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Technical aspects to improve performance in cross-country skiing

Thesis for the degree of Philosophiae Doctor

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Abstract

Beside the athletes themselves, a number of factors influence performance in cross-country skiing. Ski technicians typically have five possible adjustments to make to the given snow, track and weather conditions. These are: (1) to choose skis with certain desired mechanical properties, (2) to apply a suitable grind to the ski base, (3) to change the material of the running surface, (4) to apply a combination of various waxes and (5) to decide the fine-tuning of the surface texture with a hand tool. Extensive testing is their major approach prior to important competitions. This thesis presents experimental studies on such methods in the field and laboratory, and is divided into four studies:

I Investigation of mechanical ski properties of classical and skate skis in laboratory tests. More than 800 racing skis from the Norwegian cross-country, biathlon and Nordic combined teams have been analysed in the laboratory in the period 2009 to 2011. The study showed that men and women chose skis with similar stiffness characteristics for classic ski in the cold category whereas women selected ski which required 5 % higher load to compress the camber down to 0.2 mm. Several significant differences in ski characteristics were found for skating skis of male athletes between the three Nordic national teams of cross-country, biathlon and Nordic combined. The ski characteristics of the teams were mostly determined by the ski brand's specific ski characteristics. This finding was also in line with the documented changes due to temperature change. Temperature changes can result in increased or decreased stiffness, but in comparison with differences in characteristics between ski brands, the magnitude of these changes is on a much smaller scale

II The resetting process of the base material after a treatment with manual rilling tools were investigated. All tested skis were tested in the laboratory and in the field. The major goal of this study was the development of a new grinding machine for cross-country skis from scratch. A comparison between traditional stone grinding and the newly developed grinding method is presented.
Initial studies showed that the newly developed method resulted in a lower coefficient of variance of the average mean roughness of the produced structure. A reproducibility within smaller tolerances is in strong demand by ski technicians.

III A new inertial measurement unit (IMU) -based sensor was developed and tested in a ski tunnel. During the gliding tests, several systems were tested and compared to each other. By using a low-cost IMU and correction methods it was possible to produce reasonable estimates and distinguish between good and bad skis with a difference in the kinetic coefficient of friction of around 0.01. The accuracy needs to be improved by a factor of ten in order to meet the precision requirement and provide a system which can distinguish between skis with similar glide performance.

IV The characteristics of two coatings and their contribution to a reduced coefficient of friction were studied. In addition, the structural changes of the ski base material due to the waxing process and subsequent skiing were studied. The Fluorine

content, both in the base material and in the wax was given special attention. Field and laboratory experiments on the ski base materials, with and without waxes, were conducted. The study showed that products containing fluorine contributed to a lower surface energy and hence a more water-repelling surface with a higher static water contact angle. Carrying out direct comparisons between the outdoor field tests and the lab tests in this study proved challenging, since the product with highest measured coefficient of friction from the laboratory tests and lowest contact angle performed best in the final gliding test after 34.1 km of skiing. Aside from this, there were many similarities.

These four studies resulted in seven publications, P1-7, which are attached in the appendices to this thesis.

The work in this thesis resulted in the development of a new grinding machine for cross-country skis, which opens up for further development in the field of surface treatments. In addition a new device to measure ski characteristics has been developed, which was used in the second half of Study I to measure ski characteristics.

Preface

This thesis is submitted to the Norwegian University of Science and Technology (NTNU) for the partial fulfilment of the requirements for the degree of philosophiae doctor.

This doctoral work has been performed at the Department of Civil and Transport Engineering, NTNU, Trondheim, with Professor Sveinung Løset (NTNU) as a main supervisor and Alex Klein Paste (NTNU) as a co-supervisor.

The experimental part of the work was performed in cooperation with the Norwegian Cross-country, Biathlon and Nordic Combined teams at various places in Norway, at NTNU and at further locations in connection with the World Cup, the World Championship and Olympic events in Antholz, Beitostølen, Davos, Gålå, Liberec, Natrudstilen, Oberhof, Oslo, Ruhpolding, Sochi, Spåtind, Torsby, Val di Fiemme, Vancouver and Östersund. The working space for the test periods, the necessary field equipment and the safety instructions were kindly provided by NTNU, The Norwegian Olympic Sports Centre and SINTEF, Trondheim.

The work was funded by The Norwegian Olympic Sports Centre and the Centre for Sports Facilities and Technology (SIAT) at NTNU.

Acknowledgements

Everything started during one of the countless training sessions with NTNUI orienteering back in the winter of 2006, when I discussed my studies of Sports Equipment Technologies to a friend. He recommended that I contact his uncle, who was involved in various Sports Technology projects at NTNU. Later that same evening, I met Sveinung Løset for the first time. He was just about to leave for the Olympic Winter Games in Torino, Italy the next day. A short time later Sveinung introduced me to Arne Lier from Olympiatoppen. This was the start of a great time at NTNU, and a cooperation with many top-level athletes, trainers and ski technicians.

Without the initiative and great support from my supervisor Sveinung Løset, this would not have been possible, and I would like to acknowledge all of his efforts in creating this opportunity for me. To be one of his PhD candidates was a great honour for me and I really appreciate his help, which was always there whenever I needed it.

I would also like to show a major appreciation for all the support I received from Arne Lier over the past few years. Thanks to his initiative, it was possible for me to receive financial support from the Norwegian Sports Centre (Olympiatoppen) to get started with this PhD study. It is a great honour for me to have the opportunity to work with some of the world's best athletes, and their drive and pursuit for perfection has been a great source of inspiration and motivation for me.

During my stay at the institute for Civil and Transport Engineering, a new virtual centre was established – SIAT – the Centre for Sports Facilities and Technology. Bjørn Åge Berntsen has done a great job in supporting all the PhD candidates of the centre, and I very much appreciate his positive attitude and energy.

I was introduced to the working environment down in the "basement" as early as when I started to work on my master's thesis, and thanks to my colleagues and friends, it was a very social and productive place to be a part of. The big blackboard always invited spontaneous discussions. Thanks to all of you: Anton and Sergey Kulyakhtin, my office mates Marat Kashafutdinov and Nicolas Serre, Wenjun Lu, Ekaterina Kim, Ivan Metrikin, Johan Wåhlin, Raed Lubbad, Torodd Nord, Andrei Tsarau, Anna Pustogvar, Farzad Faridafshin, Marit Reiso, Martin Storheim, Daniel Zwick, Ole-Christian Ekeberg, Christian Lønøy, Kenneth Eik, Ada Repetto, Oddgeir Dalane, Vegar Aksnes, Eric van Buren, Michael Muskulus, Mayilvahanan Alagan Chella, Karl Merz, Fredrik Sanquist, Arne Gürtner and Simone Philippe.
Throughout the years at the Institute for Civil and Transport Engineering, I would also like to thank Marion Beentjes, Maria Azucena Gutierrez Gonzalez, Kjerstina Røhme, Elin Tønset, Daniel Erland and Sonja Marie Ekrann Hammer, all of whom helped me to solve any practical and administrative problems.

Another person who contributed substantially to my success is my co-supervisor Alex Klein-Paste. I got to know Alex during my period as a master's student while Alex finished his PhD, and his approach to research and always asking the right questions challenged and helped me during my work. His practical experience and hands-on mentality helped to speed up several experimental setups, which I really appreciated.

I had the unique opportunity to become closely involved in many research and development projects from the Norwegian Ski, Biathlon and Nordic Combined teams. Without the help from Knut Nystad, this would not have been possible, as he always thinks in terms of solutions and finds ways to overcome any challenges. I would also like to thank my colleagues from our research projects, *Ski 2010* and *Ski 2014,* who made many trips into unforgettable experiences, including Tom Idar Haugen, Håvard Skorstad, Terje Fardal, Svein Ivar Moen, Idar Terje Belsvik, Ronnie Frydenlund Hansen, Jon Kristian Svaland and Thomas Söderberg.

It was a great motivation to be able to work together with some of the world's best athletes, trainers and ski technicians.

During these projects, I also came in contact with Jan Muren and John Wiig Nordby, two enthusiastic friends who never stop exploring new opportunities, and their curiosity has been a great motivation for my work.

It would not have been possible to perform all the experiments without help from others, and I received great support from Øyvind Lund and Nora Haaland, two master's students from the Department of Engineering Design and Materials. Moreover, I would like to thank Nuria Espallargas and Sergio Armada for their help in the tribology laboratory.

I would also especially like to thank Wolfgang Kampel for the countless training sessions in the beautiful nature around Trondheim, as discussing both serious and less serious subjects often made my day much easier.

I am incredibly thankful to Line for her patience, understanding and efforts during the last years of work on this thesis. You have always supported me and backed me up, and I have tested your patience more than once, but nevertheless received great encouragement in response. You are amazing.

Last but not least, I want to express my gratitude to my family for their support, including my parents Eva and Christian, as well as my sister Julia and Tobias – you rock! I am sincerely grateful for all the support I received from my grandparents, and their attitude and standards are remarkable.

Felix Breitschädel

November 2013, Trondheim, Norway

Contents

Nomenclature

μ	kinetic coefficient of friction	[-]
$\Delta\mu$	difference in the kinetic coefficient of friction	[-]
a	acceleration	[$m \cdot s^{-2}$]
A	surface area	[m^2]
a_0	initial acceleration	[$m \cdot s^{-2}$]
a_{loss}	acceleration loss	[$m \cdot s^{-2}$]
a_t	tangential acceleration	[$m \cdot s^{-2}$]
C_d	drag coefficient	[-]
f	natural frequency, or specific force	[Hz; N]
F	applied force	[N]
F_{air}	force due to air resistance	[N]
F_D	propulsive force, parallel to the slope	[N]
F_f	ski drag force	[N]
F_N	normal force, perpendicular to the slope	[N]
g	gravitational force	[$m \cdot s^{-2}$]
k	stiffness	[$N \cdot mm^{-1}$]
k_{early}	stiffness in the range from 0.3 kN to 0.5 kN	[N]
k_{late}	stiffness in the range from 0.7 kN to 0.9 kN	[N]
m	mass	[kg]
p	level of significance	[-]
r	correlation coefficient	[-]
R_a	mean roughness	[µm]
R_q	root mean square average roughness	[µm]
R_{sm}	mean value of the profile element width	[µm]
R_{sk}	skewness	[-]
R_{ku}	kurtosis	[-]
v	speed	[$m \cdot s^{-1}$]
v_t	tangential speed	[$m \cdot s^{-1}$]
z_i	discrete set of surface height points	[-]
α	slope gradient	[º]
θ	static contact angle	[º]
Λ	damping coefficient	[-]
λ_c	cut-off wavelength	[µm]
ω	angular frequency	[$rad \cdot s^{-1}$]
ρ	air density	[$kg \cdot m^{-3}$]
Xs	profile element width	[µm]

Abbreviations

BI	Biathlon
BP	Balance point
BW	Body weight
CA	Contact Area
CBS	Contact of the back section
CC	Cross-country
CFS	Contact of the front section
CH	Chamber Height
CHBP	Change of the camber height at the balance point
DSC	Differential Scanning Calorimetry
FA	load needed to compress a ski down to 0.2 mm
FBW	Full body weight
FIS	International Ski Federation
HBP	Camber Height at the balance point
HBW	Half body weight
HDPE	High Density Polyethylene
IBU	International Biathlon Union
ICP-MS	Inductively Coupled Plasma Mass Spectroscopy
IMU	Inertial Measurement Unit
MS	Mass spectroscopy
MG	Metallic grinding
NC	Nordic Combined
NTNU	Norwegian University of Science and Technology
NTNUI	NTNU's Sports club
OLT	Olympiatoppen – Norwegian Sports Centre
PCH	peak camber height
PTFE	Polytetrafluoroethylene
RQ	Research Question
SD	Standard deviation
SE	Standard error
SG	Stone grinding
SIAT	Centre for Sports Facilities and Technology (Senter for Idrettsanlegg og Teknologi)
SINTEF	Foundation for industrial and technological research at the Norwegian University of Science and Technology - Stiftelsen for industriell og teknisk forskning ved Norges tekniske høgskole
SL	Span length
SPSS	Software package used for statistical analysis, an IBM Company
SSA	Ski Surface Analyser
UHMWPE	Ultra High Molecular Weight Polyethylene
WC	World Cup
XPS	X-Ray Photoelectron Spectroscopy

1 Introduction

1.1 Problem Outline - Motivation

General research in the field of cross-country skiing identified that in the intense fight for seconds during competitions, the athlete's locomotive power has to overcome three major external forces: Drag force from the wind, gravitational force in the uphills and frictional force between ski and snow (Colbeck, 1988, 1992b; Glenne, 1987; Kaps et al., 1996; Kuroiwa, 1977; Leino et al., 1983; van Ingen Schenau and Cavanagh, 1990). The performance of a competition skier can to a remarkable extent be effected by the choice and use of skis and ski waxes of low friction and good mechanical properties, and by using suits with low drag values (Spring, 1989). The gliding speed contributes to a substantial part to success as it was shown by Street and Gregory (1994). The importance of the subject is illustrated by research showing that the majority of a group of athletes themselves maintain that the skis decide the result list among similar level athletes (Rønbeck and Vikander, 2007).

Each season, world class athletes spend a large amount of time with their ski technicians to find the best possible skis suited for their individual technique and competition form, as well as track and snow characteristics. The importance of fast gliding skis in skiing competitions is significant since the margin between no success and a place on the podium is very small. In most international races in cross-country skiing, time differences of less than 1 % to complete the race separates a first and fourth-place skier (http://www.fis-ski.com). Moxnes et al. (2013) applied a power balance to cross-country skiing investigating the influence of various parameters on the performance. Their analysis showed that increasing the kinetic coefficient of friction (μ) from 0.037 by 10 % was comparable to a 4 % increase in time. Goede (2006) ranked the snow friction the third biggest contributor to the overall result beside the absolute VO_2max of the skier and the gross mechanical efficiency.

The translation from the mainly theoretical approach of Goede into competition advantage of athletes, however, remains mainly unexplored in a scientific manner.

Raising professionalism is visible in all Nordic sports. National teams have started to spend more money on their service staff, resulting in the investment to special wax-trucks from all major nations in order to optimize working conditions. Constant improvement and evolution seems essential to stay on top of the result lists. The goal for this thesis was therefore to identify ski-parameters which affect the tribosystem, and successfully find solutions to enhance them in order to improve the sliding characteristics between cross-country skis and snow.

This thesis addresses four aspects of the equipment and its contribution to performance.

- an equipment study of how the athletes actually choose their skis;
- development of a new ski test bench and grinding machine of skis;
- a study on the effects of modern ski wax containing fluorine particles;
- development and evaluation of an advanced inertial measurement unit-based ski testing sensor.

1.2 Research Context

Competitive skiing has a long tradition in Scandinavia, and by the second half of the 19th century, the sport became more organized in Norway. The first 50 km race in Oslo, called Husebyrennet, which started from Majorstua on February 7th 1888 (Gotaas, 2010). Since then, the popularity of various forms of cross-country skiing has steadily increased over the last century. Sweden's biggest sports event - the Vasaloppet - attracts up to 60,000 participants during the week of competition. Equally telling, all of the 17,000 starting places in Norway's Birkebeinerrennet were fully booked just one hour after the registration opened in 2012 (Pettersen, 2012; Vasaloppet, 2012). These are two impressive examples of the popularity of cross-country skiing in Scandinavia among the sports interested population.

In top-level skiing, it takes serious preparation from the athletes, as well as research and development from the support team in order to succeed.
Extensive research on the subject of winter sports and especially concerning cross-country skiing has contributed to a strong position of Norwegian athletes. Norwegian athletes from Cross-Country, Nordic Combined and Biathlon contributed with 14 medals (8 Gold, 5 Silver and 2 Bronze) during the XXI Winter Olympics (OWG) in Vancouver 2010 to the medal chart. In addition, the recent World Championship from FIS and IBU in 2013 were very successful as seen from a Norwegian point of view. A total of 117 medals during the past 10 World Championships confirm Norway's leading position (see Table 1.1). One reason these continuously great performances can be found in goal-oriented research projects throughout Norway. In addition to universities and colleges, there is the Norwegian Olympic Sports Centre (Olympiatoppen, hereafter called OLT) which has an operative responsibility and authority to develop top-level Norwegian sports.

Table 1.1. Norwegian medal chart for the last FIS and IBU World Championship and Olympic Winter Games including cross-Country (CC), Nordic Combined (NC) and Biathlon (BI). *) Including World Championship Mixed Relay from Khanty-Mansiysk, RUS

Year	*FIS World Championship (CC and NC)*	***1.***	***2.***	***3.***	*IBU World Championship (BI)*	***1.***	***2.***	***3.***
2007	Sapporo, JPN	5	3	6	Antholz, ITA	3	2	2
2008	-				Österund, SWE	3	5	1
2009	Liberec, CZE	5	3	1	Peongchang, KOR	4	1	3
2010	XXI OWG, Vancouver, CAN	5	2	2	XXI OWG, Vancouver, CAN*	3	3	0
2011	Oslo, NOR	8	4	6	Khanty-Mansiysk, RUS	4	1	3
2012	-				Ruhpolding, GER	4	1	1
2013	Val di Fiemme, ITA	7	5	5	Nove Mesto, CZE	8	2	1

The project leading to this thesis was primarily financed by OLT. During the full period it has been a close collaboration between the Norwegian Cross-country (CC), Biathlon (BI) and Nordic Combined (NC) national teams and the Norwegian University for Science and Technology (NTNU). Research questions and practical challenges from the national teams influenced the project content and direction, and unfortunately this cooperation also led to restrictions when it came to publishing some of the results throughout the project.

1.3 Research Questions

One typical characteristic of top level athletes is often their aim for perfection in everything they do. Constant improvement and evolution of the equipment seems essential to stay on top of the result lists. The equipment in cross-country skiing offers many working areas to improve performance in competitive skiing. The goal for this thesis was therefore to identify ski-parameters affecting the tribosystem, and find solutions to enhance them in order to improve the sliding characteristics between cross-country skis and snow.

Due to a close cooperation with the Norwegian Nordic national teams the research goals were defined based on their challenges. This work was to identify the most important parameters which contribute to performance of cross-country skis, to develop solutions, to understand and improve ski equipment in order to improve athlete’s performance during their preparation for upcoming Olympic Games and World Championships. This approach lead to a broad focus in the various research questions but ensured high relevance for top-athletes and their support staff in competitive skiing.

Seven research questions were defined:

RQ1: How can the characteristics of classic cross-country skis be classified and described?

RQ2: Do the male Norwegian national teams (CC, BI and NC) select skating skis with similar characteristics?

RQ3: What is the effect of temperature change on cross-country ski characteristics?

RQ4: Are there new methods to manipulate the texture of cross-country ski bases?

RQ5: Which methods reset the structure made by hand tools best?

RQ6: How accurate are current test procedures to evaluate the performance of cross-country skis in the field?

RQ7: What is the effect of nano waxes on ski performance?

1.4 Research Approach

The work presented in this thesis is mainly of an experimental nature and consists of in total nine studies. Four of those studies resulted in relevant publications included in this thesis. A graphical design of the research approach with connections between the studies, publications and connections is shown in Figure 1.1.

1.5 Relevant studies for this thesis

Study I: Ski Analysis
Cross-country ski characteristics from the Norwegian Cross-country, Biathlon and Nordic Combined teams were analysed. The effects of load to the camber height, stiffness and contact area are studied, and the effects of temperature change on the ski characteristics were also investigated. A new measurement device was designed and constructed to perform the analysis, which resulted in three publications, Papers 1, 3 and 4.

Study II: Ski Base Structure
The study contained two separate parts. In the first part of the study, we investigated the resetting processes of the base material after a treatment with manual drilling tools, and the results are presented in Paper 2. The major part of this study was driven and conducted with the help of external partners (IDT AS, Norway), and a new method for the grinding of cross-country skis was developed from scratch. A comparison between traditional stone grinding and the newly developed grinding method is presented in Paper 7.

Study III: Ski Testing
This study started in the autumn of 2010 with a pilot study, which was followed up with more extensive tests in 2011. A new inertial measurement unit-based sensor (IMU) was developed and tested with external partners (Apertus, Norway), and the results were presented in Paper 5 in 2012.

Study IV: Ski Wax
The effects and benefits of nano waxes were investigated in cooperation with a master student (Nora Haaland) during the winter of 2012/13. The study resulted in one master thesis and Paper 6, which was submitted in the fall of 2013. I was in charge of the study design, data collection, as well as and contributing to the data analysis.

1.6 Secondary studies that were performed, but which have not resulted in relevant publications for this thesis:

Five secondary projects contributed with valuable data to the thesis.

Study V: Dynamic Analysis
We used our developed frequency and damping measurement devices for cross-country skis and applied it to test oar shafts. This study resulted in one secondary paper (SP1).

Study VI: Frictional Heating
Two cross-country skis were instrumented with thermocouples to measure the effects of frictional heating during skiing in free technique. The study was performed in combination with students from the course *Experts in Teams*, and shows some interesting results that need further processing before they can be published.

Study VII: Finite Element Simulation
Results from the mechanical ski analyses were used to create a finite element model of a cross-country ski, which will help to create a continuous stiffness profile of cross-country skis. The study is not finished thus far.

Study VIII: Weather and Climate
Weather, snow and climate measurements have been continuously performed throughout the previous seasons. Data has been collected and used for internal documentation, though these results have not been published by the author.

Study IX: Performance Parameters
The most recent study focused on the importance of selected parameters of gliding performance in Cross-country skiing. To be able to conclude and present significant results a sufficient amount of data has to be collected. The study has not been finished by summer 2013.

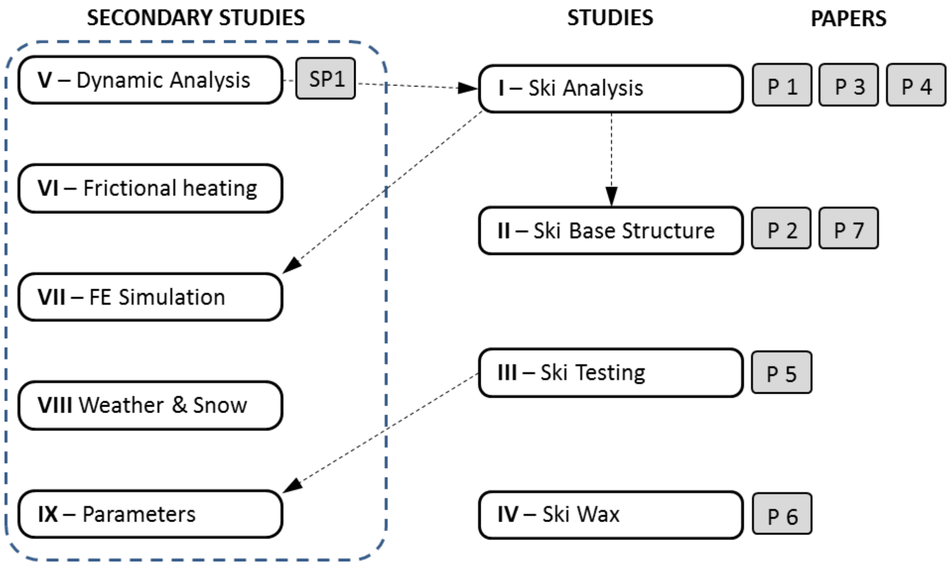

Figure 1.1: Studies vs. connections vs. papers.

1.7 List of Publications

This thesis is presented in the form of a collection of seven papers and some additional work. Paper 6 has been submitted to Procedia Engineering, and Paper 7 has been submitted to the Journal of Sports Engineering, while the others have been published. The complete papers are presented in Appendices A – H.

Main Papers

Paper 1

Breitschädel, F., Klein-Paste, A., and Løset, S., 2010a. *Effects of temperature change on cross-country ski characteristics*. Procedia Engineering 2, 2913-2918.

> **Relevance to this thesis:** Ski technicians consider ski characteristics the most important parameter for performance, and this study is important for an understanding of the mechanical behaviour of cross-country skis under changing temperatures. Knowledge about the ski's behaviour have led to a raised focus and changed testing procedures for the Norwegian ski team.

Paper 2

Breitschädel, F., Lund, Ø., and Løset, S. 2010b. *Cross-country ski base tuning with structure imprint tools*. Procedia Engineering 2, 2907-2911.

> **Relevance to this thesis:** Changing the surface texture from ski base running surfaces with manual tools is highly prioritized by ski technicians. Therefore a

series of four to eight pairs of skis is used to test and compare various manual tools. Before the series can be prepared for a new test all skis have to be “reset” which means that the viscoelastic and therefore the temporary texture change must have vanished. This paper investigated and compared several methods to reset ski bases after they were treated with manual structure tools. In order to enhance equal test conditions prior to new gliding tests it is essential to develop routines that which support and guarantee this. With this paper we contributed to the quality assurance routines of the ski teams.

Paper 3

Breitschädel, F., 2011. *Variation of Cross-Country Ski Characteristics*. In: Müller, E., Lindinger, S., Schwameder, H. and Stöggl, T. (Eds.). Int. Conference of Science and Skiing. Meyer & Meyer Sport, St. Christoph am Arlberg - Austria.

Relevance to this thesis: In their study Rønbeck and Vikander (2007) stated the importance of having good equipment. Today there is a broad consensus in the culture of competitive cross-country skiing that a number in the vicinity of 80 % of ski’s functional quality on the competition course lies in the skis when they exit the factory (Rønbeck, 1997, 2001). This paper is a result of Study I. The investigation and analysis of ski characteristics contributes substantially to success in cross-country skiing.

Paper 4

Breitschädel, F., 2012. *Variation of Nordic Classic Ski Characteristics from Norwegian national team athletes*. Procedia Engineering 2, 2913-2918

Relevance to this thesis: As with Paper 3, this paper focuses on the most important factor for success in cross-country skiing from the material point of view – the skis. Classical skis from the Norwegian cross-country team were analysed.

Paper 5

Breitschädel, F., Berre, V., Andersen, R., and Stjernstrøm, E., 2012. *A comparison between timed and IMU captured Nordic ski glide tests*. Procedia Engineering 2, 2913-2918

Relevance to this thesis: Performing and evaluating ski tests are essential in cross-country skiing. This paper focused on a new method to support traditional timed gliding tests with additional information. This study delivered a contribution for objective test methods.

Paper 6

Breitschädel, F., Haaland N., and Espallargas, N., *A tribological study of UHMWPE ski base treated with nano ski wax and its effects and benefits on performance*. Submitted to Procedia Engineering in autumn 2013, accepted for publishing, Procedia Engineering

> **Relevance to this thesis:** Ski waxing has a long tradition of improving performance in cross-country skiing. This study investigated the effects of nano waxes on the gliding performance over a distance of 34.1 km, and the findings have a great relevance for the thesis.

Paper 7

Breitschädel, F., 2013. *A new approach for the grinding of Nordic skis*. Manuscript was submitted in autumn 2013 and rejected. The Journal opened for revising and resubmitting the publication after additional documentation of the protected proprietary surface preparation method and additional quantitative measures of ski friction.

> **Relevance to this thesis:** This study contributes to this field of science in cross-country skiing. A new method for grinding skis has been developed, and this has proven to be an important parameter to improve sliding performance in cross-country skiing under certain conditions.

Secondary Papers

Paper SP1

Breitschädel, F., and Løset, S., 2010. *Vibration analyses of single scull oars*. Procedia Engineering 2, 3011-3016.

1.8 Declaration of Authorship:

Paper 1 (Breitschädel, Klein-Paste and Løset, 2010)
This paper builds from the previous work of Ronny Winther, a scientific assistant at the Department for Civil and Transport Engineering. He contributed to the study with building and maintaining the custom made measurement devices. I did all the planning of the experiments, performed all the measurements and was the leading author of the paper.

Paper 2 (Breitschädel, Lund and Løset, 2010)
This paper is a result of Study I, which was performed in cooperation with the Norwegian cross-country team and Øyvind Lund, NTNU. I have been the leading author for the paper and conducted all the measurements together with Ø. Lund, whose master’s thesis presents parts of the study.

Papers 3 and 4 (Breitschädel, 2012)
I have been in charge of all the planning and conducting of the study. A comprehensive platform and database has been developed to collect data, which serves as a basis for future analysis and research projects.

Paper 5 (Breitschädel, Berre, Andersen, Stjernstrøm, 2012)
The paper was formed based on collaboration between Vebjørn Berre, Erik Andersen and Robert Stjernstrøm. They designed and assembled the IMU sensor. I have been in charge of the study design, and performed all the experimental parts of the study.

Paper 6 (Breitschädel, Haaland and Espallargas)
I designed the experimental setup and performed all the experimental field tests. Nora Haaland performed the laboratory analyses during the study, Nuria Espallargas helped with the interpretation of the results and I was responsible for writing the paper.

Paper 7 (Breitschädel)
This study was collaboration between IDT AS (Norway), the Norwegian Olympic Sports Centre and NTNU. I was in charge of the grinding wheel design and performed the experimental tests and laboratory analyses, while IDT AS produced and assembled the prototype.

1.9 Structure of Dissertation and Readership

The thesis consists of the Introduction (Chapter 1) and five Chapters (2 – 6). Relevant papers are attached in the sequent seven Appendices (A – G).

Chapter 2 presents State-of-the-Art snow friction problems, and highlights the most relevant research covering cross-country skiing equipment. An overview about equipment testing, material developments, glide wax studies and methods is given.

Chapter 3 summarizes the context of the research and outlines the actual research design and methods for all the performed studies in this thesis, and the research questions are presented.

Chapter 4 presents the results from the studies dealing with ski characteristics, development of an alternative grinding machine, the IMU-based gliding tests and the effects of nano waxes on performance.

Chapter 5 evaluates and discusses the results from all four studies. The contributions are expressed and the results are compared to other work.

Chapter 6 concludes the study and answers the research questions. A recommendations for further work within the field of sports technology in cross-country skiing is given in this chapter.

Appendix A-G: Selected relevant papers are presented, including the full text.

Appendix H outlines the secondary paper, which was not included in this thesis.

Readership

This thesis presents technical aspects to improve performance in cross-country skiing. Results from field and laboratory tests are discussed, and provide a comprehensive foundation for further work. The primary readership of this thesis is:

- Engineers and researchers interested in sports equipment technology, especially those interested in snow friction and Nordic skiing;
- Students and teachers working with tribology or designing Nordic skis;
- Ski technicians and trainers dealing with ski selection, preparation and tuning.

2 State-of-the-Art

2.1 Competitive Skiing

Over the last two centuries, Nordic skiing has been in continuous development. Major revolutions of the equipment such as glass fibre skis and fluorine powder waxes have changed cross-country skiing. Equipment regulations from the International Ski Federation (FIS) and the International Biathlon Union (IBU) clearly define the demands and restrictions for racing skis. There are no limits for the type of construction, as well as no restrictions with regard to the rigidity in all grades of flex as long as the weight of a pair exceeds 750 grams without bindings (FIS, 2012; IBU, 2010).

A major difference between BI, NC and CC is both competition distances and course lengths. Almost all courses in World Cup (WC) events consist of several laps around a stadium to help satisfy the requirements for TV productions and spectators. NC and BI events are usually arranged on 2.0 km to 4.0 km laps, while courses from CC races can be up to 16.7 km in individual start competitions.

Street and Gregory (1994) investigated whether glide characteristics can affect the outcome of cross-country races using the free skating technique. Coaches and athletes generally agree that the top-place finishers in freestyle races have skis with better glide characteristics, with glide speeds of the entire field measured through a 20 m flat section at the bottom of a 150 m, 12º downhill. They found a significant correlation (r = -0.73) between finish time and glide speed, thereby showing that the more successful competitors tended to have faster glide speeds through this section of the course during the 50 km freestyle event at the 1992 Winter Olympics.

2.2 Forces in Skiing

In cross-country skiing the propulsive forces are produced by using both arms and legs together, as the task is to overcome the resistance forces acting on the skier. Forces which act on a skier in a gliding situation are illustrated in a free body diagram shown in Figure 2.1.

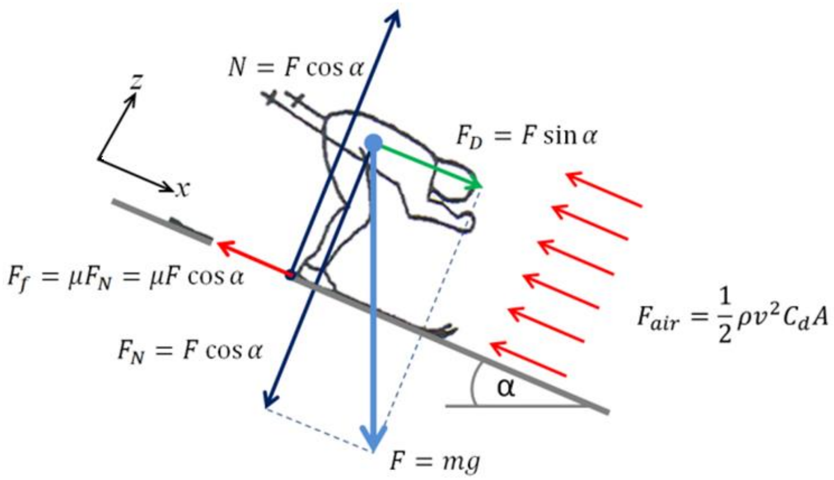

Figure 2.1: Free body diagram of forces acting on a skier in a gliding position, modified from Spring (1989).

According to Newton's 2nd law, the forces in the direction of motion (x) are equal to the skier's mass, m, times his acceleration, a. It is defined by:

$$\sum F_x = m \cdot a \tag{2.1}$$

The skier's gravitational force, F, can be decomposed into its two components: the normal force, F_N, perpendicular to the slope, and the propulsive force, F_D, parallel to the slope, and both components are a function of the slope, α. The two major forces that act against the skier are the force due to air resistance, F_{air}, and the tangential ski drag force, F_f, at the interface between the skis and the snow:

$$F_D - F_{air} - F_f = m \cdot a \tag{2.2}$$

The kinetic coefficient of friction,μ can be expressed in the following way:

$$\mu = \frac{F_f}{F_N} \tag{2.3}$$

As the ratio between the tangential ski drag force and the normal force. Assuming Coulomb friction with constant μ, and dividing by the skier's mass and supplied with the terms for F_D, F_{air} and F_f, we derive equation 2.4, where $g$is the acceleration due to gravity, v is the speed, ρ is the air density, C_d is the drag coefficient, A the surface reference area:

$$g\sin\alpha - \frac{1}{2m}\rho v^2 C_d A - \mu g\cos\alpha = \frac{dv}{dt} \tag{2.4}$$

A low body position is beneficial for enhancing leg power production and reducing air resistance by 30 % for a 30 s maximal test was shown by Leirdal et al. (2006). For longer periods of 3 min, a deep position did not increase power production, although lactate levels were increased. The textile surface roughness affects the air drag, which was shown by Oggiano (2010). The energy consumption due to the ski - snow friction is approximately 30 %, and due to drag approximately 15 % of the skier's energy cost (Spring et al., 1988).

2.3 Snow and Ice Friction

The science and technology of tribology is derived from Greek roots that originally meant τρίβω ("I rub") and the suffix λόγια ("study of"). Tribology includes the topics of friction, lubrication and wear (Persson, 2000), and in skiing the ski base and snow are the two surfaces in relative motion to each other such as illustrated in Figure 2.2.

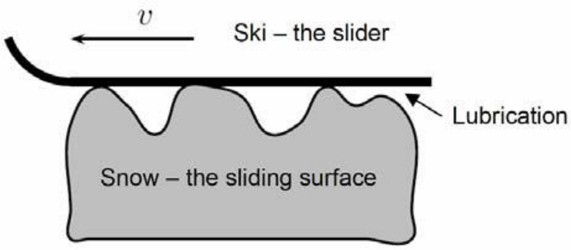

Figure 2.2: The tribological system of a ski sliding on rough snow (adapted from Bäurle (2006)).

Measurements of μ have been subject to numerous studies. Bowden and Hughes (1939) studied miniature gliders on ice and snow, concluding that the low friction coefficients obtained were due to the frictional melting of the snow or ice surface. The meltwater theory was also supported in further studies from Bowden (1953), Ambach and Mayr (1981), Colbeck (1992a, 1994), Glenne (1987), Lind and Sanders (1997) and Bäurle (2006), who provided further models and explanation.

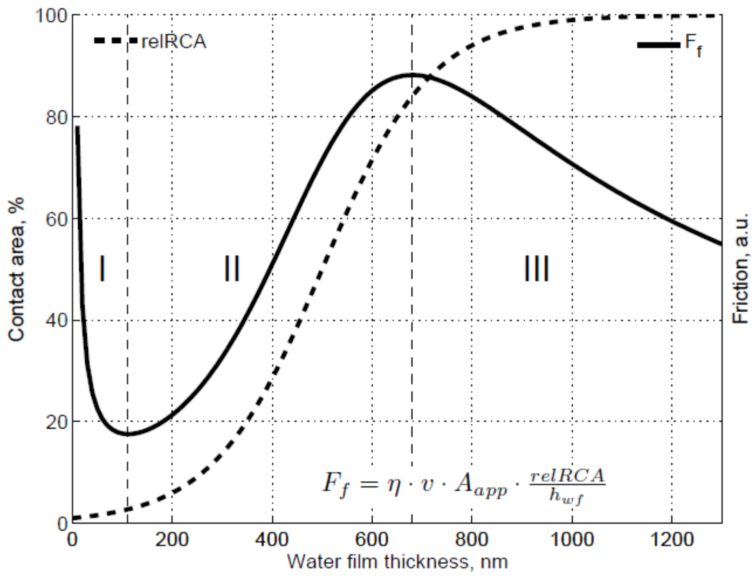

Figure 2.3: Contact area (dashed line, left axis) and friction (solid line, right axis) vs. waterfilm thickness (Bäurle, 2006).

2.4 Science of Snow Friction

2.4.1 Full-scale tests

Measurements of μ under field and laboratory conditions have been the topic of numerous studies, with Kuroiwa (1977) observing the real contact area between the surface of the slider and snow grains. For a static sample, the relative real area was 3.8 % at a temperature of -4°C and a snow density of 0.34 g/cm^3.

The kinetic coefficient of friction is affected by several parameters, and the effect of load and temperature was investigated by Buhl et al. (2001). It strongly dependent on the snow temperature. A minimum was around -3°C, increasing for colder snow temperatures as well as for snow temperatures close to 0°C. The authors found in laboratory tests that the friction depends on the load only for low temperatures below -10°C. According to Colbeck (1988) heavy skiers were faster for snow temperatures below -6°C.

Miller et al. (2006) developed a system for measuring μ between alpine skis and snow by measuring the frictional force on a towing test made on horizontal surfaces at a speed below 4 m/s with a constant velocity. They reported values of 0.0412 – 0.0422 for the friction on ice.

A method has been developed that allows for the simultaneous determination of both a skier's drag area and μ of his skis against the snow in a single measurement. An accuracy of ±10 % was reached in the determination of μ (Leino et al., 1983).

2.4.2 Laboratory tests

Stamboulides (2012) studied the mechanisms of friction of polymeric surfaces, such as ultra-high molecular weight polyethylene (UHMWPE), polytetrafluorethylene (PTFE) and polymethylmethacrylate (PMMA) on ice with velocities of up to 1.96 m/s and temperatures from -25°C to -1.5°C. Their results showed that the magnitude of the sliding velocity and temperature play important roles in ice friction. A decrease of μ with an increasing temperature at high sliding velocities was shown.

Sturesson (2008) built a simplified rotating test rig to conduct a set of experiments. Small model skis were used and different skiing conditions were simulated from cold temperatures and dry snow to above zero temperatures and wet snow, expressing a dependence of μ on velocity, load and temperature.

Extensive friction experiments were conducted by Bäurle (2006) on a large-scale tribometer. The kinetic coefficient of friction was measured as a function of temperature, velocity, load, apparent contact area and slider surface topography, while the real contact area was measured with the help of scanning electron microscopy and X-ray computer tomography.

Nikki et al. (2005) observed ski sliding features at very low speeds with a very short model ski for typical natural snow types by two means (a) rotating snow track with a static model ski method and (b) natural sliding at a snow slope with a short slider. The speeds ranged from 0.01 m/s to about 2 m/s.

2.5 Ski Running Surface (Base Material)

High density polyethylene (HDPE) and UHMWPE are linear forms of polyethylene (PE). Due to its outstanding tribological behaviour UHMWPE is the material of choice for running ski surfaces, with manufacturers substituting the semi-crystalline material with additives to further enhance its performance (Brydson, 1999; Schamesberger, 1995).

Stamboulides et al. (2013) blended various new polymer additives into UHMWPE in order to examine their effects on ice friction. A certain type of a new liquid perfluoropolyalkylether was proven to improve the surface and sliding characteristics of UHMWPE on ice, showing for the first time that an optimum concentration of 2.5 % reduced μ on ice significantly at temperatures above than -7°C. According to the friction measurements, fluorinated lubricants turned out to be effective additives when mixed in a UHMWPE matrix for decreasing the wettability of the host polymer surface as well as μ of ice, while the static contact angle increased from 88º to 114º.

Fischer et al. (2008; 2010) performed a comprehensive Raman spectroscopic morphological analysis and differential scanning calorimetry (DSC) of carbon black-filled polyethylene (PE) ski bases. Significant morphological changes in polyethylene due to processing from the raw material to the semi-finished film, in addition to the structured ski base were identified. A decrease in crystallinity and an increase in the amorphous phase fraction were reported throughout the various processes (Fischer et al., 2010).

Mathia (1992) developed a 3D metrology device, systematically studying the micro- and macro geometry of running surfaces in order to optimize the grinding process and to better understand wear mechanisms linked to friction and sliding on snow.

Moldestad and Løset (2003) developed a Ski base Structure Analyser (SSA) utilizing laser technology to analyse the detailed structure of a ski base. The SSA displays the measured surface as an image with 739 x 570 pixels, in which each pixel can have a gray level value from 0 to 255. The value of each pixel is proportional to the height at the corresponding point of the measured surface.

2.6 Snow Surface

Eriksson (1955) started to investigate the influence of different snow types on the coefficient of sliding friction, and concluded with a decreasing kinetic friction for increasing snow grain size. According to Eriksson skis glide faster on bigger snow crystals than on newly fallen snow with a small grain size.

The kinetic coefficient of friction is largely dependent on the snow surface temperature, as well as on other snow, ski and climate parameters (Buhl et al., 2001; Bäurle, 2006; Fauve et al., 2005; Peil, 2000).

Fauve et al. (2005) determined the most important snow and weather characteristics influencing the gliding properties of skis on snow to quantify their influence and to show how important small fluctuations of these parameters can be. The field test were performed with high speeds up to 115 km/h, and three main factors can influence the results of field gliding tests: The skier, the equipment and the snow and weather conditions.

Bethke et al. predicted (2005) snow conditions for the optimization of race track preparation, and temperature and liquid water content of snow strongly influence the run time for old snow. On the other hand the hardness strongly affected the run time for new snow, as the harder the snow, the faster the run times.

The complex mechanics during the snow–ski interaction were investigated by Theile (2009). Delayed elastic deformation is the dominant deformation in the ski–snow contact, and they developed a model to describe the delayed elastic behaviour of snow.

Peil (2000) investigated the effect of meteorological and glaciological parameters on the sliding velocities of cross-country skis. In addition to that, he also compared different structures and their gliding performance on various snow conditions. He concluded that the snow surface temperature showed the greatest linear relation to the gliding velocity (correlation coefficient $r = 0.84$). To help explain the characteristic gliding performance for various ski base grinds it was necessary to combine snow surface temperature, snow grain type and snow grain size to achieve sufficient results.

Large spatial and temporal variability can remain in snow surface temperatures driven by local processes (Wagner and Horel, 2011), and in their observations of the snow surface and snowpack at the Whistler Olympic Park the snow surface temperatures varied by more than 10°C around the track under clear sky conditions. The biggest local temperature changes during a day reached 16°C from morning to early afternoon. Key insights into microscale weather are essential for optimal preparation for ski technicians.

Challenges for winter weather forecasting and nowcasting in complex terrain can be considerable. Organizers of international championships often provide weather services to support teams, with the forecasts ranging from five days with 6 h resolution to nowcasts for specific venues of approximately 15 min resolution out to two hours (Joe et al., 2010). A dense network of 50 custom surface observing stations was designed, constructed and installed prior to the XXI Winter Olympic Games in Vancouver, CAN. Predictions of wind, temperature, precipitation intensity and phase, as well as visibility, were the focus of the 0 – 6 h time frame forecasts.

2.7 Ski Characteristics

Knotten (1974) was a forerunner in studying cross-country ski characteristics, while ski camber characteristics and their influence on sliding friction was also the topic of another study (Westergren, 1977). Ekström (1980) has shown that the camber of the ski was significant for classic ski performance with regard to vertical force in the ski track, pressure distribution along the ski and friction characteristics, and μ decreased with an increasing camber value. However, it is not mentioned if his findings are relevant for all snow conditions of just valid for a certain range. He placed the skis on a rigid beam and loaded them with defined loads. Since the predominant factor for glide and grip also depends on the pressure distribution of the skis, the means and method to measure this is of the greatest importance (Erkillä et al., 1986).

One approach was described by Bäckström (2008), who investigated the span curve and pressure distribution over the full length of the ski. The authors designed a measurement device to invest ski characteristics such as span curve and the ski ground-pressure distribution under load. A load cell measures the distribution of the contact force of the ski surface, which is in contact with the reference surface.

In an earlier study, Breitschädel (2007) used force sensitive mats (Tekscan™) to measure the pressure distribution between the ski running surface and a rigid aluminum beam as illustrated in Figure 2.4. Distinctive differences between pairs, which belonged to one athlete were found, with the differences among the skis being in the location and size of the contact areas.

A similar method was presented by Nilsson et al. (2013), who placed two I-Scan sensor mats on a platform. The authors demonstrated a few possible functions of the device such as comparing the force distribution and an investigation of the effect of a skier's weight distribution on force distribution when the centre of mass moved backwards from a normal tuck position.

2.8 Ski Testing

Karlöf et al. (2007) presented a test protocol for field glide tests, and interesting work regarding field test methodology was done by Coupe and Spells (2010) who worked towards a methodology for comparing the effectiveness of different alpine ski waxes. The authors listed recommendations for future measurements, including a longer course, a close matching of skiers' masses and ski sizes, all timing systems accurate to 0.001 s, a start 3 m above the first timing gate and more effective methods of wax removal.

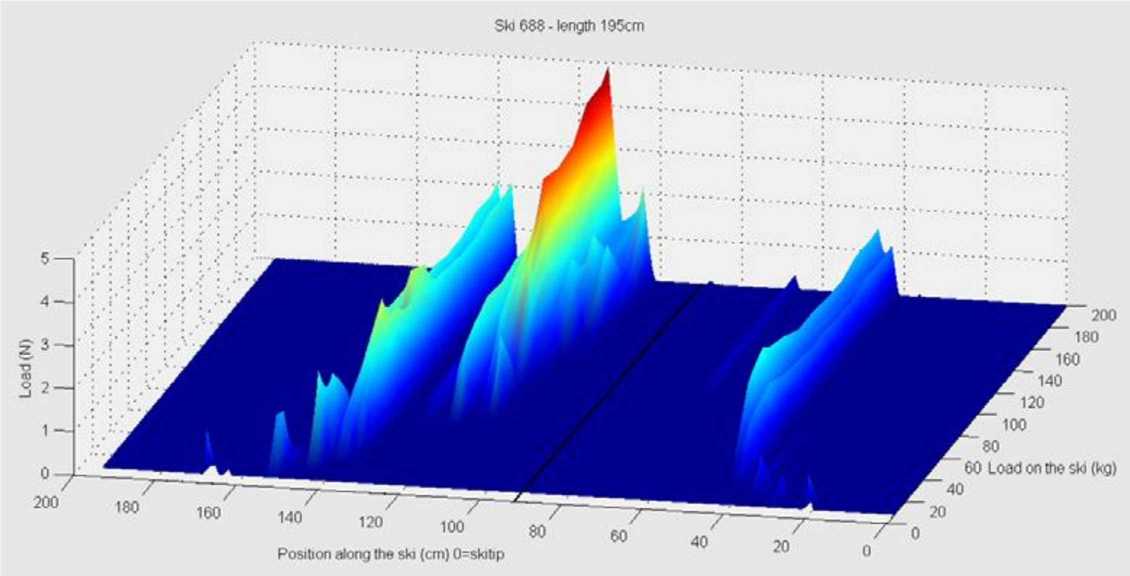

Figure 2.4: Load distribution along a ski for applied static loads ranging from 0 kg to 200 kg (Breitschädel, 2007).

2.9 Wax

A comprehensive analyses of gliding waxes was made by Rogowski et al. (2005), who analysed and compared the classification of commercial products by gas and ionic chromatography and penetration and wetting tests. The main result of their study was that the strategy in wax development by the various manufacturers follows the same general trend in relation to the alkane composition, though a fine analysis pointed out that each gliding wax manufacturer provides a specific formulation for waxes containing fluorine-based additives.

Rogowski et al. (2007) investigated the influence of the fluorine-based additive content on the physical and physicochemical properties of paraffinic wax by penetrability tests, as well as by static and dynamic wettability measurements. A significantly increased wettability and penetrability was reported for an amount between 0 % and 4 %. The fluorine-based additives showed maximal water repellence for a content of approximately 4% when the water static contact angle reached a maximum of approximately 125º to 130º. Their results pointed out that there is a limit to the improvement of paraffinic wax properties as a function of the fluorine additive content. The static contact angle decreased between 4 % until 9 %, and increased again until 15 % to remain constant for higher contents in the fluorine-based additive.

Kuzmin and Tinnsten (2008) investigated the effect of hot glide waxes on the hardness of the ski running base. They measured a significant decrease in the hardness after a long immersion in a bath of melted glide wax, and therefore concluded that a hot wax treatment cannot make the ski running surface harder than it initially was. In further work, Kuzmin showed that waxed skis have increased dirt absorption on the ski running surface under wet conditions compared to freshly scraped ski running surfaces (Kuzmin and Tinnsten, 2007). Optimal glide on skis with hydrophobic durable polymer running surfaces such as

UHMWPE or PTFE can be achieved with an adequate surface topography that fits to the actual snow conditions (Kuzmin, 2010).

2.10 Simulations, Calculations

Goede (2006) investigated the effects and magnitude of mechanical factors on skiing performance using a mathematical model of the mechanical power equation. He showed that alterations affecting the power production of the skier have the greatest influence on performance, and that alterations to the coefficient of friction between the skis and the snow have a fairly large influence on performance. However, alterations to the aerodynamical characteristics of the skier have a relatively small impact, as only drafting behind another skier could improve performance to a large extent.

Moxnes and Hausken (2009) developed a biomechanical model of the skier and diagonal stride kicking characteristics, accounting for the physical properties of the ski and snow, as well as for friction, aerodynamic drag and gravity. Analytical results for relationships between glide length, friction and kicking force are shown, and the authors emphasize that the model can contribute to enhancing the understanding of the composition of the ski to ensure optimal velocity and kick with the terrain and waxing.

Moxnes et al. (2013) simulated cross-country skiing by using a power balance model, with the authors applying the hypothetical inductive method and comparing the simulated position along a track with actual skiing on snow. The model accounted for the physical properties of the ski and snow, and for friction by aerodynamic drag and gravity, in addition to the relationships between heart rate, metabolic rate and work rate based on the treadmill roller-ski testing of an elite cross-country skier. In the simulation model, the effects of friction and air drag on total skiing time were calculated as seen in Figure 2.5. These analyses indicated that there was a 4 % and 3 % improved skiing performance by a 10 % reduced friction or air drag coefficients, respectively.

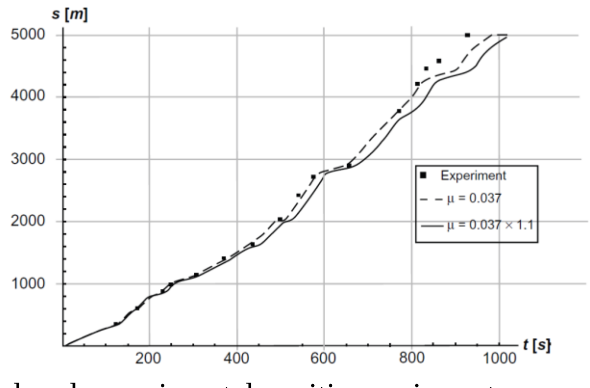

Figure 2.5: Simulated and experimental positions *s* in meters as a function of time *t* in seconds along a track while skiing on snow using the skating technique. Dashed line: $\mu = 0.037$; Solid line: $\mu = 0.037 \times 1.1$ (Moxnes et al., 2013).

2.11 Measurement Equipment – Test Benches

In order to quantify and describe ski characteristics, the development of suitable devices able to measure essential parameters is necessary. Ekström (1980) investigated the force interplay between the skier, ski and snow for the classic technique, adjusting the ski's stiffness by a screw, which was then placed in a lateral slot in the middle of ski. By turning the screw, the brackets were moved either nearer or further away from each other, thereby increasing or decreasing the ski's curvature.

Bäckström et al. (2008) presented a system to assess ski characteristics such as span curve with a very high accuracy and a good representation of the pressure distribution over the full length of the ski. The system was used to help facilitate the process of pairing two individual skis to a pair, and provided the Swedish national team with a new knowledge of the athletes' ski pressure distribution.

2.12 The Use of Inertial Measurement units (IMU)

Accelerometers have been previously used in cross-country skiing for different purposes. Pinchak et al. (1987b) attached an accelerometer to a ski and a roller ski to help analyse the basic differences between skiing techniques.

Van den Bogert et al. (1999) used triaxial accelerometers to calculate forces at the hip joints in walking, running and skiing, whereas Myklebust et al. (2011) placed four accelerometers on poles and ski boots to detect technique transitions during skiing on snow. In further studies, microsensors were used to identify different cyclical movement patterns in different XC skiing techniques, with the microsensor system placed on the skier's upper back and highly smoothened with a 2 Hz low-pass cut-off frequency (Marsland et al., 2012).

In the most recent study, accelerometers were used to describe the differences between two skating techniques (Myklebust et al., 2013).

More sophisticated technologies such as the use of a differential GPS and IMUs (which often contain accelerometers, gyroscopes and magnetometers) provide new possibilities for evaluating gliding tests. In Alpine skiing, these and similar technologies were presented in biomechanical analyses and technique studies (Brodie et al., 2008; Kirby, 2009; Supej, 2010).

3 Research Design - Methods

3.1 Research Process - Methods

To attempt to answer all research questions given in Section 1.3, the work was divided into four major studies that focused on: (I) Ski Analysis, (II) Ski Base Structure, (III) Ski Testing and (IV) Ski Wax. The research process and methods will now be presented for each study.

3.2 Study I: Ski Analysis

The start of this study was in the season of 2007, with ski characteristics measured using two different ski test benches, including the initial use of a SkiSelector^{TM} measurement device (Vendolocus Development AB, Bromma, Sweden; Figure 3.1) and later, another self-developed test bench that was built in cooperation with IDT AS (Lena, Norway; Figure 3.2).

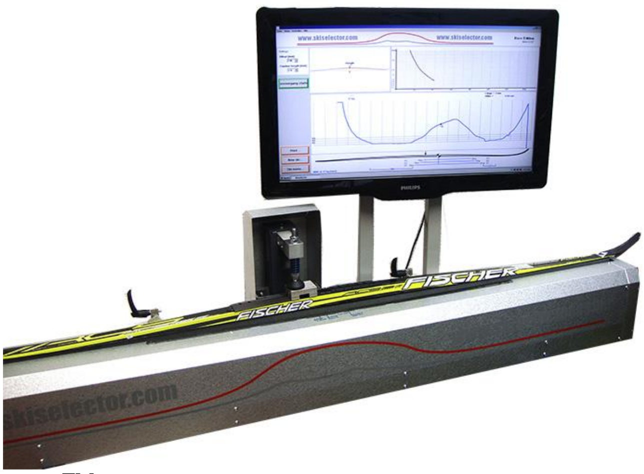

Figure 3.1: SkiSelector^{TM} test bench for cross-country skis.

Figure 3.2: Ski Analyzer, the developed ski test bench in cooperation with IDT AS, Lena.

The SkiSelector™ device consists of a rigid aluminum frame with a steel plate on top upon which the ski is placed. The vertical load unit is controlled by a computer, and the load can be applied in steps of 10 N up to a maximum of approximately 1500 N. A span curve showing the height along the ski length (illustrated in Figure 3.3) is obtained by a height sensor that travels along the ski and measures the distance between the ski base and the steel plate. The sampling rate of the height sensor is 200 Hz, which results in a longitudinal resolution of approximately 1 mm per measurement.

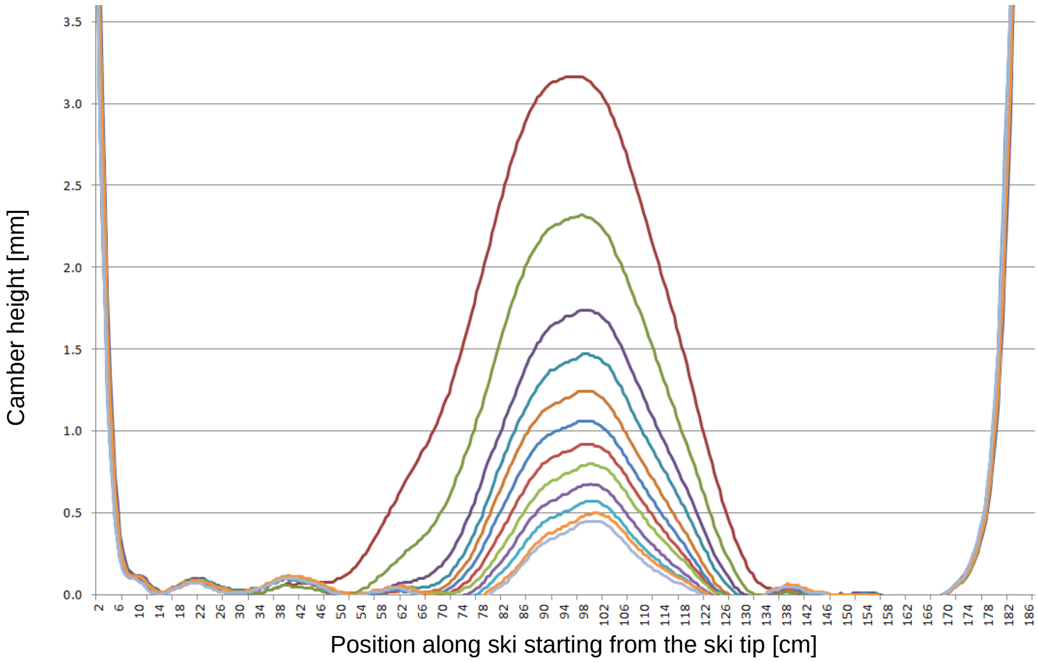

Figure 3.3: Example span curves of a classic ski loaded from 200 N to 1500 N.

The development of one new test bench was a part of this thesis, which resulted in the production of the Ski Analyzer device. The goal was to acquire essential ski characteristic parameters in a fast laboratory test, while it was also important to achieve a higher precision in the measurements due to the use of high-quality components during the manufacturing. An emphasis was put on a rigid, plane steel foundation where the ski is placed on. An optical photocell travels along the ski and detects the camber height, with an accuracy of 0.25 µm in the vertical direction. The applied load is computer steered and monitored by an HBM load cell, and the device is able to measure static and partly dynamic loads. All camber profiles from athlete skis were saved and used for further analyses in this study.

3.2.1 Methods for the ski analysis

Both test benches had in common that most of the ski was placed on the rigid plate, while approximately one centimetre of the ski overlapped the edge. The camber height was measured on the downside of this section. This method opened up for a certain measurement uncertainty since cross-country ski running surfaces are often slightly twisted or the ski running surface is not perfectly plane across the ski width. This can lead to measured camber height values that never show 0.0 mm, or contact. To account for such circumstances a threshold value of 0.1 mm was set for the SkiSelector test bench and 0.05 mm for the SkiAnalyzer. Camber height values below the threshold were defined as contact.

Each ski was loaded with the half and full body weight (BW) of the skier, and according to the usage of the skis, three categories were defined: cold, medium and warm skis.
An additional load of 40 N was added to in the measurements for BI athletes to compensate for the weight of their weapon.

3.2.2 Measured skis

It was a goal in this study to measure as many athlete racing skis as possible. In the period from 2009 to 2011, more than 816 pairs from CC, BI and NC were tested on a test bench to acquire valuable information. Both new and old racing skis were tested, though just skis that were selected in competitions were included in this study.
In Paper 3, the focus was set on cross-country skating skis from the male Norwegian national teams in CC (n = 81), BI (n = 106) and NC (n = 53) from four different ski brands (C = 38, A = 187, B = 161 and D = 34).
In Paper 4 results from lab tests of classic cross-country skis (205 pairs) from the Norwegian men's and women's national ski teams were presented. The study considered skis from the 2009 – 2011 seasons for four different brands.
In Paper 1, the effect of temperature change was documented by seven skating skis from four different manufacturers, which were tested under three different temperatures regimes.

3.2.3 Parameters of interest

Out of the span curve data, parameters such as camber height at the balance point (BP), peak camber height (PCH), the nominal contact length of the front and back section (CFS and CBS) and the ski tip and tail opening characteristics were calculated. For the ski tip and tail opening characteristics, two points in front of and behind the BP were chosen. Two different approaches were followed. For the first, a defined distance in both directions from the BP was chosen to measure the camber height, and the distance was equal to ± 41.6 % of the nominal ski lengths. This resulted in a distance 780 mm to 810 mm according to the actual ski length. In another project four points, two in front of and two behind the BP at a camber height of 0.05 mm and 0.30 mm were chosen to represent the ski tip and tail opening characteristics. The span from BP to the position with a 0.30 mm camber height were presented as fractions of the total ski length.

Another interesting parameter was the load needed to compress a ski down to a camber height of 0.20 mm, called FA. The FA measurement was made 80 mm behind the BP at the same location as the point the load application. The change of camber height (in mm) at the BP when loaded from 0.5 to 1 times the BW was defined as the camber response, while the stiffness, k (N/mm), was defined as half the BW divided by the camber response.

In addition to the static analysis, dynamic properties were measured for a selected group of skis, including natural frequency f and damping coefficient, λ for both the front and back section of the skis. Eight acceleration sensors were attached to the front section with a spacing of 0.10 m starting 0.10 m from the ski tip. On the back section of the ski, five accelerometers were attached 0.10 m from the back end of the ski to the back end of the binding. The skis were mounted on a solid welding table to avoid resonance vibration according to ÖNORM S 4025. For the measurements on the front ski, the BP was the last attachment. The measurements on the back section were performed with a defined length of 0.65 m from the back end of the ski. The skis were then loaded at the end with a defined weight, which was released by a simple mechanism to start a free vibration. The sampling rate was 1 kHz for all sensors. Data was processed in a LabView application, which calculated the natural frequency out of a discrete Fourier transformation analysis and the damping coefficient, λ of all sensors. A detailed description of the measurement device was given by Breitschädel and Løset (2010), and the damping coefficient was calculated according to the exponential decay of the oscillation:

$$a = a_0 \cdot e^{-\lambda t} \cdot cos(\varpi t) \qquad (3.1)$$

where a_0 is the initial acceleration amplitude and ω is the angular frequency.

3.2.4 Measurement alternation (temperature change)

Both the SkiSelector™ and the vibration-analysing devices were placed at room temperature, T_1 during all measurements to avoid any temperature dependent errors from the devices. After the first measurements at T_1, all skis were kept in a freezing lab for several hours at the two other defined temperatures, T_2 = 0°C and T_3 = -15°C, to reach the defined temperature. Only one ski was taken out of the cold room to perform either the static or dynamic measurements, and the ski was immediately placed back in the cold room. Each test was completed within five minutes.

3.3 Study II: Ski Base Structure

After the athletes finished their process of ski selection in between two seasons, ski technicians start to take care of the equipment. With the introduction of UHMWPE as a standard base material, new forms of surface treatments have been possible. It is a common routine and best practice to apply specific grinds to the running surfaces, which are best tested for certain ski, snow, weather and track conditions.

The importance of the right structure for Nordic skis was extensively studied by Moldestad (1999) and Bäurle (2006). Both authors pointed out the role of a proper surface topography, and research done by Giesbrecht et al. (2010) further supported this.
For the last 25 years stone grinding has been the preferred method to prepare the surface texture of a ski base. The task of this study was to develop a new grinding machine that combines the advantages of stone grinding machines, while at the same time looking to further improve the process. A major goal was to develop a system that can reproduce a chosen surface texture to a high extent within narrow tolerances.

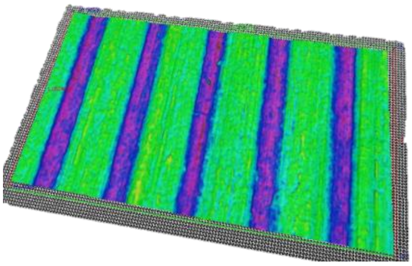

Figure 3.4: A colour-coded example of a linear stone ground structure on a ski, picture taken with an Alicona 3D microscope.

3.3.1 Development of a new grinding machine

A solid steel frame serves as a foundation and guarantees a low vibration operation during the grinding process. The developed grinding machine has three axes of freedom of motion: two linear (longitudinal - feed, vertical - cutting tool head) and one rotational (spindle) freedom of motion. The upside down ski is placed in a specially designed ski bed unit that can be adjusted for different ski lengths and curvatures. The operating grinding unit moves along the full horizontal length of the ski while staying statically locked during the entire process. An electric motor controls the horizontal feed speed of the grinding unit, with the maximum feed speed limited to 300 mm/s. The spindle is balanced and controlled in a vertical direction via pneumatic pressure units that allow an accurate load control up to 300 N during the operation. The maximum rotational speed of the cutting tool is 600 rpm, and the assembled prototype can be seen in Figure 3.5:

Figure 3.5: Steel grinding machine.

3.3.2 The cutting tool

The cutting tool is made of metallic material, with clearly defined geometries designed using 3D CAD programmes. The advanced production process and cutting geometries of the wheel cannot be revealed in their full details due to corporate rights. The cutting process is comparable to a milling operation rather than to a traditional grinding operation, which allows for a number of versatile machining operations. A certain number of clearly defined cutting edges interact with the ski base, thereby resulting in a material removing process. The chip formation is affected by the cutting tool design and process parameters such as circumferential speed, load and feed velocity, and a smooth cutting process is achieved through the use of sharp teeth. Moreover, factors such as feed per cutting edge, cutting depth and cutting length are a result of the cutting tool design.

3.3.3 Operational setup

A cross-country ski is placed in the ski bed unit before the operations starts, and a cutting wheel is attached to the spindle and locked by a hexagonal socket screw. The operator has to select parameters for feed speed, circumferential speed and cutting load. All parameters can be a function of the ski length, and can be monitored and continuously changed, and the operation duration primarily depends on the feed speed.

In the setup with the new grinding approach, the ski is placed upside down and stationary in its natural shape, thus resulting in a curved surface that the metallic grinding wheel follows. A solid foundation holds the ski in place and levels it in the horizontal plane, and the grinding pressure is continuously adjusted by the pneumatic controlled grinding head since the tool has to follow the curvature of the ski.

3.3.4 Sample structures

In the first step, two grinds were prepared with both a traditional stone grinding machine and the new metal cutting machine. A fine and medium structure was chosen to illustrate the optical results of both surface treatments. Two metallic cutting tools with different

geometries and different designed cutting edges were tested, and all operations were performed on high-quality race running surface material.
All four samples were investigated with an Alicona *InfiniteFocus* 3D microscope (Raaba/Graz, AUT) after grinding, and image fields of up to 10.29 mm × 5.30 mm were taken with a lateral resolution of 1.749 µm × 1.749 µm and a vertical resolution of 400 nm.

3.3.5 Measured roughness parameter

One way to categorize the ski base surface is to measure the roughness. The arithmetic mean deviation, R_a of the assessed roughness profile is usually calculated based on five sequent samples, which can be defined by:

$$R_a = \frac{1}{n}\int_0^n |Z(x)|dx \tag{3.2}$$

where $Z(x)$ is a discrete set of surface height points of the ski base. According to Moldestad [15], typical R_a values for cross-country skis range from approximately 1 µm for the finest to 10 µm for the coarsest structures. Another often-used parameter is the root mean square deviation, R_q of the profile:

$$R_q = \sqrt{\frac{1}{n}\int_0^n Z^2(x)dx} \tag{3.3}$$

The mean peak to valley height of the roughness profile, R_z takes random extreme irregularities of the surface into account, and is therefore a suitable complement of parameters R_a and R_q. When analysing and comparing the results of the R_a and R_q values, it must be considered that they only depend on the profile in a vertical direction, which does not offer any information about the period length, shape, slope or size of the asperities or the regularity of their occurrence. The mean spacing of the profile irregularities, R_{sm} is a parameter that is used for periodic profiles and surfaces, such as structures used on ski bases. The R_{sm} is the mean value of the profile element width, Xs over the evaluation length is defined by:

$$R_{sm} = \frac{1}{m}\sum_i^m Xs_i \tag{3.4}$$

Further parameters that describe a texture in more detail are skewness, R_{sk} and kurtosis, R_{ku}. The skewness is a useful parameter, which represents a degree of symmetry of the topographic density function by:

$$R_{sk} = \frac{1}{{R_q}^3}\left[\frac{1}{nr}\int_0^{nr} Z^3(x)dx\right] \tag{3.5}$$

R_{sk} is the quotient of the mean cube value of the ordinate values $Z(x)$ and the cube of R_q, respectively, within a sampling length. The Kurtosis of the assessed profile is the quotient of the mean quartic:

$$R_{ku} = \frac{1}{{R_q}^4}\left[\frac{1}{nr}\int_0^{nr} Z^4(x)dx\right] \quad (3.6)$$

It is a measure of the sharpness of the probability density function of the ordinate values. In order to find the mean line for the roughness profile, the cut-off wavelength, λ_c for suppressing the long wave component was set to 800 µm for the samples. The roughness profiles were taken perpendicularly across the ski running surfaces, and a profile width of five points, which is equal to 17.5 µm, was chosen.

3.3.6 Comparison between stone grinding and metallic grinding

In order to compare variations of the selected roughness parameters for the two grinding methods, 10 skis were prepared under identical grinding parameters each. Surface parameters were tested with a TR200 surface roughness tester (TIME High Technology, Beijing), and the sample length, which corresponds to the cut-off length, λ_c was set to 2.5 mm for all measurements. The R_a of each profile was calculated based on the average five sequent samples. Before the study, all skis were plane ground to an R_a of 1 ± 0.20 µm. The relative variability, *CV* was defined as the quotient between the standard deviation, *SD* to average the mean roughness, R_a.

For the stone and metal ground skis, a medium-coarse structure was applied on 10 skis, with constant process parameters for the grinding wheel, feed speed and grinding pressure. Each ski was ground once by an experienced ski technician from the Norwegian National Team, and roughness measurements were performed on five positions along the ski base at 20 cm, 60 cm, 90 cm, 140 cm and 175 cm from the ski tip on all skis.

3.3.7 Base treatment with manual rilling tools

The experiments were divided in two tests: The first test was performed with the hypothesis skiing, at the location of Gålå, while the next test was performed in a laboratory in Trondheim with the hypothesis preparation.

In the first part, four Fischer RCS Carbon Lite Skating Plus skis (2009 model with a Fischer stone grinded structure) were used. Each ski was manipulated by a different manual structure tool (SV1, SV2, SV3 and Swix T0401-1mm). Each ski was analysed at three defined spots: 0.40 m in front of the BP, at the BP and 0.40 m behind the BP. The measuring points were marked on the ski, and in both parts of the experiments, the ski bases were initially measured with a Ski Surface Analyser (SSA) by Optonor (Trondheim, Norway). The instrument and its functionality are described in detail by Moldestad (1999), and the SSA calculates R_a of the area depicted.

The ski bases were also photographed through a microscope. After the initial SSA analysis, the ski bases were manipulated with the manual structure tools and different loads. The applied load was measured by two force gauges that were placed under the waxing profile's front and rear edge, respectively. After this and all the following steps the skis and measurement points were repeatedly analysed with the SSA and photographed.

In part one, all skis completed a total over 15 km, divided into four loops. Detailed weather and snow conditions are listed in Table 3.1. The skis were changed from the left to the right leg halfway on each loop, and the average speed was 27 km/h.

Table 3.1: Details to the four skating test loops. The track was freshly groomed and hard packed, and the weather conditions were cloudy and stable. The skis were analysed with the SSA and photographed before, between and after each test loop.

Loop	Length [km]	Air temp. [°C]	Snow surface temperature [°C]	Snow grain size [mm]
1	3	-1.2	-0.6	0.2 – 0.5
2	4	-1.2	-0.6	0.2 – 0.5
3	4	-2.1	-1.6	0.2 – 0.5
4	4	-2.1	-2.3	0.2 – 0.5

In the second part, five skis were investigated, and two of these were the skis from the first test that were manipulated with SV1 and SV2. In addition, two Madshus Hypersonic skating skis (2006 model with a Madshus 7-4 stone grinded structure) and two Madshus Nanosonic HP skating skis (2009 model) with a Bjørn Myhre Sport (Krogstadelva, Norway) H0 stone ground structure were used. In addition to the SV1- and SV2- manual structure tools, Red Creek (RC) 0/-10ºC and RC linear 1 mm were used. The manual structures were applied with different loads at room temperature, on both heated and newly glided skis, as well as on not newly glided skis. The newly glided skis were waxed within the previous two hours, and those not newly glided had their last waxing more than two days prior to testing.
The effects of the following ski base treatments were tested:

- Incubator / hot box with Swix HF8 glide wax (four hours at 57ºC);
- Waxing at 165ºC with topping powder (Toko Streamline Nordic 0/-15ºC 100 % Flour) applied with a Swix waxing iron;
- Waxing at 120ºC with glide wax (Swix HF8) applied with a Swix wax iron.

All points were measured and photographed before and after the preparation, and two pair of skis were also analysed and photographed before and after a period of 38 days. The skis were kept untreated during this time, without protective wax, and the temperature ranged from -10ºC to +20ºC.

3.4 Study III: Measurements

One inertial measurement unit (IMU) was mounted on the left ski in front of the binding. The same sensor was used on all the tested pairs. A calibration sequence (5-10 seconds at a standstill) was performed before the start of each run. Accelerometers measured specific force, *f*, which is the acceleration relative to free-fall, while gyrometers measured angular rate, ω. A test procedure using three pairs of skis in consecutive runs was performed, and data were recorded during consecutive descents. The sensor resolution was 10 bits and the recording frequency was 100 Hz. Data were captured unfiltered and transmitted to a PC for further analyses. The tangential acceleration in the direction of motion, a_t, is the result of the air and ski friction acting against the skier and gravity due to the slope. We define acceleration loss, a_{loss}, as the sum of forces acting against the skier in the direction of movement divided by mass, such as air resistance, F_{air}/m, snow friction, F_f/m, and other unknown factors.

The mathematical model (Figure 3.7) developed included standard methods for strapdown inertial navigation systems to calculate the motion of the sensor (Broxmeyer, 1964; Kritting, 1971) and non-standard methods to calculate the snow friction. A better model to calculate the glide and friction was developed during the interval between the two test sessions (July and October 2011). The model was improved to reduce the effects of the cyclic variations in the acceleration loss, including the effects of air drag. The enhanced model was then used to calculate the friction estimate for Test 2 and to recalculate the glide estimate from Test 1. Lastly, the results were compared to each other and discussed.

Test procedures (B and E) were conducted simultaneously, and two tests using three pairs each were performed. All the tests were performed in a ski tunnel (Torsby, Sweden) under stable snow and weather conditions.

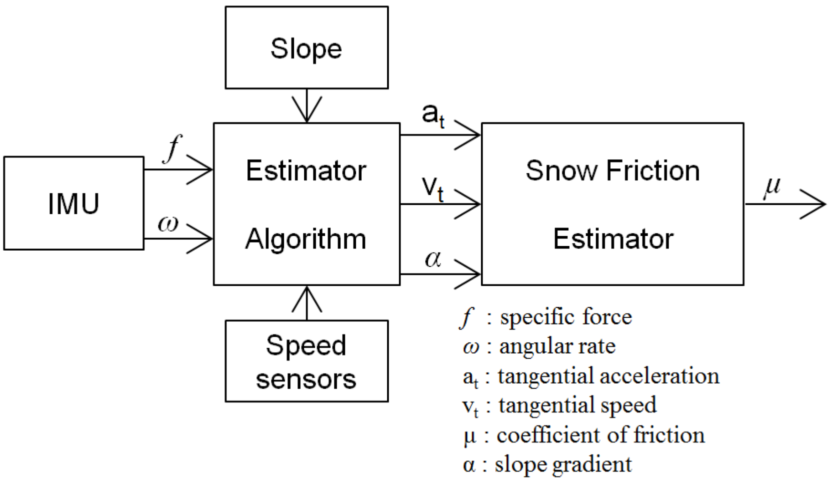

Figure 3.6: Schematic sketch of the model design for the IMU system (E).

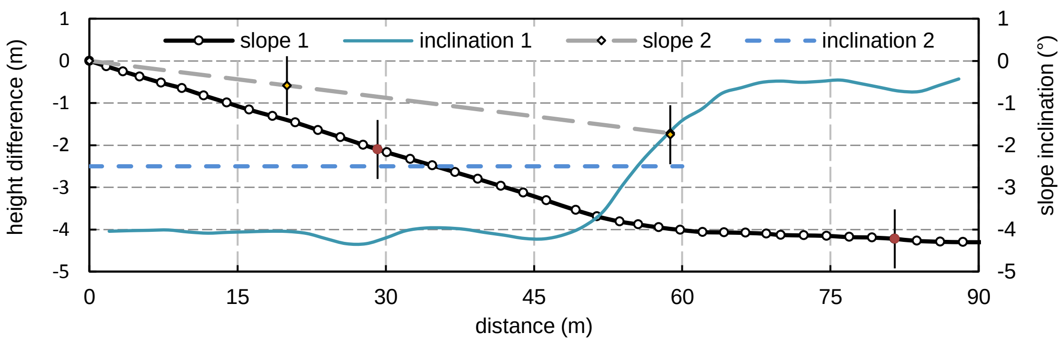

Figure 3.7: Slope and inclination from test Tracks 1 and 2. The location of both photo cell units is marked with vertical black bars.

The test track length and slope were documented using a tape measure and inclinometer. The slope of the track in Test 1 was measured every second meter. The downhill inclination of the test track was approximately -4° in the first half and flattened out towards the end (Figure 3.7), and there was a right turn between 48 m and 70 m in the test track (30°). During Test 1, the skier started at a defined start position, released himself by lifting the poles, and continued, in a semi-squat position, down the entire test track. The initial velocity at the start point was 0 $m \cdot s^{-1}$.

The focus in Test 2 was on the IMU-captured measurement trials. The test setup was amended and the track was relocated to a straight part in the ski tunnel in order to avoid measurement errors. In Test 2, the height difference between end points was measured using surveying equipment (tripod and rod for leveling), and the average inclination was -2.5° between the start and end point. In order to achieve sufficient speed, the skier started each run with one double pole push.

Two units with two photocells each were installed next to the track in both tests. In Test 1 the units were placed 29.3 m and 80.6 m down the track (horizontal distance) after the starting point, and 20.0 m and 58.8 m in Test 2, respectively. The speed at both units was calculated, as well as the time difference and average velocity between the units. All tests were performed in a classic track by an experienced skier.

3.5 Study IV: Ski Wax

This study included both lab and experimental field tests. For a greater understanding of the ski base and the impact of waxes, two UHMWPE ski running surfaces from Isosport (Eisenstadt, AUT) with an identical content of carbon black, but with a different molecular weight and additives (PTFE), were chosen (hereafter called IS-4 and IS-5). Both materials were treated with three different products (referred as Glider A, Liq.-A and Liq.-B) from two producers (referred as A, NOR; B, JPN). The liquid waxes were applied on top of the basic wax, Glider-A, and rubbed into the running surface according to the producers' recommendations. The same type of surface stone grinding was used on the ski bases prior the wax treatment.

3.5.1 Material characterization

To obtain chemical information about the material composition from the surface, X-ray photoelectron spectroscopy (XPS) analyses were conducted that caused the ejection of core-level electrons. The energy of core electrons is a function of its binding energy and is characteristic of the element, with XPS indicating the chemical state and giving a measure of the relative amount of the element stated by Materials Evaluation and Engineering, Inc. (2013). Moreover, a Kratos Axis Ultra (Shimadzu Corporation of Kyoto, JPN) instrument was used in this project to perform the analyses, and the ski base samples tested were cut into small square samples (10 mm x 5 mm).

Contact angle, θ, measurements were conducted to characterize the hydrophobic properties of the untreated and waxed running surfaces. The static wettability measurements were carried out through the use of a sessile drop technique. The angle between the horizontal and the tangent line at the triple point was defined as the contact angle. All samples were tested with ten drops each and the results illustrate an average ± SD.

For a precise determination of metallic ion concentrations in liquid solutions, the Inductively Coupled Plasma Mass Spectrometry (ICP-MS) technique was used. The liquid solutions were heated with a plasma torch at approximately 7000°C, the metal ions were separated in a magnetic field chamber, and the different species were detected by mass spectroscopy (MS). An ICP-MS was performed in order to measure the Gallium ion concentration in the liquid waxes, and the solutions were injected in the Finnigan ELEMENT 2 high resolution ICP-MS equipment (available at NTNU, Trondheim, NOR).

3.5.2 Sliding tests

Outdoor sliding tests were conducted stepwise to monitor the change in gliding performance between the two different running surfaces and one reference ski. An experienced ski technician from the Norwegian Ski Team carried out all the gliding tests, and two different test areas were used in this study (Holmenkollen in Oslo and Granåsen in Trondheim). An ethic approval was not necessary for this study. Both test tracks had similar profiles, with a slight downhill in the beginning that flattened out towards the end. The skier stood still in a crouched position, and time was measured between two photocells along the track. Furthermore, weather and snow conditions were monitored throughout the tests, thereby assuring that changes in the kinetic friction counted as the main source for time changes. The three pairs were tested six times in an afferent and declined order (ski no. 1-2-3-3-2-1), thus resulting in 18 runs for each test. In total, six gliding tests were performed: (1) unwaxed, (2) waxed with Glider-A and Liq.-A wax, (3) after 9.7 km of skating and (4) after 19.1 km of skating. Due to a change in the weather and track conditions in Oslo, the tests were stopped and continued two days later in Trondheim with (5) an initial gliding test after 20.7 km and (6) after 32.7 km of skiing (distance accumulated includes all distances after the skis were treated with wax). The reference ski was only included in the gliding tests, and the average gliding time is illustrated in the results.

The coefficient of friction (COF) of the different ski base materials sliding against snow was measured using the TE88 multi-station friction and wear test machine from Phoenix Tribology (Kingsclere, GBR), hereafter called a *tribometer*. The pin-on-plate module was used for testing square 20 mm x 20 mm ski base samples, with Bäckström et al. (2008) reporting values up to 330 N in their proportional pressure distribution measurements. A load of 150 N was chosen for the tests, which resulted in a nominal contact pressure of 375 kPa. The snow holder was made of a 78 mm x 80 mm hollow on the inside brass plate where a coolant circulated, and the chosen sliding distance was 50 mm. Fine grained snow was collected at -2 °C and stored at -18 °C, and the tests were run for 30 min. First, the tests were run for 10 minutes at a speed of 0.1 m/s, followed by 10 minutes at 0.2 m/s and 10 minutes at 0.1 m/s again. This procedure was repeated one additional time, and the results illustrated are the average of these six measurements. Finally, all samples were investigated with an Alicona *InfiniteFocus* 3D microscope (Raaba/Graz, AUT) before, between and after testing.

4 Results

4.1 Study I: Ski Analysis

4.1.1 Effects of temperature change on ski characteristics

The skis from the four analysed brands showed a very wide range of characteristics (Figure 4.1 and 4.2), with the PCH at 0.2 kN vertical load and T_1 ranging from 3.19 mm from brand A to 5.74 mm from ski D (Figure 4.2). The horizontal position of the PCH varied from -14.1 mm behind the balance point for brand C to 73.9 mm in front of the BP for the brand D. Moreover, all skis showed a special progression of the PCH horizontal position with an increasing load as shown in Figure 4.2, however, there were no significant changes according between T_1 and T_3 (Table 4.1).

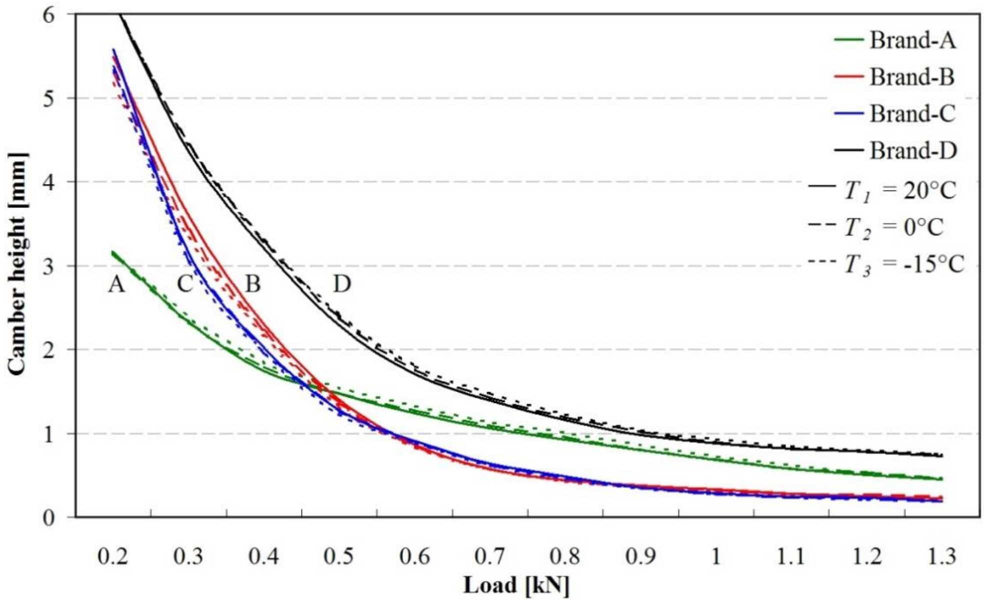

Figure 4.1: Average peak Camber height for all brands at loads from 0.2 kN to 1.3 kN and the three different temperatures T_1 (solid), T_2 (dashed) and T_3 (dotted line).

All skis measured at -15ºC showed a decrease in both contacts at the front and back part of the ski, and on average, the contact lengths were shortened by 42.7 mm in the back and 82.2 mm in the front section, respectively. There was a high significance for most skis regarding the CFS, except for the left brand A ski. All skis exhibited a highly significant decrease in the CBS between T_1 and T_3 (Table 4.1). The results for the temperature effect on the span length were not as uniform. The SL increased for brand A and D skis (12.4 and 5.5 mm), whereas brands B and C displayed a significant decrease of the SL, with up to -6.8 mm from T_1 to T_3.

A significant or highly significant change was found for the natural frequency and the damping coefficient for all skis between T_1 and T_3. For both brand A skis, the left brand B and the right brand D ski, the frequency increased, while whereas for the others it decreased on the front part of the ski. The skis' dynamic properties changed slightly at the back part of the ski. Except for the right brand B ski (-0.01 Hz), the natural frequency increased by 0.58 Hz, which was significant except for the brand C ski. The damping coefficient of the back part also generally increased by 0.5 , though not for the left brand A ski, which stayed constant and for the right brand B ski, which dropped by -0.58 (Table 4.1).

The stiffness, k of all the skis and temperatures revealed a clear trend (Table 4.1). At T_3 all skis had a higher k in the early phase, k_{early} of the attenuation. The difference in k between the ski brands varied by as much as 126.5 N/mm between the softest (D) and the stiffest (A). The results for the later phase, k_{late} were not clear.

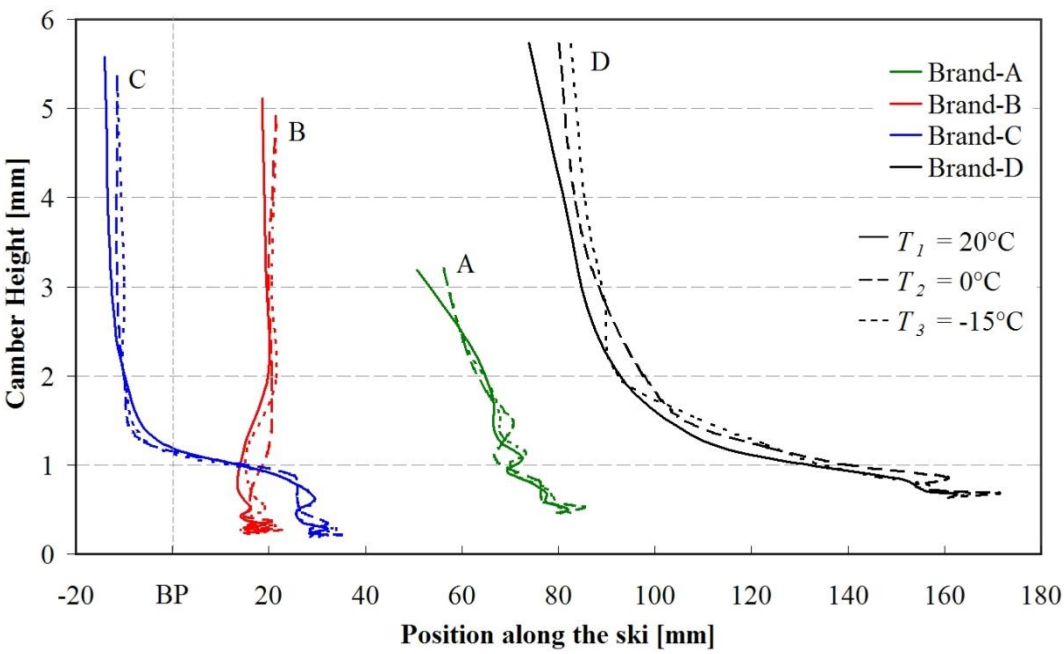

Figure 4.2: The movement of the peak camber height and its location along the ski is shown for each brand (mean of both skis), as well as for the three different temperatures T_1 (solid line), T_2 (dashed line) and T_3 (dotted line). The applied load increased from 0.2 kN to 1.3 kN, and just one ski was tested for brand C.

Table 4.1: Results from the statistically paired-sample T-tests for all T1 to T3 combinations and the 10 parameters: natural frequency (*f*) front and back, damping (λ) front and back, peak camber height (PCH), position of PCH, span length (SL), contact length back (CBS) and front (CFS) and height at the balance point (BP).

		Static measurements						Dynamic measurements			
Brand	Side	Δz BP [mm]	Δx PCH [mm]	Δz PCH [mm]	Δ SL [mm]	Δ CBS [mm]	Δ CFS [mm]	f_{Front} [Hz]	$\Delta\lambda_{Front}$ **[-]**	f_{Back} [Hz]	$\Delta\lambda_{Back}$ [-]
A	left	**0.09****	0.00	**0.1****	12.40	**-23.3****	-55.60	**0.02****	**-1.54****	0.00	**0.81****
A	right	**0.07****	0.00	**0.08****	5.50	**-49.1****	**-61.4****	**0.31****	**-2.08****	0.30	**0.76****
B	left	-0.14*	0.00	-0.14*	**-6.8****	-16.40	**-68.2****	**0.15****	**-1.94****	**-0.58****	**0.89****
B	right	-0.1*	2.70	-0.09*	**-5.5****	**-43.7****	**-98.1****	**-0.07****	**-2.18****	**1.12****	-0.01
C	left	-0.06*	0.00	-0.06*	-1*	**-9.5****	**-30.4****	**-0.21****	**-0.31****	0.64*	0.05
D	left	**0.08****	4.10	**0.1****	5.40	**-54.6****	**-204.5****	-0.02*	**-1.71****	0.29	**0.93****
D	right	0.12*	2.70	0.12*	12.40	**-102.3****	**-57.3****	**0.08****	**-1.16****	0.14	**0.06****

4.1.2 Results from classic ski analysis

The 14 tested male skiers had an average weight of 77.1 kg (± 4.2 kg), which was 18.5 kg heavier than the average of the nine female skiers. When considering the stiffness, both men and women chose very similar skis for cold conditions. It took 66 % and 67 % of the BW for men and women, respectively, to press the skis down to a spacing of 0.2 mm (Figure 4.3b). A bigger difference could be seen for the *warm* skis, in which the women used stiffer skis that required 77 % of their BW on average to press the skis down to a spacing of 0.2 mm, while the men used on average of 5 % less. The women's skis also showed a greater variation in stiffness (± 21 %).

Table 4.2: Number of included classic ski pairs in this study from the Norwegian ski team.

Gender	Athletes	*Cold*	*Warm*	Brand A	Brand B	Brand C	Brand D	Total
Female	9	51	42		48	45		93
Male	14	67	45	25	51	9	27	112
Total	23	118	87	25	105	56	30	205

Camber height

The camber height measured at the balance point showed similar results for the two groups, and there was no significant difference of the CHBP between men and women in either temperature category. Men's *warm* skis exhibited the highest camber height when loaded with either half BW or full BW at 1.63 mm and 0.56 mm, respectively (Figure 4.3a). They also had the highest camber response with 1.07 mm, which was just slightly higher (0.01 mm) than the women's *warm* skis, and a significant difference could be seen between the mean CHBP for men's *cold* and *warm* skis. Women's *cold* and *warm* skis were compressed approximately 4 % more, and they also had lower camber heights when loaded with FBW. A slight difference could be seen at the height and position of the peak camber height (Figure 4.3c). Women's skis had their peak camber point 9.2 mm and 6.4 mm further in front of the balance point even if the women had shorter skis on average.

Camber length

Men's skis, with an average length of 206 cm, are 8 cm longer than the average women's skis, although their camber lengths are very similar. The maximum difference was 2.1 % for *cold* skis, while both men's and women's *cold* skis had a significantly shorter camber length at 69.7 cm and 70.0 cm, respectively. *Warm* skis had between a 5.2 % (74.0 cm; women) and 8.1 % (74.4 cm; men) longer camber length.

Nominal contact area

The nominal contact area (herein shortened to *contact area*) between the skis and the flat rigid beam of the measurement device showed some variations. The *contact area* increased in all sub groups when the load changed from half to full BW, and it was also interesting to see that the contact area for the men's skis increased less than for the women's skis. The *contact area* at the back part of the ski increased by 35.9 % and 39.4 % for men's *cold* and *warm* skis, respectively, also increasing by 54.7 % and 63.8 % for the women's skis, respectively. The front contact area also revealed a positive but smaller change at 16.5 % (men, *cold*) to 22.8 % (men, *warm*).

There was a significant mean difference between the *contact area* of men's and women's *cold* skis loaded with half BW, in addition to full BW loaded for the front *contact area*. Besides having absolutely shorter *contact areas*, women's skis also had relatively shorter contact zones in comparison to the mean ski length.
A continuous trend showed that *warm* skis have smaller *contact areas* for both men's and women's skis, and the difference was significant for the front *contact area* at half BW and full BW with a difference of -21.5 % and -17.2 % (men). Lastly women's *warm* ski's showed a decrease of -14.5 % and -13.8 % for the different loads.

Opening characteristics

The length of the skis varied from 190 to 210 cm, depending on the height and weight of the skier. The results (distance from BP to the position with a 0.3 mm camber height) are presented as fractions of the total ski length (Table 4.3), and a clear trend was revealed for all groups. *Cold* skis for men and women always exhibited a longer distance to the opening, both at the front and the back part of the ski. By increasing the load from half BW to full BW, the opening tended to move between 0.7 % to 1.0 % closer towards the balance point, except for men's *warm* skis, where the first contact moved 2 % further away.

Table 4.3: Position of the opening (0.3 mm) of the ski tip and tail distance from the balance point relative to ski length. All results shown are the average ± SD, Men = M and Women = W.

Avg. ± SD [%]	M - *cold*	M – *warm*	W - *cold*	W - *warm*
Half BW front	38.3 ± 3.5	33.4 ± 9.7	36.3 ± 3.8	34.4 ± 4.1
Full BW front	37.6 ± 4.0	35.3 ± 3.8	35.6 ± 4.3	33.3 ± 4.3
Half BW back	-38.3 ± 3.8	-33.4 ± 4.5	-36.3 ± 4.3	-34.4 ± 4.9
Full BW back	-37.6 ± 4.5	-35.3 ± 4.1	-35.6 ± 4.8	-33.3 ± 5.1

Analyses in respect to the ski brands

Brands B and C were the only two ski brands used by the Norwegian women's team. For the men's team four brands (A – D) were included in this study, and Brands B and C contributed 75 % of the analysed skis (Table 4.2).

Camber height and camber response at balance point

The same uniform trend with higher a CHBP could be seen for all *warm* ski brands (Figure 4.4a). Women and men who used Brand B selected skis had an almost identical CHBP, while men had just a 0.01 mm higher camber height for both categories.
The camber response was highest for *warm* skis of all brands, and on average it was 0.16 mm more for *cold* skis. No significant differences could be seen, although the *warm* skis from Brands A (men) and C (men) displayed particularly high values.

Table 4.4: Detailed results divided by the four ski brands, CA = Contact Area; *(% of ski length).

Ski brand	A		B				C				D	
Group	Men		Men		Women		Men		Women		Men	
Temperature category	*cold*	*warm*	*cold*	*warm*	*cold*	*warm*	*cold*	*warm*	*cold*	*warm*	*cold*	*warm*
CHBP - HBW [mm]	1.33	1.83	1.32	1.52	1.31	1.51	1.44	1.91	1.45	1.55	1.40	1.53
CHBP - FBW [mm]	0.43	0.55	0.47	0.52	0.47	0.52	0.39	0.70	0.39	0.40	0.54	0.61
Stiffness [% of BW]	64.3	76.6	65.4	72.7	67.6	74.3	66.5	68.0	66.4	80.8	68.6	66.7
Camber length-FBW [%]*	44.7	50.3	47.0	47.4	44.1	46.8	42.4	51.5	43.6	48.1	40.5	42.8
CA front- FBW [%]*	13.9	9.7	13.7	11.0	10.7	8.9	12.0	10.3	14.3	13.0	16.6	15.1
CA back- FBW [%]*	19.0	18.1	20.1	16.9	18.5	17.1	17.4	13.7	17.0	16.2	18.2	18.7

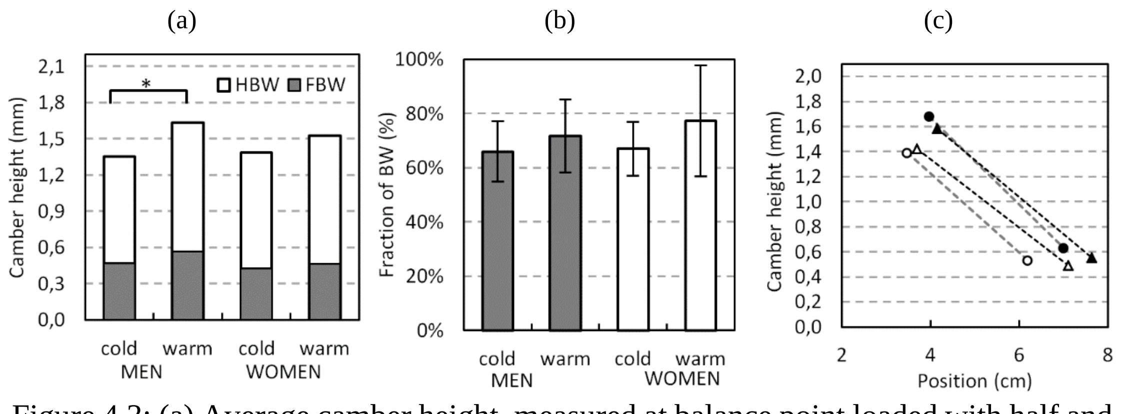

Figure 4.3: (a) Average camber height, measured at balance point loaded with half and full BW for both temperature categories and gender; (b) Average relative stiffness ± SD for both temperatures and gender. Fraction of BW to compress the ski down to 0.2 mm camber height. (c) Average movement of the PCH when loaded with half and full BW; open symbols = *cold*; filled open symbols = *cold*; filled symbols = *warm* temperature category; circle = men; triangle = women). Significantly different between conditions at $*p \leq 0.05$.

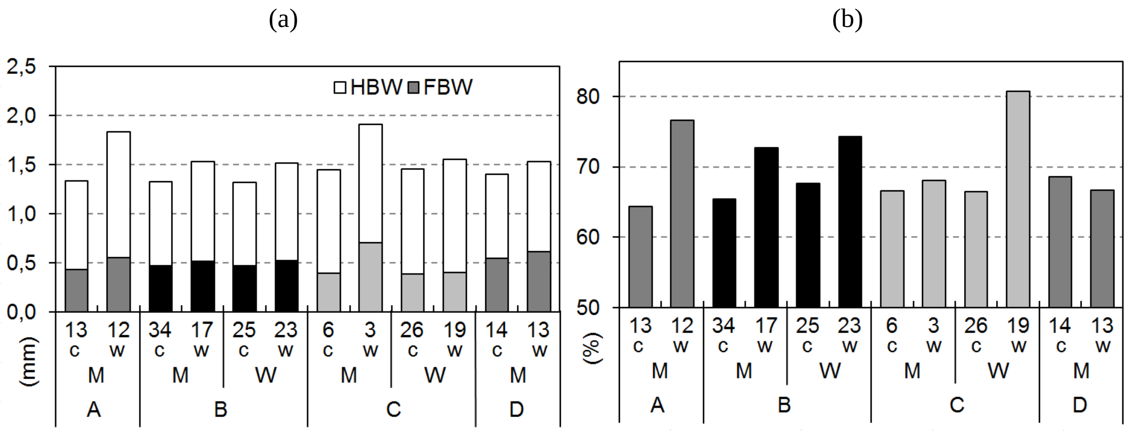

Figure 4.4: a) Camber height at the balance point for all four ski brands (A – D), both gender groups (M, W) and temperature categories (*cold* and *warm*); b) Average load necessary to compress the ski down to 0.2 mm camber height as a fraction of the skier's body weight.

Stiffness

Brand D reversed the stiffness characteristic between *cold* and *warm* skis, as *warm* Brand D skis tended to be 1.9 % softer than *cold* skis from the same brand (Figure 4.4b). On average, all other *warm* skis clearly required more load to be compressed to 0.2 mm, and there were two significant differences between *cold* and *warm* skis from Brands A (men) and C (women).

Contact area

The Brand D skis represented yet another exception regarding the contact area loaded with a full BW. They demonstrated an increasing contact area at the back part of the ski, whereas all other brands showed a ecreasing contact area for the *warm* ski models. Brand D also had the longest contact zone at the front part for both the *cold* and *warm* skis at 17 % and 15 % of total length. Their span length was also the shortest at 40.5 % and 42.8 % of the total length. Brands A (*warm*) and C (*warm*), which had the highest CHBP, also revealed the longest span length at 50.3 % and 51.5 %, respectively. A detailed summary of the results is shown in Table 4.4.

4.1.3 Results from skating ski analysis

Ski stiffness

Among the three male groups, NC skiers used the stiffest skis (k = 251 ± 52 N/mm) according to the performed measurements. Athletes from CC had slightly softer skis (245 ± 70 N/mm) and BI skiers had the softest ones (192 ± 52 N/mm), and the difference was highly significant for the cold category skis and significant for the warm ones.

Camber response

The highest camber response between half and full BW was shown for skis from BI athletes. Warm BI skis reached a change of -2.35 mm when loaded from half to full BW, while skis from the NC team had the smallest camber response in all the categories, with an average change of -1.45 mm. There was a highly significant difference of the mean camber response between the BI, CC and NC ski in the cold and warm category. A significant difference was also found between the cold CC and NC and the universal BI and CC ski.

Contact length

On average, the NC ski had in average a nominal contact length corresponding to 50.8 % of the total ski length, which was significantly more than CC and BI at 47.9 % and 45.4 %, respectively.

Analyses in respect to the ski brands

The four major used ski brands of the Norwegian athletes are not equally represented within the three national teams, which had a major effect on the presented results both for classic and skating skis.

Camber stiffness and camber characteristics

Brand A is the dominant brand in CC and NC, whereas brand B was mostly used by BI athletes according to the analysed skis. Brands A and B, which are the most used brands, had a significant difference in all of the assessed ski categories. Moreover, brand A skis were significantly stiffer than all other skis in each temperature category, with the exception of warm brand D skis (Figure 4.5). On average, their stiffness, *k* was 55 % higher in comparison to the others, and there was no significant difference among ski brands and the three temperature categories. The camber characteristics from the four brands also demonstrated significant differences in their camber response (Figure 4.6). Brand A skis showed the lowest camber height at half BW in all temperature categories, as well as the smallest camber response between half and full BW, thereby resulting in the stiffest camber measurements. On average, the highest camber response was measured for brand B skis at -2.27 mm. Brands A and B, which are the most used brands, had a significant difference in all of the assessed ski categories.

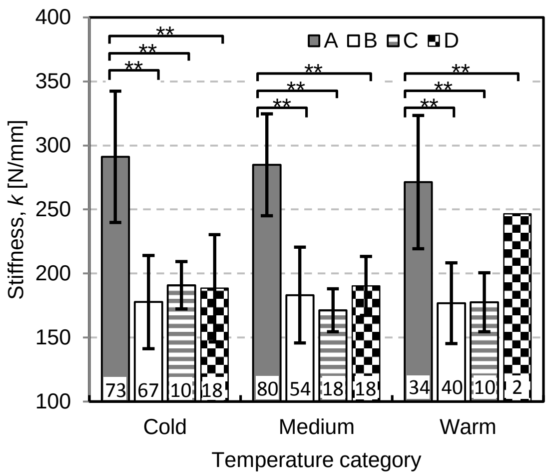

Figure 4.5: Camber stiffness, *k* for the four tested ski brands and all three temperature categories for male skating skis.

More detailed and combined results from Figure 4.5 and Table 4.5 can be seen in Figure 4.7, which presents the stiffness for all measured skis as a function of their relative nominal contact length. A wide range of both the stiffness and contact lengths can be seen, with clear differences between the two selected ski brands, and a lack of correlation was observed for brand A skis, with an $r^2 = 0.0039$. The coefficient of determination was slightly higher for all brand B skis with 0.2051, though still not strong.

Ski tip and tail opening and contact length

One common ski characteristic was shown by a bigger opening gap on both the ski tip and tail in the warm category for all three teams with clearly higher values for brand B skis compared to the three included ski brands and temperature categories.
Brand B skis exhibited a significantly shorter average net contact length in all three temperature categories compared to skis from the three other brands (Table 4.4).

Table 4.5: Average net contact length for the four ski brands and three temperature categories.

Ski brand	A	B	C	D
Cold	49.2 %	42.0 %*	49.8 %	42.4 %
Medium	46.8 %	41.0 %*	46.8 %	46.8 %
Warm	47.0 %	38.3 %*	46.6 %	44.6 %

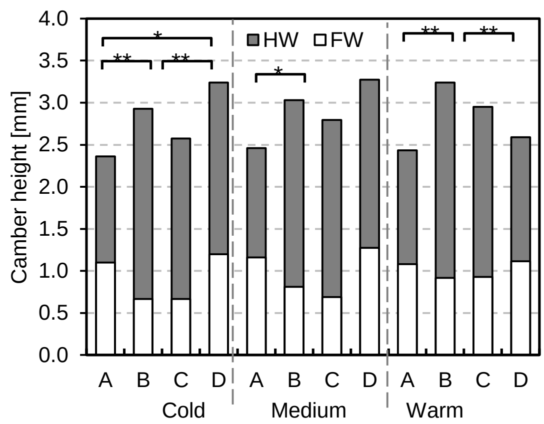

Figure 4.6: Camber height measured at balance point loaded with half and full BW for all four ski brands and temperature categories, with significant difference between conditions at $*p \leq 0.05$ and $**p \leq 0.01$.

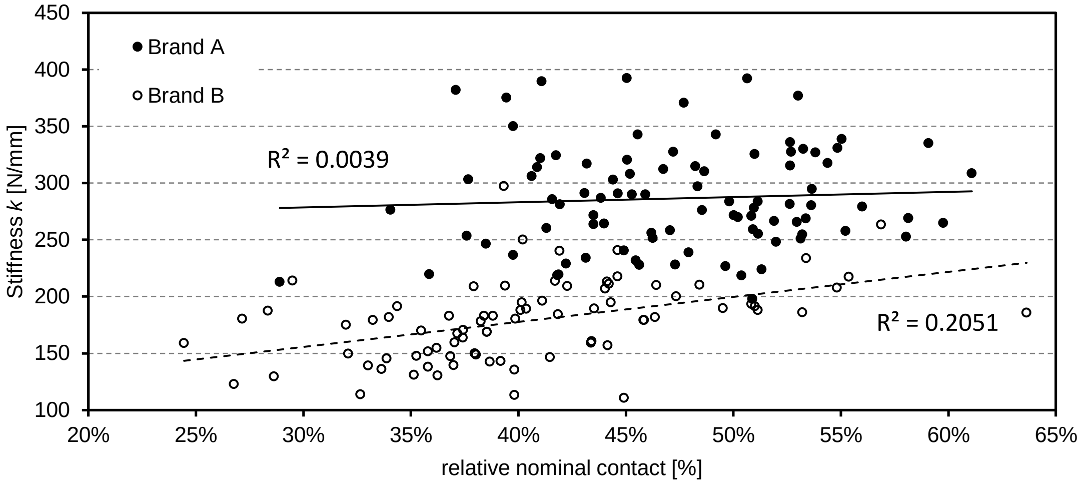

Figure 4.7: Ski camber stiffness as a function of the relative nominal contact length for two selected ski brands. All measured skis are plotted. Linear regression lines are drawn in the figure.

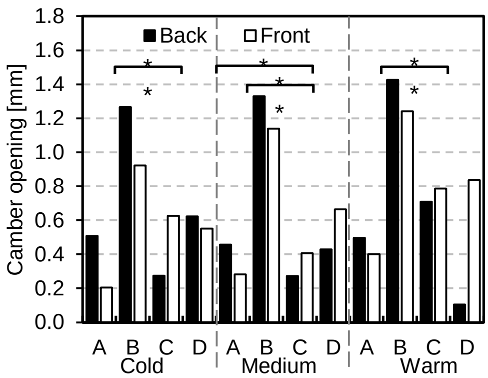

Figure 4.8: Camber opening height measured with full BW at ± 41.6 % of the ski length in front (white) of and behind (black) the BP, with significant difference between conditions at *$p \leq 0.05$ and **$p \leq 0.01$.

4.2 Study II: Ski Base Structure

4.2.1 Range of structures produced with metal grinding

To a certain degree, the geometry of the grinding wheel and cutting edges predefines the resulting structure, and two clearly different structures from metallic grinding and stone grinding can be seen in Figure 4.9A-D. Samples B and D can be described as fine structures, with an R_a of 3.3 µm and 3.5 µm, whereas A and D are medium coarse ones with an R_a of 4.1 µm and 4.8 µm, respectively (Table 4.6).

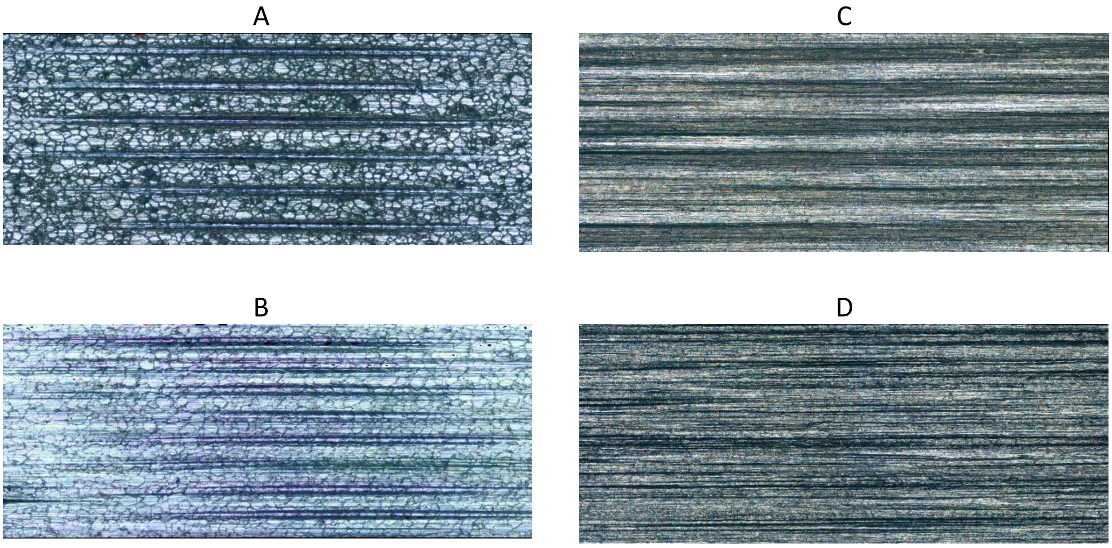

Figure 4.9: Sample surface textures from metal cutting (A, B) and stone grinding (C, D), the image size is 2.16 mm × 5.25 mm.

As seen in Figure 4.9, a distinctive linear structure is visible for samples A and C, while the roughness profiles in Figure 4.10 illustrate the differences and similarities between the fine (B, D) and medium coarse (A, C) structures. Distinct grooves with a proportionally flat area in between characterize structures A and C, and the average spacing between the grooves increases for both medium coarse structures. A higher mean roughness also led to a negative skewness and positive kurtosis, which can be described as leptokurtic for the MG structure and platykurtic for the SG structure, though the fine structure from tool B is less clear. An R_z value of 15.9 µm is clearly lower than from the other MG structure. In addition, the R_{sm} value of 107.7 µm expresses a considerably lower average mean periodic spacing than the metallic grind of tool A with 270.8 µm, respectively.

Table 4.6: Average amplitude and spacing parameters for the two sample structures made by metallic and stone grinding

Method	Metallic grinding		Stone grinding	
Sample	A	B	C	D
R_a	4.1	3.3	4.8	3.5
R_q	5.8	4.0	5.5	4.2
R_z	25.0	15.9	18.3	22.9
R_{sm}	270.8	107.7	323.4	242.4
R_{sk}	-0.74	0.04	-0.61	0.11
R_{ku}	4.19	2.38	1.93	2.43

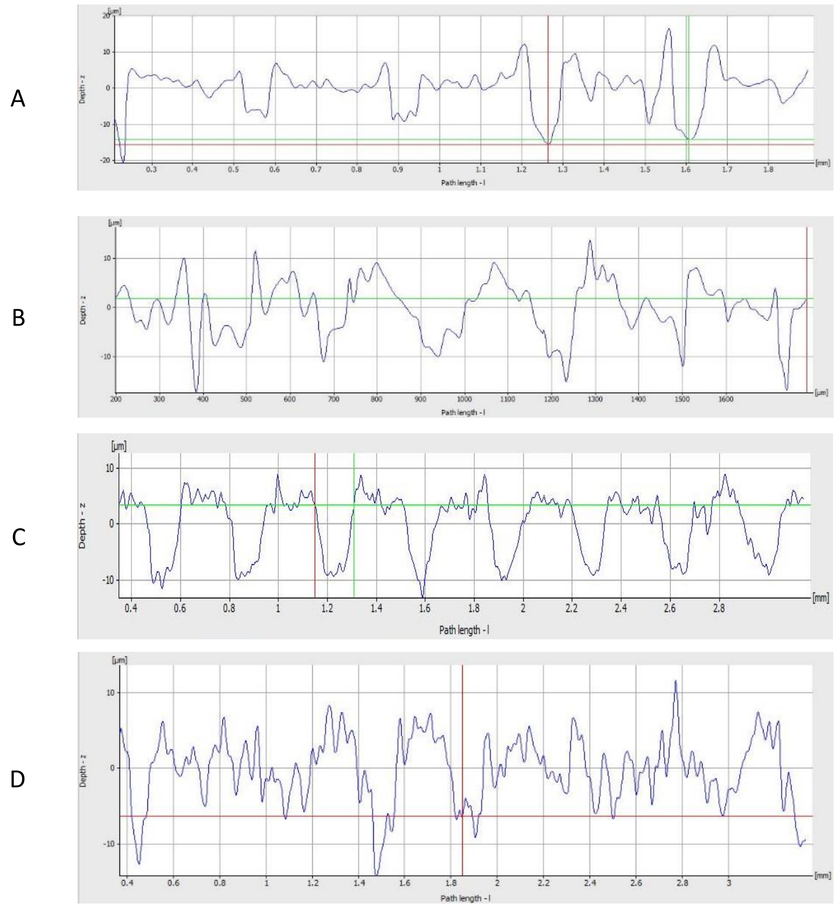

Figure 4.10: Roughness profiles from two metal cutting structures (A, B) and stone ground structures (C, D).

4.2.2 Comparison between stone ground and metal ground structures

The stone ground skis showed a greater variation in the mean roughness, R_a along the ski. R_a values were constant at 20 cm and 60 cm behind the ski tip with a value of 5.2 µm (Figure 4.11), and the mean was highest at 90 cm and 140 cm from the ski tip with values of 5.6 µm and 5.58 µm, respectively. The lowest mean was measured at 180 cm with 5.07 µm, which was significantly lower compared to the 90 cm measurement point (Table 4.7). The average standard deviation (SD) from all measurement points was 0.45 µm, whereas the biggest variation was shown on the front part of the ski for the 60 cm and 90 cm measurement points with 0.52 µm (Figure 4.12).

Table 4.7: Average mean roughness (R_a), standard deviation (SD) and relative variability (*CV*) from the profile roughness measurements for the stone ground (SG) and metallic ground (MG) samples based on n = 10 samples for each position.

Position [cm]	SG R_a [µm]	SG SD. [µm]	SG *CV* [%]	MG R_a [µm]	MG SD. [µm]	MG *CV* [%]
20	5.25	0.327	6.2	5.59	0.225	4.0
60	5.23	0.518	9.9	5.36	0.147	2.8
90	5.60	0.515	9.2	5.70	0.335	5.9
140	5.58	0.313	5.6	5.52	0.295	5.3
180	5.07	0.388	7.6	5.57	0.320	5.7
Average	5.34	0.450	8.4	5.56	0.283	5.1

(a) (b)

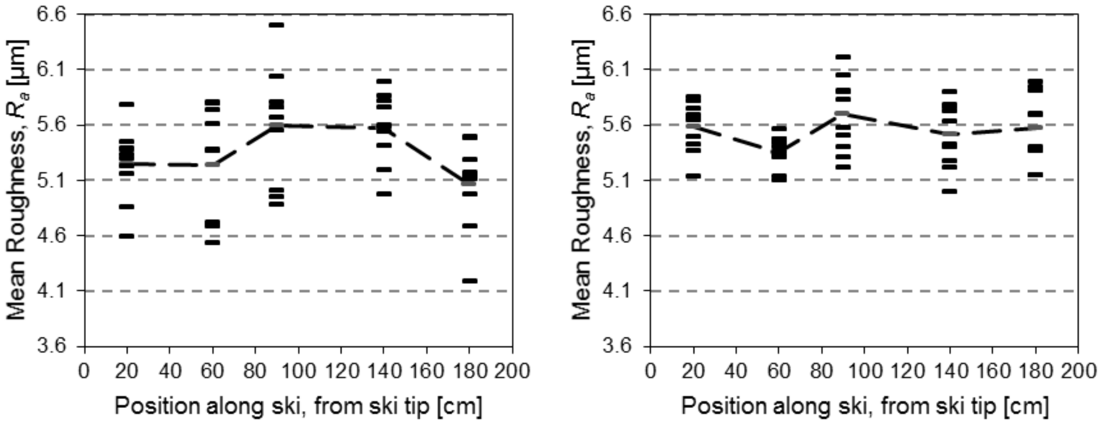

Figure 4.11: Mean roughness, R_a results for all measurement points for the five chosen points along the ski. The average of each point is connected with a dashed line; (a) stone ground skis and (b) metal ground skis.

(a) (b)

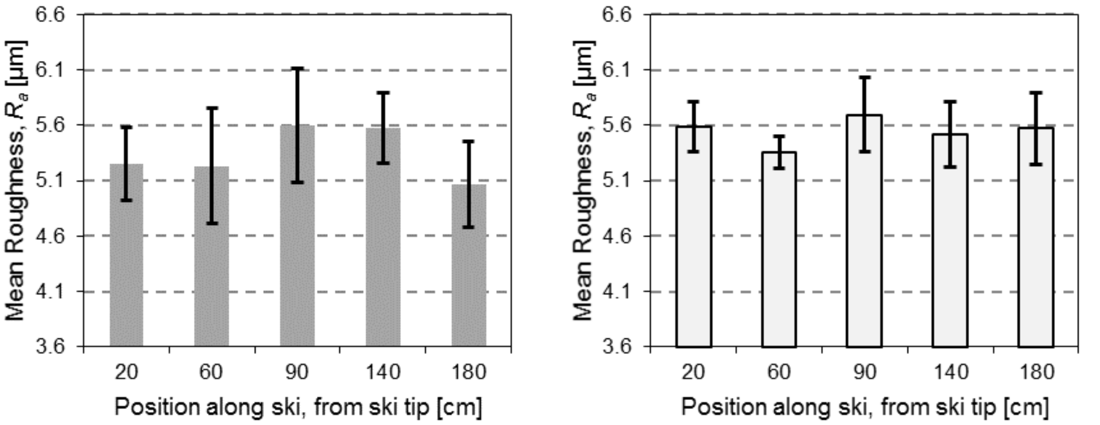

Figure 4.12: Average mean roughness, R_a ± SD for all five chosen measurement points along the ski; (a) stone ground skis and (b) metal ground skis

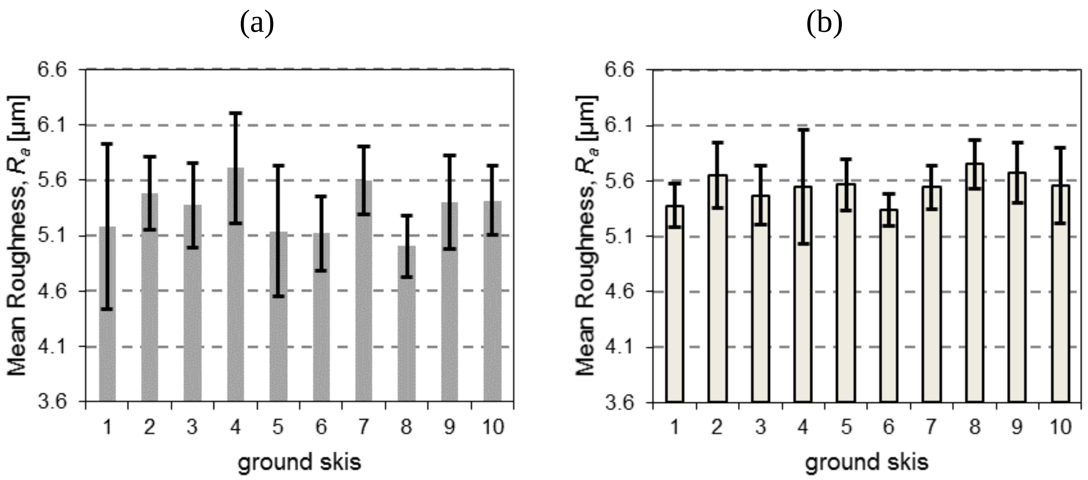

Figure 4.13: Average mean roughness, R_a ± SD for the 10 ground skis; (a) stone ground skis and (b) metal ground skis.

The metal ground skis exhibited the lowest mean roughness at 60 cm and the highest at 90 cm from the ski tip (Figure 4.12b). The standard deviation varied between 0.15 µm to 0.34 µm, and showed a total average of 0.283 µm for all 50 measured roughness profiles. There was no clear trend for the mean roughness after 10 ground skis for both grinding methods (Figure 4.13b), and the new metallic grinding process demonstrated a lower variation of the mean roughness along the five measured positions with 0.12 µm, whereas the stone ground skis had a standard deviation of 0.23 µm. The *CV* of the metallic ground skis was 5.1 %, while the stone ground skis showed a *CV* of 8.4 %.

It is important to enable reproduction of a goal structure. The value of this new and innovative method of producing a structure should be obvious.

4.3 Study III: Measurement Equipment

During the first test, a negative trend concerning the gliding could be seen (Figure 4.15), though it was not possible to find significant differences in the running times between the various heats or skis (Figure 4.15). A linear regression line was added to Figure 4.14 to help visualize the increasing trend of the gliding times. Ski pair 101 showed the fastest average gliding time at 9.121 s, which was 0.05 s faster than ski pair 102 (p = 0.621). Ski pair 107 was the slowest at 9.238 s (p = 0.09) on average. By looking at the results from Heat three the continuous acceleration loss and speed can be observed (Figure 4.16). The average acceleration loss for pair 107 was lowest from the start to the first photo cell. Also, the maximum speed of 6.26 $m \cdot s^{-1}$ was 0.06 $m \cdot s^{-1}$ slower than for pair 102, and 0.3 $m \cdot s^{-1}$ slower than pair 101. It could be seen that the speed started decreasing after approximately 62 m of the track when the inclination flattened (-1.13°). Pairs 101 and 102 had a speed loss of -1.13 and -1.14 $m \cdot s^{-1}$, respectively, whereas pair 107 lost 1.5 $m \cdot s^{-1}$, which resulted in a time loss of + 0.18 s and + 0.12 s compared to the two other skis. Both test procedures resulted in the same ranking in Test 1.

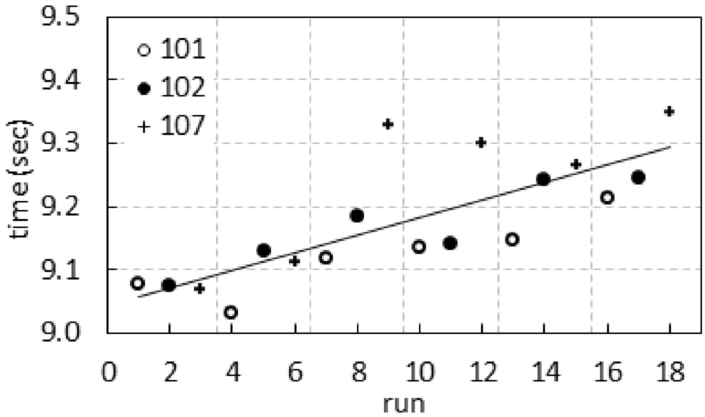

Figure 4.14: Test 1: Sliding times for each run (a) with a linear regression line in black.

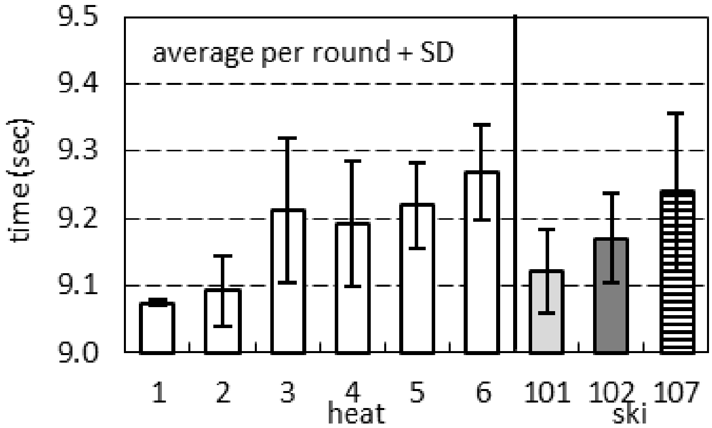

Figure 4.15: Average gilding times ± SD for each heat and ski to the right.

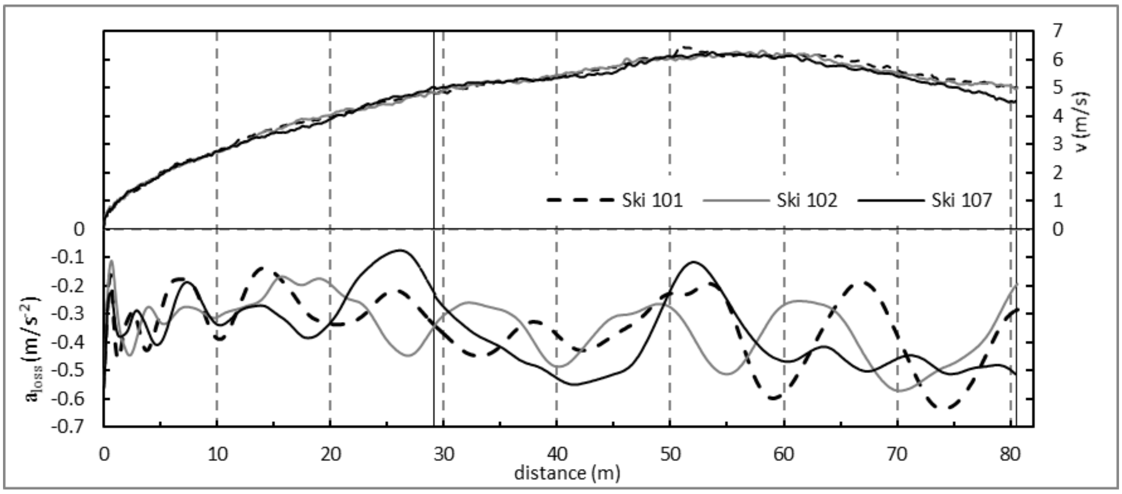

Figure 4.16: Results from the inertial measurement unit (Test 1, Heat 3). The two photocell units are marked with vertical black lines at 29.5 m and 80.2 m into the test track.

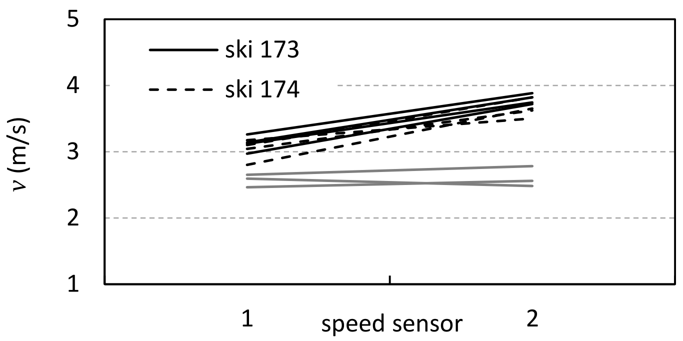

Figure 4.17: Skier's speed at photocell one and two for each run in Test 2.

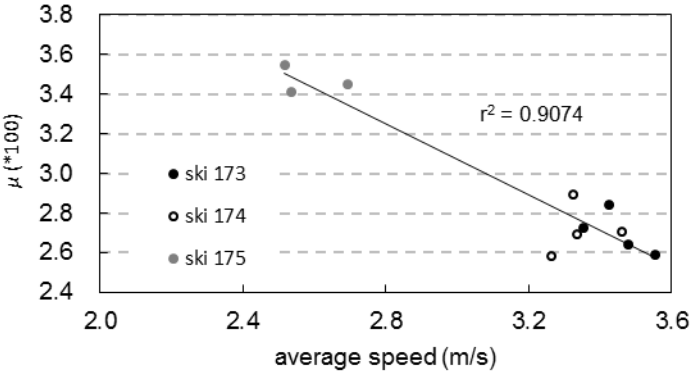

Figure 4.18: Average speed versus calculated coefficient of friction, μ for each heat and ski with a linear regression line in black to the right.

4.3.1 Test 2

The initial speed after 20 m and the exit speed at the end of the test track after 58.8 m can be seen in Figure 4.18. Ski pair 173 increased its speed on average from 3.12 by 0.67 to 3.79 $m\cdot s^{-1}$. A similar result can be seen for pair 174 (from 3.03 $m\cdot s^{-1}$ to 3.64 $m\cdot s^{-1}$), whereas pair 175 increased its speed by only 0.04 $m\cdot s^{-1}$ to 2.6 $m\cdot s^{-1}$ during the gliding test. The split times from the timed gliding tests (B) were used to compute the average velocity between the speed sensors. The average velocities from the speed sensors (B) were compared to the calculated μ from the IMU sensor model (E). A strong correlation between the timed gliding test (B) and the IMU-based sensor system (E) $r^2 = 0.907$ could be seen (Figure 4.18). The calculated average μ was identical for ski pair 173 and 174 with $\mu = 0.027$. Pair 175 showed an average coefficient of friction of 0.034.

4.4 Study IV: Ski Wax

Based on the intensity and area of the peaks as a function of the binding energy, results from the XPS measurements (Table 4.8) present an approximate element composition for each material. The Fluorine content in the IS-4 and IS-5 materials without any wax are very similar (Figure 4.19). IS-5 contains small PTFE particles, which exhibited higher Fluorine content. Gallium could not be detected in any of the materials with the XPS. The results for the liquid waxes from the ICP-MS showed 17.6 ng/mL of Gallium (Ga) for the Liq.-B product, which is a very low concentration to be detected by XPS. After melting

Glider-A onto the running surfaces, the contact angle increased for both ski bases, while μ declined. The hydrophobicity and μ of the materials showed a negative correlation of r = -0.69. The application of Liq.-A led to a decrease of the contact angle although the COF tested with the TE88 device resulted in a further decrease of -8.5 % (IS-4) and -19.4 % (IS-5), which was also the lowest μ measured in this study with 0.016.

The highest contact angle was measured before skiing with the Liq.-B applied on IS-5 with 121°. The materials with the lowest contact angle and the highest μ are the ones after use in the gliding field tests. The roughness, R_q of the tested bases was also measured, as it can affect the contact angle. However, the roughness for the tests were designed to be equal, with the area the roughness was measured on only representing a part of the area where the contact angle test was performed on. It is therefore assumed that little differences on friction will appear due to roughness since it was very similar for all materials. After skiing 34.1 km, the Fluor content clearly decreased at both base materials, whereas IS-5 preserved the wax better by keeping 2.3 % of its original 5.3 %. Another interesting finding is the raised value of Nitrogen in all samples after 34.1 km of skiing with values between 0.5 % and 1.9 %.

The outdoor gliding tests were performed under stable conditions within each test, albeit with a slight change between the tests, with IS-5 always performing better than IS-4. All results are only relative compared to the reference pair, which was just skied during the timed gliding tests, whereas the two other pairs were skied on for a total of 34.1 km split into three laps (8.1 km; 7.8 km and 10.6 km), including each gliding test of 1380 m to 1600 m of skiing. During the first four gliding tests, the two running surfaces displayed very similar results. Both responded with an improvement of 4 % due to wax, though the further development was not as uniform as expected. After the last loop of 10.6 km IS-4 and IS-5 improved on average by 3.2 % compared to the reference ski (Table 4.9).

The tribometer measurements revealed the highest coefficient of friction for unwaxed ski bases and the ones that were skied on for 34.1 km, with the exception of IS-5 + Liq.-B. However, applying Liq.-A on top of the materials with Glider-A resulted in a small difference in performance for the two materials, favouring IS-5. IS-5 with Liq.-A wax was the material with the lowest μ tested in the tribometer, which was 0.0022 lower than IS-4, and the contact angle was 3.8° larger. The contact angle for IS-5 + Liq.-B was the highest of all the contact angles, with 121.3°, which is followed by IS-4 + Liq.-B with 106.8°. For the friction measured, IS-4 had the second lowest, while IS-5 had the third lowest μ. After the full skiing length, IS-4 + Glider-A and Liq.-A revealed a 2.9 % higher μ compared to the unwaxed material, while IS-5 was raised by 16.9 %. The rise in μ got even higher when comparing the newly waxed materials to the skied samples. A rise of 55.4 % (IS-4) and 96.3 % (IS-5) were measured on the newly waxed samples.

The surface topography gave no remarkable changes after the friction measurements with the setup used in this project, which corresponds to approximately 500 m of skiing. There was neither a notable difference in the topography of the ski bases that had skied for 34.1 km, nor for the newly ground skis with the same roughness.

Table 4.8: XPS results from the first test of each sample. The IS-5 running surface contains small PTFE particles, and one measurement focused on such a particle. All values are in approximate atomic percentage [%], and based on the intensity and area of the peaks as a function of the binding energy. Roughness, R_q, [µm] measured during the TE 88 test. Time [%] for the field test compared to the reference ski. Note: a negative percentage means the skis were faster than the reference ski. Contact angle, θ, [°] and μ measured with TE 88.

Sample	C	O	F	N	Ga	B	Na	S	Si	R_q	time	θ	μ
IS-4 no wax	92.7	3.1	2.7	-	-	0.1	0.6	0.6	-	3.09	5.83	86.9	0.0278
IS-4 Glider-A	92.4	5.0	0.9	-	-	0.3	0.7	0.6	0.2	2.83	-	98.5	0.0201
IS-4 Liq.-A	93.9	1.7	3.8	-	-	-	0.2	0.2	-	3.00	2.05	93.6	0.0184
IS-4 Liq.-B	94.4	2.3	2.4	-	-	-	0.4	0.4	-	2.47	-	106.8	0.0165
IS-4 Liq.-A 34.1 km	83.1	10.6	0.4	1.9	-	0.2	1.4	0.8	0.7	2.44	0.02	85.3	0.0286
IS-4 Liq.-B 34.1 km	86.1	9.5	0.3	1.3	-	0.1	0.7	0.7	0.7	2.54	-	81.4	0.0275
IS-5 no wax	89.2	5.1	2.6	-	-	0.6	1.0	1.0	-	3.24	5.51	93.8	0.0272
IS-5 Glider-A	89.5	5.4	2.5	-	-	0.1	0.7	0.7	0.4	3.33	-	99.6	0.0204
IS-5 Liq.-A	82.1	7.5	5.3	-	-	1.5	1.4	1.4	0.2	2.53	1.64	97.4	0.0162
IS-5 Liq.-B	90.5	3.2	4.8	-	-	0.1	0.6	0.6	0.1	3.05	-	121.3	0.0180
IS-5 Liq.-A 34.1 km	87.8	6.7	2.3	1.6	-	0.2	0.4	0.4	0.5	3.56	-2.4	77.5	0.0318
IS-5 Liq.-A 34.1 km - PTFE	80.2	6.5	9.4	1.8	-	-	0.3	0.3	0.5	-	-	-	-
IS-5 Liq.-B	86.6	7.4	2.6	0.5	-	0.1	0.8	0.8	0.6	2.84	-	81.0	0.0194
Reference ski	-	-	-	-	-	-	-	-	-	2.95	0	-	0.0155

Table 4.9: Average gliding times for all tests during the field campaign including percentage deviation compared to the reference ski. *) tested at Holmenkollen, Oslo. **) tested at Granåsen, Trondheim.

	no wax*	Glider-A + Liq.-A*	Loop 1*	Loop 2*	Test 5 **	Loop 3**	Average
acc. skiing [km]	1.6	1.6	11.3	20.7	22.1	34.1	
Ref [sec.]	12.767	13.279	13.113	12.926	13.230	12.956	13.045
IS-4 [sec.]	13.557	13.492	13.388	13.090	13.623	12.953	13.351
IS-5 [sec.]	13.512	13.519	13.332	13.081	13.374	12.655	13.246
IS-4 [%]	5.83	1.58	2.05	1.25	2.89	-0.02	2.285
IS-5 [%]	5.51	1.78	1.64	1.19	1.08	-2.38	1.517

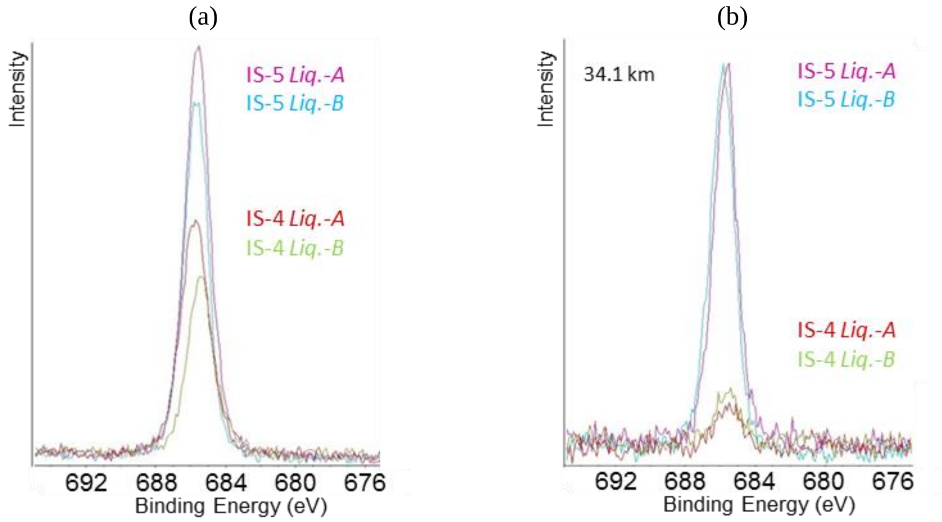

Figure 4.19: (a). XPS analyses from both base materials compared with Glider-A + Liq.-A and Liq.-B wax before skiing and (b) after skiing 34.1 km (in the spectra F 1s).

5 Evaluation and Discussion of Results

5.1 Study I: Ski Analysis

Each athlete in one of the Norwegians national teams of CC, BI or NC has approximately 12 pairs of racing skis. This number is usually double for CC athletes since they also compete in the classic technique. A balanced ski park has to contain skis with various characteristics to fit all possible track and snow conditions, ranging from cold, fine-grained fresh snow on the one end of the spectrum to transformed coarse old snow close to the melting point. Track conditions can range from very hard and icy to soft and loose conditions, and the systematic screening and testing of ski characteristics has been of interest in previous research (Bäckström et al., 2008; Ekström, 1981; Erkkilä et al., 1986; Evertsen, 1989; Pinchak et al., 1987a; Rønbeck, 2001).

This comprehensive study was done on both skating and classic skis from three different teams and on both genders, and data from 816 pairs of skis were collected. To the best of the author's knowledge, no studies of this scope have been published. The importance of the ski properties on performance is well known among ski technicians, and was confirmed by Rønbeck and Vikander (2007). Furthermore, numerous studies in the field of snow and ice friction have investigated factors that affect the kinetic coefficient of friction under a broad range of various conditions (Buhl et al., 2001; Colbeck, 1992b; Giesbrecht et al., 2010; Glenne, 1987; Kuroiwa, 1977; Nikki et al., 2005; Outwater, 1970; Spring et al., 1985; Sturesson, 2008).

It has been shown in previous studies that friction depends on the applied load at low temperatures (Buhl et al., 2001). Below -10ºC, μ is significantly higher for lower loads. Moreover, a higher contact pressure leads to more heat being produced by friction, which warms up the snow surface, thereby causing a more extensive liquid-like layer that supports melt-water production. Hence, this implies that a heavy skier has an advantage. A smaller contact area would enhance these findings, as skis investigated in this study demonstrate the opposite effect. On average, cold skis from all brands have a 7.5 % longer nominal contact area than warm skis, while in a more recent study, it was shown that even at higher temperatures, there was a beneficial effect for heavier skiers. The kinetic friction decreases with an increasing load, particularly at higher temperatures (Bäurle, 2006). In real skiing, multiple factors affect the total frictional force, and the variation in the relative nominal contact area might possibly be explained by the great track and snow condition differences in real skiing. In addition to theoretical optimum contact characteristics, skis have to be prepared to fit the track properties. Skis must be stable on hard and icy tracks, as well as under soft track conditions.

A ski has to fulfil many requirements. For example, gliding experiments are often performed under either lab conditions on tribometers or on straight gliding tests in the field. In pure gliding tests, others important factors cannot be considered. In real cross-country skiing, a skier has to handle many different situations, such as steep uphills and technical downhills under various snow and track conditions. The edging during the push-off phase will lead to torsional stresses in the ski that were not investigated in this study. In real skiing, the feeling and response from the equipment is essential. Top speed is just one of the key requirements in a selection process, with other essential characteristics being acceleration and ski stability. Athletes often talk about “feeling”, which is hard to measure or quantify. With the developed SkiAnalyzer test bench, the continuous screening of new racing skis and the proper documentation of usage of all skis is a goal in order to be able to identify potential winning skis as early as in the laboratory.

5.2 Study II: Ski Base Structure

The stone grinding of cross-country ski bases has been widely used since the end of the 1980s. Racing skis are regularly reground due to structure wear, after base damage and often due to a desire to improve the original structure. Unfortunately, the stone grinding process is not highly automated and reliable, and different inaccuracies in the process can lead to irregularities of the results, thereby not necessarily giving the same structure from time to time despite an equal adjustment of the stone grinding machine parameters (Moldestad, 1999).

In this study a new and innovative approach for the grinding of cross-country skis has been presented using a metallic cutting tool instead of traditional stone grinding. Such a method has not been published earlier, and the stone and metallic grinding processes are completely different from each other. Abrasive particles from a grinding stone wear down, causing continuous changes of the grinding surface, which results in a varying result of the structure on the ski base.

The development and construction process of the new grinding machine has lasted for several years, and demanded many iteration loops with modifications of the device. The contribution to the construction of the grinding wheel was based on expertise from analysing more than 200 ski base samples in an earlier study (Breitschädel, 2007). The geometry of the cutting tools has been designed using 3D CAD programmes, and due to the superior hardness compared to the ski base material, a long lifespan is guaranteed. One advantage of stone grinding is that with the help of one diamond and one grinding stone, an almost endless combination of structures can be designed and ground to the skis. Grinding with a metallic cutting tool does not offer the same possibilities whereas a certain variety can be achieved by changing one of the process factors, namely the cutting tool circumferential speed, the grinding feed speed and the load. The freedom to alternate all factors along the entire ski length opens up for further research and gliding tests.

The successful implementation of this new technology has already contributed to several outstanding results in international championships for Norwegian athletes. During the XXI Olympic Winter Games in Vancouver in 2010 and the FIS World Championship in Oslo 2011, several medal-winning racing skis were ground with the newly developed grinding method.

5.3 Study III: Ski Testing

Cross-country ski testing can be a time-consuming process with many possible sources of error. An objective test setup is necessary for all ski technicians in order to find the properly tested winning factor, with Karlöf et al. (2007) presenting a test protocol for timed gliding tests. There can be many challenges that influence the outcome of a gliding test in a negative way, and changes of the track condition due to polishing of the snow surface is a known problem. As shown by Fauve et al. (2005) and Peil (2000), precipitation and a change of snow or weather conditions can affect the gliding properties of skis. Ski technicians therefore try to limit the test duration to a minimum, and the development of an IMU-based system that can replace a traditional timed gliding test was the goal of this study.

The results of the study showed that IMU sensors in gliding tests may find the best skis. By using a low-cost IMU and correction methods, it was possible to produce reasonable estimates close to the precision requirement of detecting a difference of 0.30 m in a 100-m-long gliding test. The required accuracy to differentiate between skis with a similar glide performance corresponds to a $\Delta\mu$ of approximately 0.001, whereas the developed system could distinguish between gliding performances that correspond to a $\Delta\mu \sim 0.01$. The limitations are connected to challenges such as measurement noise, drift, precision, accuracy and weaknesses in the mathematical model.

There are several unsolved problems with the developed IMU system, and large, cyclic variations in the acceleration loss of up to 0.44 $m \cdot s^{-2}$ were observed. Barely noticeable movements of the skier relative to the skis is one cause of these fluctuations, while other important sources such as ski edging, wind gusts, instable balance and further unknown factors may also influence the acceleration loss. The challenge is therefore to isolate the effects of the controllable factors and to eliminate the effects of irrelevant influences in an improved model.

More sensitive sensors should be used in order to detect the small differences that distinguish good from winning skis. Further work needs to be carried out to improve the estimation model based on more precise sensors, and a better model seems to be essential to help distinguish between the factors affecting acceleration loss.

5.4 Study IV: Ski Wax

This study combined both laboratory tests and experimental field work. This setup led to several challenges during and after all data acquisition, and the outdoor sliding tests were performed under stable, but slightly changing conditions.

The XPS analysis showed an accurate element composition on the sample surface according to the elements' response. One of the included products was expected to contain Gallium, which was not detected by the measurement instrument. The liquid state and the vacuum system could be factors influencing the lack of detection for this element.

The XPS analysis revealed an increase of nitrogen and oxygen for all samples between after skiing 34.1 km compared to tests before skiing, which was in the range from 0.5% to 1.9% for nitrogen and 6.5% to 10.6% for oxygen in the atomic percentage. These findings are in line with research from Stamboulides et al. (2013), who also documented an increase of nitrogen from 1.2% prior to sliding to 3.3% and 7.3%, to 14.6% for oxygen after sliding. The nitrogen may be a contaminant found in the snow or due to the handling process of the skis during the field tests. For confirming the origin, a sample of liquid snow should be tested in ICP for identifying the elements. IS-5 and Liq.-B contained less Nitrogen, which could imply that the Liq.-B wax prevents the accumulation of dirt and contamination better than the Liq.-A wax.

6 Conclusions and Recommendations for Future Work

6.1 Conclusions

RQ1: How can the characteristics of classic cross-country skis be classified and described?

When considering the stiffness, both men and women chose very similar skis for *cold* conditions, which further results in a lower mean camber height. For the *warm* skis, the women used stiffer skis that required 77% of their BW on average to press the skis down to a spacing of 0.2 mm, while on average the men used 5 % less. Another clear trend was revealed for all groups: The c*old* skis for men and women always displayed a longer distance from the BP to the opening, both at the front and back part of the ski, which implies a larger contact area for the *cold* ski. It was interesting to see that the characteristics were mostly affected by differences between the different ski brands.

RQ2: Do the male Norwegian national teams (CC, BI and NC) select skating skis with similar characteristics?

Several significant differences between the three teams could be found. Athletes from BI had significantly softer skis, with a higher mean dynamic response in the cold and warm ski category. All three teams chose skis with a bigger opening gap on both the ski tip and tail in the warm category compared to the cold ones, and cold skis showed the flattest characteristics for all teams and categories. These findings can be explained by the different track conditions. Moreover, soft snow and track conditions demand a ski construction with a bigger opening gap.

The ski characteristics of the teams were mostly affected by the brand’s specific ski characteristics, and within the three teams, the ski brands were not equally represented, which had a major effect on the presented results. On average, cold skis from all brands had a 7.5% longer nominal contact than warm skis, and this finding is identical for both classical and skating skis.

RQ3: What is the effect of temperature change on cross-country ski characteristics?

A significant decrease of -34.3 % in the damping coefficient for the front section of the skis was found. The ski stiffness increased for all skis, with a decreasing temperature in the early load range from 0.3 kN to 0.5 kN. At the higher load range from 0.7 kN to 0.9 kN, the stiffness results were not that uniform. No brand increased its stiffness between 20°C to 0°C, although three brands became stiffer at -15ºC, with the exception of brand D, which decreased by -6.49 %.

Contact at both the front and back sections became 95 % shorter for all skis in the investigated ski and temperature combinations when the skis became colder. Skis might change their characteristics in either way, but compared with the differences found between ski brands, the magnitude is on a much smaller scale, and a clear difference between the included ski brands could be seen. The measurements presented make it possible to both compare and match skis from one brand, as well as comparing ski brands to each other. Ski producers use different core and cap materials, production methods and shapes for their skis, thereby resulting in different thermal behaviours. Nevertheless, it is not possible to state a general trend about thermo-dependent characteristic changes over all measured brands.

RQ4: Are there new methods to manipulate the texture of cross-country ski bases?

The developed grinding machine presents a new method with fewer parts involved in the grinding operation, in addition to less maintenance requirements. It is a clean process that does not use any cooling liquids, which opens up new possibilities in the field of ski base grinding. New cutting tools can be designed, with alterations in material, cutting edge implementation and dimensions. Another improvement was a reduced *CV* of the mean roughness for the metallic ground skis. The newly presented grinding approach had a *CV* of 5.1 %, while the stone ground samples showed a *CV* of 8.4 %. The new grinding machine offers interesting surface textures that contribute to an optimized performance.

RQ5: Which methods reset the structure made by hand tools best?

For the resetting of a structure after treatment with a manual drilling tool, it was concluded that large differences in the change of the *Ra* between the various methods took place. The most effective method to reset the base was to melt in topping powders, with 11.2% reset per minute. The temperature was the most important factor for resetting.

RQ6: How accurate are current test procedures to evaluate the performance of cross-country skis in the field?

The use of IMU sensors in gliding tests may find the best skis. By using a low-cost IMU and advanced correction methods the developed system could distinguish between good and bad skis, with an $\Delta\mu \sim 0.01$. The accuracy has to be improved by a factor of 10 to get a system that can distinguish between skis with a similar glide performance. Major challenges were measurement noise, drift, accuracy, precision and developing a suitable mathematical method for the IMU system, and further sources such as ski edging, wind gusts, instable balance and further unknown factors may influence the acceleration loss. In future work, more sensitive sensors should be used to detect the small differences that distinguish between good and very good skis.

RQ7: What is the effect of nano waxes on ski performance?

Products containing fluorine contributed to a lower surface energy, which made the material more water repellent, hence resulting in a higher contact angle. However, the fluorine content was not proportional to the contact angle of the material tested, and both the fluorine content and the static water contact angle of the material tested were close to the results found by Stamboulides et al. (2012, 2013) using XPS and the sessile drop technique.

An indication was found that Nitrogen acts as a contaminant in the snow, and one product, which led to a reduced Nitrogen, performed better in the post test.

It was difficult to carry out direct comparisons between the outdoor field tests and the lab tests in this study. One material was a large exception insofar as being the best in the field while performing the worst in the lab. Other than that, there were many similarities.

6.2 Future Work

There is great potential for further research projects in the field of winter sports in general and cross-country skiing in particular. New sensor technology already offers great opportunities that can be utilized, as micro sensors, IMUs and smartphones allow data collection in a much wider and less expensive perspective than just a few years ago.

More studies have to be done to improve IMU-based systems, which should offer an objective alternative to subjective ski testing. Ski technicians often talk about “feeling” when a decision has to be made among several skis. To help quantify these ski characteristics, it takes very sensitive measurement devices and further development. Micro-sensor systems are already good enough to distinguish between various skiing techniques (Marsland et al., 2012; Myklebust et al., 2011), although the accuracy has to be improved by an approximate factor of 10 to clearly measure the fine differences between good and very good skis in a gliding test.

Preparation of the surface texture by stone grinding has a long tradition in all gliding sports such as Alpine skiing, Snowboarding and Nordic skiing, and the relative real contact area between the slider and the snow surface determines the friction coefficient to a great extent (Bäurle, 2006). A potential for further improvement of the gliding performance can be seen in custom-made surface textures, which are adjusted to each ski’s characteristics and pressure distribution.

UHMWPE has been the material of choice for ski running surfaces for the last four decades, and research has proven that various additives can enhance performance

(Rogowski et al., 2007). Super hydrophobic coatings are little tested in skiing thus far, and the potential for improvement in the area of ski base material is a given.

In recent years, several studies concerning the finite element modelling of alpine skis and advanced measurement test benches have been published (Federolf, 2005; Federolf et al., 2006; Rainer et al., 2005). To the best of the author's knowledge, no sufficient model has been developed to model a cross-country ski. Better laboratory test devices have to be developed to be able to measure all important ski characteristics, including torsional and bending stiffness, contact pressure distribution and other relevant span curve parameters in a short time. This kind of test bench could help to describe and understand why some skis perform better than others.

6.3 Concluding Remarks

It was an honour to be able to spend my PhD work with such an interesting and practical topic, as snow and ice friction offer many more unanswered questions. New technologies allow unproven approaches to solve these challenges, and I can heartily recommend and encourage students to dive into the researching of sports technologies.

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Effects of Temperature change on Cross-country Ski Characteristics

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Abstract

Mechanical properties of Cross-country Skis are usually measured in a lab under standard conditions of 20°C whereas athlete's race at temperatures down to -20°C. Static and dynamic properties of seven skating skis from four different brands were tested at three different temperatures of 20°C, 0°C and -15°C to investigate temperature dependencies. Span curve measurements were performed at loads from 0.2 kN to 1.3 kN and the natural frequency and damping coefficient were recorded for the front and rear section of the skis. All skis showed a high significant change in the damping coefficient of the front section and a significant change of the natural frequency. All skis increased their stiffness with decreasing temperature in an early loading phase. The results did not show a uniform trend regarding the recorded parameters. The peak camber height increases for two brands (A, D) whereas it decreases for others (B, C).

A.1 Introduction

Mechanical ski properties make a major contribution to the performance in cross-country skiing. Ski span characteristics have already been reported to have a major effect on gliding results by Ekström [1] in 1981. It is essential to select skis according to the given snow and track conditions and with suitable properties and behavior in order to minimize kinetic friction and optimize the gliding speed in skating technique. To achieve this, world-class athletes usually spend a great amount of time testing new skis each year. Laboratory tests of skis are an important supplement to field tests and help both athletes and ski technicians gain a better understanding of an athlete's ski selection. They allow the collection of important data like span characteristics, flexural behaviour and contact between ski and snow. Backström et al. [2] described a procedure to pair matching skis by analysing the ski span characteristics and the contact pressure. Usually all laboratory testing is done under standardized conditions, often at room temperature, because the accuracy of the measurement devices relies on a constant operating temperature. The lower temperature limit for cross-country races is set by the International Ski Federation [3] at temperature of -20 °C, measured at the coldest point of the course. The average air temperature during the Cross-country and Biathlon World Cup events from the seasons 2004 to 2006 was -4.6 °C with 80 % of all races above -8 °C [4]. The purpose of this paper is to determine if static characteristics such as camber height (CH), span length (SL), contact length and dynamic characteristics such as natural frequency, f and damping coefficient, λ of skating skis are temperature dependent in a temperature range from -15 °C to 20 °C.

A.2 Methods

Seven skating skis from four different manufactures were tested with a SkiSelectorTM measurement device (Vendolocus Development AB, Bromma, Sweden). The SkiSelectorTM device consists of a rigid aluminum frame with a steel plate on top upon which the ski is placed [5]. The vertical load unit is controlled by computer. The load can be applied in steps of 10 N up to a maximum of 1.5 kN The span curve is obtained by a height sensor which travels along the ski and measures the distance between the ski base and the steel plate. The sampling rate of the height sensor is 200 Hz, which results in a longitudinal resolution of about 1 mm per measurement. The following parameters were calculated using the span curve data: peak camber height (PCH), the height at the balance point (BP), the contact length of the front section (CFS) and back section (CBS). Camber height values below 0.1 mm were defined as contact. The load needed to compress a ski down to 0.2 mm is called FA. The FA measurement was made 80 mm behind the BP, just below the point of the load application.

In addition to the static analysis, dynamic properties were measured, including natural frequency and damping coefficient of both front and back section. Eight acceleration sensors were attached to the front section with 0.1 m spacing starting 0.1 m from the ski tip. On the back section of the ski, five acceleration sensors were attached 0.1 m from the back end of the ski to the back end of the binding. The skis were mounted on a solid welding table to avoid resonance vibration according to [6]. For the measurements on the front ski, the balance point was the last attachment. The measurements on the back section were performed with a defined length of 0.65 m from the end. The skis were loaded at the end with a defined weight, which was released by a simple mechanism to start a free vibration. The sampling rate was 1 kHz for all sensors. Data was processed in a LabView application, which calculated the natural frequency out of a discrete Fourier transformation analysis and the damping coefficient of all sensors. A detailed description of the measurement device can be found in [7]. The damping coefficient, λ is calculated according to the exponential decay of the oscillation

$$a = a_0 \cdot e^{-\lambda t} \cdot cos(\varpi t) \quad \text{(A.1)}$$

where a_0 is the initial acceleration amplitude and ω is the angular frequency. Both the SkiSelectorTM and the vibration analyzing devices were placed at room temperature, T_1 during all measurements to avoid any temperature dependent errors from the devices. After the first measurements at T_1 all skis were kept in a freezing lab for several hours at the two other defined temperatures T_2 = 0 °C and T_3 = -15 °C, to reach the defined temperature. Only one ski was taken out of the cold room to perform either the static or dynamic measurements and the ski was immediately placed back in the cold room. Each test was completed within 5 minutes.

For the statistical analysis of the results, the SPSS statistical program was used. Averages or differences of means from parameters of interest were compared from all three temperatures. The two-sided level of significance, p was calculated. The level of significance was set to $p \leq 0.05$ and highly significant was defined as $p \leq 0.01$.

A.3 Results

A.3.1 Repeatability test

The device's height and longitudinal accuracy was investigated by n = 100 test measurements of one skating test ski. A one sample Kolmogorov-Smirnov Test of the data showed a normal distribution. A summary of the accuracy tests is listed in Table A.1. The left brand A ski was used to perform all the repeatability tests at T_1. The tests were performed with the SkiSelector^{TM} device at a vertical load of 0.6 kN. The excitation load for the free oscillation and damping tests was 10 N in the front section and 22.3 N for the back. The standard error (SE) for the CH measurements was 0.0023 mm and 0.5 mm for the SL.

Prior to the vibration damping tests at different temperatures, the accuracy of the instrument was tested on both the front and back section with n = 100 measurements. The results showed a normal distribution for the measurements.

Table A.1. Summary of the repeatability tests done with the left brand-A ski at T1. A load of 0.6 kN was applied 80 mm behind the balance point (BP) to measure the span related parameters. SE = standard error, SD = standard deviation, SL = span length. Sample size n = 100 for static and dynamic measurements.

	Static measurements				Dynamic measurements			
	z of BP [mm]	*x* of PCH [mm]	PCH [mm]	SL [mm]	f_{Front} [Hz]	λ_{Front} [-]	f_{Back} [Hz]	λ_{Back} [-]
Mean	1.162	69.281	1.238	536.7	17.390	5.365	46.285	6.014
SE	0.0017	0.3403	0.0023	0.50	0.0095	0.0426	0.0005	0.0454
SD	0.0171	3.4032	0.0227	5.00	0.0973	0.4366	0.0056	0.4648

A.3.2 Differences within a pair of skis

The span curves shown in Figure A.1 illustrate the differences within the left and right ski of one pair. In Table A.2 some of the parameters are listed to classify the characteristics for Cross-country skis. The skis were loaded 80 mm behind the BP with 0.4 kN. The two brand A skis were most alike in their span curves as well as in the other recorded values. The FA value varied with 50 N between the brand A skis, whereas the difference was biggest among the brand B pair, with 88 N. The biggest difference in PCH and the height at the BP was measured for the brand D skis with 0.81 mm and 0.92 mm, respectively (Table A.2). The net contact lengths in the front section showed up to 50.7 % difference for the two brand B skis whereas brand A skis were very alike, with 422 and 418 mm of contact length in average. The differences between skis were highly significant for the SL, CFS, CBS, height at BP and PCH. The following temperature related results are split up for each ski of each producer. Just one ski of brand C was tested.

Table A.2. Differences between the two skis of a pair for each brand. The left ski acts as reference for the right one. The skis were loaded with F = 0.4 kN at 80 mm behind the balance point. The averages from all three temperatures were taken. Just one ski of brand C was tested.

Ski Brand	FA [N]		Height BP. [mm]		PCH [mm]		Pos of Peak [mm]	
Side	L	R	L	R	L	R	L	R
A	1070	+50	1.69	+0.08	1.79	+0.06	68	-4
B	705	-88	2.20	-0.48	2.23	-0.48	24	-7
C	879		1.97		1.98		-10	
D	905	+65	2.95	-0.81	3.26	-0.92	91	-5

Ski Brand	SL [mm]		CFS [mm]		CBS [mm]		Start of SL [mm]	
Side	L	R	L	R	L	R	L	R
A	660	+3	422	-4	489	+14	-301	-1
B	771	-56	174	+119	157	+37	-353	+17
C	764		379		331		-371	
D	835	-42	261	-76	415	-13	-352	+12

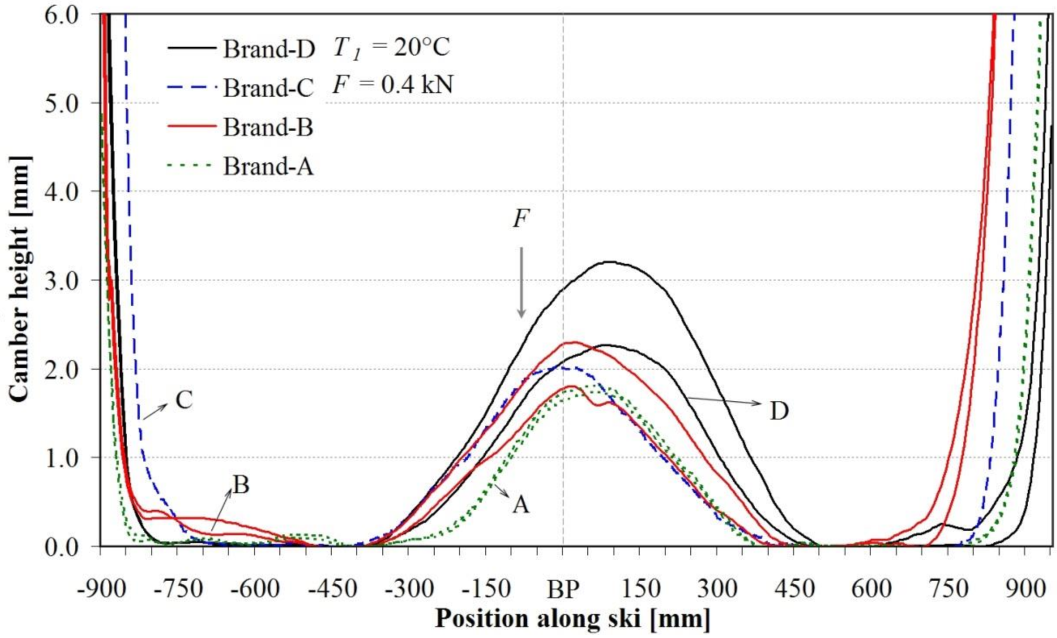

Figure A.1: The different Span-curves for all measured skis at the T_1 loaded with F = 0.4 kN. On the horizontal axis is the position along the ski with the rear ski end at about -900 mm and with the balance point (BP) at 0 mm. Camber height is on the vertical axis in mm.

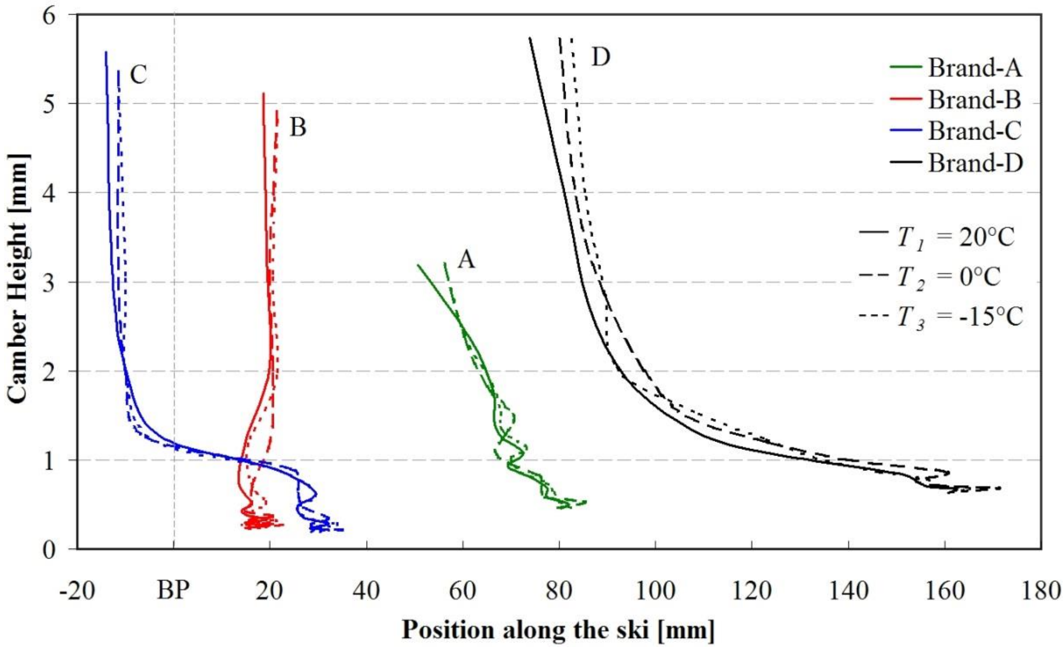

Figure A.2: The movement of the peak camber height and its location along the ski is shown for each brand (mean of both skis) and for the three different temperatures T_1 (solid line), T_2 (dashed line) and T_3 (dotted line). The applied load increased from 0.2 kN to 1.3 kN. Just one ski was tested for brand-C.

A.3.3 Differences between ski brands at T_1

The four selected brands showed a very wide range of characteristics (Figure A.1 and Figure A.2). The PCH at 0.2 kN vertical load at T_1 ranged from 3.19 mm from brand A to 5.74 mm from ski D (Figure A.2). The position of the peak height varied from -14.1 mm behind the balance point for brand C to 73.9 mm in front of the BP for the brand D. All skis showed a special progression of the peak camber position with increasing load as shown in Figure A.2. The PCH gets pushed forward on all skis with increasing load to 1.3 kN. The movement was smallest for brand B skis with 9.3 mm in average. The peaks moved most on the brand D skis with 87.6 mm on average.

Brand A skis had the lowest camber and in addition were the stiffest ones as shown in Figure A.4. In an early loading phase from 0.3 to 0.5 kN the stiffness, k_{early} was more than twice as high as any other ski with 229.9 N/mm. Brand B, D and C had a k_{early} of 104 N/mm to 109.8 N/mm and 109.6 N/mm. In the load range from 0.7 kN to 0.9 kN, also denoted as k_{late} the skis became more similar ranging from 657.6 N/mm (D), 726.7 N/mm (C) to 809.2 N/mm (A). The Brand B skis had a low camber height of 0.18 mm and 0.07 mm when loaded with 0.7 kN to 0.9 kN so they showed very little vertical displacement in that range which resulted in a k_{late} value of 1790.7 N/mm.

A.3.4 Temperature effect on ski characteristics

The stiffness, k of all the skis and temperatures show a clear trend (Table A.4 and Figure A.5). At T_3 all skis had a higher stiffness in the early phase, k_{early} of the attenuation. The difference in stiffness between the ski brands varied by as much as 126.5 N/mm between the softest (D) and stiffest (A). The results for the later phase, k_{late} are not clear.

Brand A skis were also stiffest in the higher loaded range, aside from brand B (which practically showed no further displacement, resulting in very high k values of 1703.1 N/mm and 2102.1 N/mm). The camber height for brand A varied between 0.67 mm to 0.42 mm in this load range, resulting in k_{late} values of 740.6 and 891.8 N/mm. Both brand A and the right brand D ski showed a highly significant increase in the PCH between all three temperatures as well as at the BP. Brand C and the two brand B skis had a significant decrease of the PCH and BP height (Table 4). The position of the PCH showed a significant change in 4 of the 21 ski/temperature combinations; the right brand D ski between T_1 to T_2 and T_2 to T_3, brand C between at T_2 to T_3 and brand B right ski between T_1 to T_2. In all other ski/temperatures combinations the position of the PCH did not show temperature dependence.

All skis showed a decrease in both CFS and CBS. In average the contact lengths were shortened by 42.7 mm in the back and 82.2 mm in the front section, respectively. There was a high significance for most skis regarding the CFS, except for the left brand A ski. All skis showed a highly significant decrease in the CBS between T_1 and T_3.
The SL increased for brand A and D skis (12.4 and 5.5 mm) but not significantly ($p = 0.938$ and $p = 0.162$). Brand B and C showed a significant decrease in SL with up to -6.8 mm between T_1 and T_3.

A highly significant change was found between the natural frequency and damping coefficient for all skis between T_1 and T_3, except for the left brand D ski, which showed a significant change in frequency with $p = 0.047$. For both brand A skis, the left brand B and the right brand D ski, the frequency increased whereas for the others it decreased on the front part of the ski.

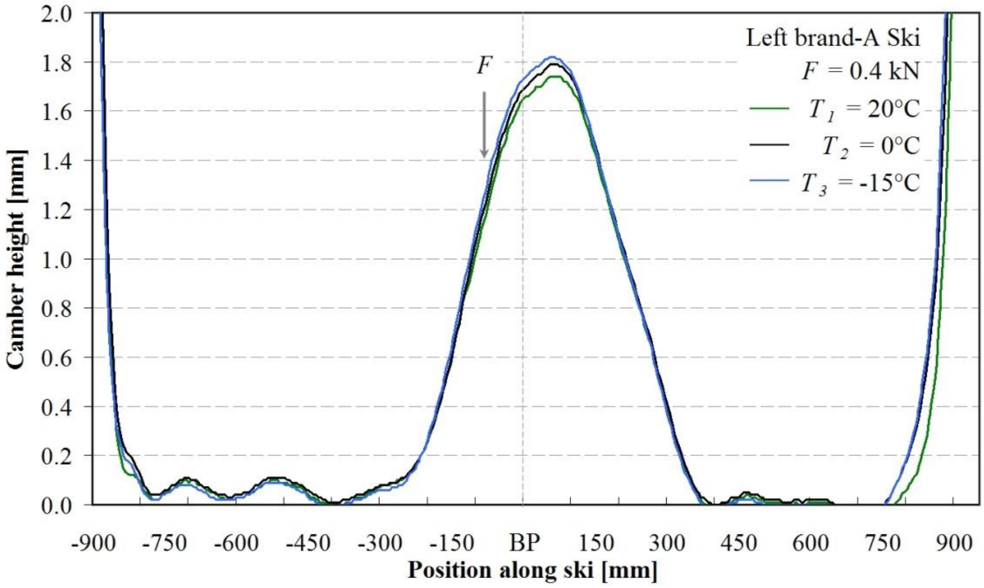

Figure A.3: Comparison of the Span-Curves for a brand-A ski loaded with 0.4 kN at three different temperatures

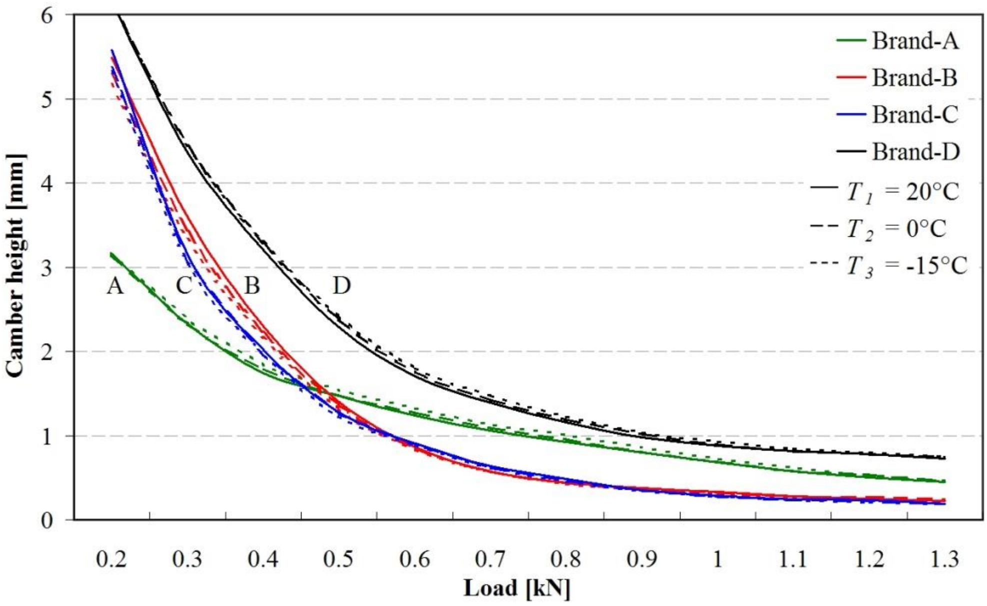

Figure A.4: Average peak Camber height for all brands at loads from 0.2 kN to 1.3 kN and the three different temperatures T_1 (solid), T_2 (dashed) and T_3 (dotted line).

Table A.3. Results from the statistic paired-sample T-Tests for all 21 ski/temperature combinations and the 10 parameters: natural frequency front and back, damping front and back, peak camber height, position of peak camber height, camber length (CL), contact length back and front and height at the balance point (BP).

Pair	Brand	Side	Temp.	Static measurements						Dynamic measurements			
				Δz BP [mm]	Δx PCH [mm]	Δz PCH [mm]	Δ SL [mm]	Δ CBS [mm]	Δ CFS [mm]	f_{Front} [Hz]	$\Delta \lambda_{Front}$ **[-]**	F_{Back} [Hz]	$\Delta \lambda_{Back}$ [-]
1	A	left	T_1 - T_2	0,04	-4,10	**0,05****	5,50	**-11****	-31,40	**-0,03****	**2****	-0,10	**0,59****
2	A	left	T_2 - T_3	**0,05****	4,10	**0,05****	6,90	-12,30	-24,20	**0,06****	**-3,54****	0,09	0,22*
3	A	left	T_1 - T_3	**0,09****	0,00	**0,1****	12,40	**-23,3****	-55,60	**0,02****	**-1,54****	0,00	**0,81****
4	A	right	T_1 - T_2	**0,04****	1,40	**0,05****	10,90	**-19,1****	**-53,2****	**0,34****	**-0,77****	-0,04	0,13
5	A	right	T_2 - T_3	**0,03****	-1,40	**0,03****	-5,4*	-30,00	**-8,2****	-0,02*	**-1,31****	0,34*	**0,63****
6	A	right	T_1 - T_3	**0,07****	0,00	**0,08****	5,50	**-49,1****	**-61,4****	**0,31****	**-2,08****	0,30	**0,76****
7	B	left	T_1 - T_2	-0,09	0,00	-0,08	-0,10	-20,40	**-53,2****	**0,27****	**-0,9****	-0,22	0,38*
8	B	left	T_2 - T_3	**-0,05****	0,00	**-0,06****	-6,7*	4,00	-15,00	-0,11*	**-1,04****	-0,35*	0,5*
9	B	left	T_1 - T_3	-0,14*	0,00	-0,14*	**-6,8****	-16,40	**-68,2****	**0,15****	**-1,94****	**-0,58****	**0,89****
10	B	right	T_1 - T_2	-0,08*	**1,3****	-0,07	**1,3****	**-36,9****	**-23,1****	**0,04****	**-0,27****	**0,23****	-0,02*
11	B	right	T_2 - T_3	-0,02*	1,40	-0,02*	**-6,8****	-6,8*	**-75****	**-0,12****	**-1,91****	**0,89****	0,01
12	B	right	T_1 - T_3	-0,1*	2,70	-0,09*	**-5,5****	**-43,7****	**-98,1****	**-0,07****	**-2,18****	**1,12****	-0,01
13	C	left	T_1 - T_2	-0,06	0,00	-0,06	**-1,3****	**-9,6****	**-19,1****	**0,02****	-0,18	**0,47****	**-0,33****
14	C	left	T_2 - T_3	0*	0,00	0*	0,30	0,10	-11,30	**-0,23****	-0,13	0,17	0,39
15	C	left	T_1 - T_3	-0,06*	**0****	-0,06*	-1*	**-9,5****	**-30,4****	**-0,21****	**-0,31****	0,64*	0,05
16	D	left	T_1 - T_2	**0,08****	0,00	**0,08****	8,20	**-11,3****	**-136,3****	-0,13	0,47*	0,51	**0,6****
17	D	left	T_2 - T_3	0,00	4,10	**0,02****	-2,80	-43,3*	**-68,2****	0,11	**-2,18****	-0,22	0,34*
18	D	left	T_1 - T_3	**0,08****	4,10	**0,1****	5,40	**-54,6****	**-204,5****	-0,02*	**-1,71****	0,29	**0,93****
19	D	right	T_1 - T_2	0,07*	**6,8****	**0,09****	**13,7****	**-36,9****	**-39,5****	**0,02****	**1,59****	**0,4****	**-0,23****
20	D	right	T_2 - T_3	0,05	**-4,1****	0,03	-1,3*	**-65,4****	**-17,8****	**0,06****	**-2,75****	-0,25*	**0,29****
21	D	right	T_1 - T_3	0,12*	2,70	0,12*	12,40	**-102,3****	**-57,3****	**0,08****	**-1,16****	0,14	**0,06****

Table A.4. Ski Stiffness, k mean for each brand at the three measured temperatures T_1, T_2 and T_3 split up into an early stiffness, k_{early} from the range of 0.3 kN to 0.5 kN and a late stiffness, k_{late} calculated between 0.7 kN to 0.9 kN. The measurements were taken 80 mm behind the balance point, which is a standardized measurement point. The percentages in parentheses show the change regarding to the initial value at T_1.

Brand	T_1	T_2	T_3	T_1	T_2	T_3
	k_{early}	k_{early}	k_{early}	k_{late}	k_{late}	k_{late}
A	229.9	234.8 (+2.13 %)	236.5 (+2.87 %)	809.2	740.6 (-8.48 %)	891.8 (+10.21 %)
B	104	109.8 (+5.58 %)	114.4 (+10 %)	1790.7	1703.1 (-4.9 %)	2102.1 (+17.39 %)
C	109.6	114.1 (+4.11 %)	114.1 (+4.11 %)	726.7	726.7 (+0 %)	754.6 (+3.84 %)
D	109.8	113.9 (+3.73 %)	110 (+0.18 %)	657.6	635.8 (-3.32 %)	614.9 (-6.49 %)

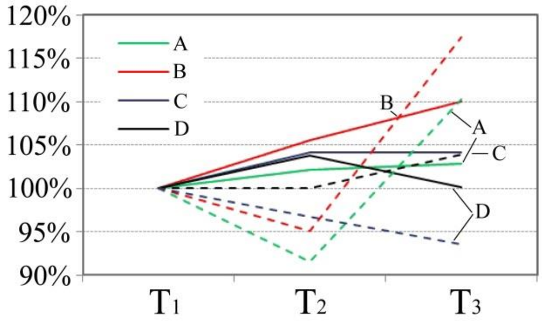

Figure A.5: Shows the early (full lines) and late (dashed lines) stiffness, *k* for all brands and the three different temperatures T_1, T_2 and T_3.

The skis' dynamic properties changed slightly at the back part of the ski. Except for the right brand B ski (-0.01 Hz), the natural frequency increased by 0.58 Hz, which was significant except for the brand C ski. The damping coefficient of the back part also generally increased by 0.5 but not for the left brand A ski, which stayed constant and for the right brand B ski, which dropped by -0.58.

A.4 Conclusions

The major finding in the present study was that static and dynamic ski characteristics change for skating skis in the temperature range between 20°C and -15°C.

- There was a significant decrease in the damping coefficient, λ of -34.3 % for the front section of the skis.
- Ski stiffness increased for all skis with decreasing temperature at the early load range from 0.3 kN to 0.5 kN. At the higher load range from 0.7 kN to 0.9 kN load, the stiffness results were not that uniform. No brand increased its stiffness between T_1 to T_2 but three brands became stiffer at T_3, except brand D which decreased by -6.49 %.
- Both, contact at the front and back sections became shorter for 40 out of the 42 ski / temperature combinations skis at all temperatures.
- Skis might change their characteristics in either way, but compared with the differences between ski brands the magnitude is of a much smaller scale.

The measurements presented make it possible to both compare and match skis from one brand, as well as ski brands compared to each other. Ski producers use different core and cap materials, production methods and shapes for their skis. This results in different thermal behaviour. It is not possible to state a general trend about thermo-dependent characteristic changes over all measured brands.
This study was only done on skating skis. Thermo-dependent changes could play an even more important role for classic-style cross-country skis. The kick-wax zone is usually determined by measurements at room temperature. Changes in camber height and length according to thermo-related property changes might have an effect in the length of these zones, especially for colder skis.

A.5 Acknowledgements

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Cross-country Ski Base Tuning with Structure Imprint Tools

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Abstract

The importance of skis that have optimal glide in ski competitions is significant, since the margin between success and failure is often just seconds. The ski base structure is one of the most important factors that affects the glide. The structure can be divided into a permanent grind and a manual structure made by a hand tool. The use of structure hand tools has increased during recent years. This method allows the skier to continue to use the same skis from race to race but with the possibility of having a different ski base structure to suit the conditions. However, this approach depends on a good method for resetting the manual structure after the first race. Experiments were performed to investigate methods for resetting the structure made by hand tools. Currently, the most common method is to melt in glide wax. This was shown to be satisfactory but, as full resetting is not necessarily achieved after one treatment, the use of an incubator or a hot box would be preferential.

B.1 Introduction

To achieve an optimal glide in Cross-country skiing, it is essential to consider and understand the contributing factors to the tribosystem of ski base against snow. One major parameter of the frictional process is the ski base and how its structure affects the kinetic friction. Ski bases for Cross-country skis are usually made of ultra high molecular polyethylene (UHMWPE). One of the advantages of UHMWPE is that its surface easily can be manipulated. Stone grinding is a common procedure to modify the ski base surface to achieve a variety of different structures. In recent years, there have been several studies [1, 2, 3] which have concentrated on the correlation between ski base structure and friction. Bäurle [1] described the importance of the relative real contact area between the ski and snow on the final coefficient of friction. Peil [2] investigated the characteristic gliding performance for various structures under different snow and weather conditions. The right structure in relation to the given snow conditions is one of the most important factors for the glide. Selecting the right structure can account for up to ten percent of the skis speed on snow [5].

The total ski base structure can be divided into a permanent structure made by grinding or scraping, and a manual structure that is made by a hand tool before each competition. The manual structure can be adapted specifically to suit the exact snow conditions at the competition site. The other advantage of the manual structure is that it is pushed down into the ski base, creating an elastic deformation. After the competition, the imprint can be taken away again. This reset is important as the ski base will be ready for a new type of manual structure at the next competition.

The purpose of this study was to find out whether the manual structure can be reset and how well it remains during the competition. The tests were based on two hypotheses to remove the manual structure, use of skis (skiing) and preparation of the skis (thermal exposure - preparation).

B.2 Methods

The experiments were divided in two. The first tests were performed with the hypothesis skiing, at the location Gålå. The next tests were performed in a laboratory in Trondheim with the hypothesis preparation.

In the first part, four Fischer RCS Carbon Lite Skating Plus skis (2009 model with a Fischer stone grinded structure) were used. Each ski was manipulated by a different manual structure tool (SV1, SV2, SV3 and Swix T0401-1mm). Each ski was analysed at three defined spots; 0.4 m in front of the balance point (BP), at the BP and 0.4 m behind the BP. The measuring points were marked on the ski. In both parts of the experiments, the ski bases were initially measured with a Ski Surface Analyser (SSA) by Optonor (Trondheim, Norway). The instrument and its functionality are in detail described by Moldestad [5]. The SSA calculates the arithmetic mean roughness, R_a of the area depicted. It can be defined by

$$R_a = \frac{1}{n}\sum_{i=1}^{n}|z_i| \qquad \text{B.1}$$

where z_i is a discrete set of surface height points of the ski base. The ski bases were also

Table B.1. Details to the 4 skating test loops. The track was freshly groomed and hard packed. The weather conditions were cloudy and stable. The skis were analysed with the SSA and photographed before, between and after each test loop.

Loop	Length [km]	Air Temp. [°C]	Snow Surface Temperature [°C]	Snow grain size [mm]
1	3	-1.2	-0.6	0.2 – 0.5
2	4	-1.2	-0.6	0.2 – 0.5
3	4	-2.1	-1.6	0.2 – 0.5
4	4	-2.1	-2.3	0.2 – 0.5

photographed through a microscope. After the initial SSA analysis, the ski bases were manipulated with the manual structure tools and different loads. The applied load as measured by two force gauges which were placed under the waxing profile's front and rear edge, respectively. After this and all the following steps the skis and measurement points were repeatedly analysed with the SSA and photographed.
In part one all skis completed a total over 15 km, divided into 4 loops. Detailed weather and snow conditions are listed in Table B.1. The skis were changed from the left to the right leg halfway on each loop. The average speed was 27 km/h.

In the second part, five skis were investigated. Two of these were the skis from the first test that were manipulated with SV1 and SV2. In addition, two Madshus Hypersonic skating skis (2006 model with a Madshus 7-4 stone grinded structure) and two Madshus Nanosonic HP skating skis, 2009 model with a Bjørn Myhre Sport (Krogstadelva, Norway) H0 stone grinded structure were used. In addition to the SV1- and SV2- manual structure tools, Red Creek (RC) 0/-10ºC and RC linear 1 mm were used. The manual structures were applied with different loads at room temperature, on both heated and newly glided skis and on not newly glided skis. The newly glided skis were waxed within the previous 2 hours. Those not newly glided had their last waxing more than 2 days prior to testing.
The effects of the following ski base treatments were tested:

- Incubator / hot box with Swix HF8 glide wax (four hours at 57ºC).
- Waxing at 165ºC with topping powder (Toko Streamline Nordic 0/-15ºC 100 % Flour) applied with a Swix waxing iron
- Waxing at 120ºC with glide wax (Swix HF8) applied with a Swix wax iron.

All points were measured and photographed before and after the preparation. In addition two pair of skis were also analysed and photographed before and after a period of 38 days. The skis were kept untreated during this time, without protective wax. The temperature ranged from -10ºC to +20ºC.

B.3 Results

In total, the average change of roughness by manual structure imprint was +0.148 µm with average added force equal to 332.7 N. Average change in roughness of the treatments "topping powder", "glide wax", "incubator", "time" and "skiing" was -0.04 µm.
The test with hand tool RC 0 / -10ºC with a force equal to 213.9 N gave the least change in roughness (+0.025 µm), with the exception of one test where there was less roughness after adding the manual structure (measurement error). The test with RC 0 / -10 ºC and force equal to 213.9 N was the test with the lowest used force of the experiment, and the ski base was not newly glided. The hand tool RC linear 1 mm with applied force 372.8 N gave the largest change in roughness (+0.294 µm). The test ski in this case was newly glided when the manual structure was added, and it was the second largest force used in the experiment. The trend implies increased roughness with higher applied forces and that greater roughness is expected after manual structure imprint on newly glided skis than on not newly glided skis. The average changes given by the respectable hand tools are pointed out in Table B.2.

Table B.2. Results measured in change of R_a when using the imprint hand tools

Imprint hand tool	Average change in R_a after use	Average used force	Effectiveness change per N
SV1	+8 %	265.9 N	0.029 % / N
SV2	+1 %	302.1 N	0.004 % / N
RC 0 / -10ºC	+5 %	285.5 N	0.019 % / N
RC linear 1 mm	+12 %	372.8 N	0.033 % / N

The change in roughness when melting in topping powder at 165ºC was measured, on average, to be -0.029 µm. Some of the test results showed illogically high positive changes. Once these results were excluded, the average was -0.133 µm. The average R_a when melting in glide wax at 120ºC was measured to be -0.082 µm. The average when using the incubator at 57ºC for four hours was -0.041 µm. On the skis that went 38 days without treatment or protective wax in the temperature range -10ºC to +20ºC, the R_a average change was -0.378 µm. However, once again one outlier needed to be excluded, and without it the average was -0.265 µm.

After 3 and 4 km skiing, the change in roughness on average was -0.057 µm, and -0.001 µm, respectively. Once the clearly erroneous measurements were excluded for the 4 km analysis, the average was -0.034 µm.
The trend implies a greater change from preparation with high temperatures than with low temperatures. Roughness for added manual structure will decrease with time and physical impact. The average changes after the respective reset-treatments are shown in Table B.3.

Table B.3. Reset methods and their effect on the manual structure.

Resetting method	Average reset of the manual structure after one treatment	Effectiveness change per time (1 minute)
Melting in topping powder	56 %	11.17 % / min.
Melting in glide wax	32 %	10.77 % / min.
Glide wax and incubator	57 %	0.24 % / min.
Time (38 days)	179 %	0.003 % / min.
3 km skiing	10 %	1.13 % / min.
4 km skiing	28 %	2.30 % / min.

B.4 Discussion

In order to compare the tools and their ability to provide a good imprint, the percentage change in roughness of the structure per force unit (1 N) was calculated (see Table B.2). The results indicated that the RC linear 1 mm was the tool that gave the most change per force unit (0.033 %/N), while the SV2 gave the least change per force unit (0.004 %/N). The RC linear 1 mm tool is often used during warm snow conditions, while SV2 is a tool for cold conditions. These results support the practice that more structure is needed during the warmer and softer snow conditions. It is evident that the change of roughness is greatly influenced by whether the skis have been newly glide-waxed or not. Using the RC linear 1 mm in both tests, the change was 6 % on a not newly glide-waxed ski (with 375.7 N applied force) as opposed to 12 % on a newly glide-waxed ski (with 372.8 N applied force). This is a significant difference that should be taken into account when using structure hand tools. If a ski technician wants a given embossing with a manual structure, he or she must take into account both what tool is used and whether the ski base has been newly treated or not.

By resetting methods, "time" was the method that gave the most reset of manual structure (179 % reset). The measurements before and after a period of 38 days were done in two different premises. Therefore there is a possibility that the structure has changed somewhat in the period because of ski transportation. The method that gave the least percentage of reset was 3 km skiing (10 % reset). These results only consider the final reset result without considering the time used for each treatment. When looking at efficiency, clearly the “time method” was not the most time efficient, with a rate of 0.003 % resetting per minute (see Table B.3). The most effective method was to melt in topping powder at 165 ºC (11.2 %/min), which in turn was just slightly more efficient than melting in glide wax at 120 ºC (10.8 %/min). However, the duration of these treatments can vary dependent on the ski technician and for each individual, it can vary from day to day. Therefore the times used here to calculate efficiency were estimates (5 and 3 minutes for topping powder and glide wax, respectively). The length of time for 3 km and 4 km of skiing was rounded to 9 and 12 minutes, respectively.

These results indicate that the common practice of melting glide wax at 120 ºC is a good and efficient method. Because high temperatures on the ski base can destroy it and form surfaces similar to cellulites, it is recommended that a glide wax treatment at 120 ºC be used instead of topping powder treatment at 165 ºC. In terms of cost, the glide wax treatment is much more reasonable than the topping powder treatment. The effectiveness of resetting in the incubator was 0.24 % / min in the experiment, where the duration of the treatment was considered to be four hours in the incubator plus 3 minutes added for melting in glide wax. Since the ski technician is not concerned with the reset as long as the ski is in the incubator, one can also consider the duration of this method to be equal to the time just spent on melting in glide wax. Resetting in the incubator tests was measured as 57 %. Resetting when only melting in glide wax was measured as 32 %. Therefore, if the ski technician has until the next day to clear the ski base, it would be most effective to use the incubator method.

In the introduction it was emphasized how important it is that the skis are reset before the next race. But in the experiments, only the reset method "time" (38 days) gave more 100 % reset of the change in roughness caused by the structure hand tools. Since the method of "time" is too inefficient, we need to look at other methods. Of those, the incubator and glide wax showed a small advantage over the topping powder. However, it remains an open question as to how close to the starting point the roughness in the ski base structure has to be, before, in practical terms, it can be considered fully reset. A better answer could be provided through a more thorough test protocol that shows the error margins of the measurements, along with a practical field test that gives the glide difference.

The reset methods can be divided into groups dependent on their main focus; heat, time and physical impact. The heat methods (topping powders, glide wax and the incubator) were shown to have the greatest impact. Physical force was shown to have the next largest effect, ahead of time.

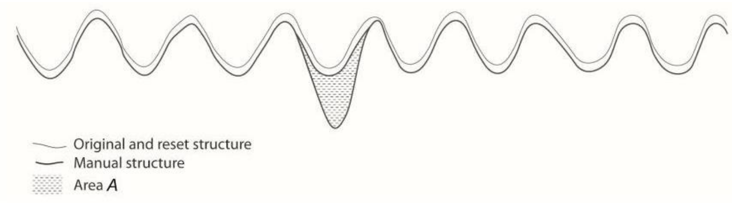

Figure B.1: Sketch of the resetting process.

In the experiments, roughness was measured in *Ra* over a given area (50 to 70 mm2). A *Ra* - measurement is currently the most common measurement value for roughness in ski bases, but it still does not give the full picture of the roughness. Some structures may have different forms and still provide the same *Ra* value. When using the manual structure, it will change the structure in such way that it almost always changes the *Ra* value, as demonstrated by the results of our experiments. The resetting could have alternatively been evaluated by comparing the topography lines at the same place across the manual structure. The area *A* in Figure B.1, between the topography lines at the grooves, should increase from zero to a positive value after adding manual structure, and then return to zero when reset.

B.5 Conclusion

The major finding in the present study was that there is a large difference in change in roughness between the various resetting methods.

- Temperature is the most important factor for resetting.
- The best method for resetting the ski base in the experiments performed was the method "time" (38 days without treatment) which gave more than 100 % reset. The second best method was the use of an incubator.
- The most effective method of resetting in the experiments was to melt in topping powders, with 11.17 % reset per minute.

In the experiments, the structure hand tools gave, on average, an increased roughness in the ski base equal to 6 % compared to the permanent stone ground structure.
If the risk of destroying the ski base is taken into account, melting in glide wax and using an incubator will be the best and most effective method to clear the manual structure. One glide wax treatment is not enough to provide a complete reset. The percentage of reset that is necessary for the ski base to be cleared in practice may still be an open question, but it can currently be determined that multiple treatments improve the resetting.

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C Paper 3

Variation of cross-country ski characteristics

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C.1 Introduction

In cross-country skiing the technical equipment of an athlete constitutes a substantial part of the end performance. A major effect of ski span characteristics on gliding results was reported as far back as the 1980s (Ekström, 1980). Each season, world class athletes spend a large amount of time with their ski technicians to find the best possible skis suited for their individual technique, competition form and track characteristics. Equipment regulations from the International Ski Federation (FIS) and the International Biathlon Union (IBU) clearly define the demands and restrictions for racing skis. There are no limits for the type of construction, as well as no restrictions with regard to the rigidity in all grades of flex as long as the weight of a pair exceeds 750 grams without bindings (FIS, 2012, IBU 2010a).

Cross-country courses are described as a combination of uphill climbs of various gradients, undulating flat terrain and technical downhills (FIS, 2008a, b). The competition rules from the IBU are less descriptive, although their specification of the ratio between total climb to competition distance of 2.7 to 4.5 % is in accordance with FIS rules (IBU, 2010). A major difference between Biathlon (BI), Nordic Combined (NC) and Cross-Country (CC) is both competition distances and course lengths. Almost all courses in World Cup (WC) events consist of several laps around a stadium with respect to TV productions and spectators. NC and BI events are usually arranged on 2.0 – 4.0 km laps, while courses from CC races can be up to 16.7 km in individual start competitions (Table C.1). Exceptions to the FIS WC rules are some stages from the Tour de Ski (2010). The longest course was 36.1 km on Stage 6, while Stage 8 was the steepest with a maximum climb of 407 m, which clearly exceeds the norms of courses.

Table C.1 Minimum and maximum competition and course lengths according to the FIS and IBU rules (FIS, 2008a b; IBU, 2010)

Sports	Min. Competition length (km)	Max. Competition length (km)	Min. Course (lap) length (km)	Max. Course (lap) length (km)
Biathlon	7.5	20.0	2.5	4.0
Cross-country - Sprint	1.0	1.8	0.5	1.8
Cross-country - Distance	3.8	50.0	2.5	16.7
Nordic Combined	5.0	10.0	2.0	2.5

A further difference between CC, NC and BI is the competition distances performed during a World Cup season. The range in NC races is limited to either 5 or 10 km and from 7.5 to 20 km in BI. In CC skiing, sprint races are the shortest at approximately 1.2 km, with the longest competitions in the FIS WC program up to 50 km. Differences in course length lead to variations in racing speed. The range of the winning speed reaches from 6.34 ms^{-1} (30km free; La Clusaz, FRA; mass start; 18th Dec. 2010) to 9.11 ms^{-1} (1.64 km free Sprint; Drammen, NOR; prologue; 20th Feb. 2011) for the 2010/2011 season. Differences in lap length may have an effect on the general course profile, in addition to the snow and track conditions.

The primary interest of this study is to identify whether the male Norwegian national teams select skating skis with similar characteristics.

C.2 Methods

Cross-country skating skis from the male Norwegian national teams in CC (n = 81), BI (n = 106) and NC (n = 53) from four different ski brands (C = 38, A = 187, B = 161 and D = 34) were tested under lab conditions (Figure C.3). The camber characteristics were measured with the SkiSelector™ (Vendolocus Development AB, Bromma, Sweden) measurement device. Out of the span curve data, parameters such as stiffness, camber height at the balance point (*HBP*), the nominal contact length and the ski tip and tail opening characteristics were calculated. The SkiSelector™ device consists of a rigid aluminium frame with a steel plate on top where a ski is placed. The span curve is obtained by use of a height measuring sensor that travels along the ski and measures the distance between the ski base and the steel plate. The sampling rate of the height measuring sensor is 200 Hz, which results in a longitudinal resolution of about 1 mm per measurement. Camber height values below 0.1 mm were defined as contact, and each ski was loaded with the half and full body weight (*BW*) of the skier. An additional load of 40 N was added to BI athletes to compensate for the weight of their weapon. According to the usage of the skis, three categories were defined: cold, medium and warm skis. The change of camber height (in mm) when loaded from 0.5 to 1 times the *BW* was defined as dynamic response. The stiffness, k (N/mm), was defined as half the *BW* divided by dynamic response.

For the ski tip and tail opening characteristics, two points in front of and behind the balance point were chosen. The distance is equal to, ± 41.6 % of the nominal ski lengths which results in 780 – 810 mm according to the actual ski length.

For the statistical analysis of the results, the SPSS Statistics (SPSS for Windows, Rel. 17.0.0. 2008. Chicago: SPSS Inc.) programme was used. The averages or differences of means from parameters of interest were compared from all three temperature categories and brands. The two-sided level of significance, p, was then calculated, the level of significance was set to $p \leq 0.05$ and highly significant was defined as $p \leq 0.01$.

C.3 RESULTS

C.3.1 Stiffness

The NC skiers were the lightest group with an average of 70.0 kg, though they generally used the stiffest skis (k = 251 ± 52 N/mm). CC skiers (77.2 kg) had slightly softer skis (245 ± 70 N/mm) and BI skiers (75.7 + 4 kg) had the softest ones (192 ± 52 N/mm). The difference was highly significant in the cold category and significant in the warm (Figure C.1). There were no significant differences between CC and NC skis in either category, and no significant differences were found within the temperature categories from any team.

C.3.2 Camber height and dynamic response

BI skis demonstrated the highest camber height when loaded with half bodyweight (*HBW*) and the lowest camber height when loaded with full bodyweight (*FBW*), which resulted in the highest dynamic response. Warm BI skis reached 3.22 mm at *HBP* and a change of - 2.35 mm when loaded from *HBW* to *FBW* (Figure C.2). Skis from the NC team had the smallest dynamic response in all the categories, with an average change of -1.45 mm. There was a highly significant difference of the mean dynamic response between the BI and the CC and NC ski in the cold and warm category. A significant difference was also found between the cold CC and NC and the universal BI and CC ski.

C.3.3 Contact length

There was a significant difference in the total nominal contact length between skis from NC and the two other teams. NC skis had an average nominal contact of 50.8 % of the total ski length, whereas CC and BI had 47.9 % and 45.4 %, respectively.

C.3.4 Opening characteristics

All three teams chose skis with a bigger opening gap on both the ski tip and tail in the warm category. Cold skis showed the flattest characteristics for all teams and categories. BI skis, which are primarily skis from brand B, revealed significantly higher opening gaps than all other skis from both CC and NC except for the CC skis from the warm category (Figure C.4). There was no clear trend for skis in the medium temperature category.

C.3.5 Analyses made in respect to the ski brands

Ski brands were not equally represented within the three national teams, which had a major effect on the presented results. Brands C and D are part of the CC team, Brand A is the dominant brand in CC and NC, while brand B is mostly used by BI athletes (see Table C.2). Brand A skis were significantly stiffer than all other skis in each temperature category with the exception of warm brand D skis (see Figure C.5). On average, their stiffness was 55 % higher in comparison to the others. There was no significant difference among ski brands and the three temperature categories. The camber characteristics from the four brands also demonstrated significant differences in their dynamic response (see Figure C.6). Brand A skis showed the lowest camber height at *HBW* in all temperature categories as well as the smallest dynamic response between *HBW* and *FBW*, thereby resulting in the stiffest camber measurements. The highest dynamic response on average was measured for brand B skis with -2.27 mm. Brands A and B, which are the most used brands, had a significant difference in all assessed ski categories.

More detailed and combined results from Figure C.5 and Table C.3 can be seen in Figure C.7, which presents the stiffness for all measured ski as a function of the relative nominal contact length. A wide range of both the stiffness and contact lengths can be seen, with clear differences between the two selected ski brands in Figure C.7. A lack of correlation was observed for brand A skis, with an r^2 of 0.0039. The coefficient of determination was slightly higher for all brand B skis with 0.2051, but still not strong.

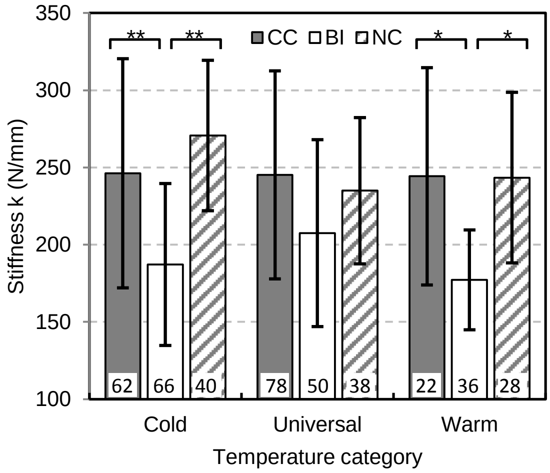

Figure C.1: Mean camber stiffness for all measured skis from CC, BI and NC split into three temperature categories. Significantly different between conditions at $*P \leq 0.05$ and $**P \leq 0.01$.

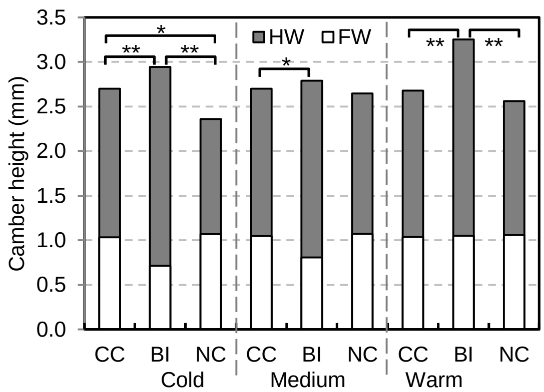

Figure C.2: Camber height at the balance point, loaded with *HBW* and *FBW* of the skiers. Significantly different between conditions at $*P \leq 0.05$ and $**P \leq 0.01$.

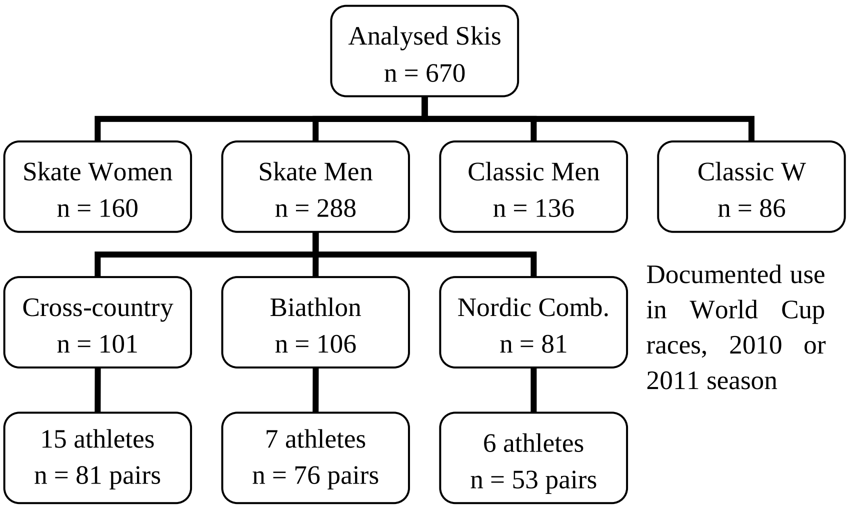

Figure C.3: In total, 670 pairs from the Norwegian CC, BI and NC teams were analysed. Only skating skis from the men teams were considered in this study. Several analysed skis were excluded (*n* = 50) due to no reported use during the previous two WC seasons.

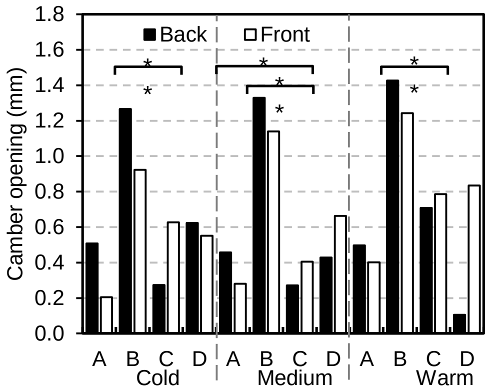

Figure C.4: Camber opening height measured with *FBW* at ± 41.6 % of the ski length in front (white) of and behind (black) the *BP*. Significantly different between conditions at $*P \leq 0.05$ and $**P \leq 0.01$.

Table C.2 - Number of analysed pairs from the four ski brands from each team

Ski brand	A	B	C	D
CC	40	5	19	17
BI	8	68		
NC	46	7		

Table C.3 Net contact length for the four ski brands and three temperature categories

Ski brand	A	B	C	D
Cold	49.2 %	42.0 %*	49.8 %	42.4 %

Medium	46.8 %	41.0 %*	46.8 %	46.8 %
Warm	47.0 %	38.3 %*	46.6 %	44.6 %

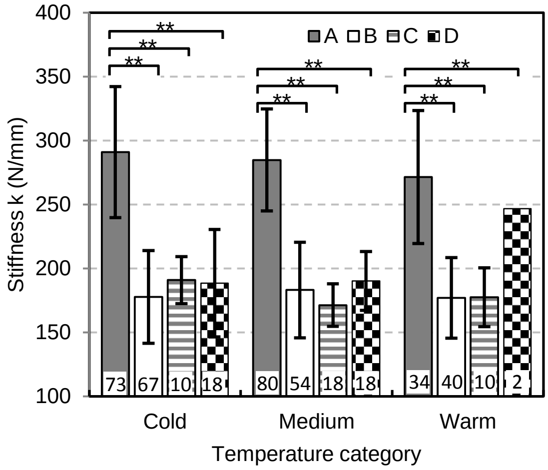

Figure C.5: Ski stiffness as a function of ski brands used by the Norwegian national teams divided into three temperature categories. Significantly different between conditions at **$P \leq 0.01$.

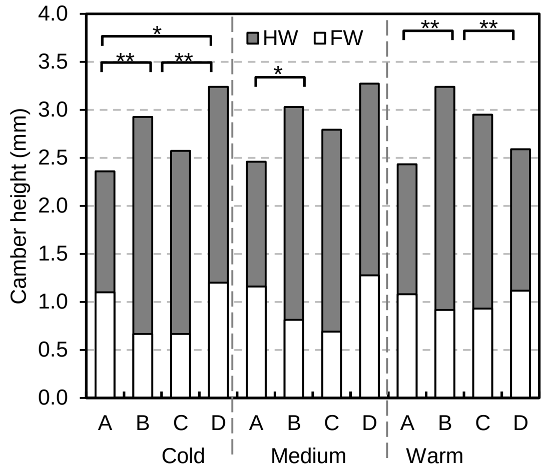

Figure C.6: Camber height measured at balance point loaded with half and full weight for all four ski brands and temperature categories. Significantly different between conditions at *P ≤ 0.05 and **P ≤ 0.01.

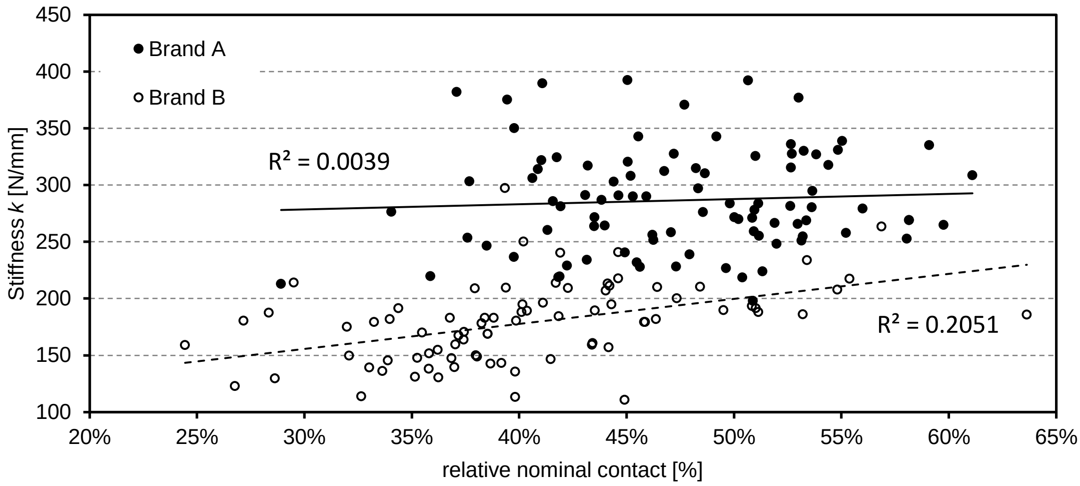

Figure C.7: Ski camber stiffness as a function of the relative nominal contact length for two selected ski brands. All measured skis are plotted. Linear regression lines are drawn in the figure.

C.4 Discussion

There are differences in cross-country ski characteristics between the Norwegian CC, BI and NC teams. The *BW* alone is not decisive enough to explain the differences between the teams in regard to ski stiffness. The ski characteristics of the teams are mostly affected by the brand's specific ski characteristics. Skis from four different brands were analysed in this study, while brands C and D are only used by the CC team. Significant differences in stiffness, camber height, ski opening height and nominal contact length were found. The influence of competition style, length or course characteristics could not be considered in this study. Moreover, there was not distinction between characteristics for certain disciplines such as sprint or long distance skiing. The skis were divided into the categories of Cold, Medium and Warm according to the suited temperature and track conditions of the skis, although this does not consider the wide variety of possible snow and track conditions.

It has been shown in previous studies that the friction only depends on the load at low temperatures (Buhl et al., 2001). Below -10ºC, the coefficient of friction is significantly higher for lower loads. A higher contact pressure leads to more heat being produced by friction, thus implying that a heavy skier has an advantage. A smaller contact area would enhance these findings, as skis investigated in this study demonstrate the opposite effect. On average, cold skis from all brands have a 7.5 % longer nominal contact than Warm skis. In a more recent study, it was shown that even at higher temperatures, there was a beneficial effect for heavier skiers. The friction coefficient decreases with an increasing load, particularly at higher temperatures (Bäurle, 2006). In real skiing, multiple factors affect the total frictional force. The variation in the relative nominal contact might possibly be explained by the great track and snow condition differences in real skiing. In addition to theoretical optimum contact characteristics, skis also have to fit to the given ski track. Skis must be stable on hard and icy tracks, as well as under soft track conditions.

A ski has to fulfil many requirements. For example, gliding experiments are often performed either under lab conditions on tribometers or on straight gliding tests in the field. In pure gliding tests, others important factors cannot be considered. In real cross-country skiing, a skier has to handle many different situations, such as steep uphills and technical downhills, on various snow and track conditions. The edging during the push-off phase will lead to torsional stresses in the ski that were not investigated in this study. In real skiing, the feeling and response from the equipment is essential. Top speed is just one of the key requirements in a selection process, with other essential characteristics being acceleration and ski stability. Athletes often talk about a "feeling", which is hard to measure or quantify.

There is a need for more studies to investigate whether there are differences within ski characteristics between long distance and sprint athletes. Force measurements in the binding and contact pressure distribution measurements between the ski and snow surface during competitive skiing could yield interesting insights to better understand the requirements of skiing equipment.

Acknowledgements

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D Paper 4

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Variation of Nordic Classic Ski Characteristics from Norwegian national team athletes

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Abstract

In Cross-country skiing the technical equipment of an athlete constitutes a substantial part of the total performance. Thus, the focus of this study was (1) to determine if different Norwegian national athletes select Classic skis with similar characteristics and (2) to describe the key parameters for the two ski categories (*warm* and *cold*). Classic Cross-country skis (205 pairs) from the Norwegian men's and women's national ski teams were tested under lab conditions. Clear differences between various factors (camber height at the balance point, stiffness, length of contact zone and opening characteristics) were found. Lower camber height for *cold* skis and higher ones for *warm* skis can be explained by the wax routines and their necessities. The nominal contact zones for both men's and women's skis from the *warm* category are shorter than corresponding contact zones from skis of the *cold* category.

D.1 Introduction

In Cross-country skiing the technical equipment of an athlete constitutes a substantial part of the total performance. A major effect of the ski span characteristics on the gliding results was already reported by Ekström in the early 1980's [1]. In the Classic technique not only the gliding performance is important. Sufficient grip during the kick phase is essential to achieve good results. Each year world class athletes spend a large amount of time together with their ski technicians to find the best possible skis. Therefore the ski span characteristics of both the glide and kick phase are of interest. The knowledge about ski span characteristics, bending stiffness and pressure distribution, has been of great interest in previous years. A detailed procedure to measure the span curve and bending stiffness were given by Bäckström et al. [2]. In an earlier study skating skis were analysed [3].

The primary interest of this study was (1) to determine if different Norwegian national athletes select Classic skis with similar characteristics and (2) to describe the key parameters for each ski category.

D.2 Methods

Classic Cross-country skis (205 pairs) from the Norwegian men's and women's national ski teams were tested under lab conditions. The study considered skis from seasons 2009 – 2011 from four different brands (see Table D.1).

Camber characteristics were measured with a SkiSelectorTM (Vendolocus Development AB, Bromma, Sweden) measurement device. The SkiSelector^{TM} device consisted of a rigid aluminium frame with a steel plate on top where a ski was placed. The span curve was obtained by use of a height measuring sensor that travelled along the ski and measured the spacing between the ski base and the steel plate. The sampling rate of the height measuring sensor was 200 Hz, which resulted in a longitudinal resolution of about 1 mm. The data was smoothed and interpolated by a LOESS filter in MS Excel. Out of the span curve data, parameters like stiffness, camber height at the balance point (HBP), and the net contact length were calculated. According to the usage of the skis, two categories were defined: *cold* and *warm*. The transition between the two categories was blurred. Skis for the *cold* category were in general chosen for new or partly transformed snow with low snow humidity and snow temperatures below -3 °C. *Warm* skis were defined as skis for soft tracks with wet snow conditions and transformed snow grains.

Camber height values below 0.05 mm were defined as contact, and each ski was loaded with half and full body weight (HBW and FBW) of the skier. The change of camber height at the balance point (CHBP) when loaded from 0.5 to 1 times the BW was defined as camber response (in mm). The stiffness, k (N/mm), was defined as the load which was necessary to press the ski down to a spacing of 0.2 mm. The load for the stiffness measurement was applied 80 mm behind the balance point and the camber height was measured at the same position. For the ski tip and tail opening characteristics, two points, one in front of and one behind the balance point at a camber height of 0.05 and 0.3 mm were chosen to represent the ski tip and tail opening characteristics, respectively. The length of the skis varied from 190 to 210 cm, depending on the height and weight of the skier. The results (distance from BP to the position with 0.3 mm camber height) are presented as fractions of the total ski length.

For the statistical analysis of the results, the SPSS Statistics programme (SPSS for Windows, Rel. 19.0.0. 2010. Chicago: SPSS Inc.) was used. The averages or differences of means from parameters of interest were compared from both temperature categories and brands. The standard deviation is denoted in brackets if not stated differently. The two-sided level of significance, *P*, was then calculated. The level of significance was set to $P \leq 0.05$ and highly significant was defined as $P \leq 0.01$.

D.3 Results

D.3.1 Men and women

The fourteen tested male skiers had an average weight of 77.1 kg (± 4.2 kg) which was 18.5 kg heavier than the average of the nine female skiers. When considering the stiffness, both men and women chose very similar skis for cold conditions. It took 66 % and 67 % of the BW for men and women, respectively, to press the skis down to a spacing of 0.2 mm (Figure D.1b). A bigger difference could be seen for the *warm* skis, where the women used stiffer skis that required 77 % of their BW on average to press the skis down to a spacing of 0.2 mm, while the men used on average 5 % less. The women's skis also showed a greater variation in stiffness (± 21 %).

Table D.1. Number of included Classic ski pairs in this study from the Norwegian ski team.

Gender	Athletes	*Cold*	*Warm*	Brand A	Brand B	Brand C	Brand D	Total
Female	9	51	42		48	45		93
Male	14	67	45	25	51	9	27	112
Total	23	118	87	25	105	56	30	205

D.3.2 Camber height

The camber height measured at the balance point showed similar results for the two groups. There was no significant difference of the CHBP between men and women in either temperature category. Men's *warm* skis showed the highest camber height when loaded with either HBW or FBW with 1.63 mm and 0.56 mm, respectively (Figure D.1a). They also had the highest camber response with 1.07 mm, just slightly higher (0.01 mm) than the women's *warm* skis. A significant difference could be seen between the mean CHBP for men's *cold* and *warm* skis. Women's *cold* and *warm* skis got compressed about 4 % more, and they also had lower camber heights when loaded with FBW. A slight difference could be seen at the height and position of the peak camber height (Figure D.1c). Women's skis had their peak camber point 9.2 and 6.4 mm further in front of the balance point even if the women had shorter skis on average.

D.3.3 Camber length

Men's skis, with an average length of 206 cm, are 8 cm longer than the average women's skis, although their camber lengths are very similar. The maximum difference was 2.1 % for *cold* skis. Both men's and women's *cold* skis had a significantly shorter camber length with 69.7 cm and 70.0 cm, respectively. *Warm* skis had between 5.2 % (74.0 cm; women) and 8.1 % (74.4 cm; men) longer camber length.

D.3.4 Nominal contact area

The nominal contact area (herein shortened to *contact area*) between the skis and the flat rigid beam of the measurement device showed variations. The *contact area* increased in all sub groups when the load changed from HBW to FBW. It was interesting to see that the contact area for the men's skis increased less than for the women's skis. The *contact area* at the back part of the ski increased by 35.9 % and 39.4 % for men's *cold* and *warm* skis, respectively, whereas, it increased by 54.7 % and 63.8 % for the women's skis, respectively. The front contact area also revealed a positive but smaller change with 16.5 % (men, *cold*) to 22.8 % (men, *warm*).
There was a significant mean difference between the *contact area* of men's and women's *cold* skis loaded with HBW as well as at FBW loaded for the front *contact area*. Besides having absolutely shorter *contact areas*, women's skis also had relatively shorter contact zones in comparison to the mean ski length.
A continuous trend showed that *warm* skis have smaller *contact areas* for both men's and women's skis. The difference was significant for the front *contact area* at HBW and FBW with a difference of -21.5 % and -17.2 % (men). Women's *warm* ski's showed a decrease of -14.5 % and -13.8 % for the different loads.

D.3.5 Opening characteristics

The length of the skis varied from 190 to 210 cm, depending on the height and weight of the skier. The results (distance from BP to the position with 0.3 mm camber height) are presented as fractions of the total ski length (Table D.2). A clear trend was revealed for all groups. *Cold* skis for men and women always showed a longer distance to the opening, both at the front and at the back part of the ski. By increasing the load from HBW to FBW, the opening tended to move between 0.7 to 1.0 % closer towards the balance point, except for men's *warm* skis where the first contact moved 2 % further away.

Table D.2 Position of the opening (0.3 mm) of the ski tip and tail distance from the balance point relative to ski length. All results shown are the average ± standard deviation. Men = M and Women = W

Avg. ± SD (%)	M - *cold*	M - *warm*	W - *cold*	W - *warm*
HBW front	38.3 ± 3.5	33.4 ± 9.7	36.3 ± 3.8	34.4 ± 4.1
FBW front	37.6 ± 4.0	35.3 ± 3.8	35.6 ± 4.3	33.3 ± 4.3
HBW back	-38.3 ± 3.8	-33.4 ± 4.5	-36.3 ± 4.3	-34.4 ± 4.9
FBW back	-37.6 ± 4.5	-35.3 ± 4.1	-35.6 ± 4.8	-33.3 ± 5.1

D.3.6 Analyses in respect to the ski brands

Brands B and C were the only two ski brands used by the Norwegian women's team. From the men's team four brands (A – D) were included in this study. Brands B and C contributed 75 % of the analysed skis (Table D.1).

D.3.7 Camber height at balance point

The same uniform trend with higher CHBP could be seen for all *warm* ski brands (Figure D.2 a). Women and men who used Brand B selected skis with almost identical CHBP. Men had just 0.01 mm higher camber height for both categories.

Table D.3 Detailed results divided by the four ski brands. CA = Contact Area; *(% of ski length)

Ski brand	A		B				C				D	
Group	Men		Men		Women		Men		Women		Men	
Temperature category	*cold*	*warm*	*cold*	*warm*	*cold*	*warm*	*cold*	*warm*	*cold*	*warm*	*cold*	*warm*
CHBP - HBW (mm)	1.33	1.83	1.32	1.52	1.31	1.51	1.44	1.91	1.45	1.55	1.40	1.53
CHBP - FBW (mm)	0.43	0.55	0.47	0.52	0.47	0.52	0.39	0.70	0.39	0.40	0.54	0.61
Stiffness (% of BW)	64.3	76.6	65.4	72.7	67.6	74.3	66.5	68.0	66.4	80.8	68.6	66.7
Camber length-FBW (%)*	44.7	50.3	47.0	47.4	44.1	46.8	42.4	51.5	43.6	48.1	40.5	42.8
CA front- FBW (%)*	13.9	9.7	13.7	11.0	10.7	8.9	12.0	10.3	14.3	13.0	16.6	15.1
CA back- FBW (%)*	19.0	18.1	20.1	16.9	18.5	17.1	17.4	13.7	17.0	16.2	18.2	18.7

The camber response was highest for *warm* skis of all brands. It was on average 0.16 mm more for *cold* skis. No significant differences could be seen, although the *warm* skis from Brands A (men) and C (men) showed especially high values.

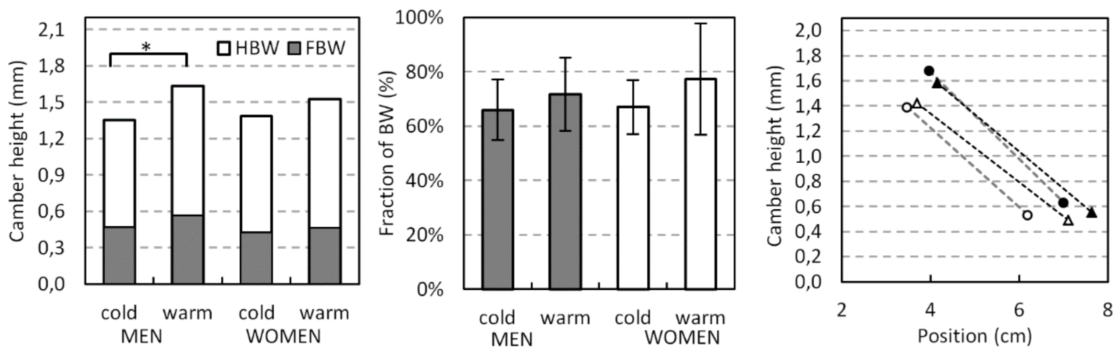
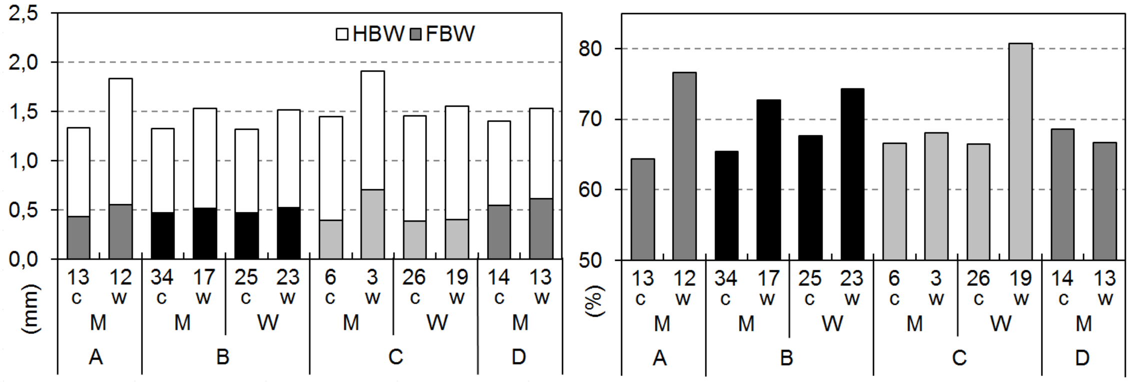


Figure D.1 (a) Average camber height, measured at balance point loaded with half and full weight for both temperature categories and gender. (b) Average relative stiffness ± standard deviation for both temperatures and gender. Fraction of bodyweight to compress the ski down to 0.2 mm camber height. (c) Average movement of the peak camber height when loaded with half and full body weight. Open symbols = *cold*; filled Open symbols = *cold*; filled symbols = *warm* temperature category; circle = men; triangle = women). Significantly different between conditions at $*P \leq 0.05$.



a) b)

Figure D.2: a) Camber Height at the balance point for all four ski brands (A – D), both gender groups (M, W) and temperature categories (*cold* and *warm*). b) Average load which is necessary to compress the ski down to 0.2 mm camber height as fraction of the skier's body weight.

D.3.8 Stiffness

Brand D reversed the stiffness characteristic between *cold* and *warm* skis. *Warm* Brand D skis tended to be 1.9 % softer than *cold* skis from the same brand (Figure D.2b). Clearly all other *warm* skis required on average more load to be compressed to 0.2 mm. There are two significant differences between *cold* and *warm* skis from Brands A (men) and C (women).

D.3.9 Contact area

The Brand D skis represented another exception regarding contact area loaded with FBW. They showed increasing contact area at the back part of the ski whereas all other brands showed decreasing contact area for the *warm* ski models. Brand D also had the longest contact zone at the front part for both the *cold* and *warm* skis with 17 and 15 % of total length. Their span length was also shortest with 40.5 % and 42.8 % of the total length. Brands A (*warm*) and C (*warm*), which had the highest CHBP, also revealed the longest span length with 50.3 % and 51.5 %, respectively. A detailed summary of the results is shown in Table D.3.

D.4 Discussion

Skis for *cold* and *warm* conditions are designed for different snow and waxing conditions. A lower mean camber height for *cold* skis reveals the expected results. Hard waxes in the kick zone are usually applied in thin layers and uniformly rubbed by cork into the base. The application of klister wax for warmer conditions requires higher camber constructions in order to avoid increased ski drag due to a thicker wax layer. Shorter contact areas and an earlier ski tip opening can also be seen on skating skis for the same track and snow conditions [3].

Ski properties are considered to be the most important factor which contributes to the total performance on Cross-country skiing by many ski technicians. Especially in Classic technique, the right balance between low kinetic friction in the glide zone and high static friction in the kick zone, are essential to reach a high level of performance. Parameters, like ski base texture and material, as well as wax products, enhance the performance another step. These parameters have not been considered in this study. Dynamic ski characteristics, as well as pressure distribution between skis and snow surface, should be considered in future studies.

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E Paper 5

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A comparison between timed and IMU captured Nordic ski glide tests

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Abstract

An inertial measurement unit (IMU) with six degrees of freedom (three orthogonal accelerometers and three orthogonal rate gyroscopes) was used to calculate the acceleration loss as a function of position down the test slope. A traditional timed glide test was performed at the same time. The results from both test methods were compared. To increase the accuracy of the sensor system, two speed sensors were installed at known positions. The gradient of the track was measured and utilized by the sensor system to correct measurement errors. A mathematical model, developed by Apertus AS (Asker, Norway) was used to estimate the snow friction coefficient based on the acceleration loss. The results from the IMU sensor provided more information, including peak acceleration, maximum speed, time required to reach maximum speed, and speed loss, which can easily be seen. The use of IMU sensors in gliding tests may prove useful to differ between skis ($\Delta\mu \sim 0.01$). We conclude that in order to detect the minute differences distinguishing the best skis ($\Delta\mu \sim 0.001$), sensors with an even higher degree of sensitivity than those tested in this experiment should be used.

E.1 Introduction

The testing of ski equipment is an essential step prior to major Cross-country ski events. Ski technicians spend a great amount of time to prepare, perform and validate various ski tests. Due to the circumstances and time available before competitions, the ski technicians choose mainly between different types of testing such as (A) parallel, (B) timed gliding tests, (C) glide-out tests and (D) feeling tests. Each test method has benefits, challenges and drawbacks. In recent years (E) advanced technology has provided new possibilities to monitor important parameters during gliding tests. Tests were performed to assess the usefulness of (E) inertial measurement unit (IMU)-based gliding tests in experiments similar to those for timed gliding tests (B). Comparisons of IMU-based tests (E) with other test methods (A, C and D) are carried out later, but are beyond the scope of this article.

Timed glide tests offer solid information which can best be used for further statistical analysis. A detailed protocol for gliding tests was presented by Karlöf et al. in 2007 [1]. In order to improve the quality of a test, each ski should complete at least six runs down a hill. A regular test series consists of about eight pairs of skis. The time needed to perform an average gliding test is about 45 minutes. During this time there is a risk that the track and weather conditions may change. Several studies, which focused on the effects of various processes, such as snow and climate parameters, showed significant changes in the run times due to changes in these parameters [2, 3].

More sophisticated technologies such as the use of a differential GPS and IMUs (which often contain accelerometers, gyroscopes and magnetometers) provide new possibilities for evaluating gliding tests. In Alpine skiing these and similar technologies were presented in biomechanical analyses and technique studies [4-6]. Accelerometers are also used for biomechanical research but to our knowledge not for gliding tests in Cross-country skiing [7, 8].

A high level of sensitivity of the IMU system is required. A reduction of the kinetic coefficient of friction, μ by 0.001 corresponds to a reduction of the run time of approximately 1 s/km [9]. In order to develop a device which can be interesting for World Cup level ski technicians such a variation of μ has to be detectable.

The purpose of this study was (1) to present an IMU-based measurement system adapted for ski gliding tests and (2) to assess the suitability of IMU-based gliding tests. The main method we used to assess the suitability was to compare timed gliding tests with IMU-based tests.

E.2 Methods

The forces which act on a skier in a gliding test were considered in order to develop a model to calculate a kinetic friction coefficient. Due to Newton's 2nd law, the forces in the direction of motion (x) are equal to the skier's mass, m, times his acceleration, a (E.1). A free body diagram which shows the forces acting on a skier are shown in Figure E.1.

$$\sum F_x = m \cdot a \tag{E.1}$$

The skier's gravitational force, F, can be divided into its two components: the normal force, F_N, perpendicular to the slope, and the propulsive force, F_D, parallel to the slope. Both components are a function of the slope, α. The two major forces which act against the skier are: the force due to air resistance, F_{air}, and the ski drag force, F_f, at the interface between the skis and the snow (E.2).

$$F_D - F_{air} - F_f = m \cdot a \tag{E.2}$$

Assuming Coulomb friction with a constant coefficient of friction, dividing by the skier's mass and supplied with the terms for F_D, F_{air} and F_f, we derive equation (E.3) where g is the acceleration due to gravity, v is the speed, ρ is the air density, C_d is the drag coefficient, A the surface reference area and μ is the coefficient of friction.

$$g \sin\alpha - \frac{1}{2m}\rho v^2 C_d A - \mu g \cos\alpha = \frac{dv}{dt} \tag{E.3}$$

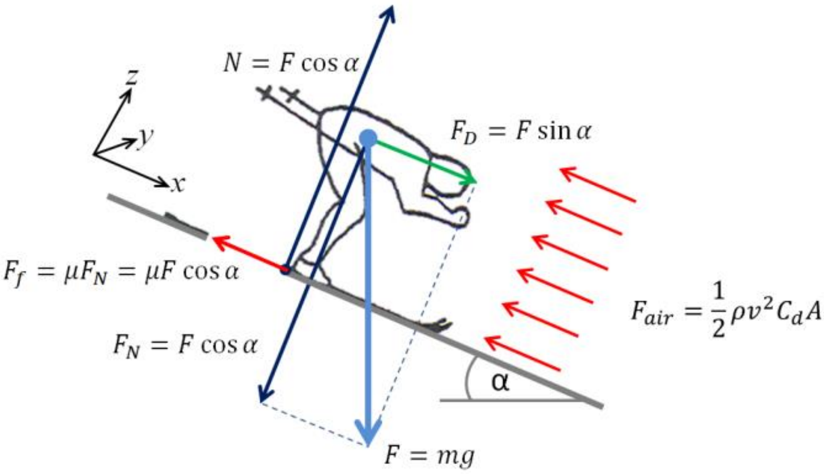

Figure E.1: Simplified forces which act on a skier in a straight downhill, modified sketch from (Spring, 1989).

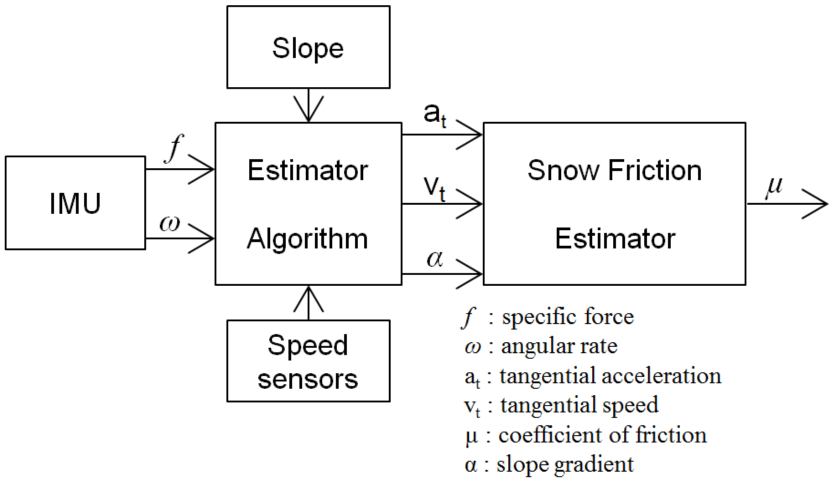

Figure E.2: Schematic sketch of the model design for the IMU system (E).

One IMU was mounted on the left ski in front of the binding. The same sensor was used on all the tested pairs. A calibration sequence (5-10 seconds at a standstill) was performed before the start of each run. Accelerometers measured specific force, f, which is the acceleration relative to free-fall. The gyrometers measured angular rate, ω. A test

procedure using 3 pairs of skis in consecutive heats was performed. Data were recorded during consecutive descents. The sensor resolution was 10 bits and the recording frequency was 100 Hz. Data were captured unfiltered and transmitted to a PC for further analyses. The tangential acceleration in the direction of motion, a_t, is the result of the air and ski friction acting against the skier and gravity due to the slope. We define acceleration loss, a_{loss}, as the sum of forces acting against the skier in the direction of movement divided by mass, like air resistance, F_{air}/m, snow friction, F_f/m, and other unknown factors.
The mathematical model (Figure E.2) developed included standard methods for strapdown inertial navigation systems to calculate the motion of the sensor [10, 11] and non-standard methods to calculate the snow friction. A better model to calculate the glide and friction was developed during the interval between the two test sessions (July and October 2011). The model was improved to reduce the effects of the cyclic variations in the acceleration loss, including the effects of air drag. The enhanced model was used to calculate the friction estimate for Test 2 and to recalculate the glide estimate from Test 1. The results were compared to each other and discussed.
Test procedures (B and E) were conducted simultaneously. Two tests using three pairs each were performed. All tests were performed in a ski tunnel (Torsby, Sweden) under stable snow and weather conditions. Test track length and slope were documented using a tape measure and inclinometer. The slope of the track in Test 1 was measured each second meter. The inclination of the test track was about -4° in the first half and flattened out towards the end (Figure E.3). There was a right turn between 48 m and 70 m in the test track (30°). During Test 1 the skier started at a defined start position, released himself by lifting the poles, and continued, in a semi-squat position, down the whole test track. The initial velocity at the start point was 0 m·s^{-1}.

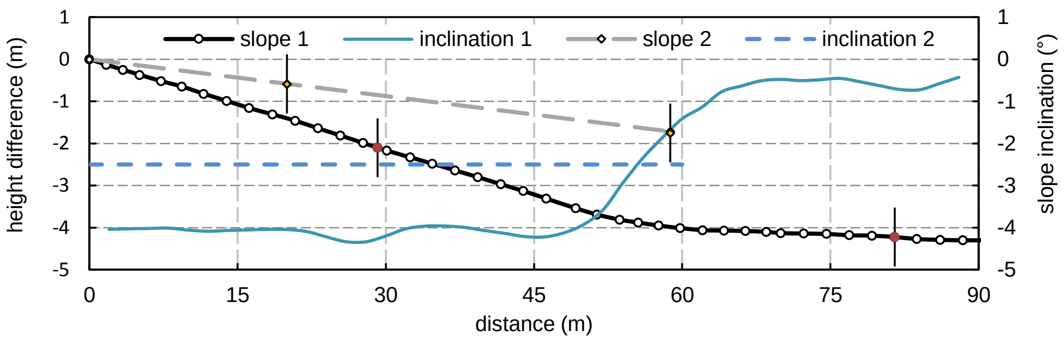

Figure E.3. Slope and inclination from test Tracks 1 and 2. The location of both photo cell units is marked with vertical black bars.

The focus in Test 2 was on the IMU captured measurement trials. The test setup was amended and the track was relocated to a straight part in the ski tunnel in order to avoid measurement errors. In Test 2 the height difference between end points was measured using surveying equipment (tripod and rod for leveling). The average inclination was -2.5° between the start and end point. In order to achieve sufficient speed the skier started each run with one double pole push.
Two units with two photocells each were installed next to the track in both tests. In Test 1 the units were placed 29.3 m and 80.6 m down the track (horizontal distance) after the

starting point, and 20.0 m and 58.8 m in Test 2, respectively. The speed at both units was calculated, as well as the time difference and average velocity between the units. All tests were performed in a classic track by an experienced skier.

E.3 Results

Test 1

During the first test a negative trend concerning the gliding could be seen (Figure E.4). It was not possible to find significant differences in the running times between the various heats or skis (Figure E.5). A linear regression line was added to Figure E.4 to visualize

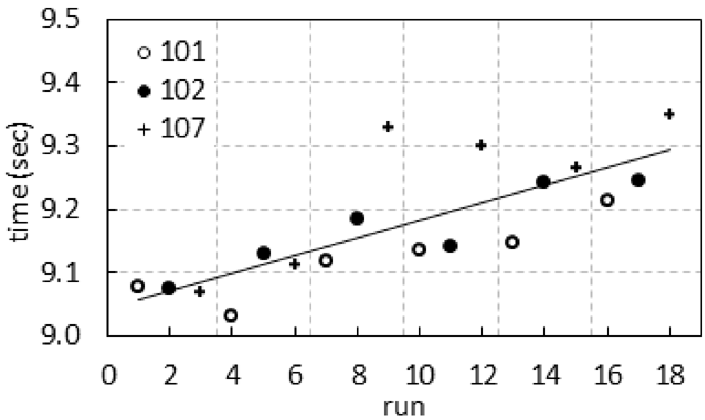

Figure E.4: Test 1: Sliding times for each run (a) with a linear regression line in black.

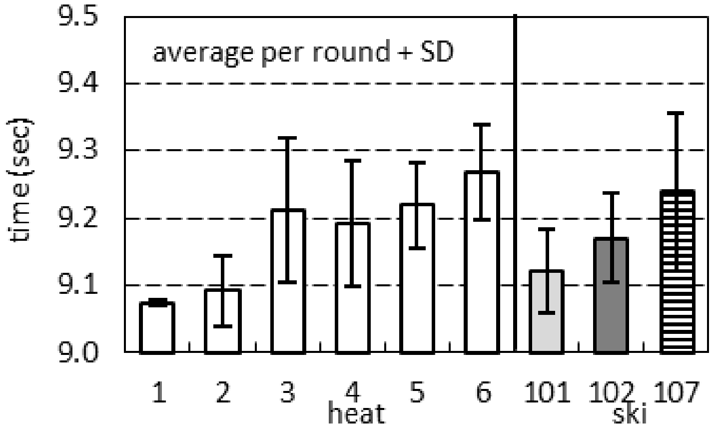

Figure E.5: Average gilding times ± standard deviation (SD) for each heat and ski to the right

the increasing trend of the gliding times. Ski pair 101 showed the fastest average gliding time with 9.121 s, which was 0.05 s faster than ski pair 102 (p = 0.621). Ski pair 107 was the slowest with 9.238 s (p = 0.09) on average. By looking at the results from heat three the continuous acceleration loss and speed can be observed (Figure E.6). The average acceleration loss for pair 107 was lowest from the start to the first photo cell. Also, the maximum speed of 6.26 $m \cdot s^{-1}$ was 0.06 $m \cdot s^{-1}$ slower than pair 102, and 0.3 $m \cdot s^{-1}$ slower than pair 101. It could be seen that the speed started decreasing after about 62 m of the track when the inclination flattened (-1.13°). Pairs 101 and 102 had a speed loss of -1.13 m·s^{-1}and -1.14 m·s^{-1}, respectively, whereas pair 107 lost -1.5 m·s^{-1} which resulted in a time loss of + 0.18 s and + 0.12 s compared to the two other skis. Both test procedures resulted in the same ranking in Test 1.

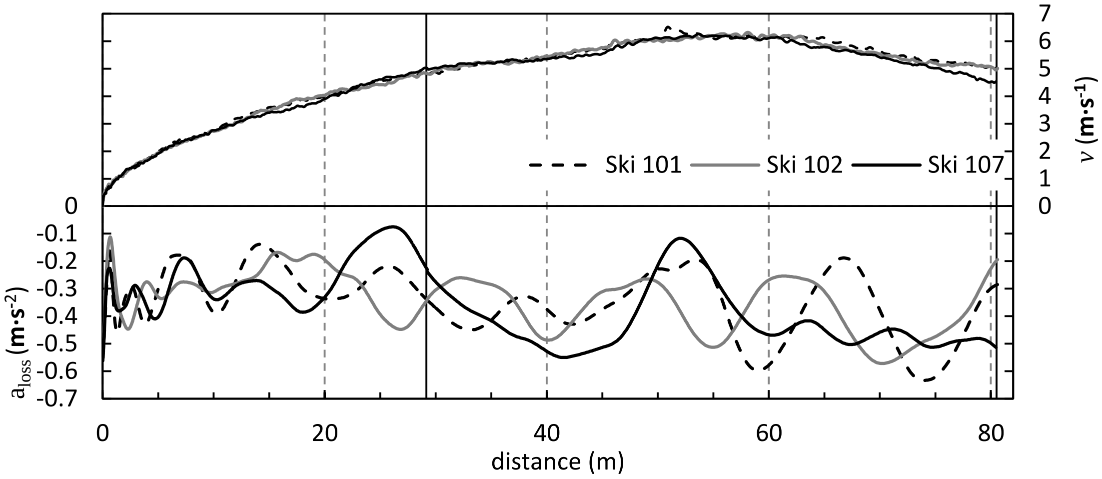

Figure E.6: Results from the inertial measurement unit (Test 1, heat 3). The two photocell units are marked with vertical black lines at 29.51 and 80.15 m into the test track.

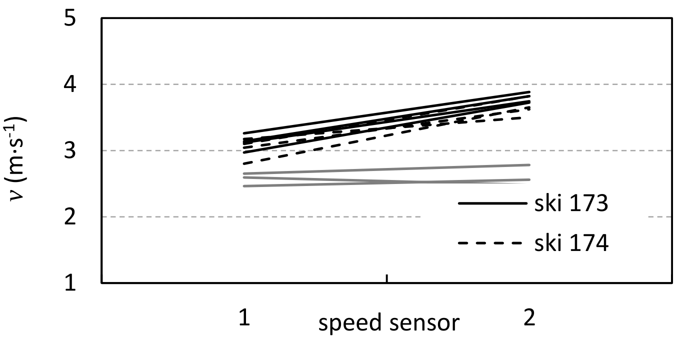

Figure E.7: Skier's speed at photocell one and two for each run in Test 2.

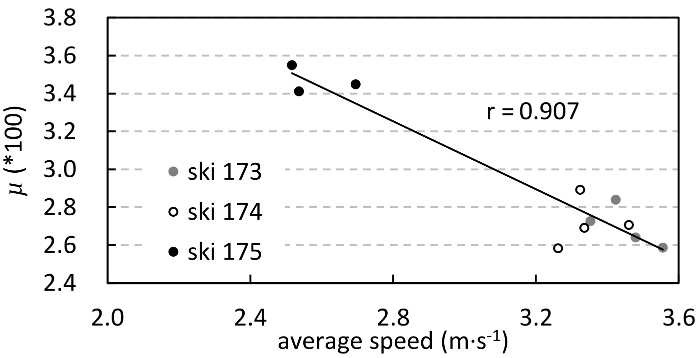

Figure E.8: Average speed versus calculated coefficient of friction, μ for each heat and ski with a linear regression line in black to the right.

Test 2

The initial speed after 20 m and the exit speed at the end of the test track after 58.8 m can be seen in Figure E.7. Ski pair 173 increased its speed on average from 3.12 by 0.67 to 3.79 $m \cdot s^{-1}$. A similar result can be seen for pair 174 (from 3.03 $m \cdot s^{-1}$ to 3.64 $m \cdot s^{-1}$), whereas pair 175 increased its speed by only 0.04 to 2.6 $m \cdot s^{-1}$ during the gliding test. The split times from the timed gliding tests (B) were used to compute the average velocity between the speed sensors. The average velocities from the speed sensors (B) were compared to the calculated coefficient of friction, μ from the IMU sensor model (E). A strong correlation between the timed gliding test (B) and the IMU based sensor system (E) r = 0.907 could be seen (Figure E.8). The calculated average μ was identical for ski pair 173 and 174 with μ = 0.027. Pair 175 showed an average coefficient of friction of 0.034.

E.4 Conclusion and Outlook

The use of IMU sensors in gliding tests may find the best skis. By using a low-cost IMU and correction methods we have been able to produce reasonable estimates close to the precision requirement. Both measurement systems (B and E) can distinguish between good and bad skies ($\Delta\mu \sim 0.01$) as seen in Test 2 but the current IMU system cannot distinguish between skis with similar glide performance ($\Delta\mu \sim 0.001$). Both test methods have limitations. We experienced challenges like measurement noise, drift, accuracy, precision and developing a suitable mathematical method for the IMU system. Although additional information compared to traditional timed gliding tests can be recorded. Timed gliding tests (B) are susceptible to external influences such as wind, weather and track changes. The risk increases with prolonged test duration. Timed tests (B) can only be used to verify the rough precision ($\Delta\mu \sim 0.01$) of the IMU-based system (E). The current experiment cannot clearly conclude on the precision and reliability of the two test methods.

Large, cyclic variations in the acceleration loss of up to 0.44 $m \cdot s^{-2}$ were observed. Barely noticeable movements of the skier relative to the skis are one cause of these fluctuations. Other important sources like ski edging, wind gusts, instable balance and further unknown factors may influence the acceleration loss. The challenge is to isolate the effects of the controllable factors and to eliminate the effects of irrelevant influences in an improved model.

We recommend that more sensitive sensors should be used in order to detect the small differences distinguishing good skis. Further work is carried out to improve the estimation model based on more precise sensors. A better model seems to be essential to distinguish between the factors affecting acceleration loss.

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F Paper 6

A tribological study of UHMWPE ski base treated with nano ski wax and its effects and benefits on performance

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Abstract

In this work, the characteristics of two coatings and their contribution to a reduced coefficient of friction were studied. In addition, the structural changes of the ski base material due to the waxing process and subsequent skiing were also studied. The Fluorine content, both in the base material and the wax, was given special attention. Field and laboratory experiments on the ski base materials, both with and without waxes, were conducted, whereas the material characterization has been evaluated by using X-Ray Photoelectron Spectroscopy (XPS), Inductively Coupled Plasma Mass Spectroscopy (ICP-MS) and contact angle measurement of water droplets on the ski base materials. The friction properties of the ski running surfaces have been tested in outdoor gliding tests in which the ski running surfaces have been compared with each other, as well as to a reference ski. A tribometer was used in the lab tests to measure the coefficient of friction (COF), and it was found that the Fluorine content on the top surface is not directly comparable with the surface energy and the contact angle. On average, skiing performance improved significantly by 4 % directly after the application of high fluorinated waxes, while the COF of the used ski base samples increased significantly by 55.4 % and 96.3 % after 34.1 km of skiing in free technique.

F.1 Introduction

In Nordic Skiing, good gliding properties are essential for success. Among many parameters, the tribological system is affected by the material properties of the ski running surface and various wax combinations that are applied on top of the ski sole to minimize kinetic friction. Due to its combination of outstanding tribological behaviour and great processability (Ducret et al., 2005, Buhl et al., 2001), the material of choice for ski running surfaces is ultra-high molecular weight polyethylene (UHMWPE), which is a linear semi-crystalline polymer with hydrophobic characteristics (Fischer et al., 2008, 2010). In order to further enhance the performance of UHMWPE, additives and solid lubricants such as graphite, polytetrafluorethylene (PTFE) and carbon black are often added in the production process according to Schamesberger (1995), Colbeck and Perovich (2004) and Brydson (1999). Before competitions it is common to wax the ski running surfaces, with the ski industry offering a wide range of petroleum-derived products such as hydrocarbons, alkanes and fluoroalkanes for waxing the skis stated by Rogowski et al. (2005).

Ski technicians generally make a great effort to find the best suitable wax combination for any snow and weather condition. The traditional way to wax skis includes several steps, starting from various hydrocarbon waxes to advanced treatments with high flour content waxes. Fluorine-based additives in the paraffinic wax can lead to a significant increase in the water static contact angle, thereby advancing the angle and penetrability property of a paraffinic wax (Rogowski et al. (2007). Fluorine-based products are available in both a solid and liquid state, and a commercial version (Cera F) was introduced to the market in 1990 as powder (Torgersen, 2010). Recently, more popularly developed liquid products are an advantage due to their fast and easy application, forming a thin coating on top of the ski base material.

Although the wax industry has created many good products and treatments, professional skiers often report a drop in performance over time. Kuzmin and Tinnsten (2005, 2007) for example reject the idea of ski wax for glide preparation due to an unnecessary dirt adhesion.

Therefore, the major research question of this study focused on the material changes due to the waxing process, in addition to the evaluation of the content of specific elements contained in the wax. How do liquid gliding products, which contain additives in nano size, interact with the ski base? Special attention has been paid to the Fluorine and Gallium content in both the materials and waxes, and a subsequent goal has been to compare field and lab tests and assess the representativeness of friction lab tests for outdoor field tests.

F.2 Methods

This study included both lab and experimental field tests, and to help achieve a greater understanding of the ski base and impact of waxes, two UHMWPE ski running surfaces from Isosport (Eisenstadt, AUT) with an identical content of carbon black, though with a different molecular weight and additives (PTFE), were chosen (hereafter called IS-4 and IS-5). Both materials were treated with three different products (referred as *Glider-A*, *Liq.-A* and *Liq.-B)* from two producers (referred as *A*, NOR; *B*, JPN). The liquid waxes were applied on top of the basic wax, *Glider-A*, and rubbed into the running surface according to the producers' recommendations. The same type of surface stone grinding was also used on the ski running surfaces prior the wax treatment.

F.2.1 Materials characterization

To obtain chemical information about the material composition from the surface, X-ray photoelectron spectroscopy (XPS) analyses were conducted that caused the ejection of core-level electrons. The energy of core electrons is a function of its binding energy and is characteristic of the element, with XPS indicating the chemical state and giving a measure of the relative amount of the element stated by Materials Evaluation and Engineering, Inc. (2013). Moreover, a Kratos Axis Ultra (Shimadzu Corporation of Kyoto, JPN) instrument was used in this project to perform the analyses, and the ski base samples tested were cut into small square samples (10 mm x 5 mm).

Contact angle, θ, measurements were conducted to help characterize the hydrophobic properties of the untreated and waxed running surfaces. The static wettability measurements were carried out through the use of a sessile drop technique. The angle between the horizontal and tangent line at the triple point was defined as a contact angle. All samples were tested with 10 drops each, and the results illustrate an average ± standard deviation.

For a precise determination of metallic ion concentrations in liquid solutions, the Inductively Coupled Plasma Mass Spectrometry (ICP-MS) technique was used. The liquid solutions were heated with a plasma torch at approximately 7000 °C, the metal ions were separated in a magnetic field chamber, and the different species were detected by mass spectroscopy (MS). An ICP-MS was performed in order to measure the Gallium ion concentration in the liquid waxes, and the solutions were injected into the Finnigan ELEMENT 2 high resolution ICP-MS equipment.

F.2.2 Gliding tests

Outdoor sliding tests were conducted stepwise to monitor the change in gliding performance between the two different running surfaces and one reference ski. An experienced ski technician from the Norwegian Ski Team carried out all the gliding tests, and two different test areas were used in this study (Holmenkollen in Oslo and Granåsen in Trondheim). An ethic approval was not necessary for this study. Both test tracks had similar profiles, with a slight downhill in the beginning that flattened out towards the end. The skier stood still in a crouched position, and time was measured between two photocells along the track. Furthermore, weather and snow conditions were monitored throughout the tests, thereby assuring that changes in the kinetic friction counted as the main source for time changes. The three pairs were tested six times in an afferent and declined order (ski no. 1-2-3-3-2-1), thus resulting in 18 runs for each test. In total, six gliding tests were performed: (1) unwaxed, (2) waxed with *Glider-A* and *Liq.-A* wax, (3) after 9.7 km of skating and (4) after 19.1 km of skating. Due to a change in the weather and track conditions in Oslo, the tests were stopped and continued two days later in Trondheim with (5) an initial gliding test after 20.7 km and (6) after 32.7 km of skiing (distance accumulated includes all distances after the skis were treated with wax). The reference ski was only included in the gliding tests, and the average gliding time is illustrated in the results.

The coefficient of friction (COF) of the different ski base materials sliding against snow was measured using the TE88 multi-station friction and wear test machine from Phoenix Tribology (Kingsclere, GBR), hereafter called a *tribometer*. The pin-on-plate module was used for testing square 20 mm x 20 mm ski base samples, with Bäckström et al. (2008) reporting values up to 330 N in their proportional pressure distribution measurements. A load of 150 N was chosen for the tests, which resulted in a nominal contact pressure of 375 kPa. The snow holder was made of a 78 mm x 80 mm hollow on the inside brass plate where a coolant circulated, and the chosen sliding distance was 50 mm. Fine grained snow was collected at -2 °C and stored at -18 °C, and the tests were run for 30 min. First, the tests were run for 10 minutes at a speed of 0.1 m/s, followed by 10 minutes at 0.2 m/s and 10 minutes at 0.1 m/s again. This procedure was repeated one additional time, and the results illustrated are the average of these six measurements. Finally, all samples were investigated with an Alicona *InfiniteFocus* 3D microscope (Raaba/Graz, AUT) before, between and after testing.

F.3 Results

Results from the XPS measurements (see Table F.1) present an approximate element composition for each material, based on the intensity and area of the peaks as a function of the binding energy, and the Fluorine content in the IS-4 and IS-5 materials without any wax are very similar (see Figure F.1). IS-5 contains small PTFE particles, which exhibited a higher Fluorine content. Gallium could not be detected in any of the materials with the XPS. The results for the liquid waxes from the ICP-MS showed 17.6 ng/mL of Gallium (Ga) for the *Liq.-B* product, which is a very low concentration to be detected by XPS. After melting *Glider-A* onto the running surfaces, the contact angle increased for both materials, while the COF declined. The COF and hydrophobicity of the materials showed a negative correlation of r = -0.69. The application of *Liq.-A* led to a decrease of the contact angle, although the COF tested with the TE88 device resulted in a further decrease of -8.5 % (IS-4) and -19.4 % (IS-5), which was also the lowest COF measured in this study with 0.016. The highest contact angle was measured before skiing with the *Liq.-B* applied on IS-5 at 121°. The materials with the lowest contact angle and the highest COF are the ones after use in the gliding field tests. The roughness of the tested bases was also measured, as it can affect the contact angle. However, the roughness for the tests is designed to be equal and the roughness area measured only represents a part of the area where the contact angle test has been performed. It is therefore assumed that little differences for friction will appear due to roughness since it will be very similar for all materials (Table F.2).

After skiing 34.1 km, the Fluorine content clearly decreased for both base materials, whereas IS-5 preserved the wax better by keeping 2.3 % of its original 5.3 %. Another interesting finding is the raised value of Nitrogen in all samples after 34.1 km of skiing, with values between 0.5 % to 1.9 %.

The outdoor gliding tests were performed under stable conditions within each test, albeit with slight changes between the tests, with IS-5 always performing better than IS-4. All results are relative compared to the reference ski, which was only skied during the timed gliding tests, whereas the two other pairs were skied on for a total of 34.1 km split into three laps (8.1 km, 7.8 km and 10.6 km), including each gliding test of 1,380-1,600 metres of skiing. During the first four gliding tests the two running surfaces displayed very similar results, while both responded with an improvement of 4 % due to wax. The further development was not uniform as expected, and after the last loop of 10.6 km, IS-4 and IS-5 improved on average by 3.2 % compared to the reference ski.

With the exception of IS-5 + *Liq.-B*, the tribometer measurements displayed the highest COF for unwaxed ski running surfaces and the ones that were skied on for 34.1 km. However, applying *Liq.-A* on top of the materials with *Glider-A* resulted in a small difference in performance for the two materials, though favouring IS-5. IS-5 with *Liq.-A* wax is the material with the lowest COF tested in the tribometer, which is 0.0022 lower than IS-4, with a contact angle that is 3.8° larger. The contact angle for IS-5 *Liq.-B* is the highest of all the contact angles, at 121.3°, which is followed by IS-4 *Liq.-B* at 106.8°. For the COF measured, IS-4 has the second lowest, while IS-5 has the third lowest. After the full skiing length, IS-4 with *Glider-A* and *Liq.-A* displayed a 2.9 % higher COF compared to the unwaxed material, while IS-5 was raised by 16.9 %. The rise in COF becomes even higher when comparing the newly waxed materials to the skied samples, with an increase of 55.4 % (IS-4) and 96.3 % (IS-5) measured on the newly waxed samples.

The surface topography yields no remarkable changes after the friction measurements with the setup used in this project, which corresponds to approximately 500 metres of skiing. There was neither a notable difference in the topography of the ski running surfaces that had skied for 34.1 km nor in the newly ground skis with the same roughness.

Table F.1. XPS results from the first test of each sample. The IS-5 running surface contains small PTFE particles, with one measurement focused on such a particle. All values are in approximate atomic percentage [%], based on the intensity and area of the peaks as a function of the binding energy. Roughness, R_q, [µm] measured during the TE 88 test. Time [%] for the field test compared to the reference ski. Note: Negative percentage means the skis were faster than the reference ski; contact angle, θ, [°] and the average coefficient of friction (COF).

Sample	C	O	F	N	Ga	B	Na	S	Si	*Rq*	time	θ	*COF*
IS-4 no wax	92.7	3.1	2.7	-	-	0.1	0.6	0.6	-	3.09	5.83	86.9	0.0278
IS-4 Glider-A	92.4	5.0	0.9	-	-	0.3	0.7	0.6	0.2	2.83	-	98.5	0.0201
IS-4 Liq.-A	93.9	1.7	3.8	-	-	-	0.2	0.2	-	3.00	2.05	93.6	0.0184
IS-4 Liq.-B	94.4	2.3	2.4	-	-	-	0.4	0.4	-	2.47	-	106.8	0.0165
IS-4 Liq.-A 34.1 km	83.1	10.6	0.4	1.9	-	0.2	1.4	0.8	0.7	2.44	0.02	85.3	0.0286
IS-4 Liq.-B 34.1 km	86.1	9.5	0.3	1.3	-	0.1	0.7	0.7	0.7	2.54	-	81.4	0.0275
IS-5 no wax	89.2	5.1	2.6	-	-	0.6	1.0	1.0	-	3.24	5.51	93.8	0.0272
IS-5 Glider-A	89.5	5.4	2.5	-	-	0.1	0.7	0.7	0.4	3.33	-	99.6	0.0204
IS-5 Liq.-A	82.1	7.5	5.3	-	-	1.5	1.4	1.4	0.2	2.53	1.64	97.4	0.0162
IS-5 Liq.-B	90.5	3.2	4.8	-	-	0.1	0.6	0.6	0.1	3.05	-	121.3	0.0180
IS-5 Liq.-A 34.1 km	87.8	6.7	2.3	1.6	-	0.2	0.4	0.4	0.5	3.56	-2.4	77.5	0.0318
IS-5 Liq.-A 34.1 km - PTFE	80.2	6.5	9.4	1.8	-	-	0.3	0.3	0.5	-	-	-	-
IS-5 Liq.-B	86.6	7.4	2.6	0.5	-	0.1	0.8	0.8	0.6	2.84	-	81.0	0.0194
Reference ski	-	-	-	-	-	-	-	-	-	2.95	0	-	0.0155

Table F.2. Average gliding times for all test during the field tests including percentage deviation compared to the reference ski. *) tested at Holmenkollen, Oslo.
**) tested at Granåsen, Trondheim.

	no wax*	Glider-A + Liq.-A *	loop 1*	loop 2*	test 5 **	loop 3**	Average
acc. skiing [km]	1.6	1.6	11.3	20.7	22.1	34.1	
Ref [sek]	12.767	13.279	13.113	12.926	13.230	12.956	13.045
IS-4 [sek]	13.557	13.492	13.388	13.090	13.623	12.953	13.351
IS-5 [sek]	13.512	13.519	13.332	13.081	13.374	12.655	13.246
IS-4 [%]	5.83	1.58	2.05	1.25	2.89	-0.02	2.285
IS-5 [%]	5.51	1.78	1.64	1.19	1.08	-2.38	1.517

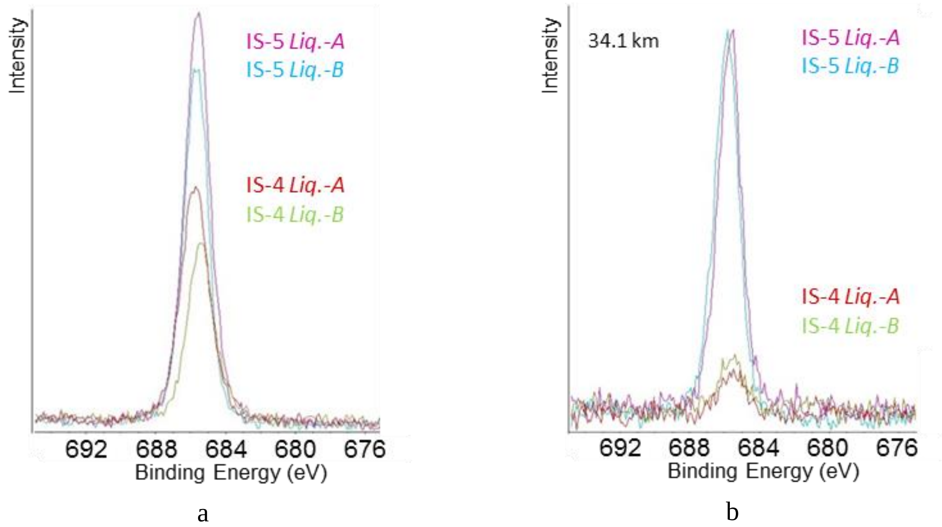

Figure F.1: (a). XPS analyses from both base materials compared with Liq.-A and Liq.-B wax before skiing and (b) after skiing 34.1 km (in the spectra F 1s).

F.4 Conclusions and Discussion

It is difficult to make any direct comparisons between the outdoor field tests and the lab tests in this project. The test material IS-5 Liq.-A 34.1 km is a large exception, insofar as being the best in the track and the worst in the lab. Nevertheless, other than that result, there are many similarities between the lab and field tests.

Fluorine contributes to a lower surface energy, which makes the material water repellent, thereby resulting in a higher contact angle. However, the Fluorine content is not proportional to the contact angle of the material tested. For both materials, Liq.-A wax contained the highest amount of Fluorine, but had a lower contact angle than Glider-A wax, which had the lowest amount of Fluorine for both materials. Compared to standard hydrocarbon, waxes like *Glider-A*, the two liquid waxes tested present high precious products, which are selection of choice of many racing skiers.

The Fluorine content and the static contact angle of the material tested are close to the results found by Stamboulides et al. (2012, 2013) using XPS and a sessile drop technique. It is also worth noting that the liquid waxes used in this work (Liq.-A and Liq.-B) might suffer some type of evaporation once in the vacuum chamber. In Sugimura et al. (1991), it is mentioned that the Gallium particles added in the wax can be in a range between 0.01 wt% to 10 wt% or even higher in order to improve performance. If the wax has a low amount of Gallium, the XPS is not sensitive enough to detect this element. In addition, the wax was spread as liquid, forming a thin layer on the base, hence making it difficult to be held on the surface after introducing the sample in the XPS vacuum chamber.
Nitrogen may be a contaminant found in the snow or due to the handling process of the skis during the field tests. To confirm the origin, a sample of liquid snow should be tested in ICP to identify the elements. IS-5 and Liq.-B contained less Nitrogen, which could

imply that the Liq.-B wax prevents the accumulation of dirt and contamination better than the Liq.-A wax.
The results from the gliding field tests showed that both of the test materials acquired significantly better gliding properties after wax treatments and further enhanced properties during skiing for a long time. Considering the literature, friction and contact angle for water droplet results obtained in the lab, this is most likely only a happy coincidence. Further gliding field tests to prove this should be performed.

Acknowledgements

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G Paper 7

A new approach for the grinding of Nordic skis

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Abstract

Stone grinding has been the state-of-the-art for Nordic ski preparation for approximately the last 2.5 decades. This paper presents a new approach to preparing ski running surfaces, and a new grinding machine has been developed. A grinding wheel made of metallic material, a stationary placed ski and fully controllable process parameters are some of the key features for this device. The processes of traditional stone grinding and the new approach with a metallic grinding wheel are presented. Two examples of both grinding methods were analysed with a 3D microscope, and amplitude and spacing parameters are presented. In a further step, a comparison between traditional stone grinding and grinding with a metallic tool was performed. A relative variability of the mean roughness of 5.1 % for the metallic ground skis was clearly lower than the 8.4 % for the stone ground ones, which emphasizes an improved control of the resulting surface texture with the presented new metallic grinding approach.

G.1 Introduction

In competitive skiing, it is essential to minimize snow friction between the ski's base and the snow surface. Nordic skiing has gone through several revolutions in the previous 100 years, and when competitive skiing became popular in Scandinavia in approximately 1850, the material used was limited to wooden skis with simple bindings. In 1965, the first skis with synthetic materials and a polypropylene base were produced by the Askjem skifabrikk [1]. The development in skiing reached new heights during the World Championships in the early 1970s, while the end of traditional wooden skis was marked by Magne Myrmo's last World Championship title in 1974 in Falun, Sweden.

Sintered thermoplastic materials became a standard in racing skiing bases, with these materials opening up for new processes and treatments. A good performance in Nordic skiing depends on a perfect glide. Among other parameters, the ski base is a very valuable part of a cross-country ski, which affects the kinetic friction, and has to meet some very special requirements. A high abrasive resistance, its natural hydrophobic behaviour and easy manufacturing processing makes ultra-high molecular weight polyethylene (UHMWPE) the number one choice for ski bases. The high density polyethylene (HDPE) and UHMWPE are linear forms of polyethylene with a semi-crystalline morphology [2].

The low coefficient of kinetic friction, μ of the ski base has been described in previous studies [3-8]. The role of surface topography is not just one of the most crucial parts in skiing, as it was shown by Giesbrecht et al. [4] that the ski soles of an arithmetic mean surface roughness, R_a of less than 0.2 µm experience a considerably higher friction with snow. A unidirectional topography along the axis of the slider improved the sliding performance for both hydrophobic and hydrophilic materials. Additionally, Kietzig [9] showed that for several metallic surfaces the roughness and hydrophobicity significantly decrease ice friction at temperatures close to the melting point and at relatively higher speeds. A comprehensive analysis of the importance of the ski base structure was presented by Moldestad [10], and friction clearly increases with an increasingly apparent contact area [11]. Figure G.1 illustrates three regions where the coefficient of friction and the relatively real contact area are plotted as a function of the water film thickness. According to the ambient snow and weather conditions, a suitable surface texture has to be chosen to minimize the kinetic friction [12,13], as the chosen surface texture depends on the competition speed. Coarser structures are chosen for alpine skiing compared to Nordic skiing, where the latter average speed is much lower [14]. An optical analysis of the ski base is essential to quantify the differences between various grinds, with such tools and routines as presented by Moldestad [15] and Mathia [8,14].

In comprehensive tests prior to cross-country races, the ski technicians select the structure that performs best under the given snow and weather conditions. Even small differences in the structure design and texture can result in higher friction, and furthermore in a worse gliding performance. Therefore it is essential to reproduce a structure as evenly as possible in order to be able to guarantee equal conditions for all the athletes.

The motivation of this study was to develop a new grinding machine that combines the experience and advantages of stone grinding machines, while at the same time looking to further improve the surface treatment process. A major goal was to develop a system that can reproduce a chosen surface texture to a higher extent within narrow tolerances.

In this study, a comparison between traditional stone grinding and a newly developed grinding method with a metallic grinding wheel is presented. A test setup to validate the grinding quality was performed and the results were compared to each other.

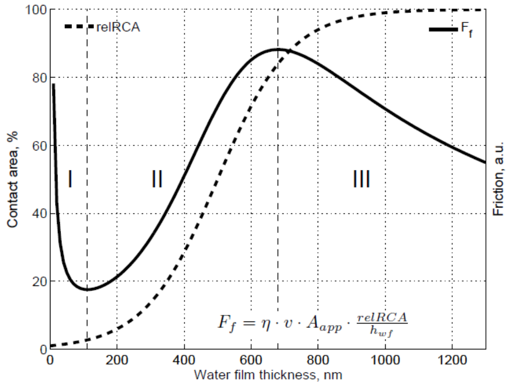

Figure G.1: Contact area (dashed line, left axis) and friction (solid line, right axis) vs. water-film thickness. Qualitative curve [11].

G.1.1 Stone grinding

For the last 2.5 decades, the procedure of choice to prepare the surface texture has been stone grinding. Grinding is basically a chip removal process, and the stone grinding of a ski base is a complex, abrasive machining process due to various adjustable parameters. It is an interaction of the dressing diamond, the rotating stone and the ski base itself. In addition, there are surrounding parameters that can have a major effect on the process and therefore also on the result. The grinding process itself is divided into two steps: First, a diamond tool dresses a groove into the rotating grinding stone by moving along the stone, and the result is a spiralled groove on the stone (the diamond itself never comes in touch with the ski surface). In the second step, this pattern can then be cut into the ski base during the grinding process.

G.2 Grinding devices and the process

G.2.1 Stone grinding

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G.2.2 The grinding stone

Unlike typical cutting tools, a porous grinding stone consists of small, hard particles with an irregular shape, and each individual abrasive grain with an irregular geometry acts as a cutting tool [16]. Abrasives have sharp edges, thereby allowing for the removal of very small quantities of the ski base material.

Conventional abrasives are Aluminium oxide (Al_2O_3) and Silicon carbide (SiC), and the size and shape of an abrasive grain affects its friability. Smaller grains are stronger and less friable than larger grains. In order to achieve the fine structures required in cross-country skiing, a grinding stone with a fine grain size is used. A grinding stone is not made of a single material, but instead is a composition of hard grains and their bonding material. In combination with the grains, the bonding material will have a special porosity that is the dominant factor for the cooling capacity and the heat generation in the contact zone [17].

G.2.3 The diamond

In the first step, a specially shaped diamond-point tool is used to dress the grinding stone. Dressing is the process of conditioning worn grains on the surface of a grinding wheel in order to produce sharp new grains and for turning out-of-round wheel, and the diamond is moved across the width of the grinding face (Figure G.3). Needle-shaped synthetic diamonds arranged in a cluster of three to five are mostly used for cross-country skiing to achieve very fine patterns.

G.2.4 How a structure is made

With modern SG machines, many different structures can be ground into the ski base. The design of the pattern is a result of the moving diamond along the rotating stone, and a variation in any of their speeds has a major effect on the produced pattern. Ski technicians differentiate between straight, linear "I" patterns, such as illustrated in Figure G.2, and optically crossed "X" patterns. A linear structure is achieved when the diamond dresses the stone by just moving once along the rotating stone. When the diamond also returns to the starting point, a crossed pattern is produced.

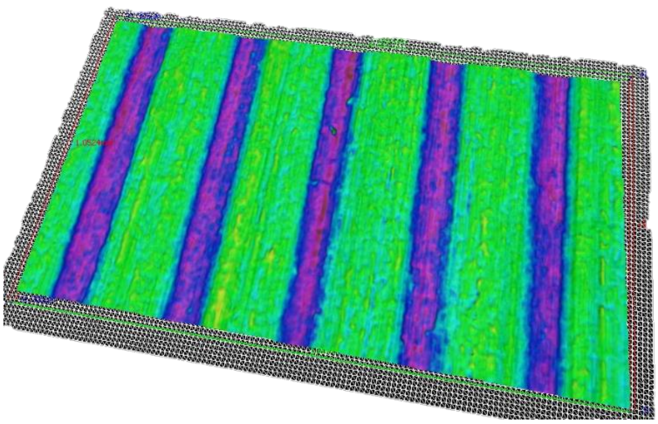

Figure G.2: An example of a linear stone ground structure on a ski, picture taken with an Alicona 3D microscope.

The different patterns are defined by adjusting these four parameters:

- The diamond and the stone circumferential speed during the dressing process;
- The stone circumferential speed during the ski base grinding;
- The pressure of the stone on the ski base, and the
- Auto feed speed of the passing ski underneath the rotating stone.

With the adjustment of the diamond speed during the dressing process, the roughness and the structure width can be manipulated. The faster the diamond moves on the stone, the further it gets during each rotation. This leads to a longer period length (PL) and a coarse structure on the stone, the effect of which can be seen in Figure G.3. The slower the dressing speed, the smaller the gap between the grooves gets. The grooves become more finely overlapped, which results in a fine structure. When the diamond moves with a continuous speed in both directions, the resulting structure will be symmetric and parallel to the ski edge. Due to variations of the diamond speed in one of the two directions, a shifted and slightly inclined structure is the result. Consequently, the difference between these speeds influences the optical structure and its angle.

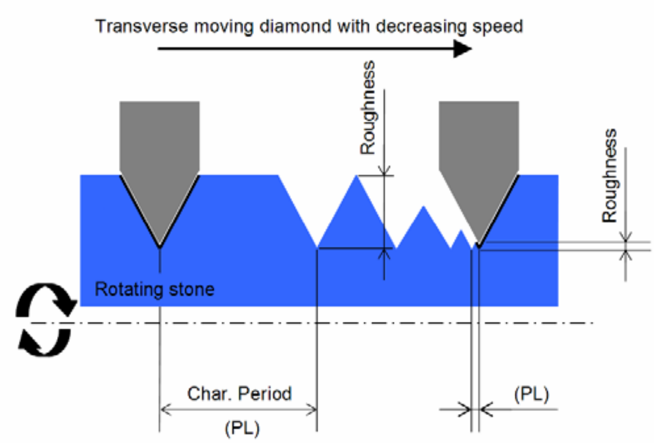

Figure G.3: Influence of the transverse diamond speed during stone dressing [17].

After the diamond has dressed a pattern into the grinding face, the actual stone grinding of the cross-country ski can start. The stone rotates at approximately 400 rpm to 750 rpm in the counter-rotating of the feed direction. The circumferential cutting speeds of grinding wheels are very high, typically up to 30 $m \cdot s^{-1}$, with the ski's auto feed speed being approximately 9 $m \cdot min^{-1}$ to 11 $m \cdot min^{-1}$. The variation of the stone circumferential speed influences the length of the grooved elements. A high speed leads to shorter elements and a finer structure, although the risk of surface burning in the contact area rises as well, while burnt spots on the surface become sealed and have a reduced ability to absorb wax. A lower circumferential speed reduces the heat production and increases the lifespan of the stone because of a reduced abrasion, and the auto feed speed of the ski has a similar effect. A high ski moving speed leads to an increase in the length of the elements, because per the rotation of the stone, it has contact with the ski on a longer area. Additionally, less heat is produced, but less material is also taken away.

Water-based emulsions are used as grinding fluids to prevent an excessive temperature rise in the ski base, as they improve the surface finish and dimensional accuracy. The common method employed is to use a circulated cooling system to maintain constant grinding processes.

When a specific texture is to be identically repeated on several skis, all previously mentioned parameters, including the dressing speed, have to be identical. Grinding wheel wear adversely affects the shape and accuracy of ground surfaces. Due to the abrasion of the stone, the sharpness of the texture on the ski's surface declines. The main wear mechanism is that of attritious wear, and when the grinding wheel becomes packed with chips the process becomes inefficient [16]. Under normal circumstances, approximately 5 to 10 pairs of skis can be ground before the stone has to be redressed with the diamond to assure comparable results.
The grinding stone is not necessarily homogeneous, i. e. the grain size of the stone is variable. Hence, a redressing of the stone with exactly the same setting of parameters does not reproduce the same structure on the ski base.

G.3 Features

G.3.1 The new steel grinding machine

A solid steel frame guarantees a low vibration operation during the grinding process, and the developed grinding machine has three axis freedom of motion: two linear (longitudinal - feed, vertical - cutting tool head) and one rotational (spindle) freedom of motion. The top surface of the ski is placed facing downward in a specially designed ski bed unit that can be adjusted for different ski lengths and curvatures. The operating grinding unit moves along the full horizontal length of the ski while it stays statically locked during the entire process. An electric motor controls the horizontal feed speed of the grinding unit, with the maximum feed speed limited to 300 $mm \cdot s^{-1}$. The spindle is balanced and controlled in a vertical direction via pneumatic pressure units that allow an accurate load control up to 300 N during the operation. The maximum rotational speed of the cutting tool is 600 rpm, and the assembled prototype can be seen in Figure G.4:

Figure G.4: Steel grinding machine with ski placed stationary in a specially designed ski bed unit and the grinding head.

G.3.2 The cutting tool

The cutting tool is made of metallic material, with clearly defined geometries designed using 3D CAD programmes. The advanced production process and cutting geometries of the wheel cannot be revealed in its full details due to corporate rights. The cutting process is comparable to a milling operation rather than to a traditional grinding operation, which allows for a number of versatile machining operations. A certain number of clearly defined cutting edges interact with the ski base, thereby resulting in a material removing process. The chip formation is affected by the cutting tool design and process parameters such as circumferential speed, load and feed velocity, and a smooth cutting process is achieved through the use of sharp teeth. Moreover, factors such as feed per cutting edge, cutting depth and cutting length are a result of the cutting tool design.

G.3.3 Operational setup

A cross-country ski is placed in the ski bed unit before the operations starts, and a cutting wheel is attached to the spindle and locked by a hexagonal socket screw. The operator has to select parameters for feed speed, circumferential speed and cutting load. All parameters can be a function of the ski length, and they can be monitored and continuously changed. The operation duration primarily depends on the feed speed.

In the setup with the new grinding approach, the ski is placed upside down and stationary in its natural shape, thus resulting in a curved surface that the metallic grinding wheel follows. A solid foundation holds the ski in place and levels it in the horizontal plane, and the grinding pressure is continuously adjusted by the pneumatic controlled grinding head since the tool has to follow the curvature of the ski.

G.4 Methods

G.4.1 Surface analysis

One way to categorize the ski base surface is to measure the roughness. The arithmetic mean deviation, R_a of the assessed roughness profile is usually calculated based on five sequent samples, which can be defined by:

$$R_a = \frac{1}{n}\int_0^n |Z(x)|dx \tag{G.1}$$

where *Z(x)* is a discrete set of surface height points of the ski base. According to Moldestad [15][15], typical R_a values for cross-country skis range from approximately 1 µm for the finest to 10 µm for the coarsest structures. Another often-used parameter is the root mean square deviation, R_q of the profile:

$$R_q = \sqrt{\frac{1}{n}\int_0^n Z^2(x)dx} \tag{G.2}$$

The mean peak to valley height of the roughness profile, R_z takes random extreme irregularities of the surface into account, and is therefore a suitable complement of parameters R_a and R_q. When analysing and comparing the results of the R_a and R_q values, it must be considered that they only depend on the profile in a vertical direction, which does not offer any information about the period length, shape, slope or size of the asperities or the regularity of their occurrence. The mean spacing of the profile irregularities, R_{sm} is a parameter that is used for periodic profiles and surfaces, such as structures used on ski bases. The R_{sm} is the mean value of the profile element width, *Xs* within a sampling length, and it is defined by:

$$R_{sm} = \frac{1}{m}\sum_i^m Xs_i \tag{G.3}$$

Further parameters that describe a texture in more detail are skewness, R_{sk} and kurtosis, R_{ku}. The skewness is a useful parameter, which represents a degree of symmetry of the topographic density function by:

$$R_{sk} = \frac{1}{{R_q}^3}\left[\frac{1}{nr}\int_0^{nr} Z^3(x)dx\right] \tag{G.4}$$

R_{sk} is the quotient of the mean cube value of the ordinate values *Z(x)* and the cube of R_q, respectively, within a sampling length. The Kurtosis of the assessed profile is the quotient of the mean quartic:

$$R_{ku} = \frac{1}{{R_q}^4}\left[\frac{1}{nr}\int_0^{nr} Z^4(x)dx\right] \tag{G.5}$$

It is a measure of the sharpness of the probability density function of the ordinate values.

G.4.2 Sample structures

In the first step, two grinds were prepared with both a traditional stone grinding machine and the new metal cutting machine. A fine and medium structure was chosen to illustrate the optical results of both surface treatments. Two metallic cutting tools with different geometries and different designed cutting edges were tested, and all operations were performed on high quality race running surface material.

All four samples were investigated with an Alicona *InfiniteFocus* 3D microscope (Raaba/Graz, AUT) after grinding, and image fields of up to 10.29 mm x 5.30 mm were taken with a lateral resolution of 1.749 µm × 1.749 µm and a vertical resolution of 400 nm. In order to find the mean line for the roughness profile, the cut-off wavelength, λ_c for suppressing the long wave component was set to 800 µm for the samples. The roughness profiles were taken perpendicularly across the ski running surfaces, and a profile width of five points, which is equal to 8.75 µm, was chosen. Several amplitude parameters of the roughness profile such as, R_a, R_q, R_z, R_{sm}, R_{sk} and R_{ku} were calculated.

G.4.3 Comparison between stone grinding and metallic grinding

In order to compare variations of the selected roughness parameters for the two grinding methods, 10 skis were prepared under identical grinding parameters each. Surface parameters were tested with a TR200 surface roughness tester (TIME High Technology, Beijing), and the sample length, which corresponds to the cut-off length, λc was set to 2.5 mm for all measurements. The arithmetic mean roughness, R_a of each profile was calculated based on the average five sequent samples. All skis were plane ground before the study to an R_a of 1 ± 0.20 µm. The relative variability, *CV* was defined as the quotient between the standard deviation, σ to average the mean roughness, R_a.

For the stone and metal ground skis, a medium-coarse structure was applied on 10 skis with constant process parameters for the grinding wheel, feed speed and grinding pressure. Each ski was ground once by an experienced ski technician from the Norwegian National Team, and roughness measurements were performed on five positions along the ski base at 20 cm, 60 cm, 90 cm, 140 cm and 175 cm from the ski tip on all skis.

G.5 Results

G.5.1 Range of structures produced with metal grinding

To a certain degree, the geometry of the grinding wheel and cutting edges predefines the resulting structure, and two clearly different structures from metallic grinding and stone grinding can be seen in Figure G.5A-D. Samples B and D can be described as fine structures with an R_a of 3.3 µm and 3.5 µm, whereas A and D are medium coarse ones with an R_a of 4.1 µm and 4.8 µm, respectively (Table G.1).
As seen in Figure G.5, a distinctive linear structure is visible for samples A and C, while the roughness profiles in Figure G.6 illustrate the differences and similarities between the fine (B, D) and medium coarse (A, C) structures. Distinct grooves with a proportionally flat area in between characterize structures A and C, and the average spacing between the

grooves increases for both medium coarse structures. A higher mean roughness also led to a negative skewness and positive kurtosis, which can be described as leptokurtic for the MG structure and platykurtic for the SG structure, though the fine structure from tool B is less clear. An R_z value of 15.9 µm is clearly lower than from the other MG structure. In addition, the R_{sm} value of 107.7 µm expresses a considerably lower average mean periodic spacing than the metallic grind of tool A with 270.8 µm, respectively.

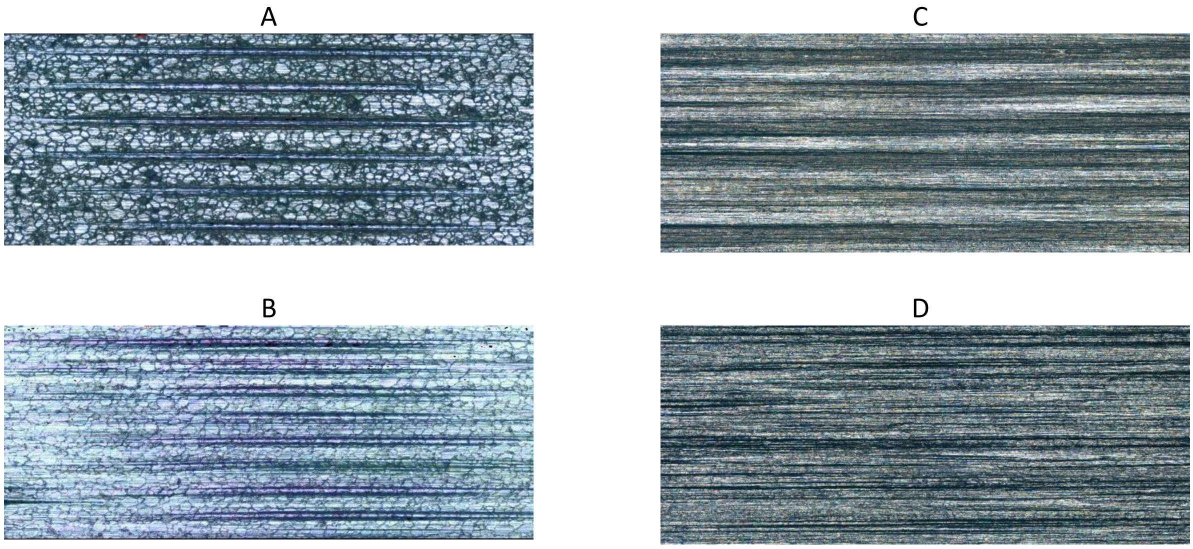

Figure G.5: Sample surface textures from metal cutting (A, B) and stone grinding (C, D), the image size is 2.16 mm × 5.25 mm.

Table G.1: Average amplitude and spacing parameters for the two sample structures made by metallic and stone grinding.

Method	Metallic grinding		Stone grinding		
Sample	A	B	C	D	
R_a	4.1	3.3	4.8	3.5	µm
R_q	5.8	4.0	5.5	4.2	µm
R_z	25.0	15.9	18.3	22.9	µm
R_{sm}	270.8	107.7	323.4	242.4	µm
R_{sk}	-0.74	0.04	-0.61	0.11	
R_{ku}	4.19	2.38	1.93	2.43	

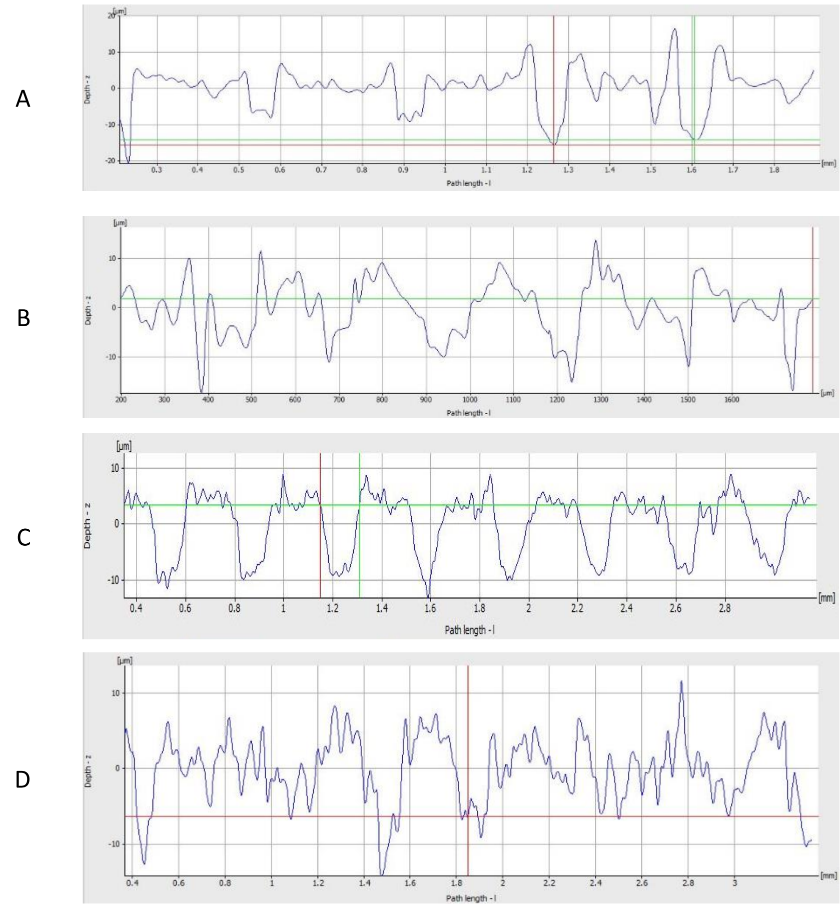

Figure G.6: Roughness profiles from to metal cutting structures (A, B) and stone ground structures (C, D).

G.5.2 Comparison between stone ground and metal ground structures

The stone ground skis showed a greater variation in the mean roughness, R_a along the ski. R_a values were constant at 20 cm and 60 cm behind the ski tip with 5.2 µm (Figure G8.a), and the mean was highest at 90 cm and 140 cm from the ski tip with 5.6 µm and 5.58 µm, respectively. The lowest mean was measured at 180 cm with an R_a of 5.07 µm, which was significantly lower compared to the 90 cm measurement point (Table G.2). The average standard deviation from all measurement points was 0.45 µm, whereas the biggest variation was shown on the front part of the ski for the 60 cm and 90 cm measurement points with σ of 0.52 µm (Figure G.8a).

Table G.2: Average mean roughness (R_a), standard deviation (σ) and relative variability (*CV*) from the profile roughness measurements for the stone ground (SG) and metallic ground (MG) samples based on n = 10 samples for each position.

Position [cm]	SG *Ra* [µm]	SG *SD.* [µm]	SG *CV* [%]	MG *Ra* [µm]	MG *SD.* [µm]	MG *CV* [%]
20	5.25	0.327	6.2	5.59	0.225	4.0
60	5.23	0.518	9.9	5.36	0.147	2.8
90	5.60	0.515	9.2	5.70	0.335	5.9
140	5.58	0.313	5.6	5.52	0.295	5.3
180	5.07	0.388	7.6	5.57	0.320	5.7
Total	5.34	0.4502	8.4	5.56	0.283	5.1

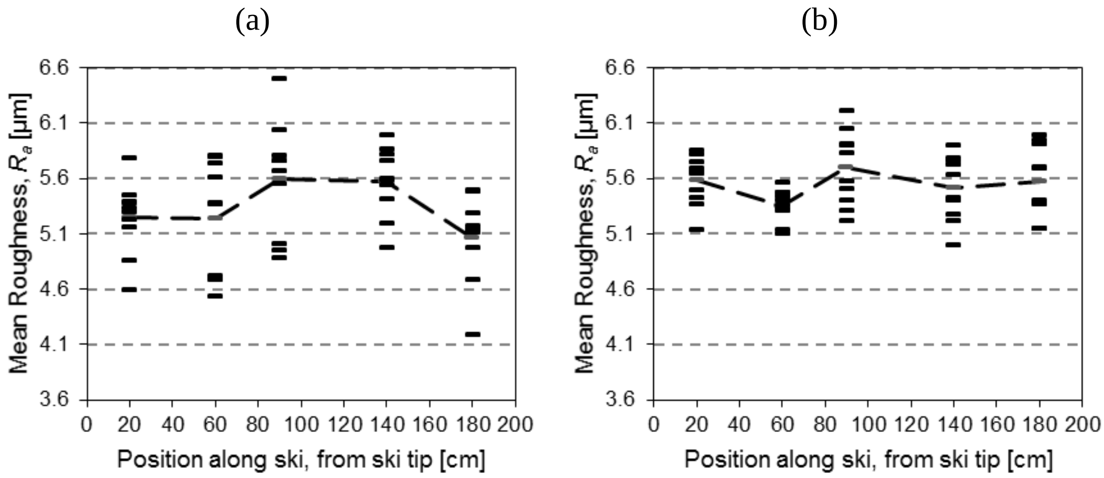

Figure G.7: Mean roughness, R_a results for all measurement points along the five chosen points along the ski. The average of each point is connected with a dashed line; (a) stone ground skis and (b) metal ground skis.

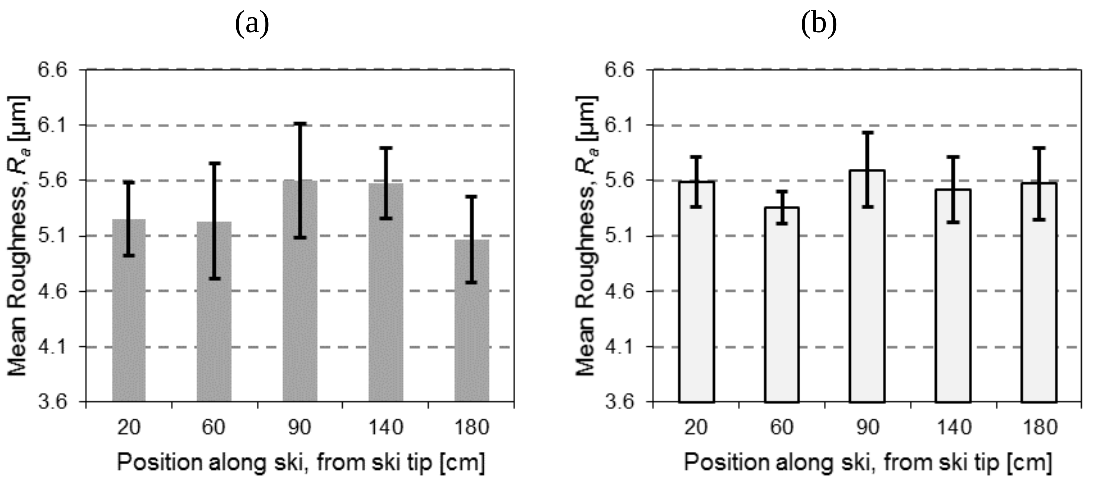

Figure G.8: Average mean roughness, $R_a \pm \sigma$ for all five chosen measurement points along the ski; (a) stone ground skis and (b) metal ground skis.

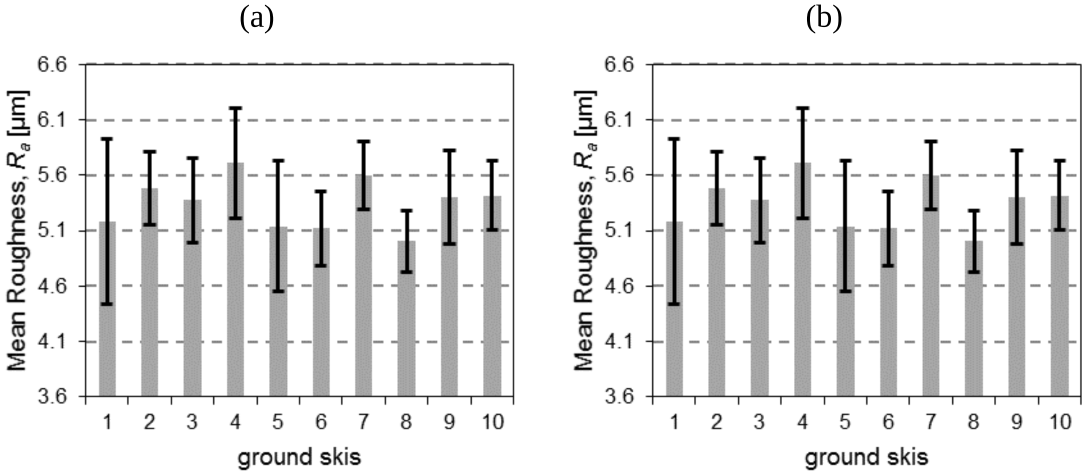

Figure G.9: Average mean roughness, $R_a \pm \sigma$ for the ten ground skis; (a) stone ground skis and (b) metal ground skis.

The metal ground skis exhibited the lowest mean roughness at 60 cm and the highest at 90 cm from the ski tip (Figure G.8b). The standard deviation varied between 0.15 µm to 0.34 µm, and showed a total average of 0.283 µm for all 50 measured roughness profiles. There was no clear trend for the mean roughness after 10 ground skis for both grinding methods (Figure G.9b), and the new metallic grinding process demonstrated a lower variation of the mean roughness along the five measured positions with 0.12 µm, whereas the stone ground skis had a standard deviation of 0.23 µm. The *CV* of the metallic ground skis was 5.1 %, while the stone ground skis showed a *CV* of 8.4 %.

G.5.3 Implementation of the new grinding tool

It is important to enable reproduction of a goal structure. The value of this new and innovative method of producing a structure enhanced the grinding process to a substantial part. The successful implementation of this new technology has already contributed to several outstanding results in international championships for Norwegian athletes. During the XXI Olympic Winter Games in Vancouver in 2010 and the FIS World Championship in Oslo 2011, several medal-winning racing skis were ground with the newly developed grinding method.

G.6 Discussion

In this study, a new and innovative approach for the grinding of cross-country skis has been presented using a metallic cutting tool instead of traditional stone grinding. Such a method has not been published earlier, and the stone and metallic grinding processes are completely different from each other.

One advantage of stone grinding is that with the help of one diamond and one grinding stone, an almost endless combination of structures can be designed and ground to the skis. Abrasive particles from a grinding stone wear down, causing continuous changes of the grinding surface, which results in a varying result of the structure on the ski base. Frequent surface tests have to be made in order to guarantee constant quality and regular re-dressing of the grinding stone is compulsory. In stone grinding, the ski is passed between the rotating grinding wheel and a downwards-pushing feeding wheel, which exerts a predefined feeding speed and loading pressure. The binding is usually removed to avoid sharp edges that could cause the ski to become stuck during the grinding. The typical ski construction shows a thicker body in the middle of the ski in a sectional view up to a maximum of 35 mm [18], as well as a reduced thickness towards both the ski tip and end. This variation in the ski-body shape seems to have an impact on the grinding results in stone grinding resulting in lower R_a values at the ski tip and tail.

The presented grinding machine presents a new method with fewer parts involved in the operation, in addition to less maintenance requirements. It is a clean process without the use of any cooling liquids involved, which opens up new possibilities in the field of ski base grinding. The development and construction process of the new machine has lasted for several years, and demanded many iteration loops with modifications of the device. The contribution to the construction of the grinding wheel was based on expertise from analysing more than 200 ski base samples in an earlier study [17]. The geometry of the cutting tools has been designed using 3D CAD programmes, and due to the superior hardness compared to the ski base material, a long lifespan is guaranteed.

Grinding with a metallic cutting tool does not offer the same possibilities as stone grinding, nonetheless a certain variety can be achieved by changing one of the process factors, namely the cutting tool circumferential speed, the grinding feed speed and the load. The freedom to alternate all factors along the entire ski length opens up for further research and gliding tests.

G.7 Conclusion

An innovative approach to grinding ski bases is presented. The new method uses a metallic mill, rather than a grinding stone to create a texture on ski bases.
The relative variability from 50 samples of metallic and stone ground skis revealed a clear difference between the two processes. The newly presented grinding approach had a *CV* of 5.1 %, while the stone ground samples showed a relative variability of 8.4 %.
The new grinding machine can offer interesting surface textures that contribute to an optimized performance. The value of this new and innovative method of producing a structure should be obvious. Nevertheless, the structure has to fit to the local snow and track conditions to achieve a perfect glide.

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Vibration Analyses of Single Scull Oars

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Abstract

There are numerous parameters which contribute to the performance in rowing. Selecting the right oars can therefore be an important factor for success. This paper describes laboratory experiments to select adequate oars. The dynamic properties of 71 oars were measured and compared with the favourite pair of oars from a Norwegian single scull rower. Free oscillation was investigated through eight acceleration sensors placed along the shaft of each oar. The investigated sculls displayed a wide range of dynamic properties and allowed the selection of new oars with similar damping characteristics to the reference pair, but with a significantly lower weight and higher natural frequency. These vibration analyses provide a valuable non-destructive method to test and select shaft personalized oars for top athletes.