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Winter Sports Tribology

An Experimental Approach To Understanding Kinetic Friction and Equipment Performance in Speed Skating

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Preface

This master thesis was carried out at the Department of Mechanical and Industrial Engineering (MTP) in collaboration with the Department of Civil and Environmental Engineering (IBM) and the Norwegian Skating Association (NSF). It is a part of the 2-year master program in Material Science and Engineering at NTNU, and was carried out during the spring of 2017. The project was first assigned towards exploiting tribological aspects of cross-country skiing, but was later changed to study the tribology in speed skating.

The project work is a continuation of a master thesis carried out by Mathis D. Fenre in the spring of 2016 for MTP, where a tribometer for cross-country skiing was designed and developed. A pre-study to this master thesis was concluded in the fall of 2016, where the behavior of the tribometer on ice with skate blades was investigated.

The field experiments for this master thesis were concluded in Sørmarka Arena in Stavanger over a period of eight days from the 20th to the 28th of February 2017.

Acknowledgements

I would like to thank my supervisor at the Department of Mechanical and Industrial Engineering, Professor Nuria Espallargas, for introducing me to the field of tribology and making it possible for me to combine my interest in sports with a master thesis in materials technology. I would also like to thank Mathis D. Fenre and associate professor Alex Klein-Paste as my co-supervisors for helping me rebuild the tribometer, and sharing their experience and resources for the field experiments.

The project was carried out in cooperation with NSF and project coordinator for “Toppfart 2018”, Håvard Myklebust. I owe him a lot of gratitude for helping me completing the experimental work, and sharing his resources and contacts in the speed skating community making the project possible. His hands-on experience with the sport and willingness to work long days in Sørmarka Arena have been crucial to complete the field experiments.

Finally, I would like to thank the staff of Sørmarka Arena for their hospitality, Preben Kristensen for designing the steel bridge, and the support I got from BAT by using their workshop and tools to complete the tribometer.

Abstract

Friction behaviour in the sport of speed skating has been investigated by use of a tribometer designed at NTNU. The objective was to study if the tribometer could measure relative differences within different skate blades. Four aspects of friction behaviour have been studied: Load, width, surface treatment, and temperature, of the skate blade. A comparison between load and width, with respect to nominal contact pressure, has found a correlation between pressure and measured coefficient of friction.

A correlation between different surface treatments of the skate blade has turned up inconclusive, and is suggested to be further evaluated with respect to poor reliability of results.

Results obtained through the experiment, with respect to temperature of the skate blade and ice surface, have not displayed a clear correlation to the measured coefficient of friction. However, a significant increase in temperature for the skate blade displayed a higher coefficient of friction for the system. This temperature dependency correlates to previous research, suggesting an optimum temperature to exist between the two gliding interfaces.

Sammendrag

Friksjonsadferd i lengdeløpsskøyter har blitt undersøkt ved bruk av et tribometer designet av NTNU. Målet var å studere om tribometeret kunne måle relative forskjeller innenfor forskjellige skøyteblader. Fire aspekter av friksjonsadferd på skøytebladet har blitt studert: Belastning, bredde, overflatebehandling og temperatur. En sammenligning mellom belastning og bredde, med hensyn til nominelt kontakttrykk, har resultert i en sammenheng mellom trykk og målt friksjonskoeffisient.

En korrelasjon mellom forskjellige overflatebehandlinger av skøytebladet har vist seg vanskelige å påvise, og foreslås å bli ytterligere evaluert med tanke på dårlig pålitelighetsgrad i resultater og metode.

Resultat oppnådd gjennom forsøket, med hensyn til temperaturen på skøytebladet og isoverflaten, har ikke vist en klar sammenheng med den målte friksjonskoeffisienten. Imidlertid viste en betydelig temperaturøkning for skøytebladet en høyere friksjonskoeffisient for systemet. Denne temperaturavhengigheten korrelerer med tidligere forskning ved De Koning (1992), som har foreslått at en optimal temperatur skal eksistere mellom de to glidende grensesnittene.

Contents

1. **Introduction**

1.1 **Background and motivation**

Norway is a nation with a long record of gold medals in winter sports; cross-country skiing, slalom, downhill, and biathlon to name a few, but also speed in skating. From the year 1924 to 2014 Norway succeeded with obtaining Olympic gold medals in 21 out of 111 different speed skating competitions in various distances for men [1].

To compete on elite level, Norway strives to have the most advanced equipment to perform research in different aspects of the sport sciences. The Norwegian Skating Association (NSF) want to assert themselves in the 2018 Winter Olympic Games in Pyeongchang, Republic of Korea. In relation to their ambition, they have an ongoing project known as “Toppfart”. The purpose is to explore the possibilities in reducing friction on skates and drag force on the body in speed skating. Toppfart is a subproject of Olympiatoppen’s project “Forsprang 2018”, of which the purpose is develop equipment and competence to measure and control the physical attributes affecting friction on equipment prior to the Olympic Games in 2018.

Friction is an important parameter to comprehend in many engineering applications, but also in sports. Enthusiastic skiers and speed skaters spend much time and money to optimize their gliding performance. However, Norwegian athletes have little knowledge of the tribological effects of how their skates behave on the ice. They try to polish their skates as smooth as possible, as they believe a smoother surface means lower friction.

As international senior elite speed skaters vary their performance as little as 1 % from race to race, an improvement of only ~0.08 seconds (1/3 standard deviation) is the smallest worthwhile effect which theoretically would result in 10% more medals for a medal candidate [2]. Combined with the fact that friction experienced on the skates is of a low magnitude (10-25%) compared to friction against body from air and wind (75-90%) a reduction of ~10 % is needed to reach the smallest worthwhile effect [3].

There are few publicly known studies on how friction behaves between ice and speed skates. The few studies indicate that the kinetic friction between sliding skates and ice are affected by several parameters. The temperature differences between the ice and skate edge material, pressure distribution, and surface finish of the blade, are assumed to have a dominant role in relation to friction force absorbed by the skate steel.

This project will try to investigate the different parameters affecting friction, and help the speed skating community in Norway to understand how their performance can be measured and how their equipment can be better utilized.

In 2015 Mathis Fenre carried out a master thesis at the Department for Engineering Design and Materials (MTP), with the purpose of designing and building the first ski tribometer in Norway [4]. The present project has continued the development of that tribometer, but with respect to the tribological aspect of speed skates gliding on ice, which is approximately one fifth of skiing friction. A pre-study was done for this master thesis by the author in the fall of 2016 [5]. The design of the tribometer has been modified to fit ice skates, and additional equipment to control the parameters of the environment has been added.

Much was learned from the pre-study to this master thesis, and the tribometer had to be modified to fit more additional weights and equipment. The test setup for measuring friction in the pre-study was evaluated in a previous report, and changes have been made to obtain more reliable data, to equipment and framework, test setup and analysis of the data [5].

1.2 Problem description

Measuring friction is a difficult task in almost any discipline of engineering. Friction depends on many factors such as load, speed, materials in contact, temperature, and environment in general.

However, friction is an important parameter to know in many engineering applications, but also in sports. Having good performance in winter sports depends very much on the interaction of the equipment with the sliding material and on the athlete. From a tribological point of view, the most important is to understand the interaction of the equipment-sliding material, which can be snow in the case of skiing or ice in the case of skating.

Getting reliable data and data that can be compared with empirical or field data is very challenging. For this reason, dedicated tribometers should be developed to match as close as possible to the field operations. In 2014-2015 NTNU designed and built its own dedicated tribometer for winter sports purposes. This tribometer will be used in this master thesis to understand winter sports performance from an experimental point of view. The experiments will be designed according to the empirical/field understanding with the aim of providing a numerical tool to decide preparation and requirements of equipment for best competition performance.

The aim of this thesis is to further develop the tribometer made by Fenre in 2015-2016 and test its reliability on ice.

In terms of friction during speed skating, little is known about:
1. Effect of load on the speed skate
2. Effect of width of the skate blade
3. Effect of surface treatment on the contact surface
4. Effect of temperature on the skate blade

1.3 Project scope

1.3.1 Goal and objectives

The objective of this master thesis is to discover how the tribological effects of speed skates on ice correlates to friction. Together with NSF and NTNU, an objective was formulated to investigate the effects of mass of the athlete, the nominal contact area of the steel surface by varying the width of the skate blade, surface treatment of the blade's contact surface, and how elevated temperatures of the skate blade affects friction.

The goal is to obtain a better understanding of how equipment can be optimized to reduce friction, and to further understand how friction behaves in relation to the parameters affecting it. The collection of friction data has been recorded by a tribometer which has been pulled across the ice, and retrieved frictional and normal forces by use of a load cell.

1.3.2 Limitations

The limitations to measuring small differences in friction in this experiment are set by the purpose of the tribometer. To find a real coefficient of friction for speed skates, values from the same movements and force an athlete would exert on the ice must be obtained.

This experiment will focus on the relative differences between the test skates, and with a skate perpendicular to the ice at all times. Having the tribometer "on a sled" across the ice will make it possible to isolate certain parameters, which will help identify the limiting factors of friction.

A prerequisite to find valuable data from the field experiment is to have environmental parameters close to constant. As the temperatures in the ice, air and skates might impact the friction values obtained by the tribometer, it is important not to change more than one parameter at a time.

Speed has also been an important parameter to have control of. The test setup is reliant on the repeatability of each run on the ice, and that the only parameters with a possibility of change is the width, weight, temperature or contact surface of the skate blade, as stated in the problem description.

1.4 Thesis Outline

This master thesis presents the factors involved for understanding the tribology in speed skating in the following order:

1. Theory of tribology, ice properties, previous research and how athletes perceive the knowledge they have at hand.
2. Present an overview of equipment, test subjects, and instruments, and how they were utilized in the field experiment
3. Description of results obtained through the field experiment.
4. A discussion of how to interpret results, and how to compare results to theory, and from one test to another.

2. Theory

2.1 Tribology

Tribology is defined as “The study of friction, wear, lubrication and the design of bearings; the science of interacting surfaces in relative motion” from the oxford dictionary [6].

In this experiment, the tribology aspect of speed skating will be investigated. A common baseline of the tribology terms for this experiment will be explained in this chapter to gain a better understanding of how the tribology mechanisms interact.

To further understand how to utilize this knowledge in selection of skate blades and surface treatment, properties of the materials in question, previous research within the field, and a background in the selection of skate blades and surface treatment from the athlete’s point of view will be presented.

2.1.1 Coefficient of friction

In the field experiment of this project, the coefficient of friction (CoF) will be the key factor when comparing the kinetic friction in two samples relative to each other. Amonton and Coulomb were pioneers within the science of mechanics and tribology. In their experimental results, they found the friction force (F_F) to be proportional to the normal force (F_N) in dry friction (sliding surfaces). The ratio of the friction force to the normal load was given the term “coefficient of friction”, seen in the formula below. However, since this “law” was formulated at the early stage of the science of mechanics, it is today recognized as only empirical values, and are suitable for relative comparison of CoF [7].

$$CoF = \frac{F_F}{F_N} \tag{1}$$

2.1.2 Friction of lubricated surfaces

When sliding two surfaces relative to each other, friction can be measured. To reduce the friction of this system, lubricants may be added to separate the two surfaces. In terms of sliding a steel skate across the surface of the ice, a lubricated layer will appear as an effect of frictional heating, which is further described in chapter 2.1.3 of this report. A lubricating layer will separate the asperities between the two interfaces and reduce the energy needed for relative motion between them [7].

2.1.3 Tribology on ice

Friction on ice is very low compared to other similar gliding systems. A ski gliding on snow would experience a coefficient of friction between 0.03 and 0.07 depending on speed and temperature, whereas a skate blade gliding on ice would experience a coefficient of friction at 0.003 to 0.007 [8]. The small variations in friction sought after in this experiment will therefore be more difficult to verify. In the following subchapters, this ice friction phenomenon will be further investigated.

Frictional heating: Friction occurs when two solid bodies slide against each other. From this friction, there are different mechanisms that need to be explained to get a better understanding of the tribological effects of different experiments, frictional heating being one of them.

By sliding a skate across the ice, friction will occur between the contact area of the ice and skate. The energy dissipated through friction affects the velocity of the sliding motion, and this mechanical energy will be transformed into heat. The exact location of this friction phenomenon is difficult to anticipate, but it is known to happen in the real area of contact between the two bodies [9].

There are various theories and experiments which state that some of the energy forms dislocations in the bulk material. For most tribologists however, it is assumed to be a known fact that most of the energy is transformed into heat and that the pressure melting of the ice is negligible.

The result of frictional heating when ice is involved in the system creates a water film between the two surfaces, as illustrated in Figure 1. The top layer of asperities in the ice will be cut loose, and the frictional heating will heat these up to the melting point creating a lubricating water film which in return is known to reduce friction. In short, frictional heating is responsible for heating up the two bodies, especially in the zones close to the area of contact where the temperature will be the highest. At low speeds, the anticipated coefficient of friction on ice has been estimated to be as high as 0.6-0.8, and for higher velocities, it is expected to be below 0.1 [10].

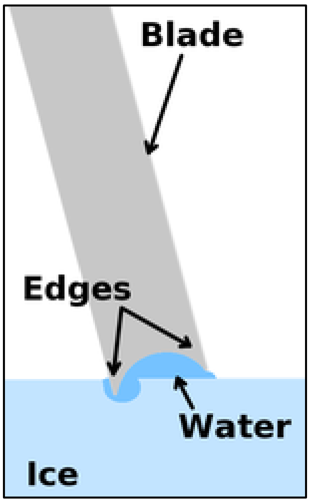

Figure 1: An illustration of a cross section from a hockey skate gliding on ice. The energy lost from kinetic friction between the blade and the ice is turned into heat which in turn melts the ice, creating a lubricating layer for the friction system [11].

Pressure melting: A second mechanism which may affect the friction between the ice and the skate is the pressure melting of the ice. This phenomenon can be explained in various ways, but the principle is best explained by Le Chatelier's principle. When any system at equilibrium is subjected to change in temperature, concentration, volume or pressure, the system readjusts itself to counteract the effect of the applied change, and a new equilibrium is established [12].

When applying this principle to the skate on the ice, the pressure from the athlete's weight to the skate edge will decrease the ice surface's melting point making it more likely to melt the ice into water and reaching a new equilibrium.

At this point, there are two key mechanisms which help lubricate the skate on the ice. The pressure melting which lowers the melting temperature of the ice, and the frictional heat that utilizes this lowered temperature to melt the ice and create a water film. Thus, the skaters can reach very high speeds due to the low friction between the sliding surfaces.

The effect of area of contact on friction: Bowden, a renowned scientist in field of friction in ice and snow, published his results from testing the effect of friction from varying loads and contact area on the top body. Although he stated his experiment had some flaws regarding repetitive conditions for the test, his results saw no clear variations in CoF. This meaning that the area of contact had a small to no significant impact in relation to the CoF [13]. An outline of his results is listed in Table 1.

Table 1: An outline from Bowden's results when testing friction in relation to the apparent area of contact. The values listed are of the kinematic friction, therefore, static friction is neglected [13].

Experiment number	**Apparent area of contact (cm^2)**	**Mean Temperature (°C)**	**μ_k**
1	0.6	-1.4	0.019
	2.3	-2.0	0.019
2	0.6	-3.0	0.017
	2.5	-3.0	0.019
3	0.2	-1 to -10	0.016
	3.1	-3.0	0.021

It can be argued that if the load is evenly distributed over the area of contact, and the pressure remains constant for the given system, the CoF will not change. This is of course when the system remains in a constant position, with no varying angle between the bodies. This would not be the case for skates which will vary both angle of contact and area of contact during their motions pushing them forward.

The impact of temperature on friction: For ice to melt, energy is required to raise the temperature up to the melting point at 0°C. The lower the temperature, the more energy is needed. This applies for both frictional heating and pressure melting, which in turn means that at lower temperatures the CoF should be higher, and vice versa. If the low friction on ice is due to the formation of a thin water film, one should expect the friction to be the function of temperature [13].

For an ice skate operating in temperatures from -9°C to 0°C the effect of temperature variation will be crucial, and a key component to controlling the measurement of friction on ice. The heat transfer coefficient of the skate steel also affects the friction, as its capacity to transfer heat from its surroundings will influence the tribological effects onto the ice. The air temperature will be transferred through the skate steel and into the water film or onto the ice.

2.1.4 Ice properties

When an athlete slide across the ice and pushes himself forward, he will try to focus all the power and motion through his legs and down on the ice. For the athlete to move forward, the ice must be able to withstand the forces projected on to it without crushing. This chapter will consider the formation of artificial ice to understand how it may affect friction.

Words from an Expert: In the Olympic Games of 1994 in Lillehammer, Professor Sveinung Løset of NTNU was brought in to revise the ice quality prior to the competitions. He is a renowned researcher within the field of ice and snow in Norway, and his experience with ice formation and characteristics have had a great impact on the knowledge of physical properties of the ice rinks in Norway. In conversations with Prof. Løset a detailed explanation, described below, was given to understand how the ice behaves when it is produced, and how the properties of the ice are affected during a race.

In short, the ice properties in the skating rinks could vary a lot depending on how the ice was formed. Ideal ice properties would entail ice temperatures as close as possible to the melting point, without losing its physical properties in terms of toughness and strength (approximately between -8ºC and -5.5ºC). To achieve this level of quality ice, there are certain parameters that are controlled to produce the same quality many times over with the ice machine (a Zamboni). These parameters consist of ice temperature, amount of ice removed, amount of water flowing onto the ice before freezing and its temperature. The velocity of the ice machine going forward must also be at a given speed to get the correct lamination of water to the surface. The end result of this process is to get small heterogeneous ice crystals with high strength properties [14].

Prof. Løset suggested waiting ten minutes after the new ice was created before testing the tribometer. This was because it takes more than 7 minutes for the ice layer to reach its previous surface temperature. When a suitable temperature was reached, the ice quality would remain the same for approximately four to five hours [14].

Ice quality of Sørmarka Arena: The ice quality in the different skating rinks varies depending on how the ice is formed. Some arenas put additives into the water (some form of glycol) to give the surface a rougher finish. The additives form small particles on top of the surface lowering the surface tension of the liquid-like layer, which in turn is thought to result in a lower coefficient of friction for the two rubbing interfaces [3].

The ice in Sørmarka Arena does not have any additives in it, but the water is repeatedly filtered and rinsed. The water will have close to no pollution from its surroundings, and is considered a homogenous liquid. As the “Zamboni” spreads the water over the newly cut ice, the water will form a very homogenous ice cover with heterogeneous ice crystals. With this method of ice production in Sørmarka Arena, a high repeatability of ice production can be made, making the ice properties similar each time, excellent for testing relative differences on skate blades in a field experiment.

2.2 Previous research in field experiments

Literature on the topic of tribology in relation to speed skating is limited. In the field of sport sciences, it is important to have a competitive edge, and revealing knowledge of improved equipment or behavior of friction on ice is not common. Because of the secrecy surrounding the different sports related to speed skating and restrictions in literature, the previous research on this topic is also very limited. The latest published article on the topic is from 1992, where Jos J. De Koning tested instrumented skates on several ice skating rinks to find actual values of coefficient of friction, as described below.

2.2.1 Speed skating experiments

Jos J. De Koning published his results in 1992 after testing friction of speed skates on ice. Prior to his experiments, Bowden and Hughes (1939) had performed similar experiments in a laboratory, with a rotating disc of ice on which metal pins slide. Kobayashi (1973) had performed tests with an instrumented sledge which was propelled by a catapult mechanism to measure friction on ice.

Jos. J. De Koning did not find the previous research to be a good representation for the friction forces a speed skater would experience. In an effort to find actual values of friction during speed skating, a pair of skates were instrumented to record friction force and normal force to obtain an actual coefficient of friction while speed skating [3].

His results found an average CoF for the skates on the straights of the ice rink to be 0.0046 (±0.0004), within a range from 0.003 to 0.007. He also found a correlation to friction and speed at an ice temperature of -4.6°C, illustrated in Figure 2. The results implied that higher values of CoF would be a result of higher speed, which is in contradiction with Bowden's (1953) results. The increase in CoF as a result of speed is not stated as a fact in his research, but is discussed in correlation to the athlete's technique when increasing the speed.

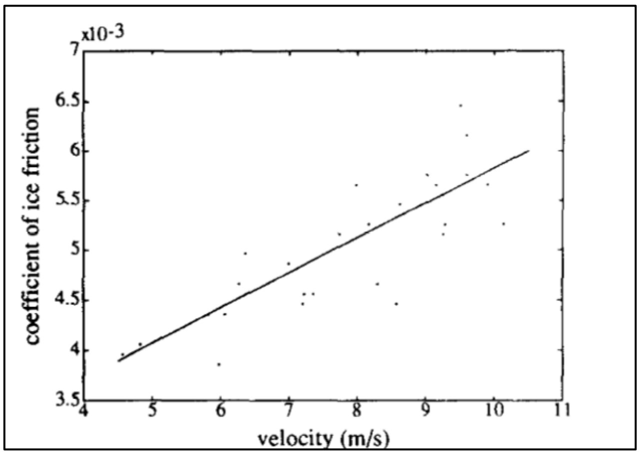

Figure 2: A plot of CoF and velocity for the experiments done by De Koning. A strong correlation can be seen, where a higher speed indicates a higher coefficient of friction [3].

De Koning's experiment was completed in several skating rinks with different ice temperatures, one of them in Heerenveen. The ice temperatures over a time span of nine hours changed from -1.8°C to -11°C. During this time, temperature data and friction data were recorded. A summarized plot can be seen in Figure 3. This plot shows a strong correlation between temperature on the ice and the measured friction data, where an optimal temperature can be found between -9°C to -6°C.

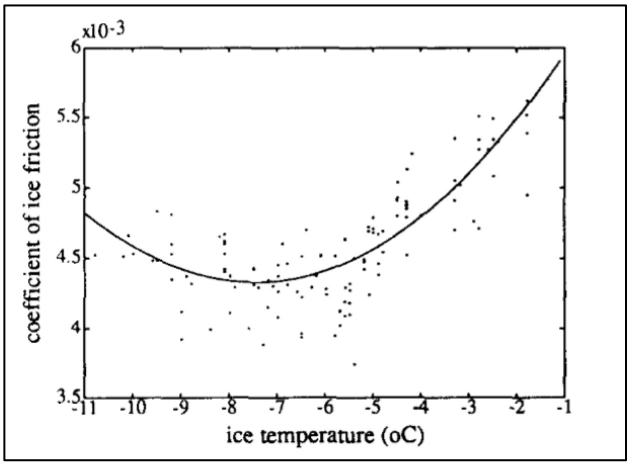

Figure 3: A plot from De Koning's measurements depicting the correlation between CoF and ice temperature. An optimal ice temperature can be seen from the curve, between -9°C and -6 °C. The plots depicted in this figure is a collection from all measurements done by De Koning in Heerenveen [3].

From the friction measurements obtained in the ice temperature test, De Koning assumed there would be an optimal temperature for reduced friction on ice. As he stated in his research; "The lubrication between the blade of the skates and the ice surface may be expected to increase with increasing ice temperatures, irrespective of the underlying mechanism. However, the friction is also determined by the hardness of the ice (deformation) and, since the hardness increases with lower temperatures, an optimum ice surface temperature is to be expected. The advantages of a higher temperature (better lubrication), and those of a lower temperature minimizing the deformation, cancel out each other at a particular ice temperature." [3].

In his article, he points to the behavior of the skate blade during the movement of the subject. As the subject pushes the skate forward, a rotational movement through the skate blade's length axis is performed. As the skate hits the ice with the outer edge it makes a groove in the ice, increasing the friction measurement. As the subject pulls through with his movement, the skate blade rotates to its inner edge creating a new groove in the ice. These penetrations of the skate edge increases the mean variation in friction for the measurements [3].

2.2.2 Surface melting in ice skating

The pressure melting phenomenon has been tested in many experiments. The results point to the fact that pressure melting cannot be the sole reason for melting the ice layer when speed skating on the ice. Frictional heating push forward as the best candidate for describing the water layer between the solid ice and the speed skate. Theories and experiments described by James D. White in 1992 concluded with the same results [15].

S. C. Colbeck (1995) has summarized the phenomena of the water film in an article by considering the theoretical physics of the matter. His findings point to a clear difference between the two most obvious explanations for the water film to form (frictional heating and pressure melting). For a skate blade to contribute with an equal amount of heat production through pressure melting (as a scenario with frictional heat), the blade’s real contact length could not be longer than 15µm (or 0.005% of the blade length). As this contact length is highly unlikely, his findings concluded that pressure melting could not be the sole reason for water film to appear between the two interfaces of steel and ice [9].

2.3 Statistic significance of friction values

To analyse data with very small numbers and with several parameters affecting these numbers at the same time makes it difficult to define a significant value. Researchers, who is in the field of tribology on ice, has isolated their experiments with respect to specific parameters they can control. To simplify obtained results and deviations, caused by the influence of temperature, air resistance, equipment vibrations and cross talk of instruments, it is a necessity to quantify the small values from the raw data.

For this experiment, similar simplifications and assumptions will be made in order to compare different values. With very small numbers the slightest deviation can have a significant impact, and this problem is unavoidable in an experiment like this.

2.4 Utilization of skate blades

The athletes competing today spend a lot of time on the ice in training and competitions. In an effort to understand why and how they treat their equipment, and how they use it, conversations with an expert on speed skating and sport sciences in general was set up to give a background of what information athletes have at hand. Håvard Myklebust is a former speed skating athlete and working for the Norwegian Skating Association in the project “Toppfart”. He has a PhD in sports sciences for biomechanics, and he is the supervisor in this master thesis from the NSF. He is renowned in the Norwegian skating community for conducting research for the Norwegian national team and has a lot of knowledge about the sport.

Working with Toppfart, he concluded a survey in February 2016 of how 55 athletes competing in the Norwegian speed skating cup prepared their sporting equipment. The following information is based on conversations with Håvard Myklebust and this survey [16].

The athletes can feel alterations on their equipment, for example when changing between brands (mainly Maple and Viking), the rocking of the skate, width, and length of the steel. However, they do not necessarily feel if the difference is performance enhancing or not. From the survey, the general observation was that athletes competing in the Norwegian speed skating cup prepared their skates prior to competitions. The awareness of different whetstones, their properties and utilization of them, seemed to reflect that they have an opinion of what is "good" and what is "bad"; the smoother the whetstone, the less friction would be experienced from the skate blade.

When preparing speed skates several whetstones are used in turn, starting with the coarsest one. From the survey, the finishing whetstone seem to vary. Fifty percent of the athletes who completed the survey said they were using what is referred to as a "triangle whetstone". It is a whetstone with three different gradients, where the smoothest side is similar to the surface of the L2-whetstone used in this experiment. Something worth pointing out is that the national ice skating team use a L4-whetstone or even a L5-whetstone, as most athletes competing in different distances use one pair of skate and one type of surface finish for all competitive distances [16].

2.5 Speed skating in competitions

The total friction experienced by the athlete comes from wind and air (75-90%) and friction from the skate blades (25-10%). To reduce friction from the skate blade in a magnitude which gives the athlete an advantage, the difference in the coefficient of friction would not have to be very big [3].

Table 2 provides an outline of different track records from Sørmarka Arena, with times recorded down to one hundredth of a second. An average top speed during a race is usually around 14.5m/s for men. This can result in very small distances on the finish line between the top three competitors during a race. Having the best equipment available and knowledge of how it behaves will be of utmost importance when competing for a medal.

To illustrate an example from the record time of Sverre Lunde Pedersen on the 3000-meter track, see Table 2, 10% of the time he spent equals to 22.23 seconds. This period represents the assumed duration of time which could be reduced by reducing friction on the skates. To improve the time of 22.23 seconds by one second, the skate blades must reduce their friction by 4.5%. This level of magnitude is not recognized as an easy or difficult task, but there has been very few known attempts to measure these differences in friction until today [17].

Table 2: An outline of track records from the ice rink in Sørmarka Arena [17].

Distance	**Time**	**Athlete**	**Date**
500 m	34.52	Pavel Kaluzhnikov (RUS)	31.01.2016
1000 m	1:08.10	Pavel Kaluzhnikov (RUS)	30.01.2016
1500 m	1:44.94	Denis Yuskov (RUS)	29.01.2016
3000 m	3:42.30	Sverre Lunde Pedersen (NOR)	24.09.2016
5000 m	6:15.71	Sven Kramer (NED)	30.01.2016
10000m	13:19.18	Thomas Søfteland (NOR)	14.02.2015

3. Experimental method

3.1 Equipment

This chapter will explain how the mechanics of the tribometer works, and how friction data was obtained to have reliable results.

Prior to this master thesis, a pre-study was conducted to investigate the possibility of measuring the small variations of coefficient of friction that was expected. Therefore, major parts of the experimental studies regarding equipment and instrument information and method of application in this report is based on this pre-study [5].

3.1.1 Framework of the tribometer

The tribometer must be as rigid as possible. Small vibrations in equipment will increase signal noise which might affect the outcome randomly, while angling of the loading cell relative to the direction of movement will result in a systematic error.

As mentioned in Chapter 1, a tribometer has been developed as a continuation from a previous master thesis by Mathis D. Fenre and a pre-study to this master thesis [4, 5]. It was originally designed to be tested on skis, and therefore alterations had to be made to fit the ice skates. These alterations were mainly in the connection points to the speed skates and in weight distribution. There are four supporting skates and one skate in the middle connected to the loading cell, as seen from Figure 4.

Figure 4: The tribometer on the ice during assembly. The tribometer is supported by five skates, where the skate in the middle is attached to the steel bridge and loading cell. The battery used to power to the instruments is in the square grey box on the left in the picture. The blue computer on top of the tribometer controls the photocells.

The framework of the tribometer is built by aluminum beams. The beams are positioned to stabilize the tribometer when loaded with equipment. The equipment was fitted to the framework, and additional weights were attached to balance the system while on the ice. Four supporting skates were placed on each corner of the tribometer to maintain balance during movement.

In this field experiment, several ice skates have been tested. To make the different skates fit, a steel bridge was constructed as a universal joint between the skate blade in question and the loading cell. This bridge has a static connection to the skate blade and loading cell, and is to be recognized as an elongation of the blade, as seen in Figure 5.

The loading cell is connected to the aluminum frame by a bolted joint, with enough room for the loading cell to move freely. The loading cell is connected the center top of the steel bridge by four bolts. The loading cells X-direction is parallel to the blades direction of movement, and will, therefore, be able to absorb the friction force absorbed by the blade gliding on the ice.

The connection between the steel bridge and the skate blade is static, meaning no room for movement. Before loading the skate blade with a normal force prior to a test, the system is set to a null point. When recording the null point, the position of the bridge is determined by using the two levelers on each side of the loading cell, depicted in Figure 5.

Figure 5: The steel bridge was installed with two levellers, one on each side, to set a null point prior to loading the skate. The bridge is connected to the loading cell with four bolts, and is parallel to the direction of movement. The connection points to the skate blade are like that of a real speed skating shoe. This is a static connection, with no room for movement.

The steel bridge between the loading cell and speed skate in Figure 5 was created to fit the skates to the design of the tribometer. The bridge makes a static connection between the two components, making it possible to measure friction.

To balance the tribometer equally on all skates when applying a force of 70 kg to the loading cell, it needs to be well balanced. Measures were taken to find the center of gravity of the aluminum frame and mounting the supporting skates relative to this center. When force was applied, the majority of the normal force would be centered down through the loading cell by the jack-up mechanism, and the excess weight would be equally distributed to the four supporting skates.

The supporting skates had a width of 1.1 mm and the skate blades were treated and polished similar to the B3 skate with a L4-whetstone, see Table 4. They were placed parallel to each other and to the blade connected to the loading cell with an equal length between them on each side. The supporting skates were levelled prior to testing in Sørmarka Arena, and the normal force is perpendicular to the skates gliding surface.

Jack-up mechanism: To exert the load from the additional weights on the tribometer and onto the test skate, a manual actuator combined with a shock absorber was used. When turning the wheel on the top of the actuator clockwise, a force was exerted through the loading cell and down on the skate. An illustration of the jack-up mechanism can be seen in Figure 6. A live feed of normal force from the load cell was displayed on the computer and the specific load in question would be reached. For offloading, the wheel would be turned counter-clockwise until the blade was in the air. The full weight of the tribometer would then rest on the four supporting skates [4].

Figure 6: A graphic presentation of the manual actuator with the shock absorber used for the tribometer. The actuator was mounted to the aluminium beams on the tribometer, in the centre of gravity. Loading and offloading of the skate blade was done by turning the wheel on the top [4].

Equipment for measuring test parameters: To have control of the different parameters that could affect friction, as described in Chapter 2.1.3, it was a necessity to measure the temperature on the ice surface, in the air and on the skate steel, as well as humidity and barometric pressure. In Table 3 the instruments used to obtain values of the parameters are listed. The temperatures were measured at the last gate of photo cells, and the values were important to know the effect they could have on friction. Humidity and air pressure were recorded to see if there were big variations over time, and to obtain values of the test environment in general. Both parameters could affect the air resistance of the tribometer system, but was assumed negligible due the constant speed in this isolated field experiment.

Table 3: The table describes the name, function and location of equipment used for measuring the environmental parameters affecting the measurement in the field experiment.

Equipment	**Function**	**Location**
Ammeter- thermometer.	To measure temperature on the skate blade during runs.	On the tribometer, in line of sight for the operator.
Digital Thermometer.	To measure air temperature 5mm and 600 mm above the ice surface.	By the last gate of photo cells.
Ice-thermometer.	To measure the temperature in the ice, 3-5 mm below the surface.	By the last gate of photo cells.
Portable weather station.	Measure relative humidity close to the ice surface.	By the last gate of photo cells.
Photocells.	To record time used by the tribometer to reach the four different gates of photo cells.	Photo cells were placed with a gap of ten meters between each gate.
Photocell’s computer.	To control start and stop function of the photo cells, displaying time values.	Placed on the top of the tribometer with easy access for the operator.
Laptop.	Recording friction data from the loading cell, operated through wireless connection by WiFi.	On top of an aluminium beam on the side of the tribometer.
Mouse.	Activating and deactivating computer software.	Placed on the top end of the rear beam close to the operator.
Electrical powered winch with wire.	Accelerating and maintaining speed of the tribometer.	At the far end of the skating rink from start.

3.1.2 Speed skating blades and preparation

The field experiment was carried out with skating blades from the same producer, "Maple", assumed to be of the same steel quality. The preparations of each blade have been done in accordance to how athletes treat their equipment prior to competitions, and with different grades of whetstone ranging from a smooth to a coarse roughness.

Preparation of the blade’s surface roughness: Prior to testing, the blades were investigated in an optic/3D-microscope, and after 20 minutes of continuous use on the ice there were no visible indentations or scratches on the blade’s surface. An assumption was made that the material properties of the blade would remain unchanged during testing in Sørmark Arena.

A pair of skates were also examined for reproducible surface treatments. By looking at the roughness profile of the skate after polishing with a L4-whetstone, the blade was once again grinded starting with the coarsest whetstone and finishing off with the L4-whetstone. The results gave approximately the same values, and an assumption was made that the surface properties of the blade would be reproducible if the same person performed the surface treatment in the same manner.

From the 3D-microscope a roughness profile was gathered from the blades for the different whetstone treatments. A collection of points within the contact zone were investigated for each skate, and the average roughness values would represent the blade's surface roughness. The roughness values for each blade were compared to the friction data gathered from the field experiment. The various whetstones have been pre-examined for roughness, and their values are listed in Table 4.

Table 4: Roughness values (Ra) of the common whetstones used by the ice skating community, measured by QualitestTR200. The average values Ra and standard deviation (SD) are from five values of each sample, where one test is an average of 5x2.5 mm.

	Ra [µm]	**SD (n=5)**
Coarse whetstone	10.77	1.65
DMT diamond duo sharp	4.05	0.39
DMT diamond duo sharp- Red	1.65	0.21
DMT diamond duo sharp- Green	1.98	0.55
Triangle Blue	8.40	0.24
Triangle Green	7.13	0.09
Triangle Pink	1.23	0.05
National team whetstone 0	2.65	0.61
National team whetstone 1	1.99	0.21
National team whetstone 2	0.99	0.15
National team whetstone 3	0.28	0.01
National team whetstone 4	0.14	0.01

Surface treatment of skate blades: When preparing the steel surface of a pair of skating blades it is important that the edge is sharp. Hence, the two blades are put into a mechanical device where they have the same height and are parallel to each other. The idea of this setup is to make it possible to use one grade of whetstone for both skates at the same time, so they are equally grinded in each movement from the operator of the whetstone. From Figure 7, one could see how the setup looks like. The operator would slide the whetstone back and forth in a lateral direction through the whole length of the blade. The operator would apply pressure to the whetstone just enough to keep it in place.

Figure 7: The whetstone in the picture is the first one to be used when preparing skate blades, a very coarse grade. The whetstone would slide back and forth until a satisfactory finish is met. Water is the most common lubricant when grinding the steel blade, this is applied by adding a few drops on the surface of the whetstone.

The operator would start off by using a coarse whetstone, and continuing with a smoother whetstone until the smoothest stone of their liking have been completed. The most common form of lubricant used for this grinding process is water, applied to the whetstone prior to grinding and if the whetstone “feels” dry. The surface treatment and utilization of whetstones used for the blades in this field experiment are listed in Table 5.

Table 5: A list of width and surface treatment for the skate blades used in this field experiment.

Name of skate blade	**Width of skate blade (mm)**	**Grade of whetstone finish**
B1 750 N L4	0.9	L4
B3 750 N L4	1.1	L4
B5 750 N L4	1.25	L4
B3 600 N L4	1.1	L4
B3 900 N L4	1.1	L4
B3 750 N Smooth	1.1	Smooth
B3 750 N L2	1.1	L2
B3 750 N Coarse	1.1	Coarse

Width of the skate blade: A motivation for selecting the different widths of the skate comes from the fact that most athletes choose a 1.1 mm width for their skate blade, unrelated to weight or gender of the athlete. In this experiment three different widths have been tested, as seen from Table 5. A blade with a width of 0.9 mm is the smallest commercially available width on the market, and 1.25 mm is the largest width. Having the spread between the width of the skates as large as possible, the experiment would have a greater chance to measure the relative difference of CoF between them.

The rocking of a skate blade: The skate blade’s curvature is determined by a “rocking”. If a skate blade was described with a rocking of 25 m, it describes the curvature of the arc from the inside of a circle with a radius of 25 meters, illustrated in Figure 8. The most commonly used radius of the skating blade is 23 meters. In this experiment, a radius of 25 meters was chosen to have the area of contact as large as possible to have a greater chance at measuring the differences in friction force absorbed by the skate. It was also thought to have better steering capabilities on the ice when keeping a straight line. All the skates in this experiment had their radius set by trained personnel, at the same radius of 25 meters.

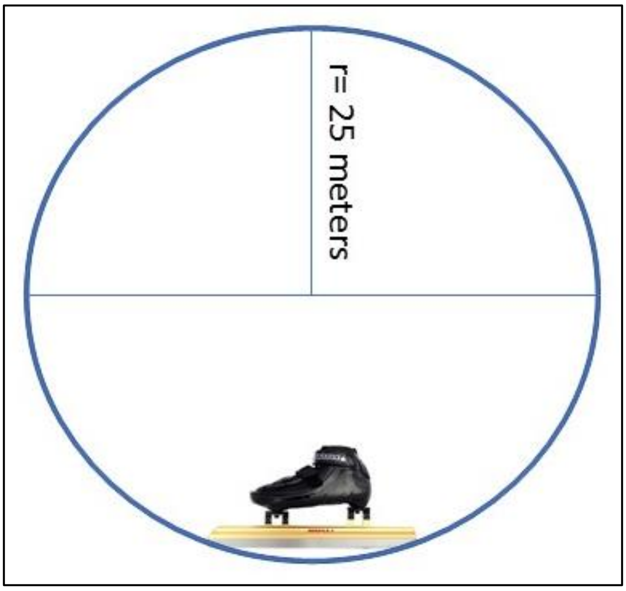

Figure 8: An illustration of a speed skate's radius or "rocking". The curvature of the skate blade would follow the arc of the circle.

3.1.3 Instrumentation

In this chapter, a short presentation of the instruments used to obtain the friction data are described. An illustration of the event circuit is illustrated in Figure 9.

The loading cell creates a charge difference from the variations in applied force. These charge outputs are received by an amplifier, and sent to a Data Acquisition (DAQ) recorder which digitizes the signals obtained by a programmable software in the computer. The software receives the charge differences in Volts and converts it to a measure in force (N). This chain of events happens continuously, and the friction data is logged on a computer.

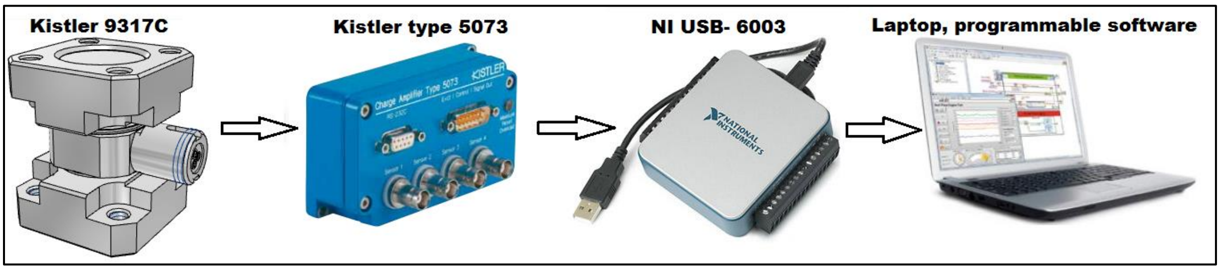

Figure 9: Illustration of instruments and the chain of events when obtaining frictional data. From the left, the loading cell (Kistler 9317C) creates a charge output received by the amplifier (Kistler type 5073) and send it to the DAQ (NI USB.6003). The charge output is digitized in the DAQ and converted to a measure of force in the computer software (LabView) [18-21].

Loading cell- Kistler 9317C: The three-component loading cell used in this field experiment is a Kistler 9317C. It is a piezoelectric loading cell with quartz crystals. The loading cell is commonly used for compression and tensile tests, and the differences in force measured in the field experiments are within the limitations of the loading cell's capability [19].

The piezoelectric loading cell measures differences in electric charge in Volts. The Britannica Academic Encyclopedia defines piezoelectricity as "appearance of positive electric charge on one side of certain non-conducting crystals and negative charge on the opposite side when the crystals are subjected to mechanical pressure". When force is applied to the loading cell in either direction (x, y or z), the size of the force is obtained through the charge created by the crystals inside it [22].

To obtain the force applied to the loading cell in Newton (N), a calibration factor for each direction was used. This calibration factor was determined by applying a known load to the loading cell in x-, y- and z-direction, and as a result getting a known voltage output. A load of 1kg was applied to each direction during calibration. The calibration factor was set to give a load of 1 kg=9.81 N.

Charge Amplifier- Kistler Type 5073: The charge amplifier used in this experiment converts the charge signal from the piezoelectric loading cell into an output voltage proportional to the mechanical input quantity. The signal from the loading cell is obtained and amplified towards a Data Acquisition recorder which digitizes the charge output to be obtained by the computer software [18].

DAQ- National Instruments USB- 6003: Data acquisition (DAQ) is the process of measuring an electrical or physical phenomenon such as voltage, current, temperature, pressure or sound with a computer. In this case, the DAQ system consists of a sensor, an amplifier, a DAQ measurement hardware and a computer with programmable software, as illustrated in Figure 9 [20].

Programmable software- LabVIEW: The LabVIEW software was used to interpret the signal output from the loading cell in this experiment. It is a graphical system design software platform, designed specifically for engineers and scientists building measurement and control systems and can be used with a variety of hardware and software applications [21].

The software programming used in this experiment is depicted in Figure 10. The module based program was made to visualize the friction data transmitted by the loading cell. Values of friction force, F_F, in the x-direction and the normal load, F_N, in the z-direction. The x-direction of the loading cell was aligned horizontally with the speed skate in the direction of movement. The z-direction, measuring the normal load, was in the vertical direction. Continuous measurements of friction force over time was logged in a separate file for each test on the computer. The sample frequency of the load cell was set to 1000 samples per second, meaning for each second of measurement 1000 values of force data was logged for all three directions of force input to the load cell.

To remote control the start and stop function of the software as the tribometer was moving on the ice, a peer to peer setup with TeamViewer was enabled. TeamViewer is a software tool which duplicates the screen of another computer via Wi-Fi. LabVIEW started to log data as the operator activated it on the tribometer along with the recording of time.

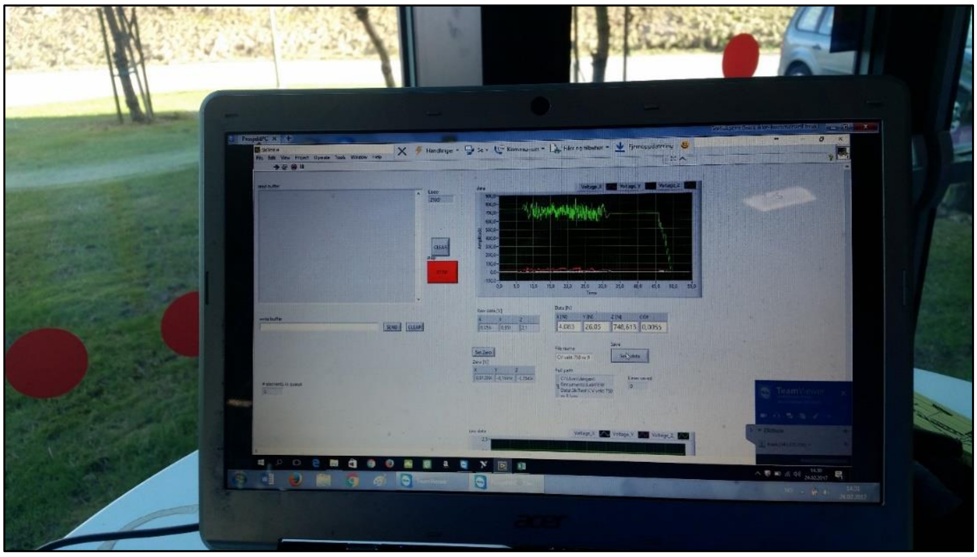

Figure 10: The picture demonstrates how the data was displayed in LabView during a run. The force in all three directions (x,y,z) and the coefficient of friction were displayed in separate columns, and a graphical presentation of different columns over time was displayed in the dark window. This computer was placed by the electrical powered winch at the end of the test track, and had a peer to peer live feed of the tribometer's computer via TeamViewer.

3.2. Test method and utilization of equipment

The experimental work for testing the friction on different skates in this master thesis was done in Sørmarka Arena in Stavanger. The indoor skating rink was chosen due to its stable conditions and availability for completing a high number of tests. The friction testing with the tribometer was completed from the 21st of February to the 28th. A total of 317 individual runs on the ice were completed for four different tests, including quality testing of the tribometer equipment, test layout, and friction tests of the different scenarios.

Four different aspects affecting friction of the speed skating blade have been in focus. Different loads, widths, surface treatments and temperature of the blade have been measured and compared to one another. The different loads (600 N, 750 N, and 900 N) and width (0.9 mm, 1.1 mm and 1.25 mm) have been compared to each other by calculating the nominal contact pressure (MPa) of each skate during testing. The pressure was determined by measuring the contact area of the skates on the ice, further described in Chapter 3.2.7. The surface treatment test was done by different roughness gradients of the blade's contact surface, and have been studied in a microscope for qualitative reasons, as described in Chapter 3.1.2.

This chapter will describe in detail how the complete test setup in Sørmarka Arena was performed during the runs of each skate, and how the different tests were done separately. Each subchapter will be a description of how the different aspects of friction were measured, and a summarized subchapter will give an explanation to how these tests could be compared.

3.2.1 Test setup

The field experiment, as previously mentioned, has been divided into to four different tests. Each test consists several runs across the test track for the skate blade in question. In each run, corresponding values of speed, and temperatures in the ice, on the blade, and in the air, have been recorded and stored on a computer. The recording of values from environmental parameters were communicated by radio between the operators of the tribometer and the electrical powered winch. An overview of how the equipment was organized can be seen in Figure 11.

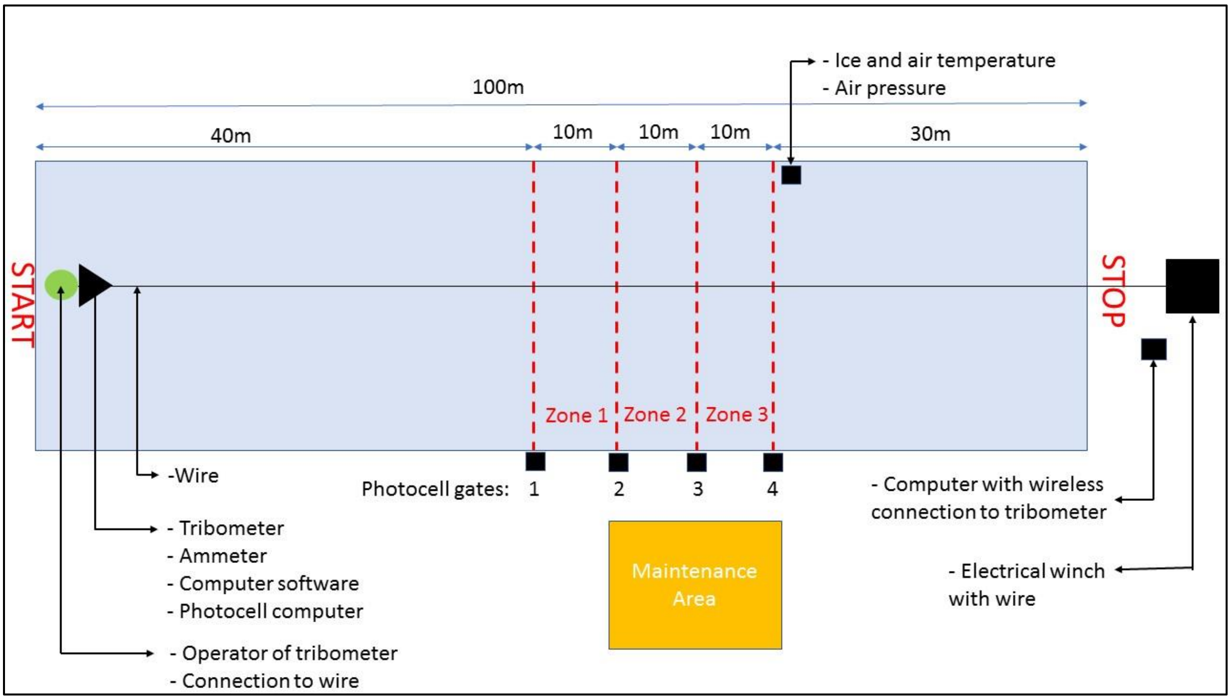

Figure 11: The illustration is an overview of location and how the equipment was organized on the ice during the field experiment. The friction data recorded from the tests were obtained during constant speed, in zones 2 and 3.

The photocells in each gate are placed four meters across from one another, with a 10 meters distance between the individual gates. After several runs utilizing the whole width of the test track, the ice surface properties would be visibly altered. The ice surface would need to have the same conditions for each run, and the staff at Sørmarka Arena would create new ice when needed. Figure 12 shows the test track during a run as the tribometer and the operator behind it enters zone 3.

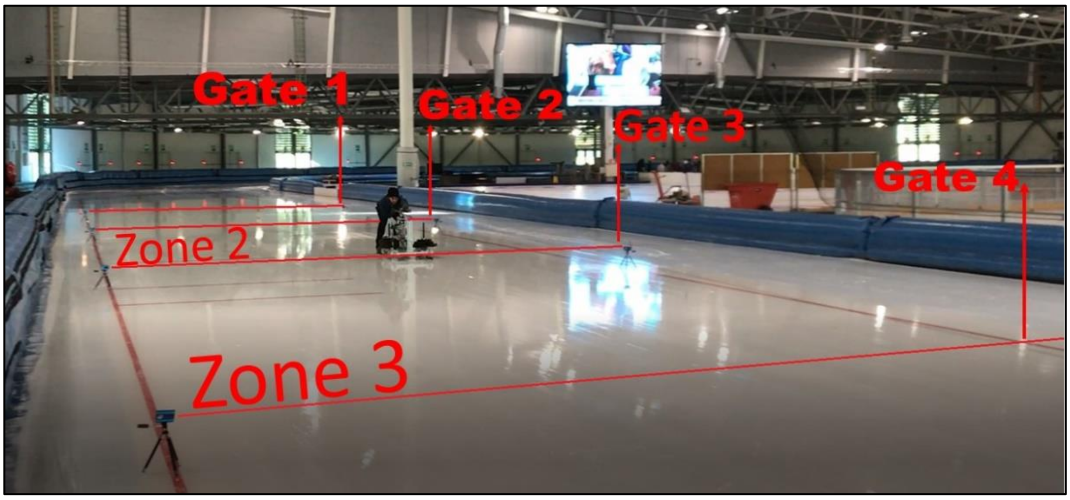

Figure 12: The illustration in the photo depicts the location of the different photocells and measuring zones. The photo is taken during a run, where the tribometer with the operator behind it can be seen leaving zone 2.

The purpose of the operator behind the tribometer was to keep the system in place, and to accelerate the tribometer in a safe and reproducible manner before stopping it after passing gate 4.

3.2.2 The complete test setup of one run-cycle

The testing took place in Sørmarka Arena on the strait line of the track closest to the maintenance hall. A lane of about 120 meters by 4 meters was available, and about 100 meters were utilized for this test setup.

To get the tribometer up to a certain speed, an electrical powered winch with a wire was used. The operator would hold the wire with one arm and the tribometer with the other. As the revolutions on the motor increased, the tribometer would accelerate along with the operator trying to maintain a static connection to the tribometer. The electric motor was set to a specific maximum limit of revolutions to 900 rpm, where the speed would be constant through zones 2 and 3. The speed was close to eight m/s for the entirety of the field experiment.

On the test track a total of eight photo cells were placed at four gates in the area of measurement. The photo cells would record the time it took for the tribometer to go from start until it reached each gate, as illustrated in Figure 11. Prior to start, the tribometer was loaded with 600 N to 900 N depending on load of interest. After loading the tribometer, the photocell recording was started at the same time as the friction data logger by a wireless connection. The operator of the tribometer would activate both recordings simultaneously, so that each value of friction data would correlate to a certain time and distance from start, by using the equation below.

$$Distance\ (m) = Speed\left(\frac{m}{s}\right) * Time\ (s) \qquad (2)$$

As the tribometer started, there would be a rapid increase in acceleration until the first gate of photo cells. The terminal velocity would be reached and a constant speed would be achieved for the last to zones of measurement.

The test was stopped manually by the operator of the tribometer by skidding with his skates. When the tribometer and the operator had come to a complete standstill, the recording of friction data would continue for another ten seconds before completely stopping. This procedure was done to make sure a definitive zero level of the loading cell was obtained, and a “set point” for friction force could be correlated to the data obtained in the measurement zone. As the recording was stopped, the tribometer was offloaded and put in a null point to slide it back towards the starting position. From Figure 13, a graph of obtained friction force and normal force during a run is displayed, marked with the various phases of the run.

When returning the tribometer to the starting position, the operator would log temperature values of the ice and air displayed on the instruments placed beside the measurement zone. The time stamps of each gate would also be noted from the photocell’s computer and logged to correlate friction data.

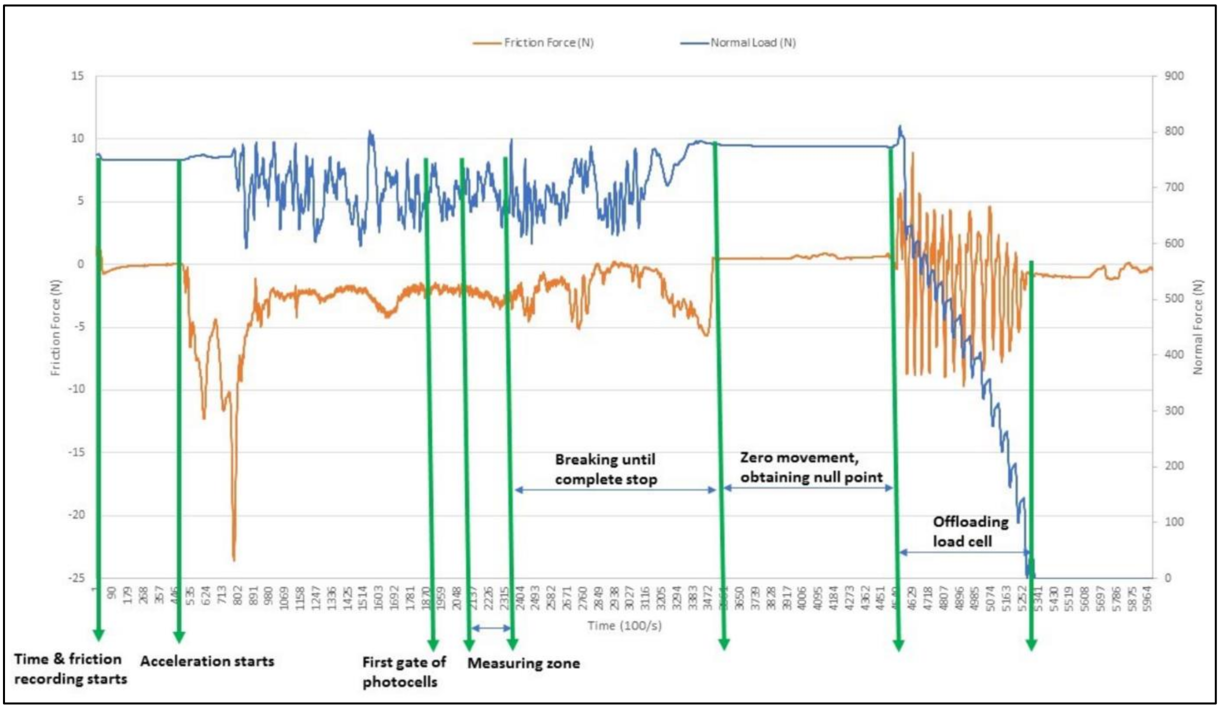

Figure 13: The different phases of a run with the B1-skate blade are illustrated in this diagram. It takes 5 seconds from the recording instruments are active until acceleration starts. As the tribometer accelerates forward, an increase in friction can be seen from the orange line (the X-direction of the loading cell, with a negative value in the movement of direction). Throughout the measurement zone, the values of friction data were collected. After passing the last gate of photocells the operator immediately started breaking, creating big alterations in the recorded friction force, as seen in the graph. The blue line represents the normal force on the skate blade. As the tribometer is completely offloaded by the jack-up mechanism, the recording instruments were stopped. This graph is an outline from the values displayed in Figure 33, found in Appendix C.

Maintaining constant speed: However, the constant speed was not maintained in all runs. Due to the wire being stretched when pulling the tribometer and operator (200kg) over the ice, some values of acceleration or retardation were recorded, and turned out to have an effect on the obtained friction force.

From the timestamps at each gate a value of retardation or acceleration could be calculated and used for adjusting the friction data to a “close to constant speed”. By using a law of movement for acceleration, see equation 3, a value of acceleration or retardation could be found. By having a time stamp for each value of friction recorded by the loading cell, a correlation between friction force and acceleration could be calculated.

$$v^2 - v_0^2 = 2 * a * S$$

$$a = \frac{v^2 - v_0^2}{2 * S}$$

$$a = \frac{\left(\frac{S}{t_1}\right)^2 - \left(\frac{S}{t_0}\right)^2}{2 * S} \qquad (3)$$

Each run would have a corresponding value of acceleration or retardation in the measurement area. The values of acceleration were plotted against the friction force, and a constant, given the symbol K, from the gradient line of a linear regression could be found to quantify the data. This constant, K (N/(m/s^2)), was found for the acceleration gradient of all collected data for one skate blade. The new value of average coefficient of friction for a run would, therefore, be calibrated for the mean acceleration or retardation depending how the tribometer behaved in the measuring zone during the number of runs in a test.

Furthermore, the constant would be used to calculate the coefficient of friction (CoF), for correlation between friction force (F_F), normal force (F_N) and acceleration from Equation 4:

$$CoF = \frac{(F_F + (a * K)}{F_N} \qquad (4)$$

The coefficient of friction from each run would correlate to the acceleration affecting the tribometer system, and a close to constant speed would make it possible to compare the different runs.

Utilization of technical instruments on the tribometer: During a run, the operator behind the tribometer would have a visual contact with the temperature display on the ammeter. The temperature values of the skate blade during and after a run, and the time from the photocells were communicated by radio after each run. The operator would reset the photocells and loading cell wirelessly prior to starting a run.

3.2.3 Normal load test with 600 N, 750 N, and 900 N

The skate used for this test was B3, with a blade width of 1.1 mm. As previously mentioned, this is the most common width used by the athletes in competitions and, therefore, a viable skate for testing weight differences in athletes. 40 consecutive runs were done for testing normal loads of 600 N and 900 N, where the only parameter subjected to change was the normal load to the skate blade. The B3 750 N- test was completed for testing the different widths.

20 runs on the ice were completed and recorded for each load. The loads were alternating every other run to make up for different conditions in the ice, air temperature and overall use by the operator of the tribometer. A normal load of 600 N and 900 N were applied by the jack-up mechanism, as described in Figure 6. The normal load was applied seconds prior to starting the test sequence.

3.2.4 Width test

Three different widths of the skate blade were tested. About 30 runs were recorded for each skate, where the only change of equipment was done by disconnecting one blade and attaching the other. Due to the time consumed by changing the blade, the individual blades were run in separate sequences. The normal load applied by the jack-up mechanism was set to 750 N for all blades prior to the starting sequence.

3.2.5 Surface treatment test

Four different blades, two pair of skates, of the same width, 1.1 mm, were tested over several days. The blades were assumed to be equal except for the surface treatment. The normal load to the skate was set at 750 N and the only parameter subjected to change was the skate blade attached to the load cell.

3.2.6 Temperature test

To test how temperature affects friction received by the skate blade, alterations were made to the speed skating blade itself. The blade was of the same width as other tests, 1.1 mm, but with heating pockets attached to the skating steel. In addition, the skate blade was indirectly heated by a heating gun (warm air) for a duration of time.

When a temperature above approximately 8°C was reached, the tribometer was loaded with 900 N and the test sequence was started. To control the temperature, an ammeter was attached with a wire to the skate’s steel surface close to the contact surface. To prevent contamination from ice debris and air temperature, the wire was covered with an isolated tape on top. The ammeter displayed a live feed of temperature, and was recorded by the operator of the tribometer before, during and after each run.

3.2.7 Finding nominal contact area

To compare friction data between different tests, a common denominator had to be found. By measuring the contact area for each blade with the different normal loads, a pressure value could be obtained.

The values were obtained by loading the tribometer with the normal load in question, and sliding a piece of paper under the skate from both sides, as illustrated in Figure 14. Due to the rocking of the blade, the thin paper would slide under the blade and stop where the contact area started. From these values, a nominal contact area was found.

Figure 14: The picture illustrates how the contact surface could be measured when applying load to the blade. A thin paper would slide under the skate steel from both sides. When the papersheet stopped, the distance from center of the blade would be noted and calculated to a nominal contact length. Pressure from the skate on the ice was calculated from known values of length, width and load on the skate.

When applying load on the blade, the tribometer was moved approximately two blade lengths forward or backwards, for the measurements to be as realistic as possible on "new ice". This procedure was repeated 10 times for each blade and each weight in question, and a common denominator was found.

3.2.8 Analysing friction data

From the field experiments over 300 runs have been completed. Each run consists of roughly 40 seconds of friction data with a sample frequency of 1000 samples per second. In addition follows the time, temperature and humidity data recorded for each run. With this large amount of data, it was necessary to have a control of which results went where, and to what extent they would be analysed.

As every measurement of friction force correlates to a certain time and distance on the test track, the last two zones were filtered out through different matrixes using Microsoft Excel.

From the raw friction data of each run, a summary of friction force and normal force has been made with respect to set points for the load cell, and a correlation to acceleration or retardation. The data extracted from these matrixes are the average values for all parameters affecting friction, and they are further analysed with a comparison to each other.

The key values of this report will rely on the average values of friction force, $F_{F,}$ and normal force, F_N, and the coefficient of friction, CoF, as the relation between them. The flowchart displayed in Figure 15 provides an overview of the described analysing method.

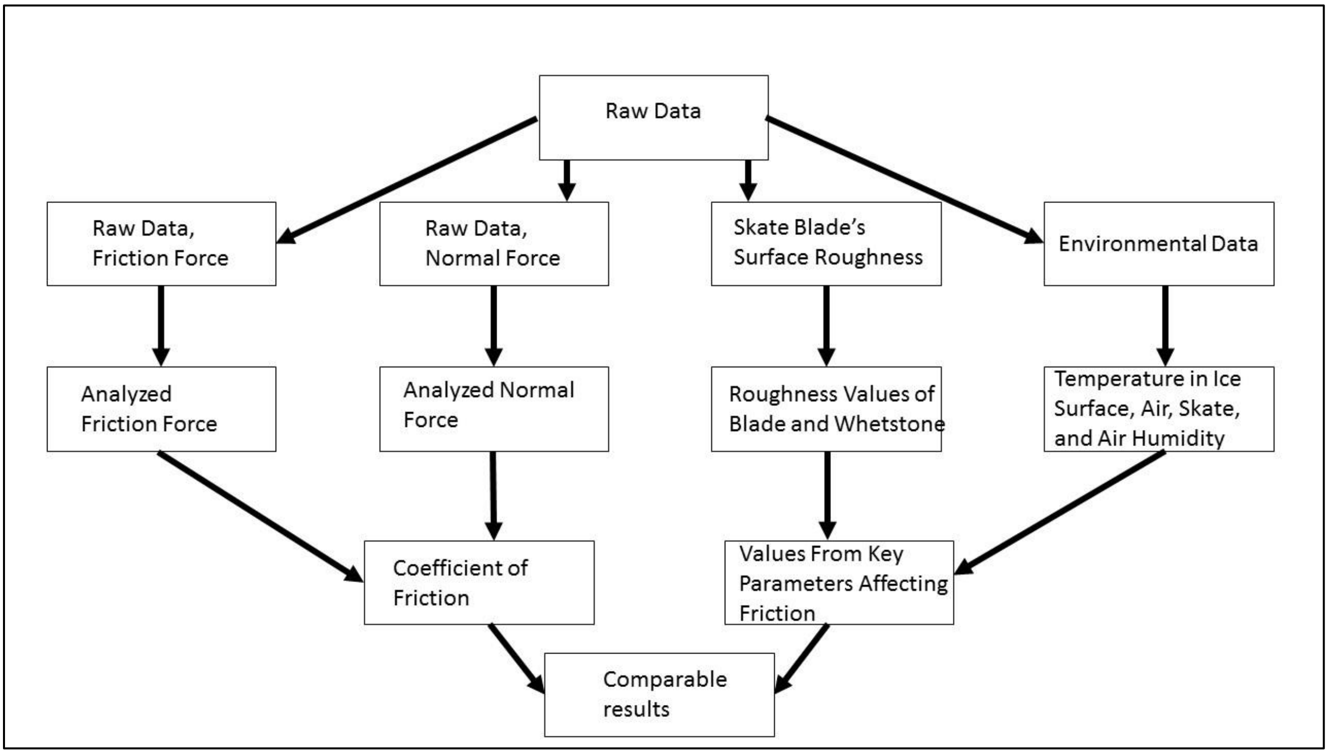

Figure 15: The flowchart describes the order of how the measurements obtained in the field experiment have been analysed. The raw data was stored as txt.- files and further analysed in Microsoft Excel. All key values used for comparable results in this report has been processed in the same manner as depicted in this flowchart.

4. Results

In this chapter, results from the field experiment will be presented as singular tests, and a comparison to each test and blade will be summarized in the end. The field experiment has retrieved information on friction behavior in speed skating and the parameters involved. The values of coefficient of friction (CoF) from each run is an average of measured friction obtained from the measuring zone, depicted in Figure 11. The average values of CoF for each test have been used for quantifying the data in this report. The CoF, a value comprised of friction recorded in the direction of movement and a normal load corresponding to each friction value is recognized as an empirical value when comparing relative tests in this report.

4.1 Influence of normal load on friction

The normal loads in this experiment was set to 600 N, 750 N and 900 N. The normal loads were set to simulate different body weights on the skate, from 60 kg (female) to 90 kg (male). The test was performed on a skate with a 1.1 mm width (the most common width used in competitions by athletes).

The results from a normal load of 750 N were obtained by testing the different widths of the skate, where a load of 750 N was used for a width of 1.1 mm. This test was completed on a different day, but was proceeded in the same manner as testing the two other loads (600 N and 900 N). The results from each test is described in the following subchapters, and finally a comparison of the three normal loads is presented. The average values of CoF are displayed as “CoF. Cal. For acceleration”. This value is calculated from equation 4, described in Chapter 3.2.2, and is to be recognized as the value used for comparing the relative tests in this report.

4.1.1 Normal Load of B3 600 N

From Table 6 and Figure 16, the collected friction data and the parameters involved are illustrated for the B3- skate with an initial normal load of 600 N. This skate blade had the highest measured friction out of all tests in the field experiment, with a CoF of 4.07x10^{-3} (SD=1.10).

Table 6: Values listed in this table is a summary of the environmental conditions and the recorded friction data for 20 runs during the test of B3 600 N- skate with a normal load of 600 N. The table shows an average value for CoF calibrated for acceleration to 4.07x10^{-3} with a std. deviation of 1.10x10^{-3}. All the data has been accounted for, meaning there are no exceptions with respect to minimum and maximum values. The values in this table is a summary of the recorded data found in Appendix A, Table 16.

	Friction Force (N)	**Normal load (N)**	**Nominal Contact Pressure (Mpa)**	**Humidity (%)**	**Ice Surface Temperature (°C)**	**Temperature 3mm above Surface (°C)**	**Air Temperature at 0,6m (°C)**	**Temp. of skate during run (°C)**	**CoF cal. For acceleration (x10^-3)**
Average	2.14	568.85	2.73	68.73	-5.21	-1.71	4.87	-1.20	4.07
S.D.	0.45	14.14	0.00	10.09	0.15	0.13	0.15	0.37	1.10
Maximum	3.26	608.07	2.73	78.40	-4.90	-1.40	5.10	-0.40	6.51
Minimum	1.42	547.01	2.73	33.90	-5.50	-1.90	4.60	-1.90	2.23

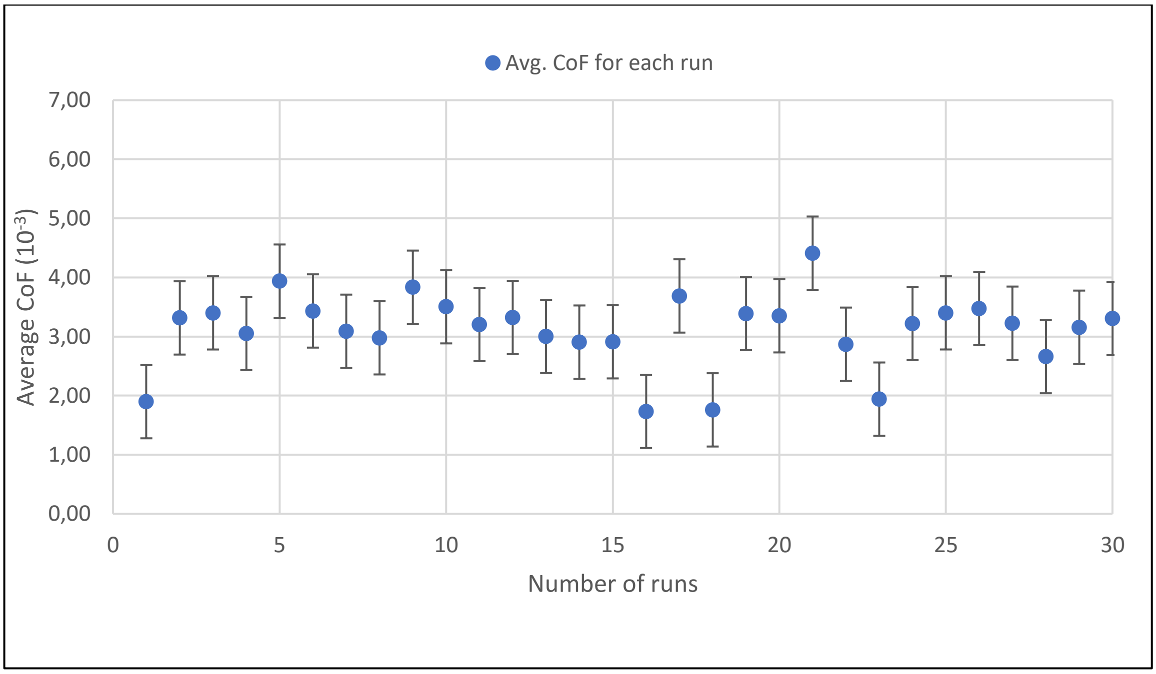

Figure 16: The plot of average values for the CoF of B3 600 N-skate is illustrated. Every point represents a single run independent from the others. From this test, an average CoF was found to be 4.07x10^{-3}. The error bars for each point represent the standard deviation.

4.1.2 Normal Load of B3 750 N

The values displayed in Table 7 and Figure 17 are derived from data collected when testing the different widths. The test has been performed in the exact same manner as other load tests.

A mean value for the coefficient of friction at 3.41x10^{-3} (SD= 0.90) has been found for the B3 750 N-skate. The test was successful regarding repetitive recordings, with low variations in environmental changes during the test period.

Table 7: Values listed in this table is a summary of the environmental conditions and the recorded data for 18 runs during tests of the B3 750 N- skate. The table shows average values for CoF calibrated for acceleration to 3.41x10^{-3} with a std. deviation of 0.90x10^{-3}. All the data has not been accounted for in this test, as two of the runs were determined as unsuccessful due to an instrument malfunction. The values in this table is a summary of the recorded data found in Appendix A, Table 17.

	Friction Force (N)	**Normal load (N)**	**CoF cal. For acceleration (x10^{-3})**	**Nominal Contact Pressure (Mpa)**	**Humidity (%)**	**Ice Surface Temperature (°C)**	**Temperature 3mm above Surface (°C)**	**Air Temperature at 0,6m (°C)**	**Temp. of skate during run (°C)**
Average	2.42	709.55	3.41	3.41	55.74	-5.74	-2.06	4.41	-1.64
S.D	0.62	15.91	0.90	0.00	6.32	0.06	0.24	0.35	0.52
Maximum	3.87	736.07	5.50	3.41	61.88	-5.70	-1.80	4.80	-0.30
Minimum	1.55	663.35	2.10	3.41	49.59	-5.90	-2.40	3.70	-2.30

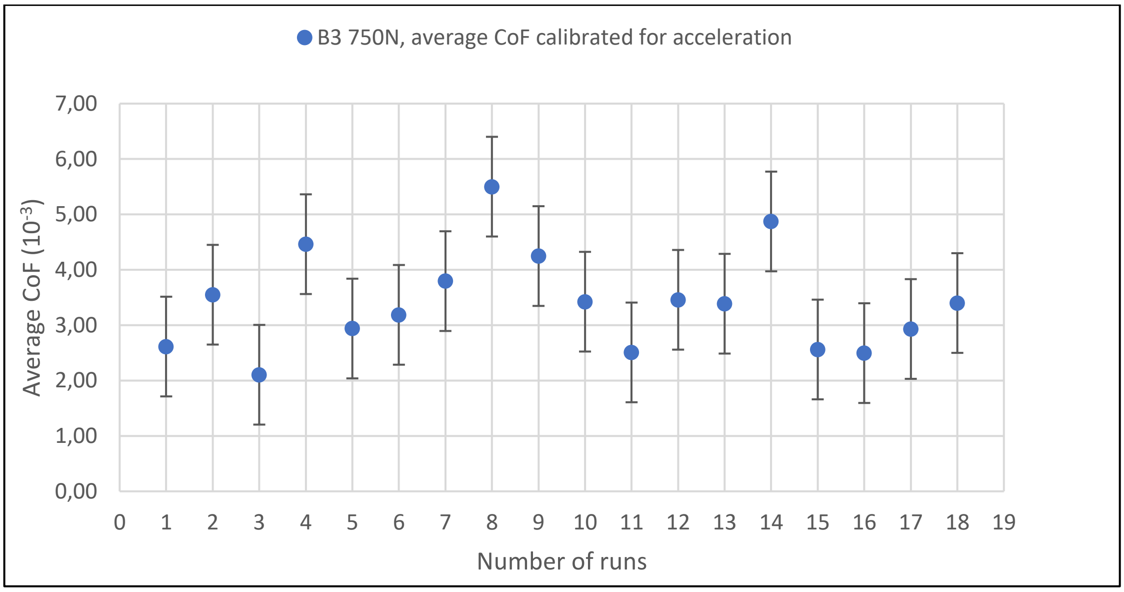

Figure 17: The plot describes the values of average CoF for each run. The highest measured CoF is 5.5x10^{-3} and the lowest at 2.10x10^{-3}, presents a big leap. With only 18 runs, the maximum and minimum values will have a great effect on the mean value of CoF used for comparison to other tests. The error bars represent the standard deviation for a given test.

4.1.3 Normal Load of B3 900 N

With a load of 900 N on the skate blade, the average frictional force was increased. Despite the increase in friction, the B3 900 N-skate had the lowest mean value of obtained coefficient of friction at 2.92x10^{-3} during the entirety of the field experiment, as listed in Table 8 and illustrated in Figure 18.

Table 8: Values listed in this table is a summary of the environmental conditions and the recorded data for 20 runs during the test of B3 900 N- skate. The table lists an average value for CoF calibrated for acceleration to 2.92x10^{-3} with a SD of 0.53. All the data obtained during testing, has been accounted for and are summarized in this table. The values presented below is a summary of the recorded data found in Appendix A, Table 18.

	Friction Force (N)	**Normal load (N)**	**Nominal Contact Pressure (Mpa)**	**Humidity (%)**	**Ice Surface Temperature (°C)**	**Temperature 3mm above Surface (°C)**	**Air Temperature at 0,6m (°C)**	**Temp. of skate during run (°C)**	**CoF cal. For acceleration (x10^{-3})**
Average	3.02	874.01	3.94	69.41	-5.21	-1.68	4.87	-1.20	2.92
S. D	0.66	15.79	0.00	7.63	0.13	0.17	0.19	0.41	0.53
Maximum	4.17	917.75	3.94	79.80	-4.90	-1.10	5.40	-0.20	3.97
Minimum	1.76	842.44	3.94	43.50	-5.40	-1.90	4.60	-2.00	2.23

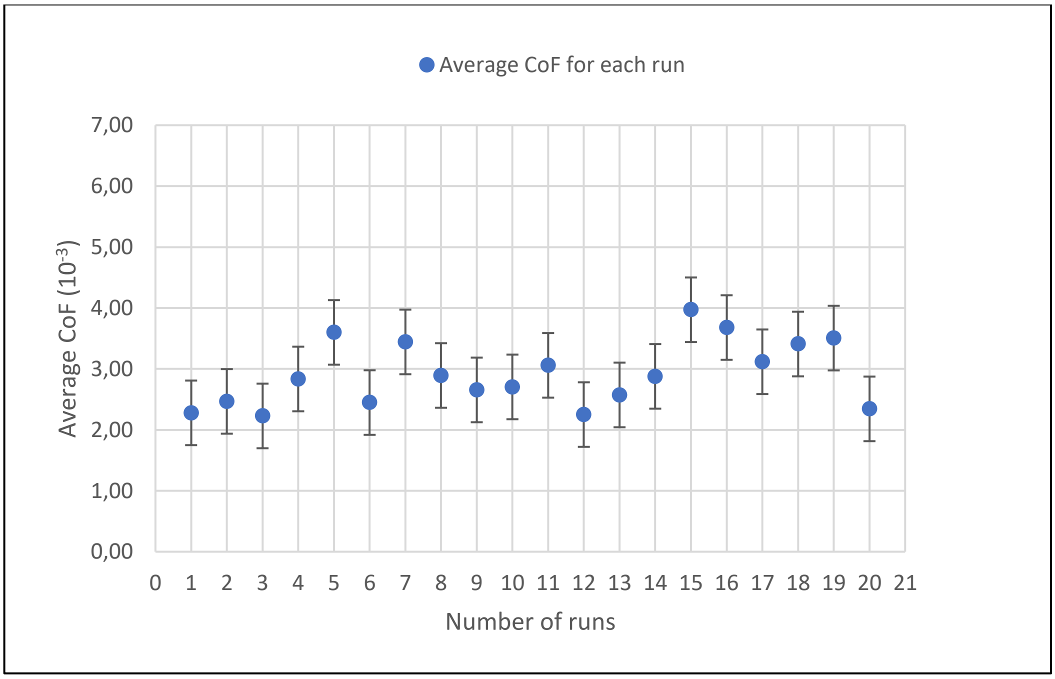

Figure 18: The plot of the average CoF describes a small variation over time. The average CoF from this plot is 2.92x10^{-3} (SD=0.53), with the largest peak at 3.97x10^{-3} and the lowest value at 2.23x10^{-3}. The collection of values is derived from Table 18, found in Appendix A.

4.2 The influence of normal contact area in friction

4.2.1 B1- skate blade with normal load of 750 N

The B1 750 N- skate had the smallest width at 1.1 mm, and the highest measured nominal contact pressure at 4.02 MPa. As listed in Table 9, the average coefficient of friction is at 3.11×10^{-3} (SD=0.62), which puts the skate blade in the lower part of the scale when it comes to relative friction differences for the field experiment. In Figure 19, the values are illustrated in a plot diagram, where the scatter among the values are low, as can be seen from the maximum and minimum values in Table 9.

Table 9: Values listed in this table is a summary of the environmental conditions and the recorded data for 30 runs during the test of the B1 750 N- skate. The table shows average values for CoF calibrated for acceleration to 3.11×10^{-3} with a std. deviation of 0.62×10^{-3}. All the data obtained during testing has been accounted for in this table. The values presented below is a summary of the recorded data found in Appendix A, Table 19

	Friction Force (N)	**Normal load (N)**	**Nominal Contact Pressure (Mpa)**	**Humidity (%)**	**Ice Surface Temperature (°C)**	**Temperature 3mm above Surface (°C)**	**Air Temperature at 0,6m (°C)**	**Temp. of skate during run (°C)**	**CoF cal. For acceleration (10^{-3})**
Average	2.33	715.81	4.02	56.65	-5.62	-1.97	4.62	-1.68	3.11
S.D.	0.51	23.64	0.00	5.54	0.19	0.26	0.37	0.46	0.62
Maximum	3.85	752.90	4.02	60.95	-5.40	-1.20	5.10	-1.00	4.41
Minimum	1.23	671.10	4.02	48.97	-6.20	-2.40	3.70	-2.50	1.73

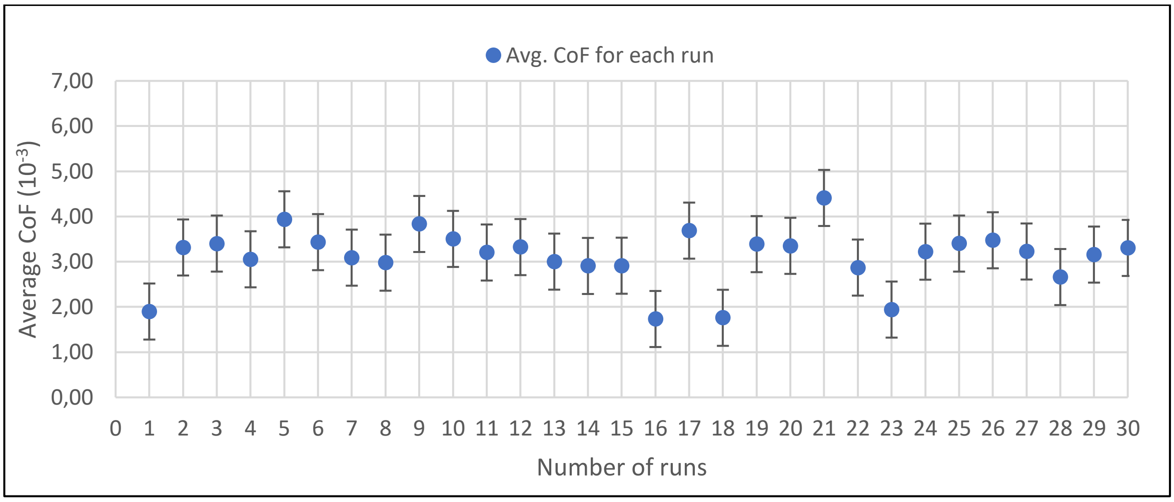

Figure 19: The plot from the average CoF displays small variations between the runs, except from run 16 to 21 where some minor adjustments were made to the tribometer due to a noise during movement. After run 21, new ice was created. The average CoF from this plot is 3.11×10^{-3} (SD=0.62×10^{-3}), with a maximum at 4.41×10^{-3} and the lowest value at 1.73×10^{-3}, for run 21 and 16, respectively. The collection of values is derived from Table 19, found in Appendix A.

4.2.2 B5- skate blade with normal load of 750 N

The B5-skate blade has the second highest measured values of CoF in this field experiment at 3.77x10^{-3}. The peak value of CoF is at 5.05x10^{-3}, and the lowest value is 1.93x10^{-3}, as listed in Table 10. The variation in values of CoF did not reflect a variation in environmental data, and the origin of the scatter is most likely of a systematic failure during testing. The scatter plot is illustrated in Figure 20.

Table 10: Values listed in this table is a summary of the environmental conditions and the recorded data for 26 runs during the test the of B5 750 N-skate. The table show a average value for CoF calibrated for acceleration to 3.77x10^{-3} (SD=0.94). All the data obtained during testing has been accounted for in this table. The values presented below is a summary of the recorded data found in Appendix A, Table 20

	Friction Force (N)	**Normal load (N)**	**CoF cal. For acceleration (x10^{-3})**	**Nominal Contact Pressure (Mpa)**	**Humidity (%)**	**Ice Surface Temperature (°C)**	**Temperature 3mm above Surface (°C)**	**Air Temperature at 0,6m (°C)**	**Temp. of skate during run (°C)**
Average	2.62	711.93	3.77	3.09	61.27	-5.45	-1.87	4.34	-1.28
S.D.	0.61	13.36	0.94	0.00	10.90	0.24	0.36	1.73	0.61
Maximum	3.50	737.95	5.43	3.09	75.90	-5.10	-1.30	5.20	-0.20
Minimum	1.41	691.05	1.99	3.09	48.97	-5.80	-2.50	3.80	-2.30

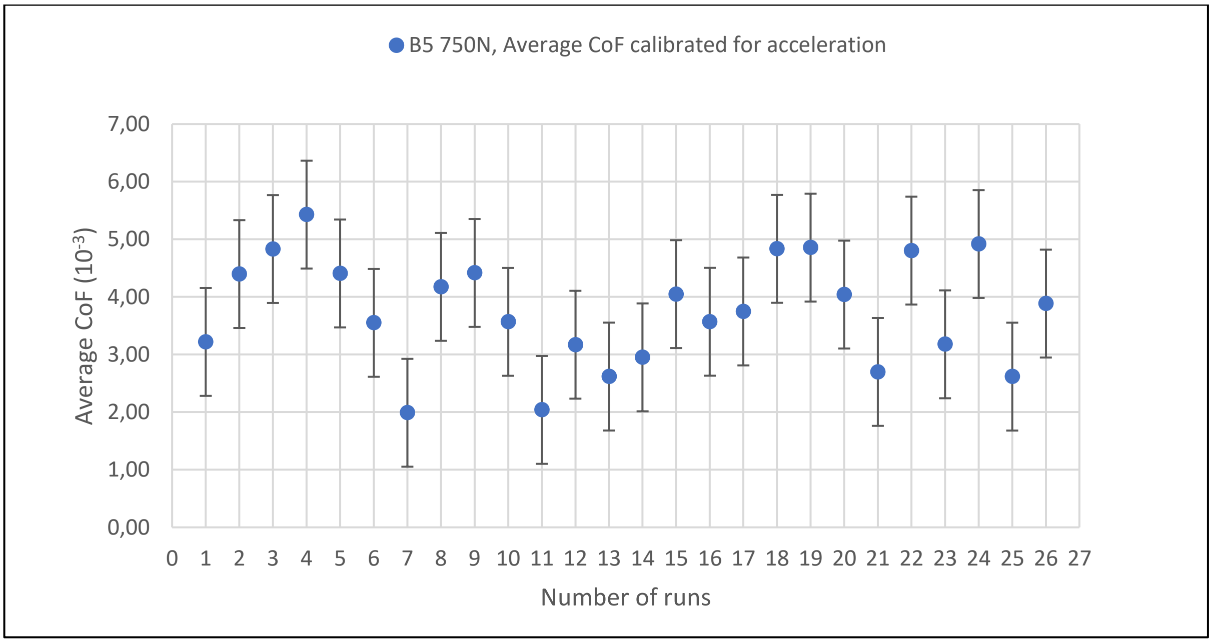

Figure 20: The average CoF from this plot is 3.77x10^{-3} (SD=0.94x10^{-3}), with a maximum at 5.43x10^{-3} and a minimum value at 1.99x10^{-3}. The scatter is obvious, and no correlation to measured environmental data has been found. New ice was created after run No. 8, and no indication of improvement can be seen in the scatter of the values. The error bars represent the standard deviation. The collection of values is derived from Table 20, found in Appendix A.

4.3 Surface roughness test

The surface roughness test was performed on a B3-skate (width of 1.1 mm) with an initial normal load of 750 N, where different surface treatments were applied prior to testing. The different treatments are described in Chapter 3.1.2 and listed in Table 5. Four different treatments were tested with the tribometer, but only two surface treatments, the L4-whetstone and the coarsest whetstone, were studied using a microscope for surface roughness profiles. The purpose of collecting these results was to compare the different surface treatments used by the athletes, where the coarse whetstone was introduced to force a measurable difference, with respect to friction.

4.3.1 Surface roughness profiles

Surface roughness profiles were taken from two skates, one with the L4-surface treatment and the other with the coarse surface treatment. The profiles for the two surface treatments were sampled through a 3D-microscope, where average values of roughness parameters were obtained through sampling 15 values from three different locations for both surface treatments. The different roughness parameters for the two surface treatments on the B3-skate blades are listed in Table 11. The L4-surface treatment displays a smaller average than the coarse surface treatment, with a Rq= 92.85 nm and a Rq= 121.54 nm, respectively.

In Figure 21, pictures of the two surface treatments can be seen. There is a visual difference between the two treatments of the B3-skate. The blade in the upper part of the figure looks to have the smoothest, and the bottom picture looks to have a coarser blade. This correlate well with the roughness parameters listed in Table 11, where a distinct difference between the roughness parameters are found.

Table 11: Surface roughness values of the two surface treatments on the B3-skate were obtained through a 3D-microscope. A total of 15 samples were taken at three different locations within the known contact zone of the skate. Listed below are the average values derived from the three locations on the skate for each surface treatment.

Roughness Parameter	**B3-skate with a very coarse surface treatment**	**B3- skate with L4 surface treatment**	**Unit**	**Description**
Ra	95.55	72.57	nm	Average roughness of profile
Rq	121.54	92.85	nm	Root-Mean-Square roughness of profile
Rt	2615.18	751.88	nm	Maximum peak to valley height of roughness profile
Rz	876.18	381.48	nm	Mean peak to valley height of roughness profile
Rmax	2482.70	715.62	nm	Maximum peak to valley height of roughness profile within a sampling length

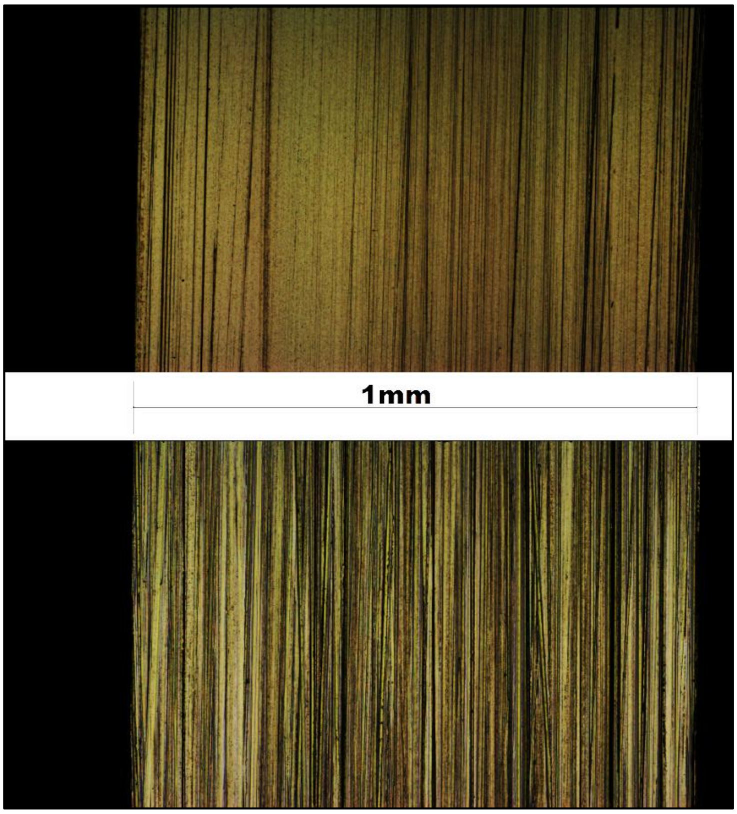

Figure 21: The top picture is of the B3 750 N-skate treated with the L4-whetstone, the bottom picture is from the B3 750 N-skate treated with the coarse whetstone. Both pictures are taken with a 20x zoom at the same location in the contact zone of the blade. The poor quality in lighting of the skate blades is due to the low diaphragm settings in the 3D-microscope, which is necessary on smooth surfaces.

4.3.2 Friction data from testing surface treatment

An outline of friction data for the different skate treatments is summarized in Table 12. There is no clear correlation between surface roughness values and measured average CoF. The uncertainty of the obtained values listed in Table 12, are displayed in Figure 22 and Figure 23.

Table 12: The average values obtained from friction and environmental data during testing of the four surface treatments are listed below. "n", equals the number of runs for each skate blade. The values are derived from their respective Tables 21 through 25, in Appendix A.

Surface treatment	**Friction Force (N)**	**Normal Load (N)**	**CoF cal. For acceleration (10^{-3})**	**Ice temperature 3 mm below surface (°C)**	**Ice temperature 3 mm above surface (°C)**	**Air temperature 60 cm above surface (°C)**
L2 treatment, n=24	2.22	709.39	3.15	-5.78	-1.53	4.60
Coarse treatment, n= 32	2.24	704.53	3.21	-5.98	-2.02	4.33
Smooth treatment, n=15	2.42	723.84	3.51	-5.59	-1.70	4.07
L4 treatment, n=55	2.48	714.44	3.52	-5.63	-1.51	4.54

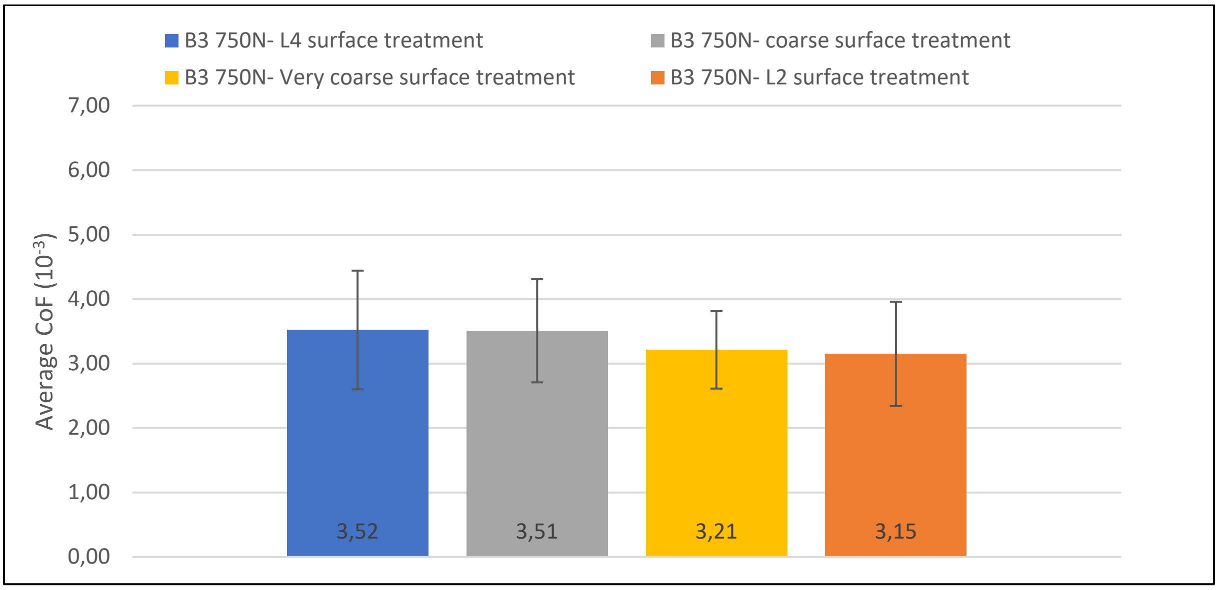

Figure 22: From the diagram above a comparison is made with respect to the average coefficient of friction obtained from the four skates in question. None of the skates show a significant change with relation to surface treatment, there is no trend with respect to the surface roughness of the skate blade. The standard deviation is represented by the error bars for each column, and are greater than 1.0×10^{-3} for all surface treatments.

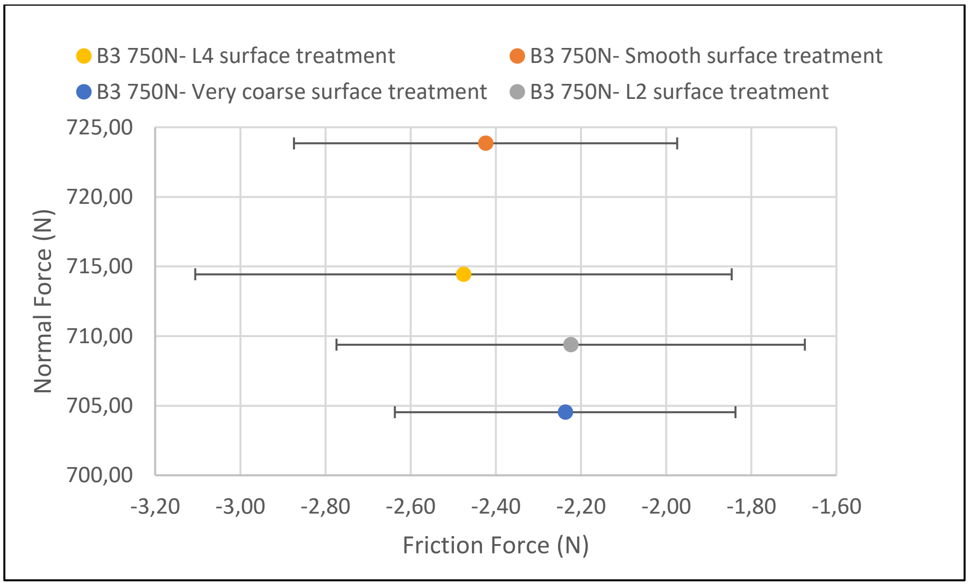

Figure 23: The plot shows no clear correlation between the measured average friction force and the average normal force. The error bars represent the standard deviation in friction force for a given test for each surface treatment. The standard deviation displays a great uncertainty for the validity of the tests.

4.4 Temperature test

The B3-skate was heated up, and loaded with 900 N. A comparison between a non-heated blade and the heated blade can be seen in Figure 24. Friction values from the non-heated blade was obtained from the load test of 900 N, presented in Chapter 4.1.3. The difference in blade temperature seem to have affected the values of friction, as the overall average is higher for the heated blade.

The temperature in the blade is dependent on the heat transfer coefficient of the steel, which is constant. The temperature dissipation of the skate blade into the ice also appear to be constant for all runs when looking at Figure 25, as expected.

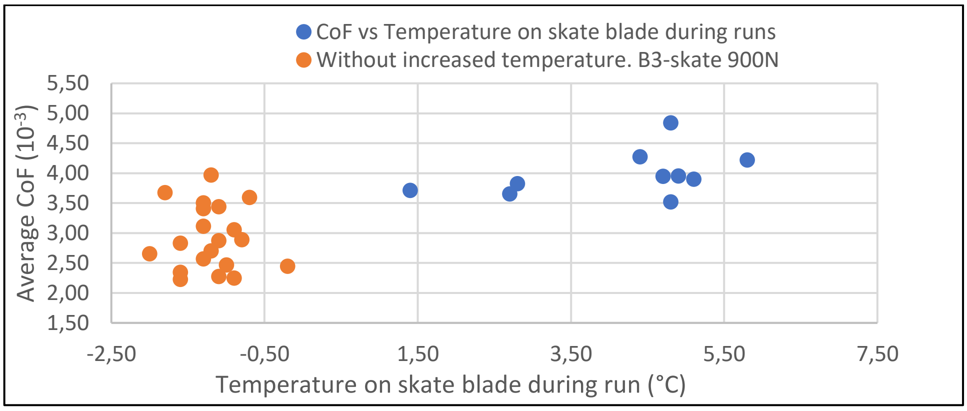

Figure 24: This plot illustrates the temperature of the skate blade and the coherent value of CoF at the time of measurement. Each point represents one run during the temperature test. As seen from the plot, there is no real correlation to the temperature of the skate and the obtained values for coefficient of friction. However, the mean value of CoF for the heated blade is clearly higher, which correlated well with theory presented by De Koning (1992) [3].

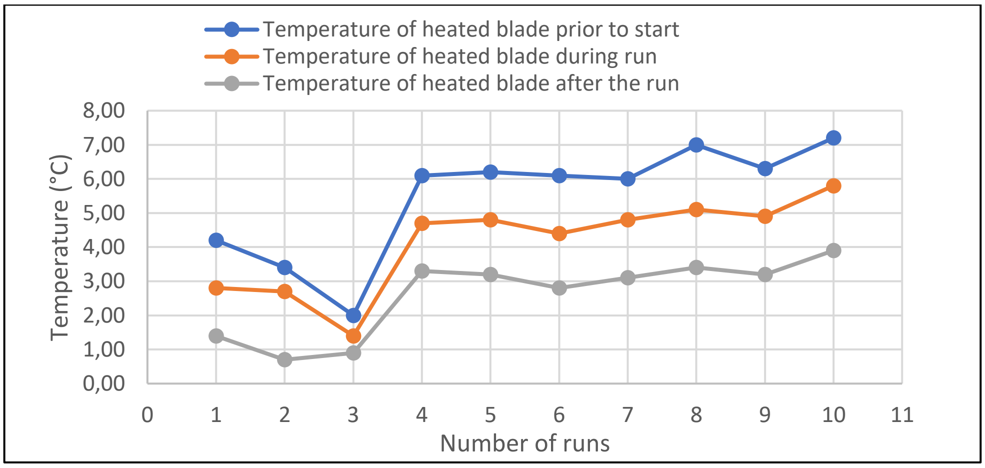

Figure 25: The temperature plot illustrates how the temperature decreases over time during a run from start to stop. The lines between the different runs is added to improve visual comparison of temperature differences an average of 40 seconds is used for one run during the tests. This plot displays an almost constant decrease in temperature for the ten runs of the heated skate blade. The heat loss from the skate is from the air and the contact zone in the ice.

4.5 Comparing friction data

For the skates tested with different loads and different widths, there was a common denominator to be found. In Table 13 a summary of the measured values to derive the nominal contact pressures are listed. The nominal contact area will be the common denominator for which the tests are compared at. An illustration of the correlation between normal load, pressure, and friction can be seen from Figure 26 and Figure 27. The data display a strong correlation between the three parameters.

Table 13: The measured data presented below displays the correlation between the skates of different widths and applied normal load. The data are a summary of averaged values derived from Table 27 in Appendix B. The pressure values were calculated to compare the skates from the different tests with a common denominator, the nominal contact pressure (MPa).

Skate Blade	Load Force (N)	Distance from center to front (cm)	Distance from center to rear contact (cm)	Normal contact length (mm)	Width of skate blade (mm)	Normal area of contact (mm^2)	Nominal Pressure (MPa)/ (N/mm2)
B3 600N	595.69	9.04	10.93	199.63	1.10	219.59	2.73
B3 750N	749.33	8.87	11.29	201.58	1.10	221.74	3.41
B3 900N	896.75	9.40	11.38	207.75	1.10	228.53	3.94
B5 750N	749.40	8.89	10.94	198.30	1.25	247.88	3.09
B1 750N	748.50	8.81	12.02	208.3	0.90	187.47	4.02

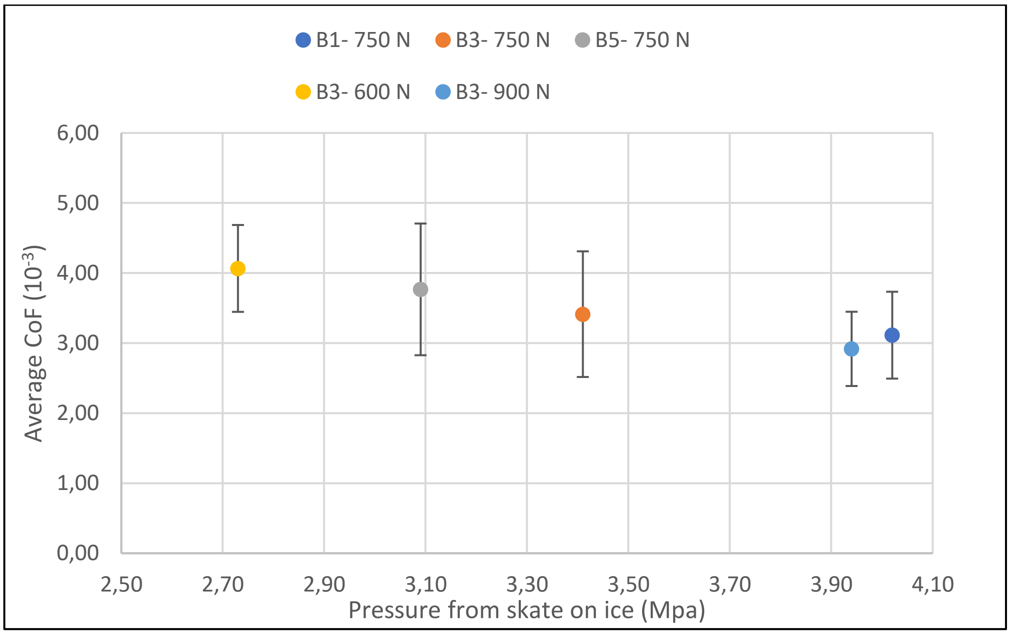

Figure 26: The plot shows the correlation between the measured friction and the nominal contact pressure from the skate on the ice. The values show a close to linear relation between friction and pressure, as pressure increases the coefficient of friction decreases, thus less resistance during movement.

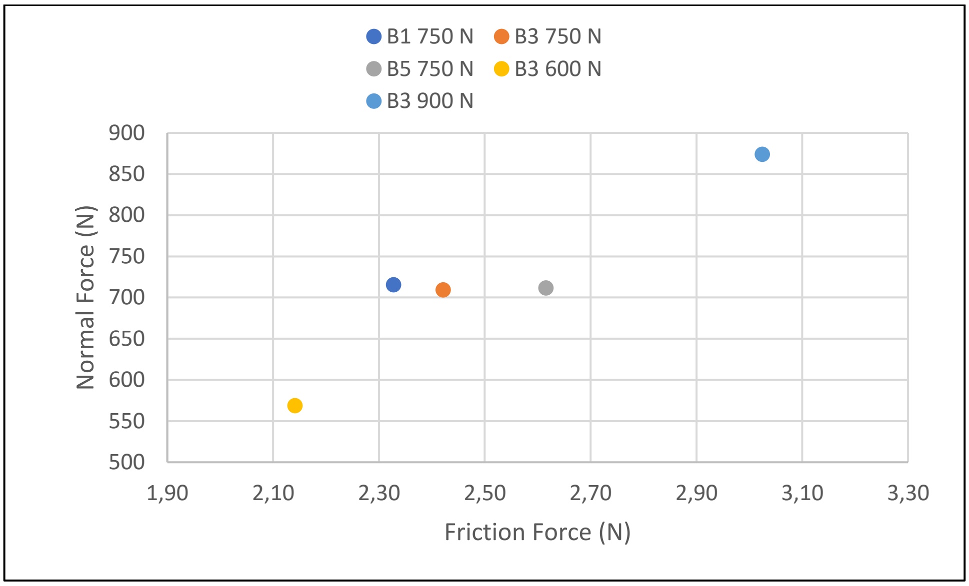

Figure 27: From this plot, a correlation between friction force and normal force can be seen, almost in a linear line, as described by Amonton [7]. B1 750 N, B3 750 N, and B5 750 N all have approximately the same normal load, but vary in friction force. These skates were tested with respect to width, and a clear difference can be seen with relation to nominal contact pressure. B3 600 N and B3 900 N display a close to linear relationship with B3 750 N. The friction force and normal force have not been calibrated for acceleration.

5. Discussion

To understand how the different tribological aspects work in speed skating, there are several main features one must bear in mind. When gliding on ice, a water film will appear between the two interfaces. The thickness of this water film and the skate's capability to displace it will have a significant impact on how friction behaves. Literature on the subject states that the water film can be formed by frictional heat, pressure melting and heat dissipation from the skate to the ice [3, 9, 15, 23]. To quantify all these factors simultaneously, to see how friction behaves, is very difficult in a field experiment like this. The various factors must, therefore, be studied as separate events.

Prior to the data obtained in this field experiment, several trial tests were completed to optimize the tribometer. These trial tests are not included in this master thesis, as the test setup was altered along the way until a satisfactory method for recording data was met. These tests were completed both in a tribology laboratory at NTNU to study surface topography, and during the first two days of the field experiment in Sørmarka Arena.

The field experiment was completed at different times of the day during the period of testing in Sørmarka Arena due to the availability of the test track and time consumed during testing. The possible variety in ice properties due to the variety in time has been controlled by creating new ice when needed and monitoring the environmental parameters.

Deviations in test method, equipment and results will be discussed with respect to the magnitude they could affect the measurements. As mentioned in Chapter 3.2.8, the statistical significance when analysing these results can be quite difficult, as the limiting factor often is unknown. As the purpose of this project was to investigate the friction absorbed by the skate blades relative to each other with a designated tribometer, the possible deviations in equipment and instruments mounted on the tribometer will not be discussed in depth regarding material selections and design, as this is covered in the thesis of Mathis D. Fenre [4].

As there are many parameters affecting the validity of the results in this experiment, only the parameters that have been measured will be thoroughly discussed.

The results from the field experiments will be reflected upon in the proceeding subchapters. The results from the individual tests in Chapter 4 will be discussed, as well as assumptions made for comparable results between the different tests. A comparison to previous research will be made, based on the findings in this report along with the associated assumptions.

5.1 Pressure dependency of friction on ice

In this field experiment, a variety of load and width of skate blades have been tested. The environmental parameters have been close to constant, with little to no visible effect on the measured friction data. The two separate tests have been compared with respect to the nominal contact pressure the skate blade exerts on the ice.

From the two tests, width and normal load, a total of 114 runs on the ice have been completed and recorded by the tribometer. The number of runs for each skate was determined by how probable it was to find a significant change in friction relative to the skates. From the pre-study to this master thesis, an amount of 20 to 30 runs were suggested to find a relative difference between the blades. The amount of runs for each skate was also limited by available time on the ice.

The nominal contact pressure of the five different combinations of width and load range from a pressure of 2.73 MPa to 4.02 MPa, as listed in Table 13.

A linear correlation between the measured coefficient of friction and the nominal contact pressure has been found. The friction's dependence on pressure is illustrated both with respect to average CoF, and for the friction forces obtained at the different loads, as seen in Figure 26 and Figure 27, respectively.

The values of friction data presented in Figure 26 and Figure 27 contradict the theory described in previous literature on the subject [3, 9, 13]. However, this literature does not eliminate the possibility of pressure being a factor of the tribology in speed skating. The literature describes the pressure dependency of friction as an unlikely, or as a non-significant factor, of contribution to reduced friction on ice.

As previously stated, this correlation between nominal contact pressure and friction has been quantified in two different methods. A clear relationship between these two factors has been found and, therefore, unlikely to be of a random order. The data obtained is within the expected area of values, 0.003-0.007, for the coefficient of friction, which strengthens the significance of the data obtained in this field experiment.

The values of CoF for the five tests of load and width, and the four tests of different surface roughness treatments are compared in Figure 28.

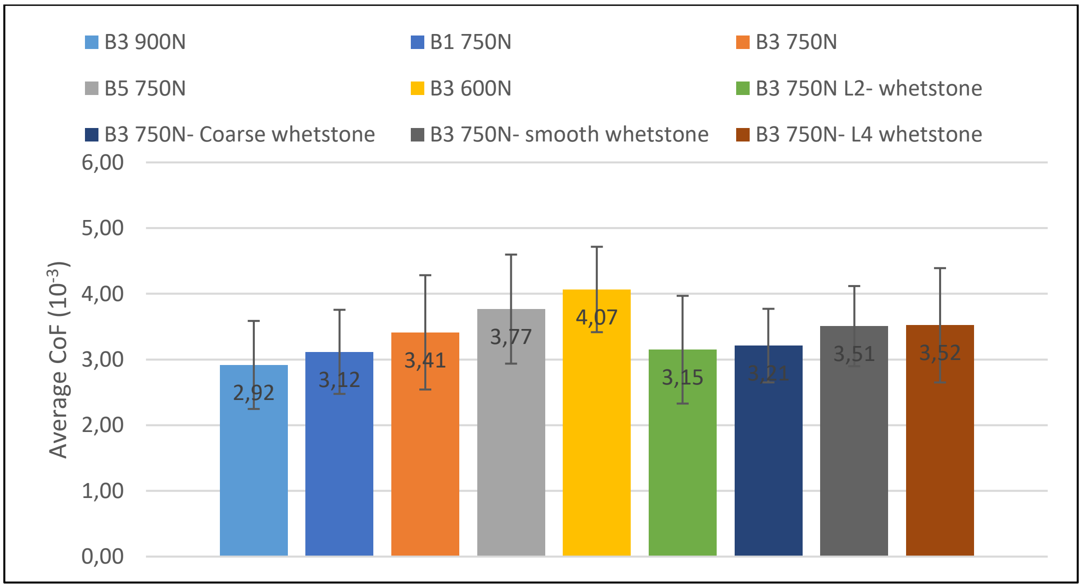

Figure 28: From the diagram, the differences in coefficient of friction for all tests in the field experiment (except the heated B3 900 N- skate blade) are displayed with their associated standard deviations, illustrated by the error bars. The comparison is made to see how the different tests differentiate from each other across different parameters.

As seen in Figure 28, all tests have a high standard deviation compared to the differences in the measured CoF between them. However, the obtained values of friction are within the anticipated values compared to the previous experiments by De Koning [3]. The values obtained throughout the experiment have not been altered. As the “real” CoF for this system is unknown, all values are accounted for, both maximum and minimum values. However, the consequence of this is that the statistical reliability of the results can be poor, which would impact how these data could help the speed skating community in Norway.

5.1.1 A comparison of results to known literature

One of the backgrounds for testing the effect of the nominal contact area is the small amount of literature on the subject. As the science of different sports hold a big secrecy due to competitive reasons, the amount of known experiments or theories on how skates behave on the ice are limited. This test is the first of its kind as far as public records go, therefore, the comparison to literature and theory is difficult.

A relation to literature that can be argued, is the pressure melting effect of skate blades on the ice. As mentioned earlier in Chapter 2.2, theory suggests pressure melting cannot have a significantly influence on friction. However, this has not been tested to this extent, and results show a clear trend of friction dependency on pressure. The theory available from previous experiments of this kind are not concluding with respect to the pressure melting phenomenon, and therefore not unlikely that the effect has a certain magnitude.

Scientists in NASA in a collaboration with the American national team in speed skating, did trial runs for an application method of the whetstone treatment. By using a polishing method from the mirrors of their spacecrafts, they found a reduction in friction by making the surface smoother. It should be noted, that there are no public records of these values or how the experiment of friction measurement was completed [24].

As mentioned in Chapter 2.4, the common understanding when it comes to friction in the sport of speed skating is that a smoother surface will give less friction [10]. However, the results from this master thesis show a correlation between friction and pressure. With respect to the pressure dependency and to the strength limiting of the crystals in the ice, one would expect an optimum surface roughness of the skate blade to be found as a consequence of an optimum real contact area.

The pressure dependency is related to the strength of the ice, which in turn is dependent on the temperature of the ice [3, 14]. As these tests had an ice surface temperature between -6 to -5°C, further comparison of results must be within this area of measurement to have comparable properties in the ice.

De Koning have done similar experiments with similar instruments to record friction data, as mentioned in Chapter 2.2.1. His findings on how friction behaves during the movement of the skate correlates well to the results described in this report. In the middle of the movement of an athlete's skate, the blade is assumed to be close to perpendicular to the ice due to the rolling effect of the athlete's movement. The athlete's skate blade would have a smaller angle relative to the ice when entering and leaving the ice with the blade edge, making the blade plough into the ice, thus increased friction. In De Koning's results displayed in Figure 29, a mean value of CoF close to 0.003 can be seen in the middle of the athlete's movement. This correlate well to the findings in this report as the temperature of around -5°C would resemble the ice properties for tests performed in De Koning's experiment. His results were also at a speed of 8 m/s, which is the mean speed throughout this field experiment in Sørmarka Arena [3].

Where De Koning's research has tested friction on an athlete's skate blade completing several laps on the ice, this experiment has only tested skate blades in one direction of movement with the skate perpendicular to the ice. The comparison gives a strong indication to the successful function of the tribometer, and that a real coefficient of friction has been found for the different skate blades when perpendicular to the ice.

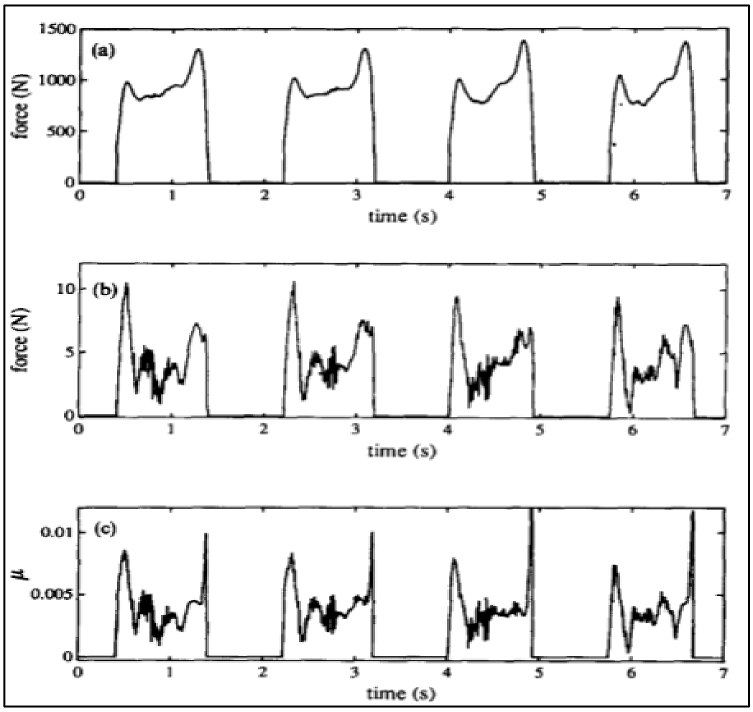

Figure 29: The illustration of friction data gathered from De Koning's experiment in 1992, displaying four strokes of movement through the strait of an ice lane with an ice temperature of -5°C. The graphs show how the movement of the blade influences the friction maximum and minimum values. The first maximum is when the skate hits the ice, the last peak is as the skate leaves the ice [3].

5.1.2 A linear relationship for friction and pressure

From Figure 30 a linear line is drawn showing a close to constant correlation between nominal contact pressure and the friction coefficient. To further relate these data to previous and future research, the equation of the linear regression can be utilized.

By finding the nominal contact pressure of an athlete's skate and adding weight to the equation, an optimal skate width can be found. By measuring an athlete's nominal output pressure on the skate, a correlation can be seen if the linear regression is extrapolated. With a correlation of 99.8 %, extrapolation is well within margin. The same assumption would apply for a different rocking of the skate.

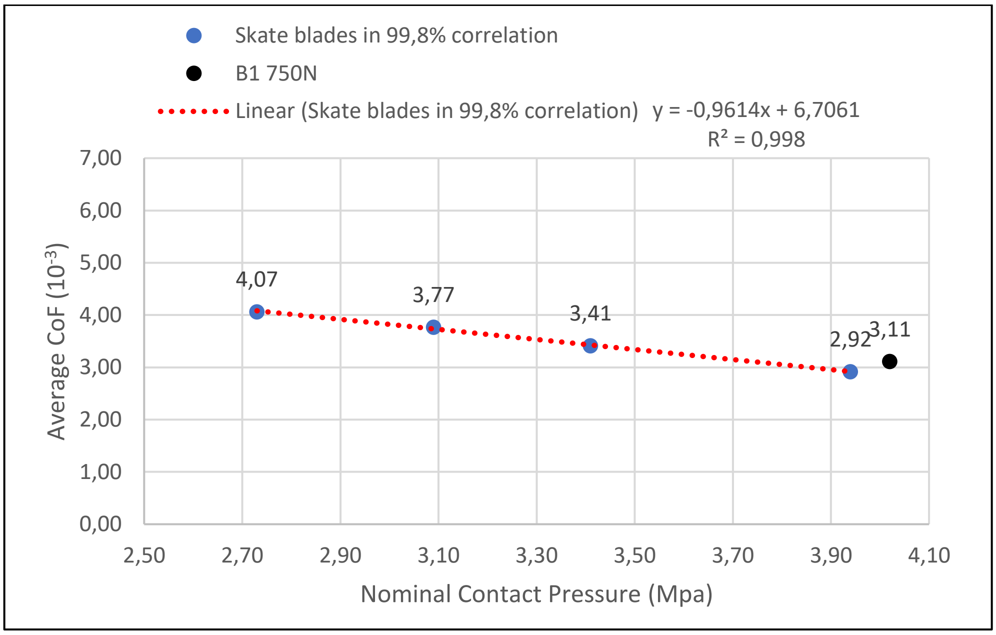

Figure 30: From the plot, a linear line is drawn between the different values of CoF in relation to the nominal contact pressure listed in Table 13. A strong correlation between the points is seen from the R^2*- values of 0,998, which represents the correlation between the individual points, and the equation of the linear line equals to y= -0.9614x + 6.7061.*

The skate in the fray, B1 750 N, is not accounted for in this linear regression. The linear line was set to illustrate the highest possible correlation between the skate blades. When accounting for the B1 750 N- skate, the correlation drops to 95 %.

Why the B1 750 N- skate does not comply with the linear correlation is not easy to point out. An anticipated value of CoF can be found by using the equation from the linear regression Y= 0.9614X+6.7061, where, Y= Coefficient of friction, and, X= 4.02, the nominal contact pressure of the blade:

$$Y = -0.9614 * 4.02 + 6.7061$$

$$Y = 2.84$$

From the collected data, there is nothing to suggest deviations of a single event with an impact big enough to lower the displayed average value of CoF from 3.11 x10^{-3} (SD=0.62) to 2.84x10^{-3}. The maximum and minimum values for this blade, 4.41 and 1.73 respectively (listed in Table 9), could give a plausible explanation to the discovery, but highly unlikely given the standard deviation of 0.62. For an impact of this magnitude to have happened it is more likely to be of a systematic failure during the test. One thing is certain, further investigation is needed, and an optimum contact pressure would be something to pursue in the future.

5.2 Surface roughness effect on measured friction

5.2.1 Surface roughness of whetstone

Analysing the friction data from the different surface treatments of the skate blade proved to be challenging. The differences in friction gives no clear indication to a linear relationship between the different gradients of the whetstone applied to the skate blade. As discussed earlier the L4- whetstone gave reason to think that the contact pressure would be decreased, hence an increase in friction.

When looking at the other gradients of surface treatment in Table 14, the L2- whetstone has the lowest value of CoF but the whetstone does not have a high surface roughness in comparison. This phenomenon also yields for the coarse whetstone, where the surface was so rough it could not be measured by the roughness measuring instrument, but its value for CoF is higher than the L2-whetstone. One could assume an optimal surface treatment as friction shows a dependency on pressure and area of contact, but this is not the case in the measurements found in this test. There is no trend with relation to surface roughness of the whetstone and measured CoF for the skate blade.

Table 14: The different values of measured surface roughness for the whetstones applied to the blade, and the resulting surface roughness values of the two skates which were studied in a microscope are listed alongside the average CoF for the respective skate blades.

Surface Treatment	**Roughness of Whetstone (μm)**	**Average CoF (10^{-3})**	**Surface Roughness Profile of treated skate, Ra/Rq (nm)**
L4- whetstone	0.14	3.52	72.57/92.85
L2- Whetstone	0.28	3.15	unkown
Smooth- Whetstone	10.77	3.51	unkown
Coarse- Whetstone	Unknown	3.11	95.55/121.54

5.2.2 Surface roughness of skate blade

For the surface roughness of the skate blades only two different gradients were studied in a microscope due to practicalities of the skate blades availability after testing. As the L2-whetstone and the smooth-whetstone do not have a surface roughness profile, their values can only be discussed in relation to the roughness of the whetstone applied.

As seen from Table 14, the blades treated with a L4-whetstone and a coarse- whetstone both have a surface roughness profile with distinct differences in Ra- and Rq- values. Values for both roughness and coefficient of friction strengthens the theory of pressure dependence regarding contact area.

Data recorded for the tests of different surface treatments could also correlate to the pressure dependence when looking at a real area of contact. The lesser surface roughness found in the skate blade treated with the L4- whetstone could imply a greater real contact zone as the surface roughness profile is smoother than that of the coarser blade treated with a coarse whetstone. The asperities for the B3 750 N L4- skate blade will be smaller, resulting in a higher area of contact with the ice surface and water film. As experienced in the tests with load and width of the skate blade, a higher contact zone will result in a reduced pressure exerted by the blade. This could be one of the factors affecting the difference in obtained CoF for the two different surface roughness tests.

5.2.3 Lack of data for surface roughness

The lack of data for the surface roughness profile of the L2- and the smooth- whetstone treatment of the blade gives light to speculation. Not knowing how their surface looks like leaves a gap in the results when it comes to the reliability of the tests. By comparing the whetstones' surface roughness, an indication of different roughness values for the blades can be made. Based on the data presented in Table 14, one would expect the L2- whetstone and the coarse- whetstone to have different qualities when applied to the blade. This assumption is not accurate, and it is not quantified by the friction data obtained from these blades during testing. To get a better understanding of this, more research will have to be done.

5.3 Influence of ice temperature on friction

In this field experiment the temperatures recorded for the ice have been stable. The measurements were recorded to control the environmental parameters that could affect the frictional data. The ice surface temperature is interesting in two aspects; the correlation to literature, and the measured CoF's correlation to temperature. These factors will be investigated in this chapter.

5.3.1 The temperature's correlation to literature.

Results from temperature measurements throughout the field experiment does not support a strong correlation to the values for average CoF. From Figure 31 the average temperatures of the ice surface for the different tests are plotted against the average CoF. As the temperature drops from -5.2°C towards -6.0°C, the value for CoF does not seem to correlate very well. Something to keep in mind while looking at the plot is that the different tests are subjected to other factors affecting the friction as well. The amount of temperature data used for the comparison in Figure 31 is not sufficient to see a potential correlation, as the temperature differences in each run is very small. To see a correlation of temperature to friction, a bigger spread of temperature values would be necessary.

When comparing to previous research in the field of tribology on ice, the expected values for coefficient of friction would be close to 3.5×10^{-3} for a temperature of -5.5°C, as seen in Figure 29 [3]. In this field experiment, values for CoF ranged from 3.1×10^{-3} to 4.07×10^{-3}. This is a clear indication that the design of the tribometer was successful in recording expected values for the coefficient of friction.

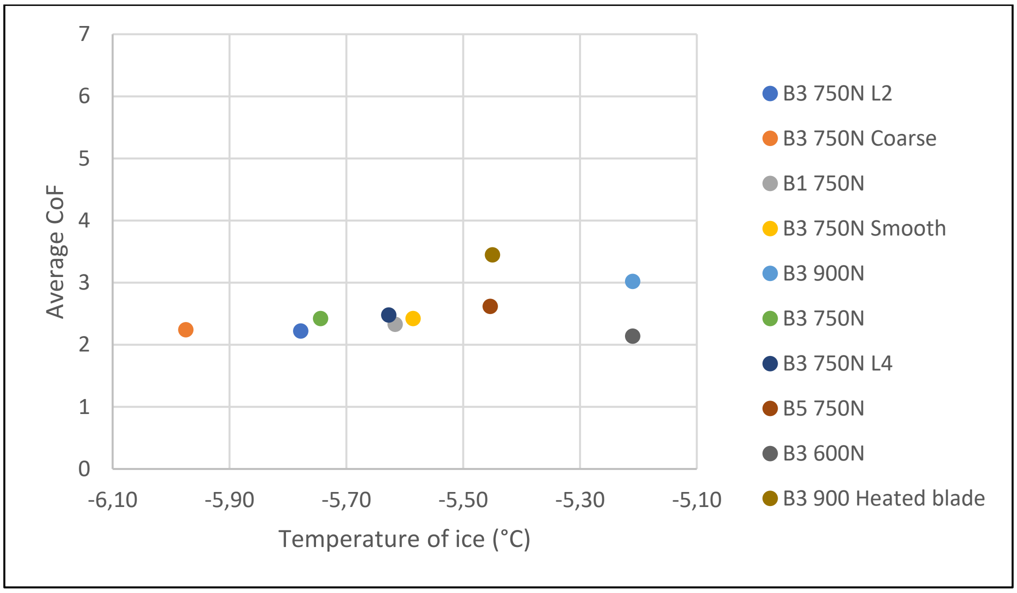

Figure 31: The plot is a summary of the mean ice surface temperatures and coefficient of friction for each test. A correlation between differences in average ice temperature and CoF does not prove itself as a limiting factor of friction behaviour in this experiment.

5.3.2 The temperature's correlation to coefficient of friction

Looking at Figure 31, where all tests are compared to average values for CoF and ice temperature, a correlation between them is hard to justify. The difference in CoF is likely to come from a limiting factor bigger than the average ice temperature. As the variation in temperature is so small, the influence of something bigger must be in play. This could be malfunction of equipment, crosstalk in the load cell or other unquantifiable factors within the tribometer system.

The temperature of the blade should influence friction values, as found in Chapter 4.4 for the temperature test. The elevated temperatures of the skate blade show a significant increase in average CoF. For the heated blade, an average CoF was found to be 3.99×10^{-3} and the non-heated blade had an average of 2.92×10^{-3}. The difference is concluding to the fact, that elevated temperatures of the skate blade do not improve friction. This could come from a water film being too thick, or that the heat dissipation from the blade to the ice is too fast, making the blade plough more into the ice.

For competition purposes, there might be a reduction in friction if an athlete keeps the skate blade cold. As seen from Figure 25 in Chapter 4.4, the temperature drops the longer the skate blade is in contact with the ice. With elevated temperatures increasing the average values for CoF, the competitors should not strive to warm the skates prior to competition.

5.4 Friction differences effect on lap times

To compare the differences in CoF for each skate, a relative comparison can be made to lap times on a skating rink. To compare these lap times to friction, certain assumptions must be made. In the literature, friction from a skate blade is listed as 25-10% of the friction loss when speed skating [3]. To compare the differences of this assumption, the criteria of the total friction loss experienced by the blade will be set to 10%, and a comparison between blades will be made. As the most common skate blade used by the athletes is a width of 1.1 mm with a very smooth polished surface, the reference skate for this comparison will be the B3 750 N-skate with the L4-whetstone treatment.

In Table 15, values of CoF are listed together with their relative differences. Their impact on lap times will be compared to the average lap times from the 2014 Olympic Games in Sochi.

Håvard Bøkko was number 6th in the 1500-meter speed skating competition in Sochi with a total time of 1:45.48, where the winner at 1st place finished a 1:45.006 [25]. Bøkko's average lap time was 35.16 seconds, where as 10% of this time, 3.516 s, have the possibility to be reduced by the friction of the skate blade. One lap time is equal to 500 meters. In Table 15, the gain and loss in time for this performance in Sochi is listed for the skate blades tested in relation to pressure.

Table 15: The listed values for time at the different distances show a potential gain compared to the reference skate B3 750 N. The difference in time is found by multiplying the percentage of improved effect in CoF by the lap time, and as a result a gain in each lap time is displayed. The lap time affected by friction is derived from the Olympic results in 2014 [25].

Skate Blade	Average CoF	Difference in CoF (%)	Time affected by skate blade's friction in lap time (s)	Time saved for 500 m (s)	Time saved for 1000 m (s)	Time saved for 1500 m (s)	Time saved for 3000 m (s)
B1 750 N	0.00311	0.088	3.516	-0.309	-0.619	-0.928	-1.237
B3 750 N	0.00341	0.000	3.516	0.000	0,000	0,000	0,000
B5 750 N	0.00377	-0.106	3.516	0.371	0.742	1.114	1.485
B3 600 N	0.00407	-0.194	3.516	0.681	1.361	2.042	2.722
B3 900 N	0.00292	0.144	3.516	-0.505	-1.010	-1.516	-2.021

At the 1500-meter finish line Håvard Bøkko could have a potential gain by 0.928 seconds with the B1 750 N-skate (0.15 mm smaller width of the skate) if it was possible to utilize the full potential around the course. To find relative differences between perpendicular skates, and comparing them to how an athlete’s time is affected are two different sciences. Therefore, a comparison to a potential gain in time, by the improvement of skate blade utilization, will have to be further evaluated.

5.5 The behaviour of the tribometer

As mentioned in the introduction of this report, this field experiment is a continuation of a tribometer that was built by Mathis D. Fenre the fall of 2016 at NTNU [4]. The tribometer was originally designed for testing skis, and alterations to the design and function of the tribometer had to made. The change of design and function was primarily done to the connection points of the skate blades, and to the stability of the whole system when put on ice. The aluminium beams in the framework were replaced to fit more instruments, and to have a centre of gravity closer to the ground. The software was modified to obtain reliable data in an easier way, and a wireless transfer of data from the tribometer was added. In the succeeding chapters, the function and reliability of the tribometer will be further discussed

5.5.1 Angle of load cell relative to direction of movement

One of the main features which turned out to be difficult to maintain was the angle between the skate blade in question and the four supporting skates on each corner. When a skate blade was replaced by another, the angle between the blades were checked to confirm a parallel setting of the blade. However, the blade replacing the other would sometimes have a change in angle relative to the direction of movement. The procedure of realigning the skate parallel to the supporting skates was done with a ruler, confirming the equal distance from the blade in the middle to the supporting skates at both the front and back. The limiting factor of this procedure was to have the distances equal to the closest millimetre. This proved challenging for some skates, and alterations to the tribometer was done prior to testing a new skate.

A consequence of not having the exact same distance between the skate blade in question and the four supporting blades is that the angle relative to the direction of movement can affect friction forces. Lateral forces would be obtained in the Y-direction of the loading cell. These forces would imply a signal crossing, where some of the friction data obtained through the X-direction of the loading cell would be obtained in the Y-direction instead. This factor would affect the friction data, but the deviation would most likely be very small compared to the forces induced by the operator of the tribometer when trying to steer the tribometer in a straight line.

Attempting to quantify the difference of one millimetre in the front and back of the blade, relative to the parallel supporting skates, the angle of the load cell relative to the direction of movement would change by 0,14°, resulting in a 0,15% deduction of friction force. With a friction force of 3 N and a normal force of 750 N as an example, the magnitude of 0,15% would have an impact on the CoF by $6x10^{-6}$.

During the field experiment this problem was evaluated, but no exemplary solution was found. It was concluded that for relative tests, the difference in over 300 runs would not be a significant change, and the tribometer was not altered as a response to this. The distance between the parallel blades were set to the closest millimetre.

5.5.2 The operators influence on friction measurement

The tribometer was controlled by an operator behind it to make sure it ran in a straight forward line, and to hold the tribometer at a constant speed. The operator had a great impact on how the tribometer behaved, in relation to the tribometer's direction of movement. The operator would hold the wire in one arm, and push the tribometer forward with the other. The forces applied to the tribometer by operator would go in both lateral and normal directions, as the lever was placed one meter behind the centre of the tribometer, as illustrated in Figure 32.

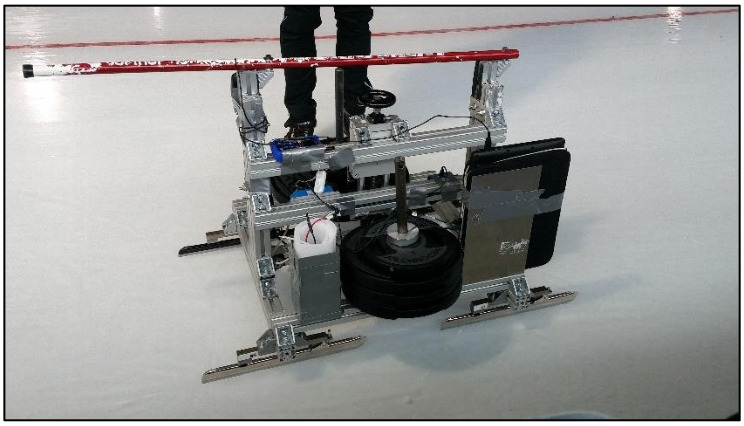

Figure 32: In this photography, the direction of movement for the tribometer is to the right. The red bar on top of the tribometer is referred to as the «lever», and is where the operator would hold on to the tribometer.

The applied force used to keep the tribometer in place would influence the friction measurements. The operator's influence on the friction recordings are not underestimated in this experiment, but has been difficult to quantify. An assumption to this problem was made during testing. The operator would try to the best of his ability to have as little impact as possible on the tribometer, and through a series of 300 runs, the effect was considered negligible. By this assumption, a generalization could be made for the tests relevant to each other.

5.5.3 Effect of supporting skates on friction measurement

The four supporting skates had a width of 1.1 mm on the skate blade with an L4- whetstone treatment on their surfaces. Their impact on recorded friction would not be of significance in the relative tests, as their settings were not altered during the entirety of this field experiment. The relative difference in each run which could be caused by the supporting skates is not quantifiable due to their small impact, and have been regarded as such when analysing friction data.

However, their impact on the actual friction data would be of a certain size. The friction the supporting skates would encounter during a run would affect the real friction value experienced by the load cell. This, in addition to the angle of the blade being perpendicular to the ice and the operator controlling the tribometer, would have the friction measurement recorded by the load cell to be slightly reduced.

5.6 Statistical analysis of friction data

When analysing friction data with such small numbers and small differences between them, the deviations are big in comparison. In the following subchapters explanations to how the deviations have been quantified will be presented.

5.6.1 Effect of acceleration and retardation on friction

During the preliminary tests in the first two days of the field experiment, an observation was made toward acceleration within the measuring zone. The wire used for pulling the tribometer (weighing about 200 kg with the operator) was elastic to some degree, giving room for acceleration and retardation in the measurement zone when stretched. This, in addition to the operator trying to hold the wire tight, gave implications to the friction measurement.

A clear correlation between the acceleration of the tribometer and the measured friction force could be seen from the recorded data. When accelerating the friction values would go up, and opposite for retardation. As the field experiment was designed for a constant speed, this could not be overlooked. To make up for the difference in friction data, the acceleration and retardation values were obtained from the photocells. As described in Chapter 3.2.2, the CoF was calibrated for acceleration values, and resulted in slightly lower or higher values of CoF than the original values depending on the mean acceleration or retardation gradient.

As the acceleration had an impact on the design and function of the tribometer, certain assumptions have been made with respect to the entirety of the field experiment. As these are relative tests, the difference in acceleration and retardation for all tests were thought to even out through the mean values obtained in the experiment. The values have been regarded as such when analysing the raw data.

5.6.2 Statistical analysis by using Microsoft Excel

For analysing the raw data obtained from the loading cell, several equations and statistical tests have been done to filter out the most reliable data. With over 300 runs, and each run lasting for approximately 40 seconds, the data obtained with a sample frequency of 100 samples per second amounts to $1.2x10^6$ lines of raw data from the load cell. To control this amount, Microsoft Excel was used as a tool to filter out about two seconds of friction data from the measurement zone. The analyses and results presented in this thesis, are from these two seconds.

In the attachment of this thesis lies two example spread sheets from Microsoft Excel, where one is for the analysing of raw data from the B1 750N- skate, and the other spread sheet displays how filtered raw data of this skate was summarized and interpreted to compare values for the different skate blades.

5.7 Reflections on future research

For a sport to develop in efficiency, speed, or tactics, new equipment or utilization of it, often plays a certain part. To develop equipment and study friction behaviour, new methods and problems must be assessed to find a small advantage for athletes in the sport. For the sport of speed skating, and especially the friction experienced by the skates, it will be important to figure out which elements of the sport that have been studied previously, and what the results were.

Reliable data when measuring friction on speed skates depend very much on the design of the test setup. For example, to find differences within surface treatments of the skate blade, the room for error must be very small. The low coefficient of friction at around 0.003, will be affected by too many parameters at a time to control which parameter is the governing factor of change in the system. To have control of the governing factor of friction is key to measuring relative differences. At the same time, not knowing the real coefficient of friction for the given system, will be a challenge when comparing results to other tests and methods.

In this field experiment, relative differences between skate blades have been put to its test with a tribometer designed for this specific experiment. Alterations to the tribometer could be made with respect to the relative differences between two blades. If a system, similar to the one used for this field experiment, with two load cells and two different test blades were put on the ice with a more accurate method of controlling the direction of the tribometer, the reliability of results could be highly improved.

The amount of runs necessary to measure differences between the skates, 20 to 30 runs, is suggested sufficient in testing normal load and width of the skate blade. For the surface treatment tests however, the number of runs might not have been sufficient. Deviations in the average coefficient of friction were higher than expected, and, therefore, a higher number of runs is suggested in future research.

The biggest challenge of doing research within sport sciences, is the limited amount of shared knowledge regarding previous research. Not knowing if the research will be worthwhile for the athletes, plays a big part in how new methods or experiments turn out. If competitors are already aware, then the edge of equipment progress could be lost.

6. Conclusions

The tribometer has proven a qualitative function, and differences within test subjects has been found. The field experiment has proved successful in measuring expected values for a coefficient of friction in relation to previous research regarding speed and temperature values experienced during testing.

114 individual tests have been successfully completed for both load and width of the skate blades. A strong correlation between friction and nominal contact pressure has been found, where higher values of nominal contact pressure equals for a lower coefficient of friction. The measured values of coefficient of friction ranged from 0.003 (SD=0.0005) to 0.004 (SD=0.0011) for a nominal contact pressure at 3.94 to 2.73MPa, respectively. The relative differences in the width of the skate blade are of a magnitude which would affect an athlete's total time in competitions.

Friction measurements from different surface roughness treatments of the skate blade was found as inconclusive. Though, as the surface roughness of a skate will influence the real area of contact, and friction is suggested to be dependent of nominal contact pressure, an optimum surface roughness is to be expected, and is suggested to be further evaluated.

Temperature values of the ice surface correlate to previous research, where a CoF of 3.5×10^{-3} can be expected for a temperature of -6 to -5°C, as it were in this field experiment.

Temperature values for skate blades has not proven a correlation to the variation of CoF values in the experiment. Elevated temperatures of the skate blade do however correlate to literature suggesting an optimum ice surface temperature between -9 and -6°C. Heating a skate blade to temperatures of 6°C was found to increase the value of CoF by a factor of 1.0×10^{-3}.

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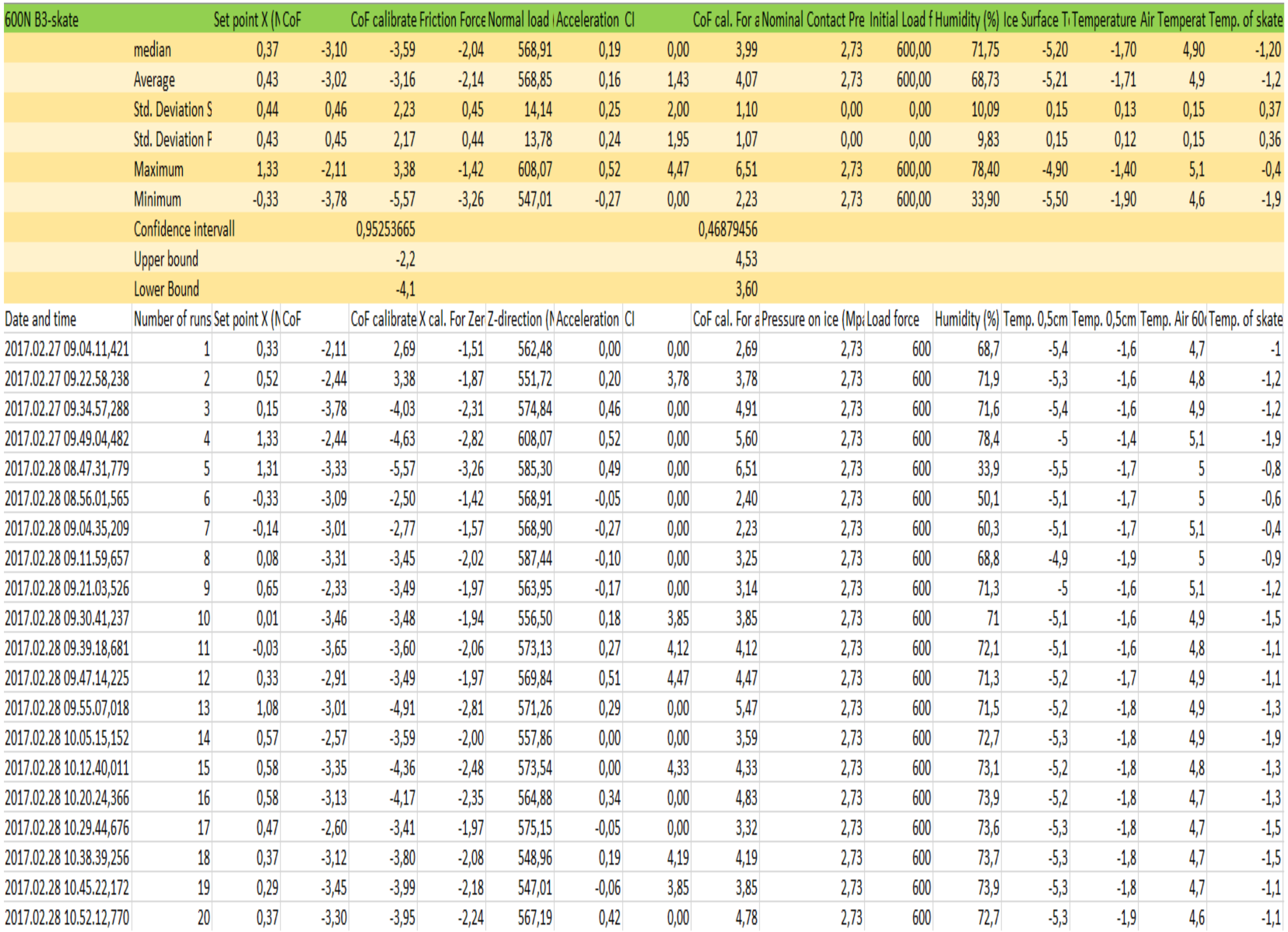
Appendix A

The following tables are summarized values of friction and environmental data for the individual runs of each test. Each table represents average values of each run retrieved from the raw data obtained in the field experiment.

Table 16: The table contains summarized values of raw friction data obtained in the field experiment for the B3 600 N-skate blade with a L4-surface

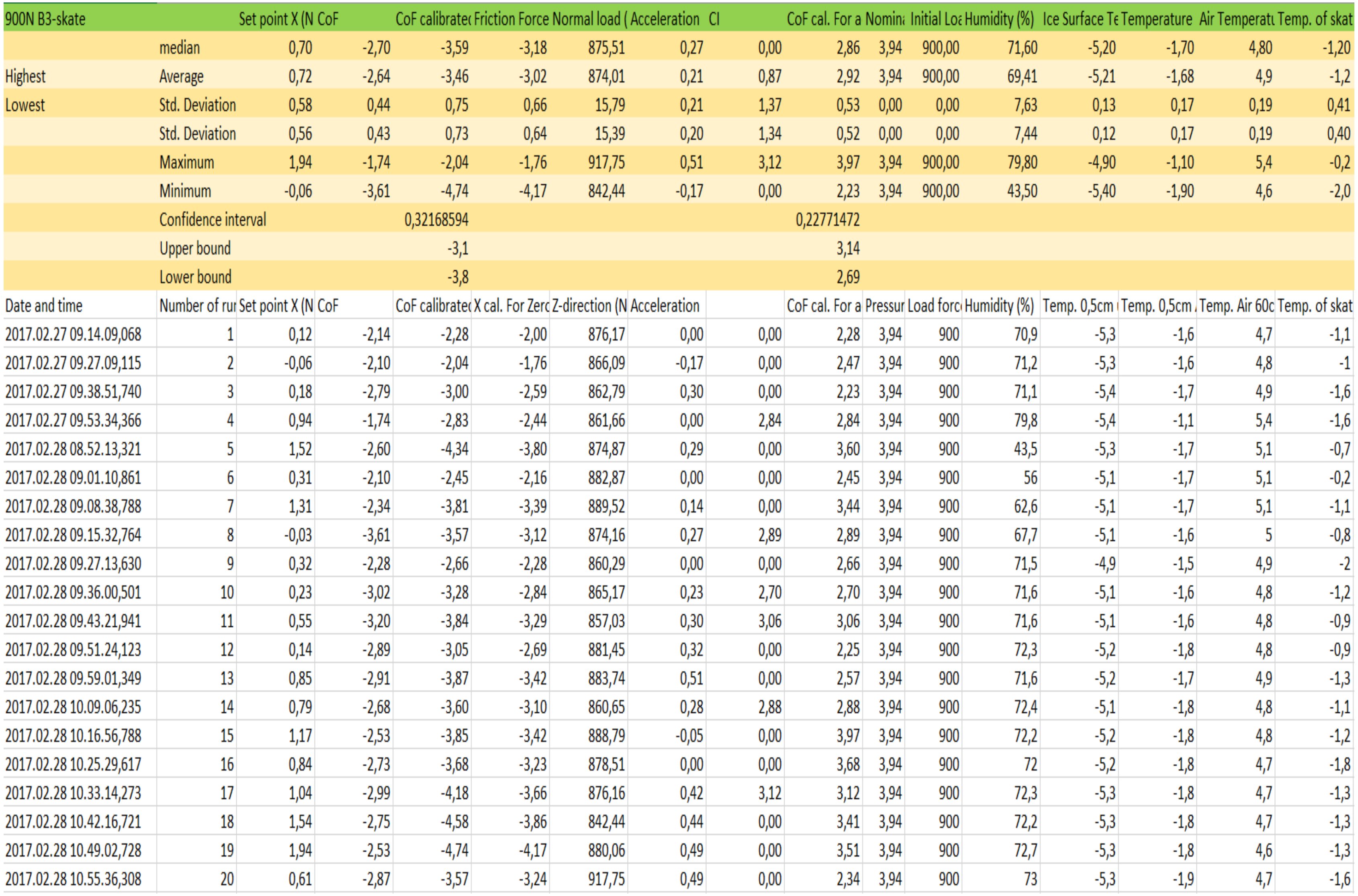


600N B3-skate		Set point X (N	CoF	CoF calibrate	Friction Force	Normal load (	Acceleration	Cl	CoF cal. For a	Nominal Contact Pre	Initial Load f	Humidity (%)	Ice Surface T	Temperature	Air Temperat	Temp. of skate
	median	0,37	-3,10	-3,59	-2,04	568,91	0,19	0,00	3,99	2,73	600,00	71,75	-5,20	-1,70	4,90	-1,20
	Average	0,43	-3,02	-3,16	-2,14	568,85	0,16	1,43	4,07	2,73	600,00	68,73	-5,21	-1,71	4,9	-1,2
	Std. Deviation S	0,44	0,46	2,23	0,45	14,14	0,25	2,00	1,10	0,00	0,00	10,09	0,15	0,13	0,15	0,37
	Std. Deviation F	0,43	0,45	2,17	0,44	13,78	0,24	1,95	1,07	0,00	0,00	9,83	0,15	0,12	0,15	0,36
	Maximum	1,33	-2,11	3,38	-1,42	608,07	0,52	4,47	6,51	2,73	600,00	78,40	-4,90	-1,40	5,1	-0,4
	Minimum	-0,33	-3,78	-5,57	-3,26	547,01	-0,27	0,00	2,23	2,73	600,00	33,90	-5,50	-1,90	4,6	-1,9
	Confidence intervall			0,95253665					0,46879456							
	Upper bound			-2,2					4,53							
	Lower Bound			-4,1					3,60							
Date and time	Number of runs	Set point X (N	CoF	CoF calibrate	X cal. For Zer	Z-direction (N	Acceleration	Cl	CoF cal. For a	Pressure on ice (Mpa	Load force	Humidity (%)	Temp. 0,5cm	Temp. 0,5cm	Temp. Air 60c	Temp. of skate
2017.02.27 09.04.11,421	1	0,33	-2,11	2,69	-1,51	562,48	0,00	0,00	2,69	2,73	600	68,7	-5,4	-1,6	4,7	-1
2017.02.27 09.22.58,238	2	0,52	-2,44	3,38	-1,87	551,72	0,20	3,78	3,78	2,73	600	71,9	-5,3	-1,6	4,8	-1,2
2017.02.27 09.34.57,288	3	0,15	-3,78	-4,03	-2,31	574,84	0,46	0,00	4,91	2,73	600	71,6	-5,4	-1,6	4,9	-1,2
2017.02.27 09.49.04,482	4	1,33	-2,44	-4,63	-2,82	608,07	0,52	0,00	5,60	2,73	600	78,4	-5	-1,4	5,1	-1,9
2017.02.28 08.47.31,779	5	1,31	-3,33	-5,57	-3,26	585,30	0,49	0,00	6,51	2,73	600	33,9	-5,5	-1,7	5	-0,8
2017.02.28 08.56.01,565	6	-0,33	-3,09	-2,50	-1,42	568,91	-0,05	0,00	2,40	2,73	600	50,1	-5,1	-1,7	5	-0,6
2017.02.28 09.04.35,209	7	-0,14	-3,01	-2,77	-1,57	568,90	-0,27	0,00	2,23	2,73	600	60,3	-5,1	-1,7	5,1	-0,4
2017.02.28 09.11.59,657	8	0,08	-3,31	-3,45	-2,02	587,44	-0,10	0,00	3,25	2,73	600	68,8	-4,9	-1,9	5	-0,9
2017.02.28 09.21.03,526	9	0,65	-2,33	-3,49	-1,97	563,95	-0,17	0,00	3,14	2,73	600	71,3	-5	-1,6	5,1	-1,2
2017.02.28 09.30.41,237	10	0,01	-3,46	-3,48	-1,94	556,50	0,18	3,85	3,85	2,73	600	71	-5,1	-1,6	4,9	-1,5
2017.02.28 09.39.18,681	11	-0,03	-3,65	-3,60	-2,06	573,13	0,27	4,12	4,12	2,73	600	72,1	-5,1	-1,6	4,8	-1,1
2017.02.28 09.47.14,225	12	0,33	-2,91	-3,49	-1,97	569,84	0,51	4,47	4,47	2,73	600	71,3	-5,2	-1,7	4,9	-1,1
2017.02.28 09.55.07,018	13	1,08	-3,01	-4,91	-2,81	571,26	0,29	0,00	5,47	2,73	600	71,5	-5,2	-1,8	4,9	-1,3
2017.02.28 10.05.15,152	14	0,57	-2,57	-3,59	-2,00	557,86	0,00	0,00	3,59	2,73	600	72,7	-5,3	-1,8	4,9	-1,9
2017.02.28 10.12.40,011	15	0,58	-3,35	-4,36	-2,48	573,54	0,00	4,33	4,33	2,73	600	73,1	-5,2	-1,8	4,8	-1,3
2017.02.28 10.20.24,366	16	0,58	-3,13	-4,17	-2,35	564,88	0,34	0,00	4,83	2,73	600	73,9	-5,2	-1,8	4,7	-1,3
2017.02.28 10.29.44,676	17	0,47	-2,60	-3,41	-1,97	575,15	-0,05	0,00	3,32	2,73	600	73,6	-5,3	-1,8	4,7	-1,5
2017.02.28 10.38.39,256	18	0,37	-3,12	-3,80	-2,08	548,96	0,19	4,19	4,19	2,73	600	73,7	-5,3	-1,8	4,7	-1,5
2017.02.28 10.45.22,172	19	0,29	-3,45	-3,99	-2,18	547,01	-0,06	3,85	3,85	2,73	600	73,9	-5,3	-1,8	4,7	-1,1
2017.02.28 10.52.12,770	20	0,37	-3,30	-3,95	-2,24	567,19	0,42	0,00	4,78	2,73	600	72,7	-5,3	-1,9	4,6	-1,1

Table 17: *The table contains summarized values of raw friction data obtained in the field experiment for the B3 750 N-skate blade with a L4-surface treatment.*

B3 Breddetest		Set point X (N)	CoF	CoF calibrate	Friction Force	Normal load (N	Acceleration	CI	CoF cal. For a	Nominal Contact Pre	Initial Load f	Humidity (%)	Ice Surface T	Temperature	Air Temperat	Temp. of ska
	median	-0,02	-3,28	-3,25	-2,36	709,29	-0,05		3,39	3,41	750,00	55,74	-5,70	-1,90	4,40	-1,50
	Average	0,10	-3,28	-3,41	-2,42	709,55	0,00		3,41	3,41	750,00	55,74	-5,74	-2,06	4,4	-1,6
	Std. Deviation S	0,54	0,82	0,87	0,62	15,91	0,19		0,90	0,00	0,00	6,32	0,06	0,24	0,35	0,52
	Std. Deviation F	0,52	0,80	0,85	0,60	15,46	0,19	1,69	0,87	0,00	0,00	6,15	0,06	0,23	0,34	0,50
	maximum	1,65	-2,00	-2,18	-1,55	736,07	0,37		5,50	3,41	750,00	61,88	-5,70	-1,80	4,8	-0,3
	mininum	-0,72	-4,68	-5,46	-3,87	663,35	-0,31		2,10	3,41	750,00	49,59	-5,90	-2,40	3,7	-2,3
	Confidence interval			0,39220601					0,40301376							
	Upper bound			-3,0					3,82							
	Lower Bound			-3,8					3,01							
Date and time	Number of runs	Set point X (N)	CoF	CoF calibrate	X cal. For Zer	Z-direction (N)	Acceleration	CI	CoF cal. For a	Pressure on ice (Mp	Load force	Humidity (%)	Temp. 0,5cm	Temp. 0,5cm	Temp. Air 60	Temp. of ska
2017.02.25 08.49.48,	1	0,35	-2,21	-2,73	-1,81	663,35	-0,17	0,00	2,61	3,41	750	49,59	-5,8	-2,4	4,1	-0,3
2017.02.25 08.52.48,	2	-0,15	-3,77	-3,56	-2,46	692,01	0,00	3,55	3,55	3,41	750	49,59	-5,8	-2,3	4,1	-1,5
2017.02.25 08.57.49,	3	-0,26	-2,56	-2,18	-1,55	709,89	-0,12	0,00	2,10	3,41	750	49,59	-5,7	-2,3	4,1	-2,3
2017.02.25 09.00.45,	4	-0,32	-4,68	-4,24	-3,03	714,03	0,34	0,00	4,46	3,41	750	49,59	-5,8	-2,3	3,7	-2,3
2017.02.25 09.03.53,	5	-0,72	-3,88	-2,86	-2,00	698,92	0,11	0,00	2,94	3,41	750	49,59	-5,8	-2,3	4,1	-2,3
2017.02.25 09.06.47,	6	-0,14	-3,42	-3,22	-2,30	712,37	-0,06	3,19	3,19	3,41	750	49,59	-5,7	-2,3	4,1	-2,1
2017.02.25 09.10.15,	7	-0,02	-3,86	-3,84	-2,80	731,93	-0,06	3,80	3,80	3,41	750	49,59	-5,8	-2,3	4,2	-2,3
2017.02.25 09.13.45,	8	1,65	-3,13	-5,46	-3,87	708,68	0,06	0,00	5,50	3,41	750	49,59	-5,8	-2,3	4,2	-2
2017.02.25 09.16.56,	9	-0,23	-4,60	-4,27	-3,01	701,56	-0,06	0,00	4,25	3,41	750	49,59	-5,9	-1,9	4,2	-1,3
2017.02.25 20.58.48,	10	0,74	-2,34	-3,39	-2,40	707,74	0,05	3,42	3,42	3,41	750	61,88	-5,7	-1,9	4,8	-1,5
2017.02.25 21.05.51,	11	0,22	-2,00	-2,31	-1,67	723,84	0,30	0,00	2,51	3,41	750	61,88	-5,7	-1,9	4,7	-1,5
2017.02.25 21.09.19,	12	0,13	-3,04	-3,22	-2,37	736,07	0,37	3,46	3,46	3,41	750	61,88	-5,7	-1,9	4,8	-1,5
2017.02.25 21.12.30,	13	-0,25	-3,63	-3,28	-2,35	715,53	0,15	3,39	3,39	3,41	750	61,88	-5,7	-1,9	4,7	-1,3
2017.02.25 21.15.57,	14	0,59	-4,13	-4,96	-3,50	706,76	-0,11	0,00	4,87	3,41	750	61,88	-5,7	-1,8	4,8	-1,2
2017.02.25 21.19.05,	15	0,31	-2,33	-2,76	-2,00	722,94	-0,31	0,00	2,56	3,41	750	61,88	-5,7	-1,8	4,7	-1,4
2017.02.25 21.24.45,	16	-0,03	-2,63	-2,59	-1,85	711,94	-0,15	0,00	2,50	3,41	750	61,88	-5,7	-1,8	4,7	-1,4
2017.02.25 21.28.08,	17	-0,47	-3,78	-3,11	-2,19	705,79	-0,27	0,00	2,93	3,41	750	61,88	-5,7	-1,8	4,6	-1,5
2017.02.25 21.31.33,	18	0,34	-2,96	-3,44	-2,43	708,61	-0,05	3,40	3,40	3,41	750	61,88	-5,7	-1,8	4,7	-1,9

Table 18: The table contains summarized values of raw friction data obtained in the field experiment for the B3 900 N-skate blade with a L4-surface treatment.



900N B3-skate		Set point X (N	CoF	CoF calibrate	Friction Force	Normal load (	Acceleration	CI	CoF cal. For a	Nomin	Initial Loa	Humidity (%)	Ice Surface Te	Temperature	Air Temperatu	Temp. of skat
	median	0,70	-2,70	-3,59	-3,18	875,51	0,27	0,00	2,86	3,94	900,00	71,60	-5,20	-1,70	4,80	-1,20
Highest	Average	0,72	-2,64	-3,46	-3,02	874,01	0,21	0,87	2,92	3,94	900,00	69,41	-5,21	-1,68	4,9	-1,2
Lowest	Std. Deviation	0,58	0,44	0,75	0,66	15,79	0,21	1,37	0,53	0,00	0,00	7,63	0,13	0,17	0,19	0,41
	Std. Deviation	0,56	0,43	0,73	0,64	15,39	0,20	1,34	0,52	0,00	0,00	7,44	0,12	0,17	0,19	0,40
	Maximum	1,94	-1,74	-2,04	-1,76	917,75	0,51	3,12	3,97	3,94	900,00	79,80	-4,90	-1,10	5,4	-0,2
	Minimum	-0,06	-3,61	-4,74	-4,17	842,44	-0,17	0,00	2,23	3,94	900,00	43,50	-5,40	-1,90	4,6	-2,0
	Confidence interval			0,32168594					0,22771472							
	Upper bound			-3,1					3,14							
	Lower bound			-3,8					2,69							
Date and time	Number of ru	Set point X (N	CoF	CoF calibrate	X cal. For Zer	Z-direction (N	Acceleration		CoF cal. For a	Pressur	Load forc	Humidity (%)	Temp. 0,5cm	Temp. 0,5cm	Temp. Air 60c	Temp. of skat
2017.02.27 09.14.09,068	1	0,12	-2,14	-2,28	-2,00	876,17	0,00	0,00	2,28	3,94	900	70,9	-5,3	-1,6	4,7	-1,1
2017.02.27 09.27.09,115	2	-0,06	-2,10	-2,04	-1,76	866,09	-0,17	0,00	2,47	3,94	900	71,2	-5,3	-1,6	4,8	-1
2017.02.27 09.38.51,740	3	0,18	-2,79	-3,00	-2,59	862,79	0,30	0,00	2,23	3,94	900	71,1	-5,4	-1,7	4,9	-1,6
2017.02.27 09.53.34,366	4	0,94	-1,74	-2,83	-2,44	861,66	0,00	2,84	2,84	3,94	900	79,8	-5,4	-1,1	5,4	-1,6
2017.02.28 08.52.13,321	5	1,52	-2,60	-4,34	-3,80	874,87	0,29	0,00	3,60	3,94	900	43,5	-5,3	-1,7	5,1	-0,7
2017.02.28 09.01.10,861	6	0,31	-2,10	-2,45	-2,16	882,87	0,00	0,00	2,45	3,94	900	56	-5,1	-1,7	5,1	-0,2
2017.02.28 09.08.38,788	7	1,31	-2,34	-3,81	-3,39	889,52	0,14	0,00	3,44	3,94	900	62,6	-5,1	-1,7	5,1	-1,1
2017.02.28 09.15.32,764	8	-0,03	-3,61	-3,57	-3,12	874,16	0,27	2,89	2,89	3,94	900	67,7	-5,1	-1,6	5	-0,8
2017.02.28 09.27.13,630	9	0,32	-2,28	-2,66	-2,28	860,29	0,00	0,00	2,66	3,94	900	71,5	-4,9	-1,5	4,9	-2
2017.02.28 09.36.00,501	10	0,23	-3,02	-3,28	-2,84	865,17	0,23	2,70	2,70	3,94	900	71,6	-5,1	-1,6	4,8	-1,2
2017.02.28 09.43.21,941	11	0,55	-3,20	-3,84	-3,29	857,03	0,30	3,06	3,06	3,94	900	71,6	-5,1	-1,6	4,8	-0,9
2017.02.28 09.51.24,123	12	0,14	-2,89	-3,05	-2,69	881,45	0,32	0,00	2,25	3,94	900	72,3	-5,2	-1,8	4,8	-0,9
2017.02.28 09.59.01,349	13	0,85	-2,91	-3,87	-3,42	883,74	0,51	0,00	2,57	3,94	900	71,6	-5,2	-1,7	4,9	-1,3
2017.02.28 10.09.06,235	14	0,79	-2,68	-3,60	-3,10	860,65	0,28	2,88	2,88	3,94	900	72,4	-5,1	-1,8	4,8	-1,1
2017.02.28 10.16.56,788	15	1,17	-2,53	-3,85	-3,42	888,79	-0,05	0,00	3,97	3,94	900	72,2	-5,2	-1,8	4,8	-1,2
2017.02.28 10.25.29,617	16	0,84	-2,73	-3,68	-3,23	878,51	0,00	0,00	3,68	3,94	900	72	-5,2	-1,8	4,7	-1,8
2017.02.28 10.33.14,273	17	1,04	-2,99	-4,18	-3,66	876,16	0,42	3,12	3,12	3,94	900	72,3	-5,3	-1,8	4,7	-1,3
2017.02.28 10.42.16,721	18	1,54	-2,75	-4,58	-3,86	842,44	0,44	0,00	3,41	3,94	900	72,2	-5,3	-1,8	4,7	-1,3
2017.02.28 10.49.02,728	19	1,94	-2,53	-4,74	-4,17	880,06	0,49	0,00	3,51	3,94	900	72,7	-5,3	-1,8	4,6	-1,3
2017.02.28 10.55.36,308	20	0,61	-2,87	-3,57	-3,24	917,75	0,49	0,00	2,34	3,94	900	73	-5,3	-1,9	4,7	-1,6

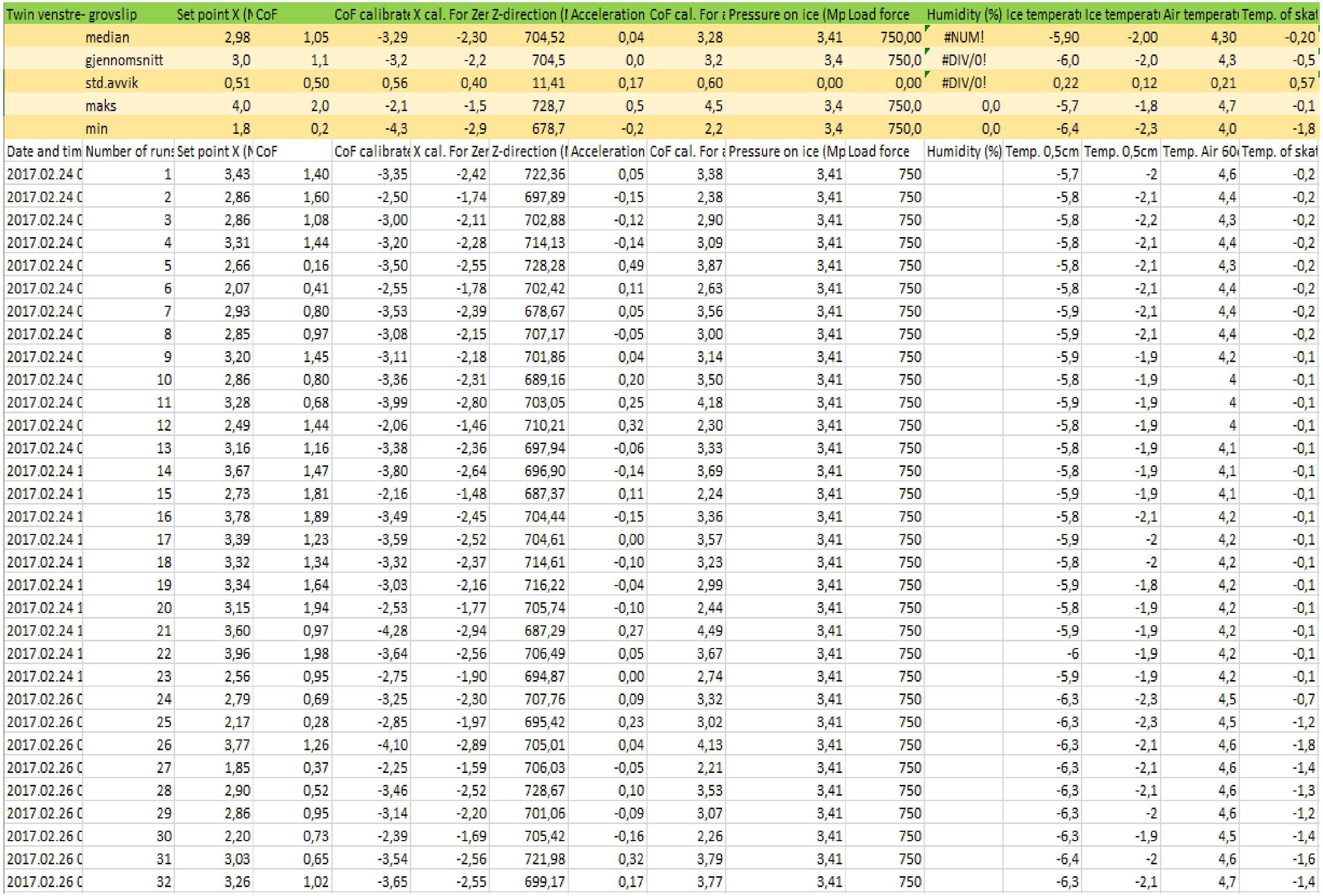
Table 19: The table contains summarized values of raw friction data obtained in the field experiment for the B1 750 N-skate blade with a L4-surface treatment.

B1 Breddetest		Set point X (	CoF	CoF calibrated	Friction Forc	Normal load	Acceleration	CI	CoF cal. For accel	Nominal Contact Pre	Initial Load f	Humidity (%)	Ice Surface T	Temperature	Air Temperat	Temp. of skate during run (°C)
	median	1,06	-1,73	-3,31	-2,41	718,18	0,00		3,23	4,02	750,00	60,03	-5,60	-1,90	4,75	-1,60
	Average	1,05	-1,79	-3,25	-2,33	715,81	0,07		3,12	4,02	750,00	56,65	-5,62	-1,97	4,6	-1,7
	Std.deviation S.pop	0,73	0,77	0,70	0,51	23,64	0,18		0,62	0,00	0,00	5,54	0,19	0,26	0,37	0,46
	Std.deviation P.pop	0,71	0,76	0,69	0,50	23,24	0,18		0,61	0,00	0,00	5,44	0,18	0,25	0,37	0,45
	maximum value	2,63	-0,28	-1,75	-1,23	752,90	0,48		4,43	4,02	750,00	60,95	-5,40	-1,20	5,1	-1,0
	minimum value	-0,83	-3,77	-5,12	-3,85	671,10	-0,17		1,75	4,02	750,00	48,97	-6,20	-2,40	3,7	-2,5
	Confidence interval			0,246908792					0,221860074							
	Upper bound			-3,0					3,34							
	Lower Bound			-3,5					2,89							
Date and time	Number of runs	Set point X (	CoF	CoF calibrated	X cal. For Zer	Z-direction (	Acceleration	CI	CoF cal. For accel	Pressure on ice (Mp	Load force	Humidity (%)	Temp. 0,5cm	Temp. 0,5cm /	Temp. Air 60	Temp. of skate during
2017.02.25 07.23.14,494	1	0,60	-1,49	-2,35	-1,66	701,25	0,24	0,00	1,91	4,02	750	48,97	-5,9	-1,9	4,4	-1,3
2017.02.25 07.29.52,294	2	1,41	-1,39	-3,32	-2,42	731,36	0,00	3,32	3,32	4,02	750	48,97	-5,8	-2,1	4,5	-1,6
2017.02.25 07.33.35,868	3	0,92	-2,05	-3,40	-2,31	679,08	0,00	0,00	3,40	4,02	750	48,97	-6,2	-2,2	4,3	-1,8
2017.02.25 07.40.50,229	4	-0,17	-3,11	-2,87	-2,02	703,06	-0,10	3,05	3,05	4,02	750	48,97	-5,8	-2,3	4,3	-1,8
2017.02.25 07.44.08,536	5	0,74	-2,57	-3,66	-2,51	686,94	-0,14	0,00	3,93	4,02	750	48,97	-5,7	-2,3	4,3	-1,8
2017.02.25 07.48.10,438	6	0,93	-2,01	-3,29	-2,40	729,24	-0,08	0,00	3,43	4,02	750	48,97	-5,7	-2,3	4,2	-2,3
2017.02.25 07.54.31,788	7	1,40	-1,81	-3,73	-2,71	730,19	0,33	3,11	3,11	4,02	750	48,97	-5,8	-2,3	4	-2,3
2017.02.25 07.57.31,002	8	0,42	-2,34	-2,92	-2,07	712,70	-0,04	2,98	2,98	4,02	750	48,97	-5,8	-2,3	3,9	-2,2
2017.02.25 08.00.48,152	9	1,29	-1,74	-3,52	-2,55	726,38	-0,17	0,00	3,83	4,02	750	48,97	-5,9	-2,4	4	-2,4
2017.02.25 08.04.26,546	10	0,48	-3,77	-4,47	-3,08	691,03	0,48	0,00	3,53	4,02	750	48,97	-5,7	-2,4	3,7	-2,5
2017.02.25 19.57.18,255	11	1,98	-0,96	-3,88	-2,63	679,32	0,33	3,22	3,22	4,02	750	60,03	-5,5	-1,8	5,1	-1
2017.02.25 20.03.55,049	12	1,08	-1,50	-3,09	-2,10	680,32	-0,12	3,32	3,32	4,02	750	60,03	-5,5	-1,8	5,1	-2
2017.02.25 20.16.20,362	13	1,04	-1,21	-2,70	-1,89	697,65	-0,15	2,99	2,99	4,02	750	60,03	-5,6	-1,8	5	-1,6
2017.02.25 20.26.03,973	14	0,69	-2,11	-3,07	-2,23	725,51	0,09	2,91	2,91	4,02	750	60,03	-5,6	-1,8	4,9	-2,1
2017.02.25 20.30.18,110	15	1,01	-1,56	-3,03	-2,09	691,35	0,06	2,91	2,91	4,02	750	60,03	-5,5	-1,8	4,8	-1,6
2017.02.25 20.33.07,146	16	-0,20	-2,50	-2,24	-1,68	752,90	0,27	0,00	1,75	4,02	750	60,03	-5,6	-1,8	4,9	-1,3
2017.02.25 20.38.04,166	17	1,83	-1,13	-3,69	-2,65	717,69	0,00	0,00	3,69	4,02	750	60,03	-5,6	-1,8	4,9	-1,7
2017.02.25 20.41.41,250	18	-0,83	-2,94	-1,75	-1,23	700,36	0,00	0,00	1,76	4,02	750	60,03	-5,6	-1,8	4,9	-1,3
2017.02.25 20.45.19,855	19	0,95	-2,34	-3,76	-2,52	671,10	0,18	0,00	3,40	4,02	750	60,03	-5,6	-1,8	4,9	-1,4
2017.02.25 20.48.39,795	20	1,58	-1,24	-3,46	-2,47	713,22	0,05	0,00	3,35	4,02	750	60,03	-5,6	-1,8	4,9	-1,6
2017.02.28 14.07.47,658	21	2,63	-1,62	-5,12	-3,85	751,63	0,38	0,00	4,43	4,02	750	60,95	-5,6	-1,2	4,9	-2,1
2017.02.28 14.10.46,780	22	1,35	-0,93	-2,75	-2,04	741,16	-0,06	0,00	2,87	4,02	750	60,95	-5,4	-2	4,8	-1,3
2017.02.28 14.15.56,195	23	1,07	-0,48	-1,94	-1,42	729,68	0,00	0,00	1,94	4,02	750	60,95	-5,5	-2	4,7	-1,1
2017.02.28 14.19.16,463	24	2,01	-0,28	-3,02	-2,22	736,31	-0,11	3,22	3,22	4,02	750	60,95	-5,5	-1,9	4,8	-1,3
2017.02.28 14.28.11,321	25	1,36	-1,72	-3,63	-2,60	715,08	0,12	0,00	3,41	4,02	750	60,95	-5,4	-1,9	4,8	-2,5
2017.02.28 14.32.08,654	26	2,09	-0,88	-3,78	-2,72	718,68	0,16	0,00	3,48	4,02	750	60,95	-5,4	-1,9	4,8	-1,8
2017.02.28 14.35.33,470	27	1,38	-1,47	-3,33	-2,48	745,25	0,06	3,23	3,23	4,02	750	60,95	-5,5	-1,9	4,7	-1,1
2017.02.28 14.38.43,690	28	0,29	-2,27	-2,66	-1,96	737,56	0,00	0,00	2,66	4,02	750	60,95	-5,4	-1,9	4,7	-1
2017.02.28 14.46.58,032	29	1,25	-2,24	-3,92	-2,92	744,89	0,41	3,18	3,18	4,02	750	60,95	-5,4	-1,9	4,7	-1,3
2017.02.28 14.50.03,323	30	1,05	-1,88	-3,31	-2,42	733,52	0,00	3,31	3,31	4,02	750	60,95	-5,4	-1,9	4,7	-1,3

Table 20: The table contains summarized values of raw friction data obtained in the field experiment for the B5 750 N-skate blade with a L4-surface treatment.

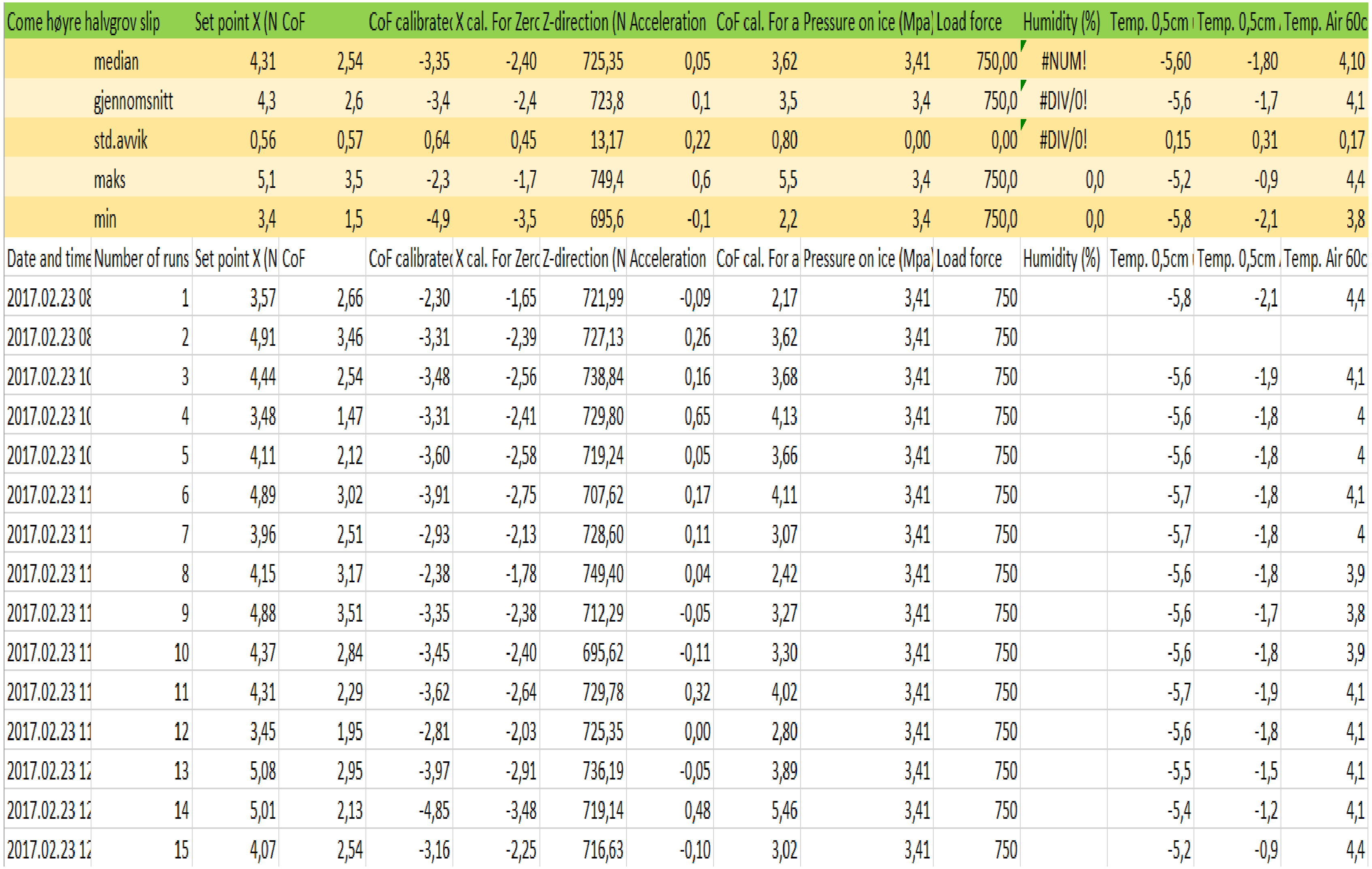
B5 Breddetest		Set point X (N	CoF	CoF calibrate	Friction Force	Normal load (	Acceleration	CI	CoF cal. For a	Nominal Contact Pre	Initial Load f	Humidity (%)	Ice Surface T	Temperature	Air Temperat	Temp. of skat
	median	1,19	-1,64	-3,63	-2,62	710,34	0,07	0,00	3,82	3,09	750,00	57,57	-5,40	-1,85	4,90	-1,30
	Average	1,17	-2,03	-3,68	-2,62	711,93	0,07	1,02	3,77	3,09	750,00	61,27	-5,45	-1,87	4,3	-1,3
	Std. Deviation S.pop	0,88	1,29	0,86	0,61	13,36	0,17	1,71	0,94	0,00	0,00	10,90	0,24	0,36	1,73	0,61
	Std. Deviation P.Pop	0,86	1,26	0,84	0,60	13,10	0,17	1,68	0,92	0,00	0,00	10,69	0,24	0,36	1,70	0,60
	Maximum	2,63	-0,69	-1,98	-1,41	737,95	0,35	4,05	5,43	3,09	750,00	75,90	-5,10	-1,30	5,2	-0,2
	Minimum	-1,98	-7,38	-5,06	-3,50	691,05	-0,38	0,00	1,99	3,09	750,00	48,97	-5,80	-2,50	-3,8	-2,3
	Confidence intervall			0,32315169					0,35284326							
	Upper bound			-3,4					4,12							
	Lower bound			-4,0					3,41							
Date and time	Number of runs	Set point X (N	CoF	CoF calibrate	X cal. For Zer	Z-direction (N	Acceleration	CI	CoF cal. For a	Pressure on ice (Mpa	Load force	Humidity (%)	Temp. 0,5cm	Temp. 0,5cm	Temp. Air 60	Temp. of skat
2017.02.25 08.16.11,850	1	1,28	-1,62	-3,47	-2,40	694,25	-0,18	0,00	3,22	3,09	750	48,97	-5,8	-2,5	-3,8	-0,8
2017.02.25 08.19.09,563	2	0,69	-3,03	-4,00	-2,85	715,39	0,32	0,00	4,40	3,09	750	48,97	-5,7	-2,4	3,7	-1,4
2017.02.25 08.22.06,436	3	-1,98	-7,38	-4,55	-3,19	700,71	0,22	0,00	4,83	3,09	750	48,97	-5,8	-2,3	3,9	-1,7
2017.02.25 08.26.03,978	4	1,63	-2,70	-5,06	-3,50	691,76	0,28	0,00	5,43	3,09	750	48,97	-5,8	-2,3	3,9	-2
2017.02.25 08.28.53,922	5	0,96	-3,02	-4,41	-3,05	691,05	0,00	0,00	4,41	3,09	750	48,97	-5,8	-2,3	4	-2,3
2017.02.25 08.31.50,016	6	0,70	-2,45	-3,43	-2,44	715,10	0,10	3,55	3,55	3,09	750	48,97	-5,8	-2,3	4	-2
2017.02.25 08.34.42,971	7	-0,13	-2,67	-2,48	-1,75	706,99	-0,38	0,00	1,99	3,09	750	48,97	-5,8	-2,3	4	-2
2017.02.25 08.40.16,472	8	1,08	-2,54	-4,04	-2,92	724,02	0,11	0,00	4,17	3,09	750	48,97	-5,8	-2,3	4	-2,3
2017.02.25 19.15.11,922	9	2,19	-1,22	-4,36	-3,04	700,25	0,06	0,00	4,42	3,09	750	57,57	-5,3	-1,3	4,9	-0,6
2017.02.25 19.18.39,370	10	1,04	-1,61	-3,10	-2,17	699,72	0,35	3,57	3,57	3,09	750	57,57	-5,1	-1,4	5	-0,3
2017.02.25 19.21.38,093	11	0,82	-0,83	-1,98	-1,41	711,90	0,04	0,00	2,04	3,09	750	57,57	-5,2	-1,4	5,1	-0,2
2017.02.25 19.28.14,080	12	1,47	-0,92	-3,01	-2,12	706,36	0,13	0,00	3,17	3,09	750	57,57	-5,3	-1,4	5,1	-0,8
2017.02.25 19.31.19,351	13	0,85	-1,27	-2,50	-1,74	697,08	0,09	0,00	2,62	3,09	750	57,57	-5,2	-1,5	5,1	-0,7
2017.02.25 19.34.30,200	14	1,18	-1,28	-2,96	-2,08	706,25	0,00	0,00	2,95	3,09	750	57,57	-5,2	-1,5	5,1	-0,7
2017.02.25 19.38.58,724	15	1,20	-2,03	-3,72	-2,64	711,02	0,26	4,05	4,05	3,09	750	57,57	-5,2	-1,5	5,2	-0,7
2017.02.25 19.42.51,076	16	1,93	-0,69	-3,41	-2,41	708,77	0,13	3,57	3,57	3,09	750	57,57	-5,3	-1,6	5,2	-1,1
2017.02.28 15.01.27,980	17	2,00	-1,11	-3,89	-2,81	722,99	-0,11	3,75	3,75	3,09	750	75,2	-5,4	-1,9	4,7	-0,8
2017.02.28 15.04.52,116	18	1,54	-2,62	-4,75	-3,43	722,95	0,07	0,00	4,83	3,09	750	74,7	-5,4	-1,9	4,7	-1,1
2017.02.28 15.08.12,196	19	1,90	-2,27	-4,97	-3,50	705,22	-0,09	0,00	4,85	3,09	750	74,3	-5,4	-1,8	4,8	-1,1
2017.02.28 15.19.52,788	20	1,40	-2,20	-4,12	-3,01	730,66	-0,06	4,04	4,04	3,09	750	74,8	-5,4	-1,8	4,9	-1,5
2017.02.28 15.24.03,406	21	0,96	-1,41	-2,77	-1,96	710,56	-0,05	0,00	2,70	3,09	750	72,7	-5,4	-1,9	4,9	-1,3
2017.02.28 15.28.13,355	22	2,21	-1,44	-4,44	-3,27	737,95	0,29	0,00	4,80	3,09	750	73,3	-5,3	-1,9	4,9	-1,6
2017.02.28 15.31.42,240	23	1,19	-1,63	-3,25	-2,39	735,83	-0,05	0,00	3,18	3,09	750	75,9	-5,3	-1,8	4,9	-1,4
2017.02.28 15.36.08,985	24	2,63	-1,19	-4,85	-3,48	720,20	0,06	0,00	4,92	3,09	750	73	-5,4	-1,7	4,9	-2,2
2017.02.28 15.39.21,625	25	0,63	-1,66	-2,55	-1,81	710,13	0,05	0,00	2,62	3,09	750	73,5	-5,3	-1,8	4,9	-1,4
2017.02.28 15.42.20,978	26	1,10	-2,04	-3,54	-2,60	733,10	0,27	3,88	3,88	3,09	750	73,4	-5,4	-1,9	4,9	-1,3

Table 21: The table contains summarized values of raw friction data obtained in the field experiment for the B3 750 N-skate blade with the coarse surface treatment.



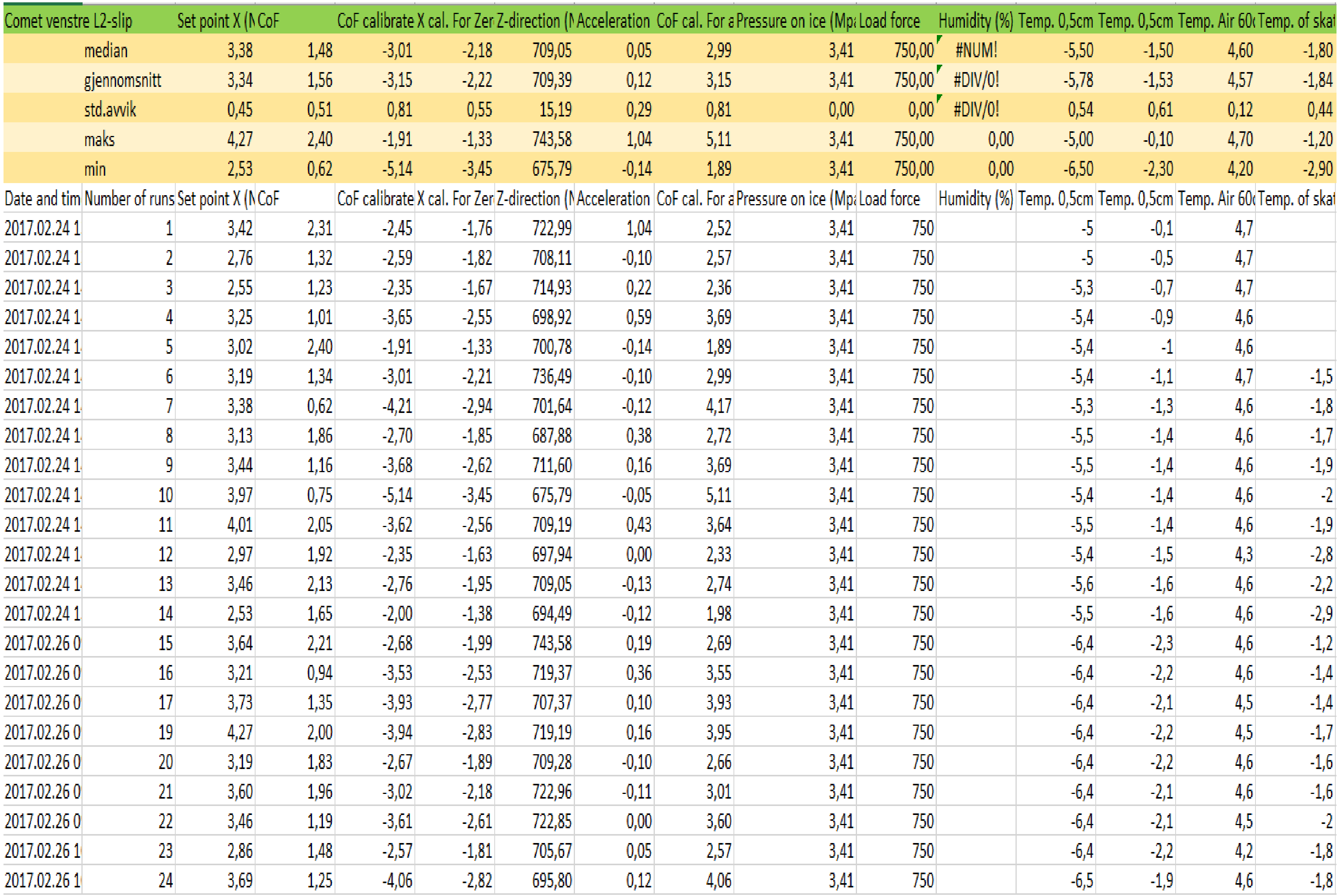
Twin venstre- grovslip		Set point X (N	CoF	CoF calibrat	X cal. For Zer	Z-direction (I	Acceleration	CoF cal. For a	Pressure on ice (Mp	Load force	Humidity (%)	Ice temperat	Ice temperat	Air temperat	Temp. of skat
	median	2,98	1,05	-3,29	-2,30	704,52	0,04	3,28	3,41	750,00	#NUM!	-5,90	-2,00	4,30	-0,20
	gjennomsnitt	3,0	1,1	-3,2	-2,2	704,5	0,0	3,2	3,4	750,0	#DIV/0!	-6,0	-2,0	4,3	-0,5
	std.avvik	0,51	0,50	0,56	0,40	11,41	0,17	0,60	0,00	0,00	#DIV/0!	0,22	0,12	0,21	0,57
	maks	4,0	2,0	-2,1	-1,5	728,7	0,5	4,5	3,4	750,0	0,0	-5,7	-1,8	4,7	-0,1
	min	1,8	0,2	-4,3	-2,9	678,7	-0,2	2,2	3,4	750,0	0,0	-6,4	-2,3	4,0	-1,8
Date and tim	Number of runs	Set point X (N	CoF	CoF calibrat	X cal. For Zer	Z-direction (I	Acceleration	CoF cal. For a	Pressure on ice (Mp	Load force	Humidity (%)	Temp. 0,5cm	Temp. 0,5cm	Temp. Air 60	Temp. of skat
2017.02.24 0	1	3,43	1,40	-3,35	-2,42	722,36	0,05	3,38	3,41	750		-5,7	-2	4,6	-0,2
2017.02.24 0	2	2,86	1,60	-2,50	-1,74	697,89	-0,15	2,38	3,41	750		-5,8	-2,1	4,4	-0,2
2017.02.24 0	3	2,86	1,08	-3,00	-2,11	702,88	-0,12	2,90	3,41	750		-5,8	-2,2	4,3	-0,2
2017.02.24 0	4	3,31	1,44	-3,20	-2,28	714,13	-0,14	3,09	3,41	750		-5,8	-2,1	4,4	-0,2
2017.02.24 0	5	2,66	0,16	-3,50	-2,55	728,28	0,49	3,87	3,41	750		-5,8	-2,1	4,3	-0,2
2017.02.24 0	6	2,07	0,41	-2,55	-1,78	702,42	0,11	2,63	3,41	750		-5,8	-2,1	4,4	-0,2
2017.02.24 0	7	2,93	0,80	-3,53	-2,39	678,67	0,05	3,56	3,41	750		-5,9	-2,1	4,4	-0,2
2017.02.24 0	8	2,85	0,97	-3,08	-2,15	707,17	-0,05	3,00	3,41	750		-5,9	-2,1	4,4	-0,2
2017.02.24 0	9	3,20	1,45	-3,11	-2,18	701,86	0,04	3,14	3,41	750		-5,9	-1,9	4,2	-0,1
2017.02.24 0	10	2,86	0,80	-3,36	-2,31	689,16	0,20	3,50	3,41	750		-5,8	-1,9	4	-0,1
2017.02.24 0	11	3,28	0,68	-3,99	-2,80	703,05	0,25	4,18	3,41	750		-5,9	-1,9	4	-0,1
2017.02.24 0	12	2,49	1,44	-2,06	-1,46	710,21	0,32	2,30	3,41	750		-5,8	-1,9	4	-0,1
2017.02.24 0	13	3,16	1,16	-3,38	-2,36	697,94	-0,06	3,33	3,41	750		-5,8	-1,9	4,1	-0,1
2017.02.24 1	14	3,67	1,47	-3,80	-2,64	696,90	-0,14	3,69	3,41	750		-5,8	-1,9	4,1	-0,1
2017.02.24 1	15	2,73	1,81	-2,16	-1,48	687,37	0,11	2,24	3,41	750		-5,9	-1,9	4,1	-0,1
2017.02.24 1	16	3,78	1,89	-3,49	-2,45	704,44	-0,15	3,36	3,41	750		-5,8	-2,1	4,2	-0,1
2017.02.24 1	17	3,39	1,23	-3,59	-2,52	704,61	0,00	3,57	3,41	750		-5,9	-2	4,2	-0,1
2017.02.24 1	18	3,32	1,34	-3,32	-2,37	714,61	-0,10	3,23	3,41	750		-5,8	-2	4,2	-0,1
2017.02.24 1	19	3,34	1,64	-3,03	-2,16	716,22	-0,04	2,99	3,41	750		-5,9	-1,8	4,2	-0,1
2017.02.24 1	20	3,15	1,94	-2,53	-1,77	705,74	-0,10	2,44	3,41	750		-5,8	-1,9	4,2	-0,1
2017.02.24 1	21	3,60	0,97	-4,28	-2,94	687,29	0,27	4,49	3,41	750		-5,9	-1,9	4,2	-0,1
2017.02.24 1	22	3,96	1,98	-3,64	-2,56	706,49	0,05	3,67	3,41	750		-6	-1,9	4,2	-0,1
2017.02.24 1	23	2,56	0,95	-2,75	-1,90	694,87	0,00	2,74	3,41	750		-5,9	-1,9	4,2	-0,1
2017.02.26 0	24	2,79	0,69	-3,25	-2,30	707,76	0,09	3,32	3,41	750		-6,3	-2,3	4,5	-0,7
2017.02.26 0	25	2,17	0,28	-2,85	-1,97	695,42	0,23	3,02	3,41	750		-6,3	-2,3	4,5	-1,2
2017.02.26 0	26	3,77	1,26	-4,10	-2,89	705,01	0,04	4,13	3,41	750		-6,3	-2,1	4,6	-1,8
2017.02.26 0	27	1,85	0,37	-2,25	-1,59	706,03	-0,05	2,21	3,41	750		-6,3	-2,1	4,6	-1,4
2017.02.26 0	28	2,90	0,52	-3,46	-2,52	728,67	0,10	3,53	3,41	750		-6,3	-2,1	4,6	-1,3
2017.02.26 0	29	2,86	0,95	-3,14	-2,20	701,06	-0,09	3,07	3,41	750		-6,3	-2	4,6	-1,2
2017.02.26 0	30	2,20	0,73	-2,39	-1,69	705,42	-0,16	2,26	3,41	750		-6,3	-1,9	4,5	-1,4
2017.02.26 0	31	3,03	0,65	-3,54	-2,56	721,98	0,32	3,79	3,41	750		-6,4	-2	4,6	-1,6
2017.02.26 0	32	3,26	1,02	-3,65	-2,55	699,17	0,17	3,77	3,41	750		-6,3	-2,1	4,7	-1,4

Table 22: The table contains summarized values of raw friction data obtained in the field experiment for the B3 750 N-skate blade with the smooth surface treatment



Come høyre halvgrov slip		Set point X (N	CoF	CoF calibrate	X cal. For Zerc	Z-direction (N	Acceleration	CoF cal. For a	Pressure on ice (Mpa	Load force	Humidity (%)	Temp. 0,5cm	Temp. 0,5cm	Temp. Air 60c
	median	4,31	2,54	-3,35	-2,40	725,35	0,05	3,62	3,41	750,00	#NUM!	-5,60	-1,80	4,10
	gjennomsnitt	4,3	2,6	-3,4	-2,4	723,8	0,1	3,5	3,4	750,0	#DIV/0!	-5,6	-1,7	4,1
	std.avvik	0,56	0,57	0,64	0,45	13,17	0,22	0,80	0,00	0,00	#DIV/0!	0,15	0,31	0,17
	maks	5,1	3,5	-2,3	-1,7	749,4	0,6	5,5	3,4	750,0	0,0	-5,2	-0,9	4,4
	min	3,4	1,5	-4,9	-3,5	695,6	-0,1	2,2	3,4	750,0	0,0	-5,8	-2,1	3,8
Date and time	Number of runs	Set point X (N	CoF	CoF calibrate	X cal. For Zerc	Z-direction (N	Acceleration	CoF cal. For a	Pressure on ice (Mpa	Load force	Humidity (%)	Temp. 0,5cm	Temp. 0,5cm	Temp. Air 60c
2017.02.23 08	1	3,57	2,66	-2,30	-1,65	721,99	-0,09	2,17	3,41	750		-5,8	-2,1	4,4
2017.02.23 08	2	4,91	3,46	-3,31	-2,39	727,13	0,26	3,62	3,41	750				
2017.02.23 10	3	4,44	2,54	-3,48	-2,56	738,84	0,16	3,68	3,41	750		-5,6	-1,9	4,1
2017.02.23 10	4	3,48	1,47	-3,31	-2,41	729,80	0,65	4,13	3,41	750		-5,6	-1,8	4
2017.02.23 10	5	4,11	2,12	-3,60	-2,58	719,24	0,05	3,66	3,41	750		-5,6	-1,8	4
2017.02.23 11	6	4,89	3,02	-3,91	-2,75	707,62	0,17	4,11	3,41	750		-5,7	-1,8	4,1
2017.02.23 11	7	3,96	2,51	-2,93	-2,13	728,60	0,11	3,07	3,41	750		-5,7	-1,8	4
2017.02.23 11	8	4,15	3,17	-2,38	-1,78	749,40	0,04	2,42	3,41	750		-5,6	-1,8	3,9
2017.02.23 11	9	4,88	3,51	-3,35	-2,38	712,29	-0,05	3,27	3,41	750		-5,6	-1,7	3,8
2017.02.23 11	10	4,37	2,84	-3,45	-2,40	695,62	-0,11	3,30	3,41	750		-5,6	-1,8	3,9
2017.02.23 11	11	4,31	2,29	-3,62	-2,64	729,78	0,32	4,02	3,41	750		-5,7	-1,9	4,1
2017.02.23 11	12	3,45	1,95	-2,81	-2,03	725,35	0,00	2,80	3,41	750		-5,6	-1,8	4,1
2017.02.23 12	13	5,08	2,95	-3,97	-2,91	736,19	-0,05	3,89	3,41	750		-5,5	-1,5	4,1
2017.02.23 12	14	5,01	2,13	-4,85	-3,48	719,14	0,48	5,46	3,41	750		-5,4	-1,2	4,1
2017.02.23 12	15	4,07	2,54	-3,16	-2,25	716,63	-0,10	3,02	3,41	750		-5,2	-0,9	4,4

Table 23: The table contains summarized values of raw friction data obtained in the field experiment for the B3 750 N-skate blade with a L2-surface treatment.

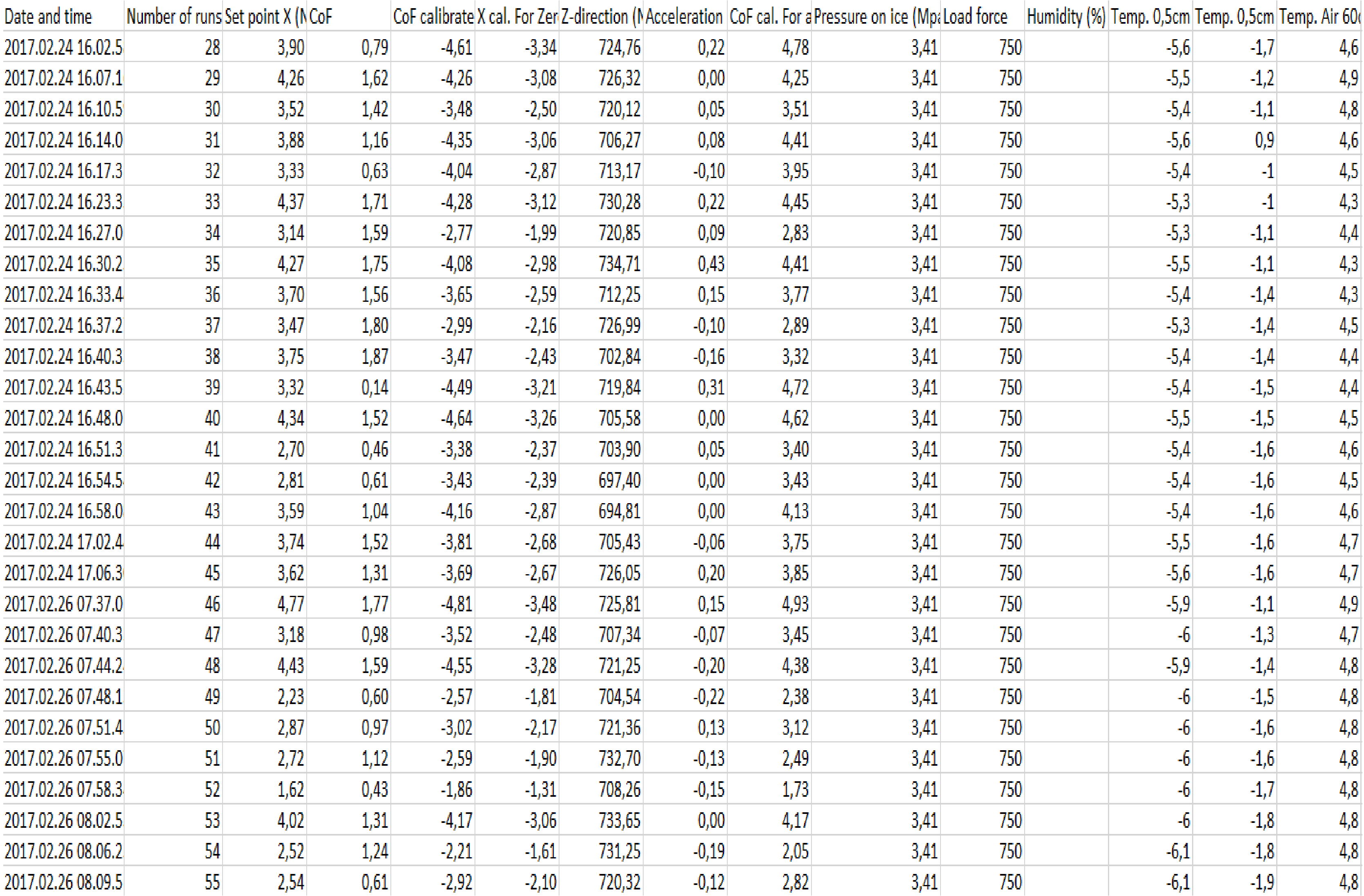


Comet venstre L2-slip		Set point X (N	CoF	CoF calibrate	X cal. For Zer	Z-direction (N	Acceleration	CoF cal. For a	Pressure on ice (Mp	Load force	Humidity (%)	Temp. 0,5cm	Temp. 0,5cm	Temp. Air 60c	Temp. of skat
	median	3,38	1,48	-3,01	-2,18	709,05	0,05	2,99	3,41	750,00	#NUM!	-5,50	-1,50	4,60	-1,80
	gjennomsnitt	3,34	1,56	-3,15	-2,22	709,39	0,12	3,15	3,41	750,00	#DIV/0!	-5,78	-1,53	4,57	-1,84
	std.avvik	0,45	0,51	0,81	0,55	15,19	0,29	0,81	0,00	0,00	#DIV/0!	0,54	0,61	0,12	0,44
	maks	4,27	2,40	-1,91	-1,33	743,58	1,04	5,11	3,41	750,00	0,00	-5,00	-0,10	4,70	-1,20
	min	2,53	0,62	-5,14	-3,45	675,79	-0,14	1,89	3,41	750,00	0,00	-6,50	-2,30	4,20	-2,90
Date and tim	Number of runs	Set point X (N	CoF	CoF calibrate	X cal. For Zer	Z-direction (N	Acceleration	CoF cal. For a	Pressure on ice (Mp	Load force	Humidity (%)	Temp. 0,5cm	Temp. 0,5cm	Temp. Air 60c	Temp. of skat
2017.02.24 1	1	3,42	2,31	-2,45	-1,76	722,99	1,04	2,52	3,41	750		-5	-0,1	4,7	
2017.02.24 1	2	2,76	1,32	-2,59	-1,82	708,11	-0,10	2,57	3,41	750		-5	-0,5	4,7	
2017.02.24 1	3	2,55	1,23	-2,35	-1,67	714,93	0,22	2,36	3,41	750		-5,3	-0,7	4,7	
2017.02.24 1	4	3,25	1,01	-3,65	-2,55	698,92	0,59	3,69	3,41	750		-5,4	-0,9	4,6	
2017.02.24 1	5	3,02	2,40	-1,91	-1,33	700,78	-0,14	1,89	3,41	750		-5,4	-1	4,6	
2017.02.24 1	6	3,19	1,34	-3,01	-2,21	736,49	-0,10	2,99	3,41	750		-5,4	-1,1	4,7	-1,5
2017.02.24 1	7	3,38	0,62	-4,21	-2,94	701,64	-0,12	4,17	3,41	750		-5,3	-1,3	4,6	-1,8
2017.02.24 1	8	3,13	1,86	-2,70	-1,85	687,88	0,38	2,72	3,41	750		-5,5	-1,4	4,6	-1,7
2017.02.24 1	9	3,44	1,16	-3,68	-2,62	711,60	0,16	3,69	3,41	750		-5,5	-1,4	4,6	-1,9
2017.02.24 1	10	3,97	0,75	-5,14	-3,45	675,79	-0,05	5,11	3,41	750		-5,4	-1,4	4,6	-2
2017.02.24 1	11	4,01	2,05	-3,62	-2,56	709,19	0,43	3,64	3,41	750		-5,5	-1,4	4,6	-1,9
2017.02.24 1	12	2,97	1,92	-2,35	-1,63	697,94	0,00	2,33	3,41	750		-5,4	-1,5	4,3	-2,8
2017.02.24 1	13	3,46	2,13	-2,76	-1,95	709,05	-0,13	2,74	3,41	750		-5,6	-1,6	4,6	-2,2
2017.02.24 1	14	2,53	1,65	-2,00	-1,38	694,49	-0,12	1,98	3,41	750		-5,5	-1,6	4,6	-2,9
2017.02.26 0	15	3,64	2,21	-2,68	-1,99	743,58	0,19	2,69	3,41	750		-6,4	-2,3	4,6	-1,2
2017.02.26 0	16	3,21	0,94	-3,53	-2,53	719,37	0,36	3,55	3,41	750		-6,4	-2,2	4,6	-1,4
2017.02.26 0	17	3,73	1,35	-3,93	-2,77	707,37	0,10	3,93	3,41	750		-6,4	-2,1	4,5	-1,4
2017.02.26 0	19	4,27	2,00	-3,94	-2,83	719,19	0,16	3,95	3,41	750		-6,4	-2,2	4,5	-1,7
2017.02.26 0	20	3,19	1,83	-2,67	-1,89	709,28	-0,10	2,66	3,41	750		-6,4	-2,2	4,6	-1,6
2017.02.26 0	21	3,60	1,96	-3,02	-2,18	722,96	-0,11	3,01	3,41	750		-6,4	-2,1	4,6	-1,6
2017.02.26 0	22	3,46	1,19	-3,61	-2,61	722,85	0,00	3,60	3,41	750		-6,4	-2,1	4,5	-2
2017.02.26 1	23	2,86	1,48	-2,57	-1,81	705,67	0,05	2,57	3,41	750		-6,4	-2,2	4,2	-1,8
2017.02.26 1	24	3,69	1,25	-4,06	-2,82	695,80	0,12	4,06	3,41	750		-6,5	-1,9	4,6	-1,8

Table 24: The table contains summarized values of raw friction data obtained in the field experiment for the B3 750 N-skate blade with a L4-surface treatment. A total of 55 runs were completed for this test, and the table is continued in Table 25.

Twin Høyre L4-slip		Set point X (N	CoF	CoF calibrate	X cal. For Zer	Z-direction (N	Acceleration	CoF cal. For a	Pressure on ice (Mp	Load force	Humidity (%)	Temp. 0,5cm	Temp. 0,5cm	Temp. Air 60
	median	3,58	1,59	-3,47	-2,48	715,09	0,05	3,44	3,41	750,00	#NUM!	-5,60	-1,55	4,50
	gjennomsnitt	3,6	1,6	-3,5	-2,5	714,4	0,1	3,5	3,4	750,0	#DIV/0!	-5,6	-1,5	4,5
	std.avvik	0,79	0,65	0,88	0,63	11,83	0,20	0,92	0,00	0,00	#DIV/0!	0,30	0,45	0,19
	maks	5,6	2,9	-1,9	-1,3	734,7	0,5	5,9	3,4	750,0	0,0	-4,9	0,9	4,9
	min	1,6	0,1	-5,7	-4,0	683,5	-0,5	1,7	3,4	750,0	0,0	-6,1	-2,3	4,2
Date and time	Number of runs	Set point X (N	CoF	CoF calibrate	X cal. For Zer	Z-direction (N	Acceleration	CoF cal. For a	Pressure on ice (Mp	Load force	Humidity (%)	Temp. 0,5cm	Temp. 0,5cm	Temp. Air 60
2017.02.23 13.59.0	1	2,99	1,71	-2,42	-1,75	724,25	0,08	2,48	3,41	750		-4,9	-1,2	4,7
2017.02.23 14.02.5	2	5,59	2,71	-5,05	-3,64	722,00	0,18	5,19	3,41	750		-5	-1,3	4,7
2017.02.23 14.06.5	3	3,77	2,46	-2,77	-2,00	721,35	0,15	2,89	3,41	750		-5,1	-1,3	4,6
2017.02.23 14.10.3	4	4,02	2,13	-3,45	-2,48	721,02	0,31	3,70	3,41	750		-5,1	-1,2	4,6
2017.02.23 14.14.1	5	4,70	2,85	-3,80	-2,68	709,27	0,27	4,01	3,41	750		-5,2	-1,3	4,5
2017.02.23 14.20.1	6	4,35	2,51	-3,54	-2,55	720,20	-0,05	3,49	3,41	750		-5,4	-1,4	4,6
2017.02.23 14.23.5	7	4,14	2,89	-2,80	-2,04	728,62	0,47	3,18	3,41	750		-5,4	-1,4	4,5
2017.02.23 14.27.1	8	3,37	1,82	-2,90	-2,07	715,48	0,33	3,17	3,41	750		-5,4	-1,4	4,5
2017.02.23 14.31.1	9	4,56	2,68	-3,77	-2,66	708,89	0,27	3,98	3,41	750		-5,5	-1,4	4,5
2017.02.24 08.24.0	10	3,36	1,20	-3,50	-2,50	714,70	0,51	3,93	3,41	750		-5,9	-2,3	4,4
2017.02.24 08.27.2	11	4,55	2,58	-4,09	-2,79	683,51	-0,08	4,01	3,41	750		-5,8	-1,9	4,3
2017.02.24 08.33.0	12	2,77	1,56	-2,36	-1,67	709,05	-0,05	2,31	3,41	750		-5,7	-1,6	4,4
2017.02.24 08.36.4	13	2,66	1,53	-2,18	-1,57	721,08	0,34	2,46	3,41	750		-5,8	-1,4	4,4
2017.02.24 08.40.2	14	3,09	1,62	-2,67	-1,93	722,21	0,38	2,99	3,41	750		-5,8	-1,5	4,2
2017.02.24 08.44.0	15	2,77	1,81	-2,10	-1,48	710,98	-0,06	2,04	3,41	750		-5,8	-1,7	4,2
2017.02.24 08.55.3	17	3,14	2,28	-2,31	-1,58	686,26	0,00	2,30	3,41	750		-5,9	-1,9	4,3
2017.02.24 08.59.0	18	3,58	2,03	-3,04	-2,15	706,40	0,05	3,09	3,41	750		-5,8	-1,9	4,3
2017.02.24 09.03.2	19	3,34	1,80	-2,89	-2,06	713,93	0,15	3,00	3,41	750		-5,8	-1,9	4,4
2017.02.24 09.08.3	20	2,94	1,56	-2,65	-1,85	700,71	0,11	2,73	3,41	750		-5,9	-1,9	4,4
2017.02.24 09.11.5	21	3,93	2,15	-3,41	-2,41	707,14	-0,50	2,98	3,41	750		-5,9	-2,1	4,4
2017.02.24 09.18.0	22	3,18	2,29	-2,22	-1,56	706,09	-0,05	2,17	3,41	750		-5,9	-2,1	4,4
2017.02.24 09.22.1	23	4,62	2,04	-4,54	-3,19	703,37	0,19	4,70	3,41	750		-5,8	-2,1	4,4
2017.02.24 09.27.3	24	5,03	2,15	-4,83	-3,48	722,39	0,16	4,95	3,41	750		-5,9	-1,9	4,3
2017.02.24 09.32.4	25	3,84	2,12	-3,37	-2,35	700,86	-0,16	3,22	3,41	750		-6	-1,9	4,3
2017.02.24 15.53.4	26	5,00	1,43	-5,74	-4,00	698,18	0,16	5,87	3,41	750		-5,5	-1,6	4,7
2017.02.24 15.59.0	27	3,51	1,36	-3,49	-2,52	723,74	-0,18	3,34	3,41	750		-5,8	-1,7	4,7

Table 25: This table is a continuation of table 24. It contains summarized values of raw friction data obtained in the field experiment for the B3 750 N-skate blade with a L4-surface treatment



Date and time	Number of runs	Set point X (N	CoF	CoF calibrate	X cal. For Zer	Z-direction (N	Acceleration	CoF cal. For a	Pressure on ice (Mpa	Load force	Humidity (%)	Temp. 0,5cm	Temp. 0,5cm	Temp. Air 60c
2017.02.24 16.02.5	28	3,90	0,79	-4,61	-3,34	724,76	0,22	4,78	3,41	750		-5,6	-1,7	4,6
2017.02.24 16.07.1	29	4,26	1,62	-4,26	-3,08	726,32	0,00	4,25	3,41	750		-5,5	-1,2	4,9
2017.02.24 16.10.5	30	3,52	1,42	-3,48	-2,50	720,12	0,05	3,51	3,41	750		-5,4	-1,1	4,8
2017.02.24 16.14.0	31	3,88	1,16	-4,35	-3,06	706,27	0,08	4,41	3,41	750		-5,6	0,9	4,6
2017.02.24 16.17.3	32	3,33	0,63	-4,04	-2,87	713,17	-0,10	3,95	3,41	750		-5,4	-1	4,5
2017.02.24 16.23.3	33	4,37	1,71	-4,28	-3,12	730,28	0,22	4,45	3,41	750		-5,3	-1	4,3
2017.02.24 16.27.0	34	3,14	1,59	-2,77	-1,99	720,85	0,09	2,83	3,41	750		-5,3	-1,1	4,4
2017.02.24 16.30.2	35	4,27	1,75	-4,08	-2,98	734,71	0,43	4,41	3,41	750		-5,5	-1,1	4,3
2017.02.24 16.33.4	36	3,70	1,56	-3,65	-2,59	712,25	0,15	3,77	3,41	750		-5,4	-1,4	4,3
2017.02.24 16.37.2	37	3,47	1,80	-2,99	-2,16	726,99	-0,10	2,89	3,41	750		-5,3	-1,4	4,5
2017.02.24 16.40.3	38	3,75	1,87	-3,47	-2,43	702,84	-0,16	3,32	3,41	750		-5,4	-1,4	4,4
2017.02.24 16.43.5	39	3,32	0,14	-4,49	-3,21	719,84	0,31	4,72	3,41	750		-5,4	-1,5	4,4
2017.02.24 16.48.0	40	4,34	1,52	-4,64	-3,26	705,58	0,00	4,62	3,41	750		-5,5	-1,5	4,5
2017.02.24 16.51.3	41	2,70	0,46	-3,38	-2,37	703,90	0,05	3,40	3,41	750		-5,4	-1,6	4,6
2017.02.24 16.54.5	42	2,81	0,61	-3,43	-2,39	697,40	0,00	3,43	3,41	750		-5,4	-1,6	4,5
2017.02.24 16.58.0	43	3,59	1,04	-4,16	-2,87	694,81	0,00	4,13	3,41	750		-5,4	-1,6	4,6
2017.02.24 17.02.4	44	3,74	1,52	-3,81	-2,68	705,43	-0,06	3,75	3,41	750		-5,5	-1,6	4,7
2017.02.24 17.06.3	45	3,62	1,31	-3,69	-2,67	726,05	0,20	3,85	3,41	750		-5,6	-1,6	4,7
2017.02.26 07.37.0	46	4,77	1,77	-4,81	-3,48	725,81	0,15	4,93	3,41	750		-5,9	-1,1	4,9
2017.02.26 07.40.3	47	3,18	0,98	-3,52	-2,48	707,34	-0,07	3,45	3,41	750		-6	-1,3	4,7
2017.02.26 07.44.2	48	4,43	1,59	-4,55	-3,28	721,25	-0,20	4,38	3,41	750		-5,9	-1,4	4,8
2017.02.26 07.48.1	49	2,23	0,60	-2,57	-1,81	704,54	-0,22	2,38	3,41	750		-6	-1,5	4,8
2017.02.26 07.51.4	50	2,87	0,97	-3,02	-2,17	721,36	0,13	3,12	3,41	750		-6	-1,6	4,8
2017.02.26 07.55.0	51	2,72	1,12	-2,59	-1,90	732,70	-0,13	2,49	3,41	750		-6	-1,6	4,8
2017.02.26 07.58.3	52	1,62	0,43	-1,86	-1,31	708,26	-0,15	1,73	3,41	750		-6	-1,7	4,8
2017.02.26 08.02.5	53	4,02	1,31	-4,17	-3,06	733,65	0,00	4,17	3,41	750		-6	-1,8	4,8
2017.02.26 08.06.2	54	2,52	1,24	-2,21	-1,61	731,25	-0,19	2,05	3,41	750		-6,1	-1,8	4,8
2017.02.26 08.09.5	55	2,54	0,61	-2,92	-2,10	720,32	-0,12	2,82	3,41	750		-6,1	-1,9	4,8

Table 26: The table contains summarized values of raw friction data obtained in the field experiment for the heated B3 900 N-skate blade with a L4-surface treatment, for the temperature test.

Temperature	B3 900N	Set point X (N	CoF	CoF calibrate	X cal. For Zer	Z-direction (N	Acceleration	CoF cal. For a	Pressure on ice (Mp	Load force	Humidity (%)	Temp. 0,5cm	Temp. 0,5cm	Temp. Air 60	Temp. of skate before	Temp. of ska	Temp. skate a
	median	1,00	-2,61	-3,81	-3,31	884,94	0,10	3,93	3,94	900,00	72,35	-5,50	-2,10	4,70	6,10	4,75	3,15
	gjennomsnitt	1,08	-2,69	-3,91	-3,45	881,47	0,09	3,99	3,94	900,00	72,47	-5,45	-2,08	4,76	5,45	4,1	2,6
	std.avvik	0,90	0,96	0,31	0,31	19,67	0,18	0,38	0,00	0,00	0,55	0,10	0,06	0,11	1,69	1,37	1,14
	maks	2,82	-1,47	-3,66	-3,20	904,90	0,33	4,84	3,94	900,00	73,70	-5,20	-2,00	4,90	7,20	5,8	3,9
	min	-0,57	-4,93	-4,59	-4,15	845,55	-0,18	3,52	3,94	900,00	71,80	-5,50	-2,20	4,60	2,00	1,4	0,7
Date and tim	Number of runs	Set point X (N	CoF	CoF calibrate	X cal. For Zer	Z-direction (N	Acceleration	CoF cal. For a	Pressure on ice (Mp	Load force	Humidity (%)	Temp. 0,5cm	Temp. 0,5cm	Temp. Air 60	Temp. of skate before	Temp. of ska	Temp. skate a
2017.02.28 1	1	0,81	-2,83	-3,79	-3,20	845,55	0,04	3,83	3,94	900,00	71,80	-5,40	-2,00	4,70	4,20	2,80	1,40
2017.02.28 1	2	0,60	-2,97	-3,66	-3,21	877,14	0,00	3,66	3,94	900,00	72,50	-5,50	-2,10	4,70	3,40	2,70	0,70
2017.02.28 1	3	0,97	-2,71	-3,85	-3,27	851,40	-0,16	3,72	3,94	900,00	72,30	-5,50	-2,10	4,70	2,00	1,40	0,90
2017.02.28 1	4	0,42	-3,23	-3,70	-3,31	895,50	0,32	3,95	3,94	900,00	72,80	-5,40	-2,10	4,70	6,10	4,70	3,30
2017.02.28 1	5	1,03	-2,52	-3,66	-3,29	899,15	-0,18	3,52	3,94	900,00	72,40	-5,20	-2,20	4,70	6,20	4,80	3,20
2017.02.28 1	6	-0,57	-4,93	-4,29	-3,81	890,70	0,00	4,28	3,94	900,00	73,70	-5,50	-2,10	4,60	6,10	4,40	2,80
2017.02.28 1	7	2,82	-1,47	-4,59	-4,15	904,90	0,33	4,84	3,94	900,00	72,30	-5,50	-2,10	4,90	6,00	4,80	3,10
2017.02.28 1	8	1,70	-1,81	-3,71	-3,31	892,11	0,24	3,90	3,94	900,00	72,90	-5,50	-2,10	4,80	7,00	5,10	3,40
2017.02.28 1	9	1,64	-1,96	-3,82	-3,36	879,08	0,16	3,95	3,94	900,00	72,00	-5,50	-2,00	4,90	6,30	4,90	3,20
2017.02.28 1	10	1,40	-2,50	-4,09	-3,59	879,19	0,17	4,22	3,94	900,00	72,00	-5,50	-2,00	4,90	7,20	5,80	3,90

Appendix B

Table 27: The table contains raw data from measuring the nominal contact pressure of the individual skate blades with the given loads. The average values highlighted in green, represent the values further evaluated in this master thesis.

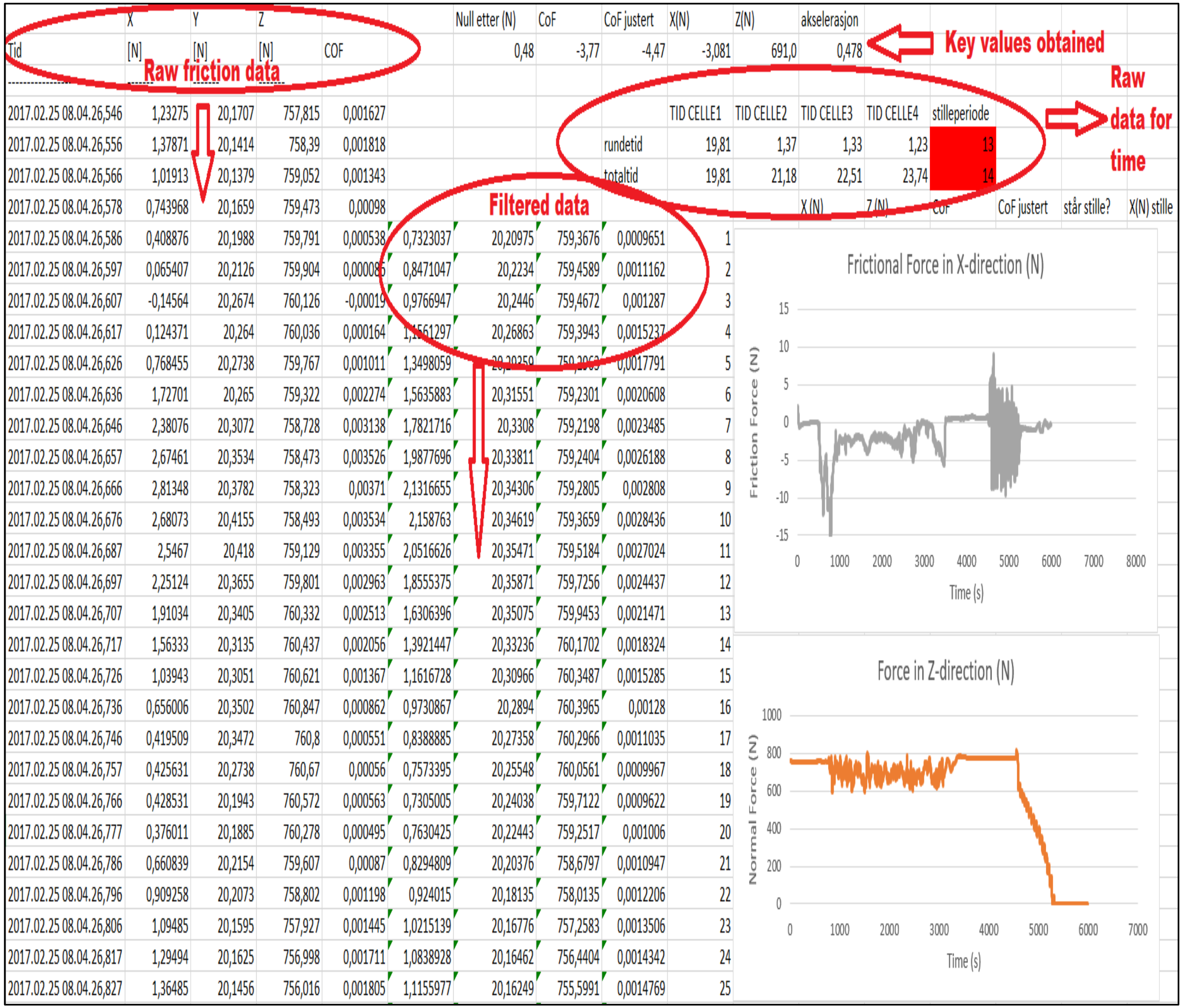
	Load	Center to front (cm)	Center to back (cm)	Nominal contact length (mm)	Width of blade (mm)	Nominal contact area (mm^2)	Nominal contact pressure (MPa)
B3	287,00	10,00	-8,50	185,00	1,10	203,50	1,41
B3	294,00	5,20	-9,60	148,00	1,10	162,80	1,81
B3	302,00	5,60	-10,00	156,00	1,10	171,60	1,76
B3	310,00	6,00	-12,70	187,00	1,10	205,70	1,51
B3	298,00	8,50	-7,50	160,00	1,10	176,00	1,69
B3	301,00	8,00	-9,50	175,00	1,10	192,50	1,56
B3	300,00	7,00	-9,50	165,00	1,10	181,50	1,65
B3	300,00	6,20	-9,80	160,00	1,10	176,00	1,70
B3	307,00	6,10	-9,10	152,00	1,10	167,20	1,84
B3	295,00	6,80	-9,70	165,00	1,10	181,50	1,63
B3	297,00	7,30	-10,50	178,00	1,10	195,80	1,52
Average	299,18	6,97	-9,67	166,45	1,10	183,10	1,64
SD	6,24	1,41	1,28	13,11	0,00	14,42	0,13
B3	597,00	10,00	-10,50	205,00	1,10	225,50	2,65
B3	597,00	10,00	-10,50	205,00	1,10	225,50	2,65
B3	599,00	9,00	-11,00	200,00	1,10	220,00	2,72
B3	594,00	7,20	-11,30	185,00	1,10	203,50	2,92
B3	588,00	9,20	-10,50	197,00	1,10	216,70	2,71
B3	590,00	9,20	-11,20	204,00	1,10	224,40	2,63
B3	594,00	9,50	-10,40	199,00	1,10	218,90	2,71
B3	602,00	8,50	-12,00	205,00	1,10	225,50	2,67
B3	593,00	9,00	-10,00	190,00	1,10	209,00	2,84
B3	595,00	9,00	-11,00	200,00	1,10	220,00	2,70
B3	593,00	5,00	-11,50	165,00	1,10	181,50	3,27
B3	603,00	10,00	-11,50	215,00	1,10	236,50	2,55
B3	585,00	10,40	-12,50	229,00	1,10	251,90	2,32
B3	598,00	8,30	-10,00	183,00	1,10	201,30	2,97
B3	590,00	10,30	-10,30	206,00	1,10	226,60	2,60
B3	613,00	10,00	-10,60	206,00	1,10	226,60	2,71
Average	595,69	9,04	-10,93	199,63	1,10	219,59	2,73
SD	6,69	1,36	0,71	14,32	0,00	15,75	0,21
B3	750,00	9,00	-12,00	210,00	1,10	231,00	3,25
B3	742,00	8,00	-13,50	215,00	1,10	236,50	3,14
B3	743,00	6,20	-13,50	197,00	1,10	216,70	3,43
B3	750,00	11,00	-9,50	205,00	1,10	225,50	3,33
B3	743,00	11,30	-10,50	218,00	1,10	239,80	3,10
B3	759,00	7,30	-11,50	188,00	1,10	206,80	3,67
B3	753,00	6,50	-9,50	160,00	1,10	176,00	4,28
B3	758,00	9,00	-10,10	191,00	1,10	210,10	3,61
B3	744,00	10,00	-12,00	220,00	1,10	242,00	3,07
B3	758,00	9,00	-13,50	225,00	1,10	247,50	3,06
B3	746,00	8,60	-11,20	198,00	1,10	217,80	3,43
B3	746,00	10,50	-8,70	192,00	1,10	211,20	3,53
Average	749,33	8,87	-11,29	201,58	1,10	221,74	3,41
SD	6,34	1,66	1,68	18,02	0,00	19,82	0,35

Continuation of table 27:

B3	900,00	9,30	-12,30	216,00	1,10	237,60	3,79
B3	896,00	11,50	-11,00	225,00	1,10	247,50	3,62
B3	900,00	7,00	-13,50	205,00	1,10	225,50	3,99
B3	892,00	6,90	-10,80	177,00	1,10	194,70	4,58
B3	890,00	11,50	-10,50	220,00	1,10	242,00	3,68
B3	894,00	10,80	-10,00	208,00	1,10	228,80	3,91
B3	892,00	10,50	-10,00	205,00	1,10	225,50	3,96
B3	900,00	7,30	-13,20	205,00	1,10	225,50	3,99
B3	895,00	9,80	-12,40	222,00	1,10	244,20	3,67
B3	892,00	8,20	-10,30	185,00	1,10	203,50	4,38
B3	900,00	11,20	-10,50	217,00	1,10	238,70	3,77
B3	910,00	8,80	-12,00	208,00	1,10	228,80	3,98
Average	896,75	9,40	-11,38	207,75	1,10	228,53	3,94
SD	5,58	1,75	1,25	14,43	0,00	15,87	0,29
B5	749,00	6,50	-6,50	130,00	1,25	162,50	4,61
B5	748,00	8,50	-10,50	190,00	1,25	237,50	3,15
B5	751,00	8,50	-11,50	200,00	1,25	250,00	3,00
B5	756,00	9,70	-10,50	202,00	1,25	252,50	2,99
B5	747,00	9,50	-13,50	230,00	1,25	287,50	2,60
B5	758,00	11,00	-10,40	214,00	1,25	267,50	2,83
B5	743,00	9,20	-12,90	221,00	1,25	276,25	2,69
B5	745,00	8,50	-11,50	200,00	1,25	250,00	2,98
B5	750,00	8,50	-11,30	198,00	1,25	247,50	3,03
B5	747,00	9,00	-10,80	198,00	1,25	247,50	3,02
Average	749,40	8,89	-10,94	198,30	1,25	247,88	3,09
SD	4,65	1,15	1,87	26,92	0,00	33,64	0,56
B1	745,00	9,50	-15,00	245,00	0,90	220,50	3,38
B1	749,00	11,30	-13,50	248,00	0,90	223,20	3,36
B1	744,00	7,50	-12,10	196,00	0,90	176,40	4,22
B1	749,00	8,00	-12,80	208,00	0,90	187,20	4,00
B1	747,00	9,50	-10,60	201,00	0,90	180,90	4,13
B1	750,00	8,50	-10,50	190,00	0,90	171,00	4,39
B1	745,00	8,50	-11,50	200,00	0,90	180,00	4,14
B1	756,00	8,20	-11,50	197,00	0,90	177,30	4,26
B1	750,00	7,50	-11,00	185,00	0,90	166,50	4,50
B1	750,00	9,60	-11,70	213,00	0,90	191,70	3,91
Average	748,50	8,81	-12,02	208,30	0,90	187,47	4,03
SD	3,50	1,18	1,40	21,66	0,00	19,50	0,39

Appendix C

The following, Figure 33, is an example of how the raw data was analysed using tools in a spread sheet in Microsoft Excel.



	X	Y	Z			Null etter (N)	CoF	CoF justert	X(N)	Z(N)	akselerasjon					
Tid	[N]	[N]	[N]	COF		0,48	-3,77	-4,47	-3,081	691,0	0,478					
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2017.02.25 08.04.26,546	1,23275	20,1707	757,815	0,001627					TID CELLE1	TID CELLE2	TID CELLE3	TID CELLE4	stilleperiode			
2017.02.25 08.04.26,556	1,37871	20,1414	758,39	0,001818				rundetid	19,81	1,37	1,33	1,23	13			
2017.02.25 08.04.26,566	1,01913	20,1379	759,052	0,001343				totaltid	19,81	21,18	22,51	23,74	14			
2017.02.25 08.04.26,578	0,743968	20,1659	759,473	0,00098							X (N)	Z (N)	CoF	CoF justert	står stille?	X(N) stille
2017.02.25 08.04.26,586	0,408876	20,1988	759,791	0,000538	0,7323037	20,20975	759,3676	0,0009651	1							
2017.02.25 08.04.26,597	0,065407	20,2126	759,904	0,000086	0,8471047	20,2234	759,4589	0,0011162	2							
2017.02.25 08.04.26,607	-0,14564	20,2674	760,126	-0,00019	0,9766947	20,2446	759,4672	0,001287	3							
2017.02.25 08.04.26,617	0,124371	20,264	760,036	0,000164	1,1561297	20,26863	759,3943	0,0015237	4							
2017.02.25 08.04.26,626	0,768455	20,2738	759,767	0,001011	1,3498059	20,29359	759,3063	0,0017791	5							
2017.02.25 08.04.26,636	1,72701	20,265	759,322	0,002274	1,5635883	20,31551	759,2301	0,0020608	6							
2017.02.25 08.04.26,646	2,38076	20,3072	758,728	0,003138	1,7821716	20,3308	759,2198	0,0023485	7							
2017.02.25 08.04.26,657	2,67461	20,3534	758,473	0,003526	1,9877696	20,33811	759,2404	0,0026188	8							
2017.02.25 08.04.26,666	2,81348	20,3782	758,323	0,00371	2,1316655	20,34306	759,2805	0,002808	9							
2017.02.25 08.04.26,676	2,68073	20,4155	758,493	0,003534	2,158763	20,34619	759,3659	0,0028436	10							
2017.02.25 08.04.26,687	2,5467	20,418	759,129	0,003355	2,0516626	20,35471	759,5184	0,0027024	11							
2017.02.25 08.04.26,697	2,25124	20,3655	759,801	0,002963	1,8555375	20,35871	759,7256	0,0024437	12							
2017.02.25 08.04.26,707	1,91034	20,3405	760,332	0,002513	1,6306396	20,35075	759,9453	0,0021471	13							
2017.02.25 08.04.26,717	1,56333	20,3135	760,437	0,002056	1,3921447	20,33236	760,1702	0,0018324	14							
2017.02.25 08.04.26,726	1,03943	20,3051	760,621	0,001367	1,1616728	20,30966	760,3487	0,0015285	15							
2017.02.25 08.04.26,736	0,656006	20,3502	760,847	0,000862	0,9730867	20,2894	760,3965	0,00128	16							
2017.02.25 08.04.26,746	0,419509	20,3472	760,8	0,000551	0,8388885	20,27358	760,2966	0,0011035	17							
2017.02.25 08.04.26,757	0,425631	20,2738	760,67	0,00056	0,7573395	20,25548	760,0561	0,0009967	18							
2017.02.25 08.04.26,766	0,428531	20,1943	760,572	0,000563	0,7305005	20,24038	759,7122	0,0009622	19							
2017.02.25 08.04.26,777	0,376011	20,1885	760,278	0,000495	0,7630425	20,22443	759,2517	0,001006	20							
2017.02.25 08.04.26,786	0,660839	20,2154	759,607	0,00087	0,8294809	20,20376	758,6797	0,0010947	21							
2017.02.25 08.04.26,796	0,909258	20,2073	758,802	0,001198	0,924015	20,18135	758,0135	0,0012206	22							
2017.02.25 08.04.26,806	1,09485	20,1595	757,927	0,001445	1,0215139	20,16776	757,2583	0,0013506	23							
2017.02.25 08.04.26,817	1,29494	20,1625	756,998	0,001711	1,0838928	20,16462	756,4404	0,0014342	24							
2017.02.25 08.04.26,827	1,36485	20,1456	756,016	0,001805	1,1155977	20,16249	755,5991	0,0014769	25							

Figure 33: The figure is screenshot of the Microsoft Excel spread sheet used for filtering out friction data obtained throughout the measurement zone. This example is from the B1 750 N- skate. With a combination of values for time and friction, key values were determined to further investigate the friction behaviour during the run. The illustrations depicted in the figure describes which data was used to obtain key values.