due to the different waxing strategies, the skis were named high performance (HP) and low performance skis (LP), respectively. All glide tests were performed by two professional test-skiers from the Swedish national cross-country team during two hours. The test-skiers had a total mass, including the ski-equipment, of 87 and 80 kg, respectively, for test-skier one (TS1) and two (TS2).

Speed-traps, consisting of two photocells, placed with a distance of 2 m, were used to measure the skiers' instantaneous velocities. The midpoint of the speed-traps were placed at the 11.12 m mark, 51.38 m mark and at the 101.74 m mark. A calibrated Doppler radar connected to a computer was positioned at the second speed-trap and aligned along the tracks. The Doppler radar collected velocity data at 35 Hz with an accuracy of  $\pm 0.04 \text{ m/s}$  and also provided distance data based on the measured velocity.

Also, each ski was equipped with one IMU unit (IMEGO AB, Gothenburg, Sweden) consisting of a 3D-accelerometer, a magnetometer and a gyroscope. The IMU units recorded movement data at 100 Hz and stored it on a SD-memory card. For positioning and synchronization purposes, stationary magnets were positioned next to the ski-track and in the middle of each speed-trap to generate a spike in the magnetometer data when passing each speed-trap. Each test run was performed to a total stand-still in order to get a zero-acceleration point for re-calibration of any drift in the IMU-units.

### Study design

Each test skiers performed 7 glide test for the HP and LP skis respectively (n=28). The skiing velocity ( $v$ ) at each speed-trap was calculated by:

$$v = s/t \quad (9)$$

where  $s$  and  $t$  are the distance and measured time between the photocells in each speed-trap, respectively. The velocities at speed-trap one, two, three and the average velocity between speed-trap one and two and two and three are called  $V_1$ ,  $V_2$ ,  $V_3$ ,  $V_{12}$  and  $V_{23}$  respectively. Based on the velocity mean values, the four most representative trials, one for each test-skier and ski-pair based on mean values, were selected for detailed analysis between speed-trap one and two. The velocity data from the Doppler radar for these four runs were synchronized with the velocities at the first and second speed-traps. Distance from the Doppler radar data was calculated and compared with the measured distance between speed-trap one and speed-trap two. The distance provided by the Doppler radar started from speed-trap one and 11.12 m were therefore added to distance value to get the total distance from the starting point.

### Data processing

The normal force,  $mg\cos(\alpha)$  was considered to be equal to  $mg$ , and the measured distance along the track equal to its horizontal projection, as the calculated average inclination ( $\alpha$ ) of the slope between the start and the second speed-trap was calculated to be  $4.1^\circ$ .

Potential energy ( $W_p$ ) along the track was calculated by:

$$W_p(t) = mgh_s \quad (10)$$

where  $m$  = the body mass of the equipped skier,  $g$  = the gravitational acceleration and  $h_s$  = the vertical elevation at each point based on the spline model of the test slope. The maximal potential energy  $W_{p(max)}$  was calculated for each test-skier by using  $h_s = 4.34$  m.

A 9:th degree polynomial was fitted to the raw-velocity data provided by the Doppler radar and the kinetic energy was calculated by:

$$W_k(t) = mv^2/2 \quad (11)$$

The skiers' total momentary energy, including accumulated energy losses, was defined as:

$$W(t) = W_k + W_p \quad (12)$$

Friction and air-drag losses were considered to be the energy difference  $\Delta W = W_{p(max)} - W(t)$ . The total energy loss rate was described by:

$$P(t) = \frac{d\Delta W}{dt} \quad (13)$$

and defined as:

$$P = P_D + P_f \quad (14)$$

The power  $P_D$  due to air drag was defined as:

$$P_D = F_D v \quad (15)$$

The drag force  $F_D$  was calculated by:

$$F_D = 0.5\rho v^2 C_d A \quad (16)$$

where  $\rho$  = air density,  $v$  = velocity against the air,  $C_d$  = drag coefficient and  $A$  = frontal area. The air density was set to  $1.3 \text{ kg/m}^3$  and 0.5 was used as drag coefficient as described by Leino et al. [53]. The friction coefficient between the first two speed-traps could then be described by:

$$\mu_1 = \frac{P - P_D}{mgv} \quad (17)$$

A 3:rd degree polynomial was fitted to the calculated friction coefficient. As described by Leino et al [53], an average friction coefficient  $\mu_2$  on flat ground was calculated as a reference value, neglecting the small effect of the slope  $\alpha$ :

$$\mu_2 = \left( m(v_0^2 - v_1^2) - A' \rho \left( \frac{v_0^2 + v_1^2}{2} \right)^2 \right) / 2mgs \quad (18)$$

where  $s$  = the distance between the two last speed-traps which was 50.36 m,  $v_0$  and  $v_1$  = skiing velocity at the second and third speed-trap respectively. The differences between  $\mu_1$  and  $\mu_2$  were calculated for each of the four tests at the same velocities as used when calculating  $\mu_2$ .

## Chapter 3. Results and discussion

### 3.1. Objective test methods

Paper 1 and 2 both resulted in new objective test methods which allow helmets and cross-country ski poles to be tested and evaluated in a sports specific and sports relevant context.

Paper 3 combined standard glide test procedures and theoretical calculations which resulted in a basic method to evaluate detailed ski glide parameters as functions of glide velocity. The experiments showed possible measurements techniques for position, velocity and acceleration data, but also pointed out the need for topography measurements.

### 3.2. Paper 1

The main result in this study was the development of a new methodology for testing alpine ski helmets in a realistic way in regard to the identified issue with repetitive impacts, when hitting the gates in alpine ski racing. The use of a 10 kHz sampling frequency for the 3D accelerometer, mounted at the COM of the headform, provided reliable translational acceleration data of the headform when exposed to impacts from the rotating pole. The foremost finding was the identification of the differences between EPS and EPP as core material, where EPS showed a higher level of breakage, peak accelerations and a shorter time to peak acceleration compared to EPP. Hence, EPP is a better suited core material in alpine ski helmets when these are exposed to repetitive low energy impacts. In addition, the findings suggest that helmets' capacity to withstand and absorb repetitive impacts is an important factor to consider when designing alpine ski helmets.

The limitations with the study was the restricted impact velocity of 13.3 m/s which is similar to reported velocities in slalom but lower than measured velocities in events like giant slalom, super G and downhill [54-57]. Another limitation in the study is how the rotating pole hits the helmets instead of vice versa, as in real skiing. The rotating slalom gate has less mass than a fast moving alpine ski racer, resulting in a smaller impact impulse in the test setup compared to the impulse that arises when skiing. However, the impracticality of building a test setup with a fast moving monitored headform, hitting a fixed slalom gate with the right movement, is considerable.

The energy absorption capacities of the helmets after withstanding 1000 impacts were not investigated here. This would require extensive test equipment which was not available at the time of the study but should be included in future studies. However, it can be hypothesized that the energy absorption capacity of a helmet after being exposed to 1000 repetitive low- to medium level impacts will decrease, especially if the impact area is the same as the area which previous has been exposed to the repetitive impacts.

### 3.3. Paper 2

The newly developed test device allowed a more skiing specific way of loading and evaluating cross-country ski poles. In the maximal load tests, all poles were deemed to be moving towards a buckling-type failure, with increasing transversal deflection, but without primary material failure. The main data finding show how each shaft reached a plateau, here named Maximal Force Transfer (MFT) where no more force could be transferred by the shaft. The MFT value was individual for each pole but clear differences in MFT were observed between the different models and pole lengths. The mean MFT for all pole models and lengths was  $577 \pm 89$  N. In general, MFT decreased with increased pole length whereas shaft deflection increased with increased pole length and applied load. The overall mean MFT for all shafts decreased by 19% between the 145 cm and 170 cm shafts, while the corresponding value for critical load, using Euler's buckling model, was calculated to a 28% decrease for the 170 cm shafts compared to the 145 cm shafts.

Peak forces from the impact test were on average 24% higher than the MFT values. The results showed up to 25% reduction of force transfer caused by the poles, 712 N compared to 955 N on a

stiff interface. The average time to peak pole force was  $18.0 \pm 1.5$  ms for all tests, which is longer compared to the mean shockwave propagation time between the ends, which was calculated to be 0.14 ms for pole lengths of 1.45-1.7 m. The resulting value for  $c_p$  and the short shockwave propagation time suggests that a quasi-static view on the loading situation is appropriate, and that the dynamic effects are limited, even in an impact situation.

On average, the MFT values were 14% lower than the calculated critical loads based on the Southwell plots, (Fig. 5). Critical load from the FEM simulation for the modeled OneWay Storm Max 10 155 cm shaft was 290 N compared to the critical load result for the shaft with constant diameter which was 2.4% higher (297 N). Calculated critical load, using Euler's buckling model (Eq. 2), for the shaft with constant outer and inner diameters of 15.8 mm and 14.2 mm, respectively, was 301 N.

### 3.4. Paper 3

The IMU-units attached to the skis provided no usable data due to high drift and variations in the units. The Doppler radar provided accurate velocity readings when compared to the speed-traps. The mean maximal velocity difference between speed-trap two and the Doppler radar was 0.6% for all tests. The distance and time data provided by the Doppler radar overestimated the distance and time between speed-traps one and two with an average of 1.0 m, 0.07 s and 0.34 m, 0.14 s respectively, for the HP and LP skis.

The difference in velocity between LP and HP increased along the test track where the LP skis were 3.0, 3.2, 3.4, 7.1 and 11.4% slower than the HP skis at  $V_1$ ,  $V_{12}$ ,  $V_2$ ,  $V_{23}$  and  $V_3$  respectively. The LP skis were in total 5.6% slower time-wise, compared to the HP skis along the whole test track. The HP skis had higher acceleration between  $V_1$  and  $V_2$  compared to the LP skis with an velocity increase of 96.1% compared to 95.2% for the LP skis. The decrease in velocity from  $V_2$  to  $V_3$  was 25.7% for the HP skis compared to 31.9% for the LP skis.

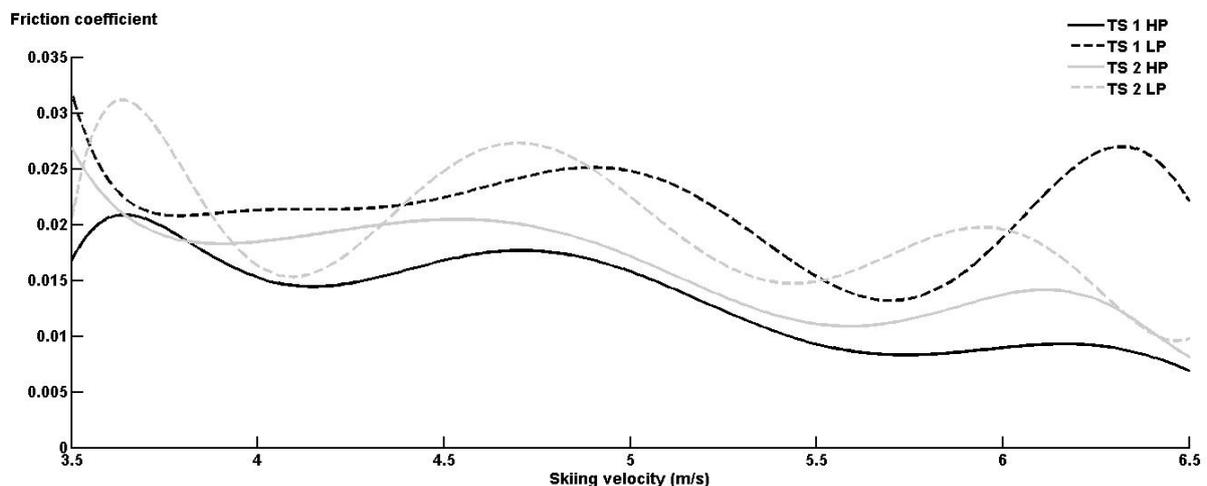


Figure 2. Comparison of the friction coefficient between the four selected trials during the acceleration phase. Notice the scaling on the x-axis.

An underestimation of  $W_p$  occurred due to too few data points for the spline model describing the track. The low  $W_p$ -values affected  $\Delta W$  which became too small at certain points, resulting in negative values of  $P$ , which is unrealistic with the used test setup. The spline model used to describe the track was therefore modified to a straight line using the equation:

$$y = mx + c \quad \text{Eq. (13)}$$

The calculated friction coefficients during the acceleration phase all showed similar sinusoidal tendencies, see Fig. 2. The mean friction coefficients for HP and LP during the acceleration phase

were 0.014 and 0.020 respectively and the mean velocity was 5.23 m/s and 5.07 m/s for the HP and LP skis respectively.

The mean calculated friction coefficients between speed-traps two and three, which were used as reference friction coefficients, were 0.021, 0.021, 0.023 and 0.024 for TS1 HP, TS2 HP, TS1 LP and TS2 LP respectively (n=7 for each ski pair and skier).



## Chapter 4. Conclusions and Future work

### 4.1. Conclusions

All papers in this thesis have approached measuring issues in sports equipment in an objective, yet sports specific way. A central part of the work has been to identify question formulations for important pieces of equipment which affect the overall performance.

The use of sports specific test methods allows for more relevant results which can be used for optimizing the equipment. Previous test methods have only used conventional tests which are designed to be applicable to a general question formulation. For example, a three point loading test which normally is used for evaluation of cross-country ski poles, is also used for baseball bats as well as for evaluation of flexural stress in concrete and metallic beams.

Two studies, *Paper 2* and *Paper 3*, deal with items of equipment which directly affect the sporting performance. In contrast, *Paper 1* presents a method to test helmets to increase the protective capacities of alpine ski race helmets which is not directly related to performance. Still, safety equipment plays an essential role in sports performance, as athletes would not be able to push themselves to their limits or be able to continue their sports careers after an accident. Therefore, all three papers are presenting new test methods for sports equipment which directly can be used for increasing sporting performance.

With the presented studies it is possible to test and evaluate different types of sports equipment for elite athletes and amateurs as well as for coaches and manufacturers. The method presented in *Paper 1* can be used for repetitive impact tests for other helmets than alpine ski helmets, for instance ice-hockey helmets, climbing helmets or boxing headgear. The developed test device allows easy adjustment of the impact velocity and easy replacement of the impact tool. Even though the test device in *Paper 2* was used for cross-country ski poles it can just as easily be used for alpine ski poles, trekking poles or Nordic walking poles. The results in *Paper 2* also show extra complexities introduced when using established mechanics calculations for calculating, e.g., the buckling failure load for struts as poles, which are constructed from highly optimized material combinations, have a tapered shape and are eccentrically loaded.

The results from these studies show the possibilities in designing test devices and test setups which mimic the situation where the equipment is used. Also, the findings show how theoretical calculations can be implemented to increase the objectivity in tests of sports equipment.

### 4.2. Future work

The results from the three different papers in this thesis all relate to different fields of biomechanics and sports mechanics. Further studies that gather every concerned field are hence difficult to design and also most likely irrelevant from an applied point of view. A more relevant and realistic approach is to divide the future studies into separate branches to achieve more in-depth knowledge.

Further studies regarding ski poles should be oriented towards skiing perception and performance relevance which are more individual and subjective matters, bearing, not least, the dynamic properties in mind. Hence, future studies based on the performed work in this thesis should be based on *Paper 1* and *Paper 3*.

#### Helmets

The results in *Paper 1* showed that repetitive violence, albeit if it is of low energy, is a significant factor for the deterioration of alpine ski helmets and should therefore be considered when designing and testing alpine ski helmets. However, the study only investigated how the repetitive violence affects the protective materials of the helmets and how to design an objective test method for testing helmets with regard to the repetitive violence that helmets are exposed to while skiing. The

study did not include any pre- and post tests where the helmets' protective capacities could be investigated. Future studies should include complete standardized tests, following the EN 1077 test procedure and with the increased impact velocity of 6.8 m/s, which is a requirement by the FIS (International Ski Federation) for all helmet used in the speed events [28]. A total of 24 helmets of the same model, designed for giant slalom and the speed events should be included in the study. The helmets should be divided into two groups of 12 helmets where one group should consist of new helmets and tested, according to the EN 1077 and FIS standards. The other group, consisting of 12 helmets, should be exposed to repetitive violence, as described in *Paper 1*, followed by the EN 1077 test with the increased impact velocity of 6.8 m/s according to the FIS regulations. Parameters to investigate would be peak acceleration, HIC, time to peak acceleration and visual controls of the helmets to identify possible damage to the different materials. The test results from the two different groups can then be compared to investigate how repetitive violence affects the protective capabilities of alpine ski helmets when exposed to a major impact. Supplementary tests should also be performed on helmets worn by elite alpine ski races during a season. This would show the tear of helmets and whether their protective capacities have been reduced or not.

Future studies regarding alpine ski helmets should include further development of the testing procedures. All test procedures that are used today consist in dropping a helmet, equipped with a monitored headform, from a certain height down onto a solid metal anvil. This test setup creates high impact energy which is important when evaluating helmets. Also, the solid anvil does not move, flex or deform which is important for standardization purposes. However, it is likely that the impact and deformation procedure is different on snow and ice. It is therefore of interest to develop an objective test method for executing drop tests of helmets on real snow, as this would create a more realistic test scenario. More relevant test results can thereby be used for designing new and better alpine ski helmets. There are different studies that describe the question formulation of more realistic test setups to obtain relevant test results for different fields of application [30, 31, 58]. However, most studies regarding improved tests for helmets are for motorcycle helmets, and they are only partially applicable to alpine ski helmets. A future project aimed to develop and evaluate a more realistic test method for ski helmets must therefore include literature studies as well as video analysis of different crash situations of alpine skiers, in order to obtain information on impact velocities, impact angles and how the head/helmet moves after the initial impact. However, Krosshaug et al. [59] investigated the accuracy of 3D joint kinematics from video sequences and found the accuracy to be poor and with high standard deviation between different observers, suggesting that results from studies using a simple visual inspection approach should be utilized with caution. Hence, more accurate video analysis is needed to obtain accurate kinematics to create a relevant test setup for alpine ski helmets. Krosshaug & Bahr [60] present a novel approach to acquire accurate kinematics from uncalibrated video sequences. Their approach is based on the usage of multiple cameras and the three dimensional modeling software Poser® 4 and the Poser® Pro Pack (Curious Labs, Inc., Santa Cruz, CA, USA). As all alpine World Cup races are TV broadcasted there are numerous crashes caught on video, simultaneously from different camera angles. Hence, future studies will therefore be needed to be divided into three steps where step i) is to identify a number of crashes causing head injuries and to use the Poser-method to estimate the kinematics of the head in the different chosen scenarios, ii) to design a test device which imitates the kinematics observed in the video analysis and which can be used on snow with repetitive and reliable results, iii) to evaluate helmets as well as the test device with the established helmets testing standards as the EN 1077 or the ASTM F2040.

### **Glide properties between skis and snow**

Future studies need to increase the precision of the test track estimations to achieve higher accuracy of the friction coefficient calculations. A differential global navigation satellite system (dGPS), as used by several authors [56, 61-63], can be used to achieve higher accuracy when measuring the test hill. A dGPS system has an accuracy of  $\pm 1$  cm and by measuring the track every 0.5 m, a detailed and

precise description of the test hill will be generated, which then can be explained as a spline function for further calculations of potential and kinetic energy. Also, more detailed measurements of the test hill permit the possibility to consider the inclination of the slope in the energy calculations. Future evaluations of the friction coefficient, based on the law of conservation of energy, must also include more accurate estimations of the test skiers' drag area to include the correct energy dissipation due to air resistance in relevant human postures and at different velocities.

Future attempts should be made to measure heat generation and heat flux which occur when a ski glides over a snow covered surface. These investigations should be performed outdoors on natural snow and during different temperature conditions. Previous studies to investigate the temperature changes which occur when polyethylene slides on snow and ice, have only been performed indoors in laboratory conditions [64, 65]. Bäurle et al [65] used a purpose-built tribometer and IR sensors to measure the track temperature in front of and behind a slider to evaluate the heat generation and temperature changes due to the friction between slider and snow. However, as these measurements were performed in a laboratory setting, the question arises if the method of using IR-sensors can be used outside to evaluate the friction between skis and snow. A future experimental setup should consist of a stationary, high definition infrared camera which monitors a short section of an accurately measured ski-track. A Doppler radar together with IMU units should be used to measure velocity and acceleration along the track while test skiers perform a number of runs with two differently prepared ski pairs. The velocity and acceleration along the track are compared to the theoretical values based on the law of energy conservation. The theoretical heat generation and heat flux are calculated by a combined dry friction and hydrodynamic approach and evaluated against the measured temperature change in the ski track [64, 65]. However, it is difficult to estimate the snow volume and the ski area which are heated and studies are needed to investigate these question formulations as well as to compare how differing contact areas affect the heat generation and heat flux.

A stationary facility for glide tests should be constructed to obtain accurate and repeatable glide data for evaluating energy losses due to friction. Such a facility needs to be wind-protected and a placing inside a ski-tunnel is therefore preferable. However, an indoor environment generates snow conditions which deviate from the natural snow, and a purpose built test facility should thus be outdoors in a wind sheltered place. The topography measurements for such a facility need to be highly detailed and accurate, as mentioned earlier in this chapter. Furthermore, it is important to facilitate re-measuring of the topography, as it will change with changing snow conditions and grooming.

A stationary test facility with constant conditions will facilitate the process of developing a portable and accurate measurement device to assist athletes and their aids when choosing skis, thought to perform optimally under the existing conditions. A portable device which accurately measures, calculates and instantly presents important glide and performance characteristics must be able to distinguish differences in friction coefficients between skis of  $\Delta\mu \leq 0.001$ , as a reduction of the kinetic ski-snow friction of 0.001 corresponds to a reduction of the run time of approximately 1s/km [48]. However, it is not obvious how to best rank different skis, based on the calculated friction coefficients, as the ski-snow friction coefficient might vary with numerous parameters which are not constant around a track e.g. skiing velocity, snow temperature, the thickness of the water film, gliding technique or UV-radiation. Future studies are needed to determine how well the friction coefficient, as a function of different parameters, correlates with ski performance.

### **Field tests combined with simulations to improve equipment and performance**

The strive in sports mechanics and performance technology should always be to try to test equipment and adjustments in as realistic a setting as possible. Sometimes, due to the nature of a sport or to the usage of the tested equipment, test setups need to be constructed to obtain objective test data. However, even though field tests are difficult to control and often involve human errors,

they can provide valuable data that would be impossible to obtain in a laboratory setup. Alpine skiing is an example where the equipment plays a significant role for performance. Alpine skiers spend hundreds of hours each season to find the best boots, bindings and ski. Still, there are just a few scientific studies that investigate how equipment and equipment settings affect skiing performance [66-71], whereas many of the equipment orientated studies in alpine skiing focus on the cause of injuries and/or injury prevention [24, 70, 72-80]. Objective and repetitive studies in alpine skiing are hard to achieve as each ski-run and every turn is unique and accurate performance orientated field studies are thus difficult to perform. Similar problems are present in other outdoor sports where the athletes move over large distances and/or where the athletes' movements alter the terrain which changes the conditions between each set of data collection. Objective field studies in sports like sailing, kayaking and rowing are also difficult to implement as the wind and wave conditions are uncontrollable. Still, field measurements are needed to optimize sports gear and also to increase the understanding of how equipment affects the performance.

Future studies, targeted towards equipment in outdoor sports like alpine skiing, trail-running and rowing should use wireless 3D kinematic suits combined with kinetic sensors to acquire the maximum quantity and quality of data. Such systems should also be complemented with an accurate positioning system to obtain accurate and continuous positioning data, which has been demonstrated to be vital in, e.g. glide tests for skis and for calculations based on the law of conservation of energy. Three-dimensional kinematics combined with kinetics give detailed descriptions of technique differences between athletes and possible technique adaptations due to different equipment and/or settings. In addition, the collected kinematic and kinetic data can be the basis of inverse dynamics, which can further increase the understanding of how equipment and different settings affect the athletes in a performance perspective, but also from an injury prevention standpoint.

Attempts should be made to perform objective field studies in alpine skiing with the use of a MyoMotion 3D kinematic suit (Noraxon U.S.A. Inc. in Scottsdale, USA), consisting of 16 IMU-units with a sampling rate of 200 Hz. Such a system is superior compared to a camera based 3D system, as it is not restricted to a pre-defined measuring volume and the measuring units can be hidden and protected underneath the clothing whereas a camera based system must have passive or active markers attached on the outside of the clothing. Plantar forces will be collected by pressure insoles (OpenGo, Moticon GmbH, Munich, Germany), placed inside the ski-boots and pole forces will be collected by a specially developed pole force measuring system, described by several authors [81-84]. A possible question formulation can be how boot settings affect the skiing performance. For instance, canting aligns the skier's foot, knee and hip in a straight or straighter line, to be able to withstand higher forces and to achieve better control of the on-edge angle while skiing. There are several different ways to measure how many degrees of canting a skier needs but most of them use a plumb line and different sized wedges and shims, which are placed underneath the boots. A more repetitive method to measure the canting angle is by placing the skier on two tiltable tables (one table per foot) and to adjust the canting angle by altering an adjusting screw, which tilts each table. The foot, knee and hip alignment is measured and visualized by a linear laser. When desired alignments for the feet are attained, the bottoms of the boots are milled down to the correct alignment angles. The effects of different degrees of canting can then be measured during skiing by using the equipment which has been described earlier in this section. Such a study can identify if the skiing kinetics and kinematics change due to different canting angles. By using inverse dynamics simulations, is it also possible to calculate the muscular work and the joint reaction forces. These types of simulations can help skiers and coaches to better understand the mechanics of canting, and will increase the knowledge regarding muscular demands. These insights are helpful, in a performance perspective, and also from injury prevention and strength training viewpoints.

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