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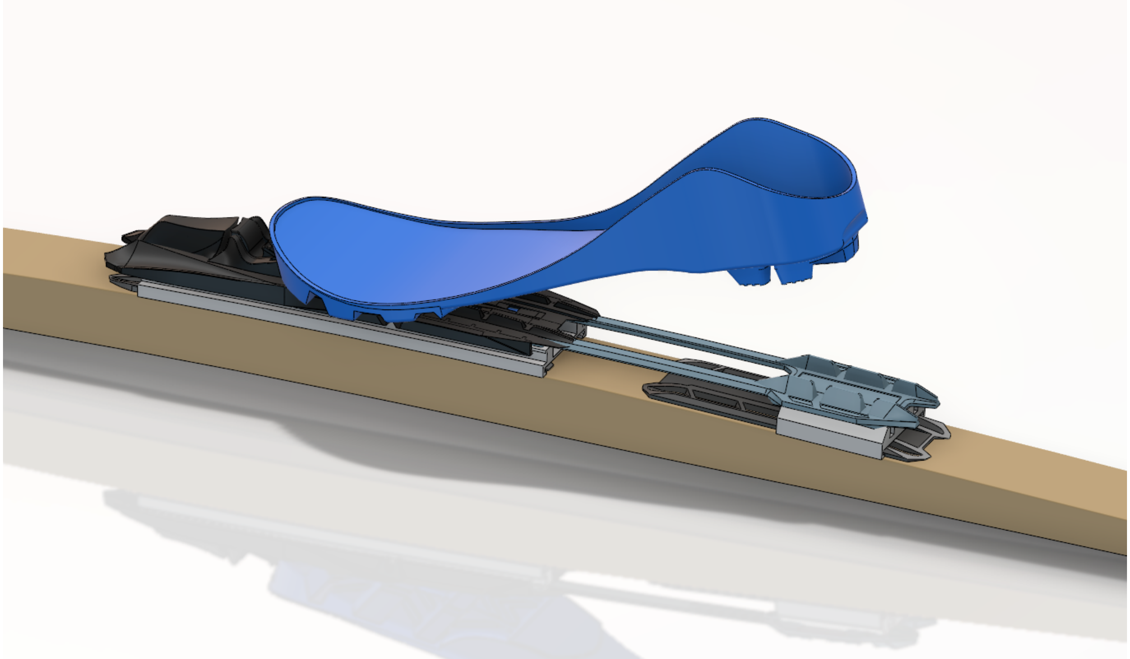

Integration of Force Sensors in Cross-Country Ski Bindings and Concept Development for Multi-Sport Measurement Platforms

Master's thesis in Material Engineering

Quentin Moulet

DEPARTMENT OF PHYSICS

CHALMERS UNIVERSITY OF TECHNOLOGY
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Master's Thesis 2025
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Cover: Concept picture of a force-measuring binding integrated into a cross-country ski.

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Abstract

Accurate force measurement is an essential component in sports science, providing valuable insights into biomechanics, performance, technique, and equipment interaction. Skisens, a Swedish sports technology company, pioneered the introduction of force measurement in cross-country skiing, through instrumented ski poles. Building on this foundation, the present thesis explores the extension of Skisens technology to other contexts. The main focus was the development and validation of a prototype ski binding equipped with integrated force sensors. Several design iterations were produced using CAD tools and 3D printing with advanced polymers, and were validated against AMTIN force plates. Data processing, filtering, and detection of push-off cycles were performed in Python. The results demonstrated a strong correlation (averaging 80 percent) between the force measurement in the binding prototype and the reference force plates. Propulsive phases were consistently detected and key biomechanical variables such as impulse, average force, and power output were calculated.

In addition to the ski binding prototype, two conceptual devices were explored: a modular force plate for dynamic sports such as athletics and strength training, and an inline traction force sensor for gym applications. Both devices were tested in a gym context, and promising results were obtained for key movement values, validated through high-speed video tracking.

This thesis highlights both the potential and the current limitations of integrating force sensors directly into sports equipment. Although prototypes remain fragile and are not yet ready for use in the field, the concepts show great potential for providing athletes and coaches with decisive information and real-time feedback on various sports equipment.

Keywords: Cross-country skiing, force measurement, strength training, ski binding, sport technology

Preface

This report presents the result of my master's thesis project carried out at the Department of Physics at Chalmers University of Technology from January to September 2025.

Acknowledgements

I would like to thank my supervisor and examiner Magnus Karlsteen for his support and guidance during my project. I also thank Skisens and Johan Högstrand for the opportunity to work on this project and for their help throughout the project.

Quentin Moulet, Gothenburg, September 2025

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

ADC	Analog to Digital Converter
ATMI	Advanced Mechanical Technology, Inc.
CAD	Computer Aided Design
IFP	Integrated Fixation Plate
IMU	Inertial measurement unit
LPT	Linear Position Transducers
MAPE	Mean absolute percentage error
MR	Maximal repetition
NIS	Nordic Integrated System
PCB	Printed Circuit Boards
RMSE	Root mean square error
R^2	Coefficient of determination
SLS	Laser sintering

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Introduction

1.1 Background

1.1.1 Importance of force measurement in sports

In competitive sports, performance is often determined by subtle differences in technique, efficiency, and force production. To optimize these elements, athletes and coaches are increasingly relying on precise biomechanical data. One of the most critical metrics is force, which directly reflects the physical interaction between the athlete and their environment. Accurate force measurement enhances training feedback and performance analysis, and aids injury prevention, rehabilitation and equipment design.

While force platforms and instrumented ergo-meters have long been used in laboratories, there is now a growing need for mobile, sports-specific solutions that provide real-time feedback in natural environments. Force sensor technology is now widely used in cycling, but other sports have not yet found a solution to obtain these values. In this context, integrating sensors directly into sports equipment, such as shoes, poles, or skis, offers an exciting opportunities, for other sports, to bridge the gap between lab-grade data and field usability.

1.1.2 Skisens and their innovation in cross-country skiing

Skisens is a Swedish sports technology company that is working on these innovations. The company has developed the world's first commercial power meter for cross-country skiing that is integrated into the handle of the ski pole. This device allows athletes to measure the propulsion forces exerted by their poles while skiing, providing real-time metrics to support the refinement of their technique, the profiling of their physiology, and the development of personalized coaching strategies. It has already gained popularity among elite skiers and national teams, demonstrating the value of integrated force measurement in top-level sports.

Skisens technology is highly versatile, with strong potential for application in other areas of skiing and sport more broadly. Integrating force sensors into ski bindings and expanding their use to other sports with force plates and traction systems could provide elite athletes with valuable training data.

This thesis responds to this opportunity by focusing on the development and validation of a force-measuring ski binding prototype, alongside conceptual designs for modular force platforms and traction sensor.

1.2 Purpose

Understanding how force is applied using ski poles only explains part of the skier's effort. Depending on the technique used, between 30 and 90 percent-of propulsion is delivered via the legs [1, 2, 3]. Access propulsion forces from the legs is so essential to understand all aspects of this complex sport, which blends glide technology and technical aspects coupled with physical demands.

For skiers, as with many athletes, training does not only take place on the skis; strength training and other types of exercise besides their main sport have been essential in reaching the top level [4, 5]. Understanding power throughout these exercises helps to learn how the body works, adapt the training, and work in a more specialized way.

In this context, there is a need for broader applications and innovations to track force and power in strength training exercises.

1.3 Goals

This thesis aims to contribute to the development of innovative, sport-specific force measurement systems by building on existing Skisens technology. The main focus is on designing, prototyping, and validating an integrated force sensing system within cross-country ski bindings.

The aim is to capture leg propulsion forces during skiing. This includes mechanical design, data acquisition, and data treatment analysis to assess the accuracy and usability of the system under real conditions.

Additionally, the thesis explores the conceptual development of two complementary devices: a modular force plate system developed for dynamic sports such as track and field or gymnastics, and a traction force sensor that can be plugged into strength training machines.

Together, these projects aim to contribute to the extension of the Skisens platform to new domains of performance diagnostics. The goal is to provide athletes, coaches, and researchers with practical tools for collecting meaningful biomechanical data.

1.4 Limitations

The majority of the project was devoted to the ski binding part, due to its application beyond the scope of Skisens. Access to qualified expertise was more limited for the other two applications (elite athletes and experts in their sport).

Due to the time constraints of this thesis and the available resources, some very desirable developments could not be implemented (such as a PCB plate connecting 4 sensors or molded plastic parts adapted for outdoor use). More details can be found in the next sections. This resulted in less integrated and robust systems.

1.5 Structure of the Thesis

The remainder of the thesis is organized as follows: Chapter 2 presents earlier research and the theory on which this work is based. Chapter 3 presents the methods for developing a ski-binding force measuring prototype and the strategies to analyze the data. The results are presented in the chapter 4, showing the solutions and comparing the data of the different tests. Chapter 5, discusses the results obtained. Appendix A presents the Python scipts used to analyze data.

2

Theory

2.1 Force measurement in sports

2.1.1 Overview of force measurements in sport

Force measurement is a very interesting data in sport. It directly quantifies the effort produced by the athlete and therefore characterizes the results of their biomechanics [6]. Force measurement historically began on force plates before applications in the field began to appear. Nowadays, ergo-meters, indoor bicycles, or strength machines can be equipped with power measurement.

Athletes and coaches can use power to quantify training intensity and follow improvement. In addition to performance measurement, force measurements are of great interest in rehabilitation and post-injury evaluation.

2.1.2 Force measurement techniques

There are two main techniques for measuring force. Piezoelectric and strain gauge sensor.

A piezometric sensor measures force by measuring the electrical charge of a piezoelectric material. When a mechanical stress is applied, the material undergoes a proportional change in its electrical charge. This signal, amplified and conditioned, allows for the precise measurement of dynamic forces or vibrations. These sensors are distinguished by their sensitivity and wide bandwidth, but have a major limitation for static measurements as the charge gradually dissipates over time. They are commonly used in laboratory force plates to analyze support and impulse phases in biomechanics.

A strain gauge force sensor operates on the principle that the electrical resistance of a material varies when it deforms under load. A thin resistive foil is bonded to a carrier structure. When this structure is stretched or compressed by mechanical stress, the strain gauge undergoes a proportional change in length and cross section, this resulting in a measurable change in resistance. Integrating these gauges into a Wheatstone bridge circuit enables small resistance variations to be converted into an electrical signal that accurately reflects the applied force. Figure 2.1 shows an overview of a strain gauge system from a manufacturer [7]. Unlike piezoelectric sensors, strain gauge sensors can measure both static and dynamic forces with high stability, although their frequency response is more limited. They are widely used in load cells for industrial weighing, structural testing, and sports equipment instrumentation.

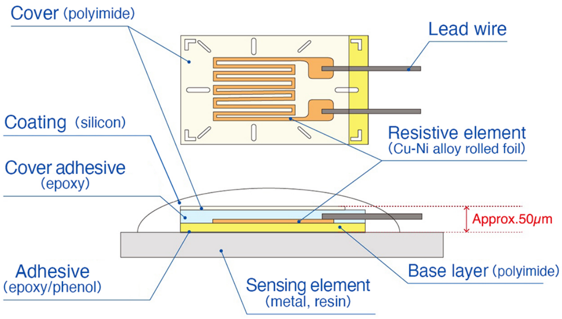


Figure 2.1: Strain gauge sensor functional diagram, from Minebea Mitsumi

2.1.3 Main measurement systems

There are three main types of force measurement systems:
Force platforms, these are often based on piezoelectric sensors. They measure reaction forces (Fx, Fy, Fz) and moments (Mx, My, Mz) in the three directions of the space. These are highly reliable systems that allow for a wide range of measurement. However, they are expensive, and their implementation is complicated and long.

Displacement or speed sensors, called Linear Position Transducers (LPT) and Inertial Measurement Unit (IMU): they estimate the kinematics of the external load and segment speed using acceleration measurements. They do not measure force directly but are very useful for applications where the insertion of force sensors is not possible. They allow the intensity of exercises and the fatigue generated to be monitored, but can only be used with consistent protocols and the same measurement environment. These sensors are used in particular, in running to quantify force via acceleration at the shoe level.

On-board sensors such as instrumented pedals, cranks, or hubs are most of the time based on strain gauge systems glued locally to the structure. These transform mechanical micro deformations (bending, torsion, or traction) into variations in electrical resistance, that are then converted into force or torque.
These gauges are sensitive to temperature, so a Wheatstone bridge or electronic corrections is often used to ensure thermal compensation and measure actual mechanical deformation. The measurements are then used to calculate the power, using the formulas:

$$P = torque * cadence \tag{2.1}$$

or

$$P = F * v \tag{2.2}$$

The validity of the systems depends on the measurement location. Mechanical losses between the site and the wheel/ground can influence the measurement, as well as some vibrations or signal processing.

2.1.4 Force and power in cycling

Cycling is undoubtedly the sport where power training is most wildly developed. Many cyclists, not just professionals, use power training on a daily basis for their training. There are different types of sensors, with different measurement locations: In the pedals, the gauges are closest to where the force is applied and also allow the cyclist's right/left balance to be calculated.
In the cranks: measurement of the torque transmitted by pedaling.
In the hub: power is measured further away from the cyclist but takes into account transmission losses.

The cycling systems used are reliable and proven, with studies reporting a maximum error rate of 2 to 5 percent [8], depending on the protocols [9].
However, the measurement location has an impact on the actual power consumption value. This is because mechanical losses in the bike's transmission chain, the path between the foot and the ground, affect the actual power transmitted. It is therefore important to calibrate these sensors and reset them regularly [9].

2.2 Existing technologies

2.2.1 Skisens ski pole force sensors

Skisens began developing its products in 2017. The start-up uses strain gauge sensors that are integrated into the handle of the poles. These sensors connect via Bluetooth to the Skisens application, which is available on Android and IOS phones. In addition to connecting the two sensors, the app also tracks all the metrics relevant to endurance sports. These include heart rate, body heat, and vision sensors. The app can also be used to connect to control an indoor ski treadmill. All data can be viewed in real time in the app and on a live platform. Everything can also be exported afterwards at a frequency of 100 Hz.
The Skisens sensor itself consists of a load cell connected by four cables to a Printed Circuit Board (PCB) containing a Bluetooth transmitter, a LED and a battery connection.
The sensors are then integrated into a 3D printed block and cast in epoxy. Then, this part is placed on the handle of a ski pole, represent in figure 2.2. The top of the pole is cut and filed with a flat piece of stainless steel to make contact with the load cell.
The aim of this master's thesis is to use the same technology for other applications, so the same sensors will be used, and data will be collected via the application.
In the field of force measurement for cross-country skiing, there is currently no portable strategy available on the market or used in scientific research. Many articles use force plate systems mounted on skis or force plate zones integrated into the ground under the snow [10].
These systems are not designed for use in the field. They also have several drawbacks, including the small size of the test area and the fact that they can only be used indoors. It is also impossible to have a portable system that can be used for ev-

ery training session. Skisens technology is reliable and is now used by scientists and top-level skiers to optimize skiing technique [11] and glide, and to monitor training load.

Figure 2.2: Skisens hand grip with integrated power measurement

2.2.2 Commercial force plates and traction sensors

Several portable force plates used to measure sports exercises are available on the market and have been proven [12]. The force plate technology is proven and especially reliable with lab plate. The use of these portable force plates remains very marginal. The challenge of this project is to reproduce this type of system with a more flexible and portable system that is integrated into the Skisens environment. Traction sensors are also poorly represented in research, and no products have been completely developed.

2.3 Biomechanics in cross-country skiing

2.3.1 Forces involved in skate and classic technique

2.3.1.1 Classic technique

In the classic technique, the movement resembles a gliding gait, involving alternating propulsion from one ski and weight transfer to the other. The thrust mainly occurs along the longitudinal axis, with significant friction between the ski and the snow contributing to this, particularly in the holding zone (the waxed area). During the propulsive phase, a vertical force is generated by the body resting on the ski, as well as a horizontal force towards the rear that reflects the skier's pushing effort. Poles also contribute to propulsion, particularly on flat ground or when climbing.

2.3.1.2 Skating technique

The skating technique is based on alternating lateral propulsion. Each thrust of the skis is made diagonally backward and outward, at an angle typical of 20 to 30 degrees to the axis of travel. This configuration induces both horizontal (forward propulsion) and transverse (lateral sliding) forces. The vertical force applied to the ski is expected to increase rapidly at the beginning of the push phase, reach a peak, and then fall sharply at the end of the cycle when support is transferred to the other ski. Figure 2.3 shows pole and ski reaction forces [13]. However, the different skating techniques may only marginally influence the force curves.

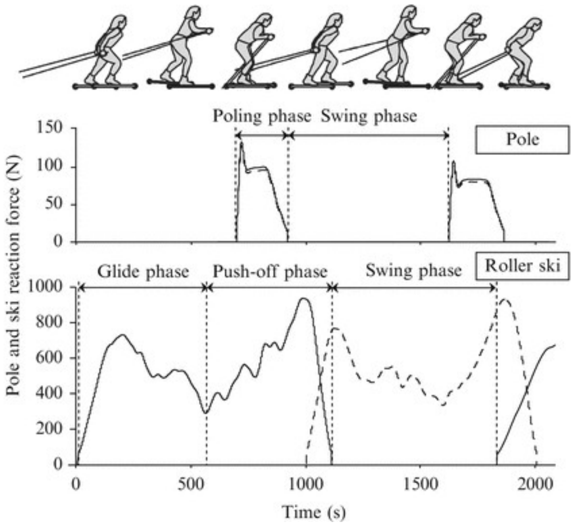


Figure 2.3: Reaction force in skating during one complete movement

2.3.1.3 Benefits of force measurement in skiing

Measurement of the forces in the bindings provides direct access to the forces generated by the legs, which play an essential role in propulsion. In combination with the sensors on the pole, a complete picture of the forces can be obtained. Then it is possible to obtain the following:

- The timing and duration of each propulsive phase
- The maximum intensity of the thrusts
- The effectiveness of the support transfer
- Potential asymmetry between left and right legs

Integrating sensors into lightweight equipment bindings is a strategic step forward in accessing this information without disrupting the skier's movements. There are many potential applications for athletes, coaches, and staff, including better understanding of glide, which is a key aspect of the sport. Skiing is also a sport where the conditions and the track are constantly changing. Power is the only reliable metric to compare the intensity of exercise in these conditions.

2.3.2 Embedded sensor design

Skisens sensors use strain gauge force sensors. They are integrated into an outer part of a cylinder made of stainless steel, the entire measuring system can be seen in figure 2.4. The dimensions are 10 mm in diameter and 6 mm in height. Skisens sensors only measure the force along one component, the vertical component in this thesis.

The Chalmers force plate is an ATMIN Net Force plate [14] which is supposed to be calibrated. To verify, known weights (10, 20, 30, 40 kg) were placed on the force plate ones and the values were correct.

The plate and the sensors must be calibrated to zero for each measurement, partly due to changes in temperature, pressure, and humidity [15]. This calibration was carried out by taking between 300 and 500 values (3 to 5 seconds) at the start of the recording. Values below 20 N are systematically deleted as these correspond to areas of no interest, which are often noisy.

The Skisens sensors send very good quality values, with an R^2 very close to 1 when compared with the force plate over most of the power spectrum. However, a slight decorrelation can be observed in the maximum values when the signal exhibits abrupt changes.

The Skisens values are always slightly lower, compared to the reference force plate. As the sensors are designed for measurements between 0 and 400 N, this discrepancy may be due to difficulty in detecting variations close to the maximum measurement limit. This problem is minor. With four sensors per foot, the maximum measurement capacity is 1,600 N. With an estimated 700 N for the skier's weight, this allows for the measurement of 900 N of thrust, or several thousand watts. This is usually sufficient for measuring the world's best sprinters.

The traction sensor uses exactly the same technology with a maximum traction force of 2000 N.

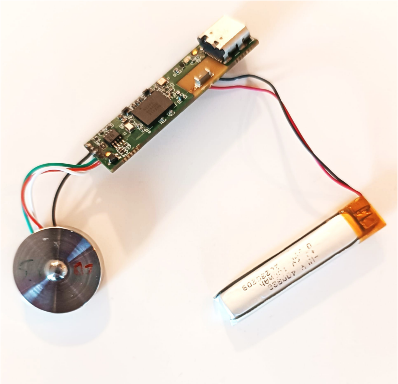


Figure 2.4: Skisens force sensor

3

Methods

3.1 Skisens technology and requirement

3.1.1 Skisens poles

Skisens sensors are designed to be placed inside ski poles, shown in figure 2.2. As described above, they are placed lengthwise in the handle. The PCB is thin and long and is connected with cables approximately 3 cm long. The system is then encased in epoxy to prevent damage.

The same system must be used for this project, but it is not possible to protect the sensors in epoxy because the prototypes are likely to change and the sensors will need to be assembled and disassembled.

Several sensors cannot be physically connected to each other, so sufficient space must be incorporated into the design for all components. However, the devices can be recharged when the system is dismantled for this project.

3.1.2 Requirements

The prototype needs to meet certain design requirements. There are several brands of bindings in cross-country skiing, each with their own technologies: Salomon Pro-Link, Rottefella, Rosignol, and Fisher. These technologies are relatively similar in shape, with the part under the front of the foot being similar in the Rottefella and Fisher/Rosignol models. The Rottefella and Rosignol technologies were chosen for this project because of the binding models available for testing. The heel sections of the two technologies are not the same shape, so two prototypes were printed to fit the two models.

The key point is to create a portable and removable system that integrates easily into the bindings. As a portable system dedicated to high performance, the prototype must also be as light as possible, without this being the most important constraint. It must not influence the skier's technique, or only to a very small extent.

All prototypes were made using 3D printing, and the quality of the plastics and printing methods varied. Design strategies must be taken into account so that prototypes are not too fragile, even if certain connection areas need to be thin. Accessible solutions exist to produce parts with sufficient robustness for high-performance use in skiing for further development.

3.2 Tools used

The project required a combination of computer-aided design (CAD), data analysis, and experimental validation tools to design, prototype, and test the proposed solutions.

All design and simulation work was done using the 3DEXPERIENCE Engineer Student License (3DX). 3DX offers advanced functionalities for solid modeling, finite element analysis, and assembly simulation. All of this function has been used in the project for the development of the ski binding prototype. The platform also allowed a good workflow from concept sketching to assembly and structural verification of the components.

An AMTIN Net Force system was used as the reference measurement device. Force plates are widely recognized as the gold standard in biomechanics for measuring forces with high precision and sampling frequency. In this project, they were used to validate the accuracy and reliability of all of the different designs and configurations. Measurements allow to directly compare the sensor output signals to the reference values from the plates.

Several tests were performed on roller ski, on the ski treadmill in the Chalmers physiology laboratory. This setup allowed for reproducible experimental conditions. Roller ski is a really good way for skiers to train in the summer when snow is not available, the technique and the movement are really similar to ski. Ski bindings were mounted on the roller skis to have a setup reproducible on snow.

Python was the main tool for data processing, calibration routines, and post-processing of force signals. A set of custom scripts was developed to handle repetitive tasks such as cycle detection, impulse calculation, and filtering. Excel was used for complementary calculations and for quick visualization, particularly in the early stages of the project. The combination of Python and Excel allows for good automation of the data, rapid processing checks during the iterative development phases.

3.3 Ski binding testing approaches

The evaluation of the ski binding prototype was carried out with an iterative experimental methodology that combined force plate measurement and data processing. Force plates were used as a reference throughout the development process. The validation procedure followed a trial-and-error approach:

1. Initial design, 3D printing and assembly of the prototype
2. Experimental testing on the force plate
3. Identification of weaknesses
4. Iterative improvements (mechanical design, calibration adjustments)
5. Re-testing for validation

This cycle was repeated several times until the measured data reached an acceptable level of consistency with the force plate output. Several other types of tests were done in between, to check part of the system, understand better how they are working, and bring new ideas. Data sets collected during treadmill and force plate tests required systematic processing. To ensure efficiency and reproducibility, Python scripts were written to automate recurring steps such as calibration of the sensors, alignment of different data sources, and filtering of raw signals. The data were typically stored in .txt or .csv formats, which were then imported and excel before each processing. Scripts were implemented to:

- Detect propulsive cycles based on local maxima and minima of the force signals
- Compute the most interesting metrics, such as impulse, average peak force, and thrust duration, etc
- Apply correction factors derived from force plate comparison tests
- Export the processed results into Excel and graph in jpeg for interpretation

3.4 Gym sensors testing approaches

As with ski bindings, the modular force platform was tested and improved through iterations and validation on the reference force plate. Know weights (20, 40, 75, 85 kg) were also loaded to track evolution and compare measurements.
The traction sensor does not need to be integrated into any system. One just needs to screw two traction rings onto the ends.
The challenge was therefore to create an algorithm that could track the speed and movement of each movement during weight training, based on force measurements. The calculation protocols and calculated data were validated by comparing these values with high-frequency videos in which the time of each movement was measured, as well as the amplitude, using a tape measure placed along the pull movement.

3.5 Correlation calculation

The correlation between the experimental data and the measurements of the reference force plate was quantified using three standard error metrics: the coefficient of determination (R^2), the root mean square error (RMSE), and the mean absolute percentage error (MAPE).
The coefficient of determination is defined as:

$$R^2 = 1 - \frac{\sum(y_{\text{exp}} - y_{\text{ref}})^2}{\sum(y_{\text{ref}} - \overline{y_{\text{ref}}})^2} \tag{3.1}$$

where y_{exp} are the experimental measurements, y_{ref} the reference values, and $\overline{y_{\text{ref}}}$ their mean. R^2 indicating the proportion of variance between data sets with a score between 0 and 1.

RMSE is defined as:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_{\text{exp},i} - y_{\text{ref},i})^2} \tag{3.2}$$

RMSE gives the average magnitude of the error, expressed in the same unit as the measured variable.

MAPE provides a direct measure of the relative error in percentage:

$$MAPE = \frac{100}{n} \sum_{i=1}^{n} \left| \frac{y_{\mathrm{exp},i} - y_{\mathrm{ref},i}}{y_{\mathrm{ref},i}} \right| \tag{3.3}$$

MAPE gives the average percentage deviation of the experimental measurements from the reference values.

These tree coefficients will be used to quantify the quality of the correlation during the test and validate configurations.

3.6 Project timeline

A diagram of the project timeline is shown in figure 3.1. The projects related to the modular force plate and drag sensor are grouped under 'Gym prototypes'.

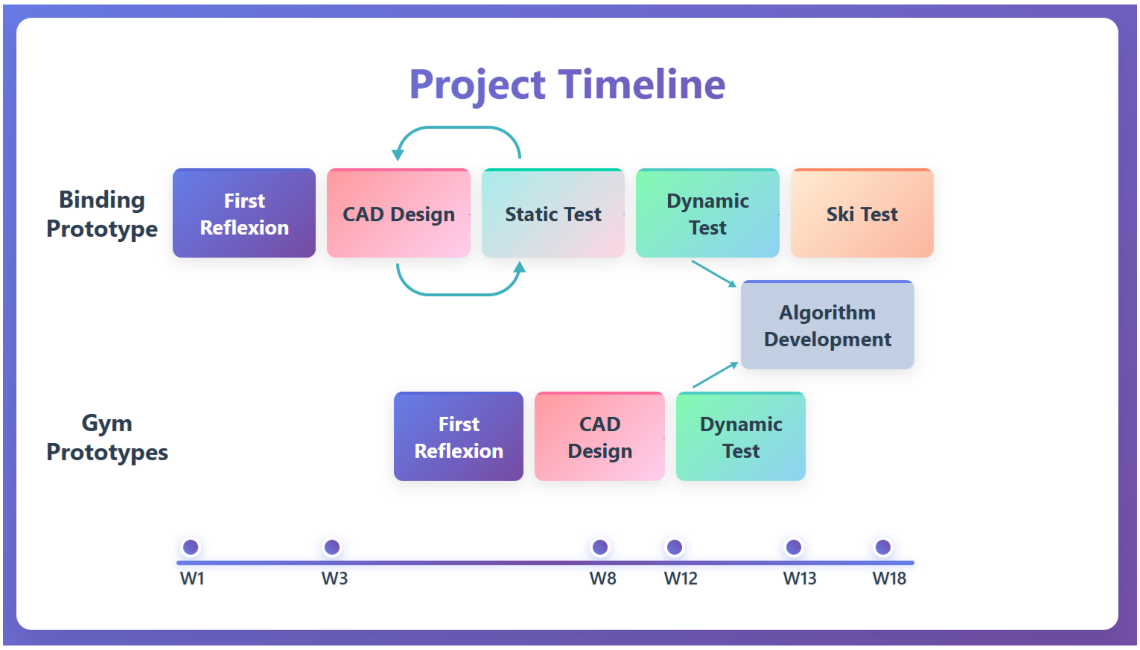


Figure 3.1: Project timeline

4

Results

4.1 Ski binding force measurement

4.1.1 Concept and design

4.1.1.1 Constraints, design choices and sensor placement

Cross-country ski bindings work on a sliding plate system. A plate is glued to the ski, and the binding part is slid over it. The left part is slid over the right part in figure 4.1 The decision was made to develop a sliding plate that slides and fits onto the glued plate and under the binding part. This makes it modular and easy for the user to use. It can be changed and is convenient for recharging the sensors and changing the pair of skis. There is no need to modify nether binding or ski, the system can fit the material used on the day by the skier. The ski shoes have two contact areas on the binding: one at the front and one at the rear. To create a more practical system, two parts containing force sensors will be created, one under the rear contact area and one under the front contact area.

Figure 4.1: Rottefella cross country ski binding (source: Rottefella)

One of the challenges is to place the sensors in the right position under the foot. A stainless steel metal plate is designed to transmit the force from the binding (in contact with the plate) to the sensors located under the plate. A triangular sensor configuration seems to be the best option, the selected configuration is shown in the figure 4.2. This is because the plate needs to be stabilized as it is not guided laterally.

The three sensors also ensure that their measurement limits are not exceeded. The part is then hollowed out in several places to accommodate the PCBs and battery, enabling Bluetooth connectivity.

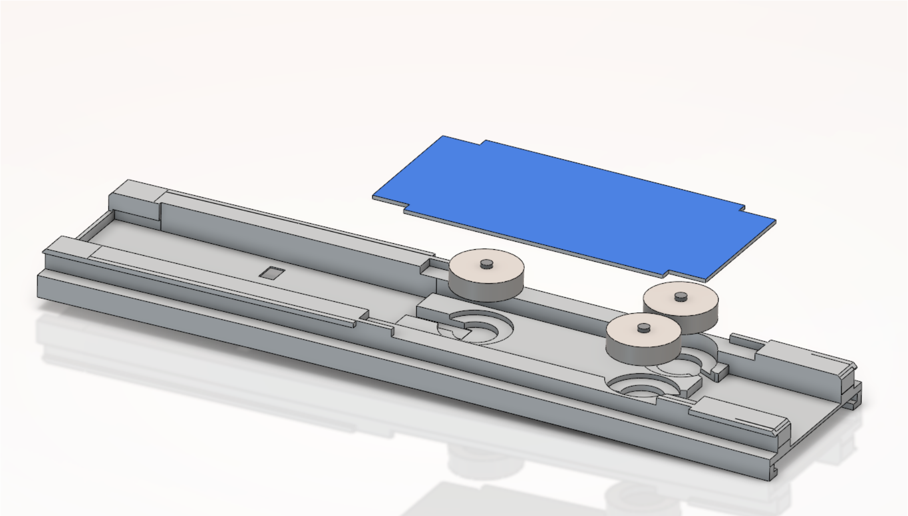


Figure 4.2: Exploded view of the assembly of the sensors and the metal plate in the frame

For the part under the heel, the goal was to use only one sensor, in order to limit the number of sensors and the space used by the components. A small metal plate was therefore used to connect the sensor to the rear part of the binding. This plate had to be locked in two dimensions so that it was only free in the vertical direction. The final design can be seen in figure 4.3. The rear part of the binding needed to be slid under four mini wedges to bring it into contact with the plate and prevent it from lifting. These mini wedges needed to be very thin and narrow to fit into the design, while still being 3D printable. This result by making this part of the design the most fragile.

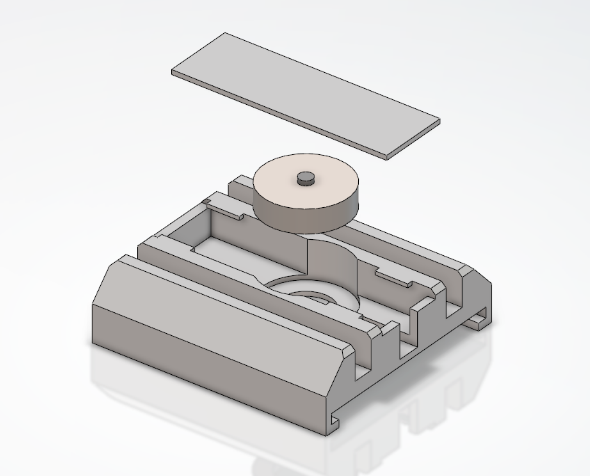


Figure 4.3: Exploded view of the assembly of the sensor and the metal plate in the frame

4.1.2 CAD models and prototyping

4.1.2.1 Versions of the design

The prototype was subjected to several iterations throughout the project, following a process of progressive refinement. Figure 4.4, 4.5 illustrates the main stages of this evolution. Although minor modifications were introduced at each step, the global geometry of the system remained mostly the same, as the initial design already provided an adequate compromise between compactness, mechanical robustness, and integration within the binding. The positioning of the sensors was guided by two approaches:

1. Biomechanical analysis: Several videos of world-class athletes were studied to identify the dominant motion patterns and to determine where the greatest forces are applied during the push-off phase.

2. Experimental analysis: Measurements with the shoe straddling the two force plates side by side, allowing the system to be separated into two and the percentage of force transmitted to both areas to be seen.

On the basis of these analyses, the sensitive area of the sole was determined, and the placement of the measurement plate was determined. However, several trial iterations were still required to optimize the positioning. The triangular arrangement of the sensors, initially oriented in one direction, was later reversed to better align with the biomechanics of the ski push. This modification concentrated the highest percentage of load on the two adjacent sensors, improving accuracy and load distribution.

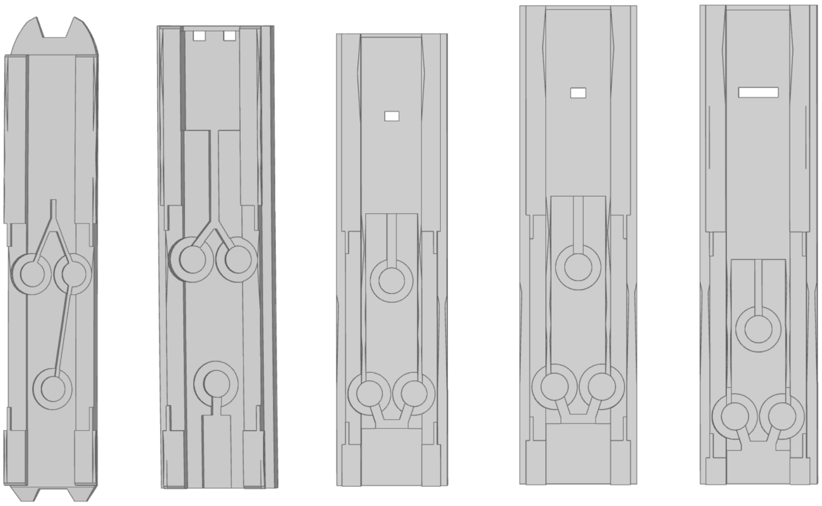


Figure 4.4: Design iteration of front part of the structure

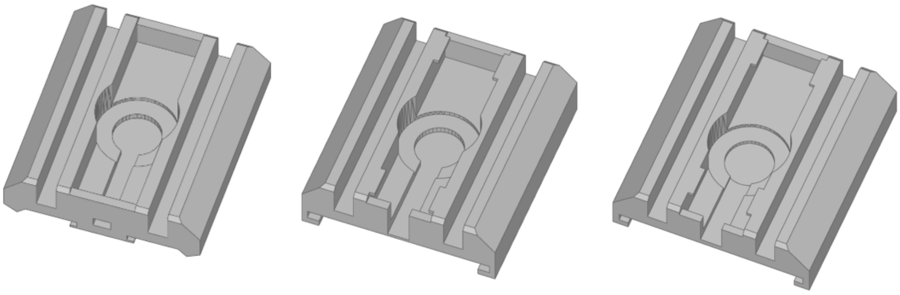


Figure 4.5: Design iteration of rear part of the structure

4.1.2.2 Manufacturing method

Two main approaches were adopted during prototyping, reflecting the iterative nature of the project:

- Early prototypes were produced using basic 3D printing plastics. These low-cost versions enabled rapid testing of the prototype. Allowing to check sensor integration, dimensional compatibility, and assembly procedures in an efficient way.
- Advanced prototypes were ordered from a manufacturer using selective laser sintering (SLS) using 3201PA-F nylon, a material offering higher stiffness, better durability, and able to handle higher load. This material is a polyamide powder specialized for SLS, which allows a really good heat stability. The manufacturer and material were already one used by Skisens in the past. The material was quite in line with the requirements of sports equipment: lightweight and robust under repeated cyclic stresses.

To complete the assembly, a machined stainless steel plate was incorporated (component in blue in figure 4.2). The plate was cut precisely with notches to ensure secure embedding within the plastic structure. The choice of metal is important, as a matching hardness between the load cell metal and the contact material is required to avoid any deformation of one of the components. This hybrid approach with the metal plate and the polymer casing ensures a really good force transmission to the measurement system, as well as a really light system.

4.1.2.3 Integration with existing bindings

The prototype was designed to integrate with existing NIS / IFP plates (used by Rottefella and Rossignol / Fischer) because the tests were performed using a combination of these components. For the forefoot connection, the Rottefella and Rossignol / Fischer systems have the same characteristics, while supporting Rossignol / Fischer bindings on the upper interface.

However, the attachment plates differ between the two manufacturers in the heel part. During the project, two separate design versions were developed to accommodate these variations.

Despite these adjustments and the different characteristics of the manufacturer systems, the measuring system was conceived as modular. The central force measurement module remains the same, with only the interface, in direct contact with the binding system, having to be adapted for compatibility. This ensures that the concept can be transferred to other commercial systems with a small redesign effort.

4.1.3 Validation tests

4.1.3.1 Setup description

Validation experiments were carried out using the force plate. Two main configurations were used:

1. Stationary tests: The binding prototype was mounted on an NIS/IFP plate together with the ski binding and placed (and taped) directly on the force plate. Additional trials were performed with a roller ski fixed to the plate with tape and wedges to ensure stability during testing.
2. Dynamic tests: When the prototype was shown to have good data correlation between the sensors and the force plate, the tests were extended to a treadmill with roller skis. These experiments enabled an initial evaluation of the signal type and quality in realistic skiing conditions before progressing to more advanced analysis.

4.1.3.2 Protocol

The testing protocols were designed to increase progressively in realism and complexity. On the force plate:

- Initial loading was applied through simple impulses to reproduce vertical push-offs: load / unload.
- A variety of loading patterns were tested to mimic potential ski movements, such as lateral skating pushes and classic vertical thrusts.
- This stage focused on identifying the basic response of the prototype and checking how well the measurements matched the reference force plate.

The roller skis were placed with one wheel on each of the two force plate, as on figure 4.6, because of their length.
On the treadmill:

- Simulations of both classic and skating ski techniques were performed.
- Different skiing techniques, slopes, and treadmill speeds were explored within the technical capacity of the experimenter. Unfortunately, it was not possible to replicate elite performance. Only speeds up to 15 km/h were tested. The objective was to ensure that the system could capture a representative load signal during relevant movements.

With this protocol, it was possible to both check the validity and the robustness of the prototype, and identify the corrective factors needed.

Finally, the final test was performed on skis at the Göteborg Skidome. The test was performed on skate skis. Two times ten-minute skating exercises were recorded. As there is no GPS signal available in the Skidome, power could not be calculated. Figure 4.8, 4.7 shows how the system was mounted on the skis.

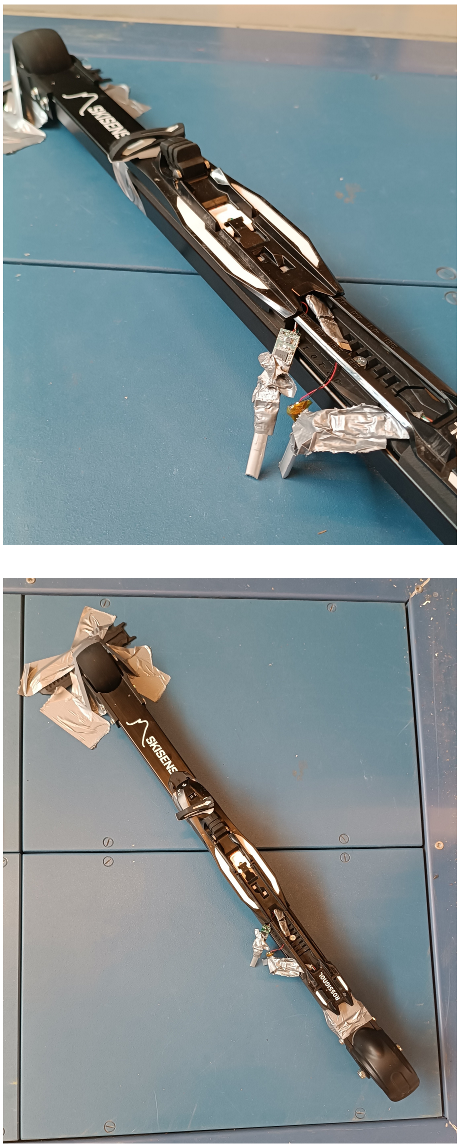


Figure 4.6: Test of the prototype mount on a roller ski on the force plate

Figure 4.7: System mounted on skis

Figure 4.8: Test of the prototype on snow in Skidome

4.1.4 Data acquisition and analysis

4.1.4.1 Sampling rate and filtering

The Skisens force system has a sampling rate of 100 Hz. However, the Skisens treadmill recording can only provide velocity and slope data at 1 Hz. So, the power calculations were based on the average force measured over each one-second interval combined with the corresponding treadmill velocity. To ensure data quality, a calibration phase was performed systematically at the beginning of each recording. The first three to four seconds were used to define the zero-force baseline. Additionally, a threshold filter was applied to suppress noise, discarding all data points below 30 N when this condition persisted for more than 25 consecutive samples (a parameter empirically determined based on observed noise fluctuations).

4.1.4.2 Data processing

The filtering, calibration, and computation of biomechanical parameters were carried out using dedicated Python scripts. Two main scripts were developed:

- A filtering script used for signal cleaning, baseline correction, and low-threshold removal.
- An analysis script used for cycle detection, calculation of mechanical variables, and data export.

The details of these scripts can be found in Appendix A.1.

4.1.4.3 Detection of push-off cycles

A central step in the analysis was the identification of push-off cycles. The detection algorithm was conducted in three stages:

- Peak detection: All local maxima of the force signal were identified, with the constraint that two consecutive peaks must be separated by at least 0.8 s, meaning that each cycle has only one dominant peak. Peaks must have values higher than 500 N.
- Cycle start: The absolute value preceding the dominant peak was detected. From this point, the beginning of a cycle was defined as the point at which the force increased by at least 350 N within 0.2 s.
- Cycle end: The cycle ended at the point following the peak where the force decreased by at least 350 N in 0.2 s.

This method enables the consistent segmentation of the data into discrete propulsion cycles. The data for each cycle were then used in all subsequent biomechanical calculations.

4.1.4.4 Computed variables

The following parameters were calculated for each identified cycle:

- Push-off time (cycle duration)
- Cadence (number of cycles per second)
- Impulse (integral of force over time)
- Peak force
- Mean force within the cycle
- Mean of the highest 20 force values within the cycle
- Force corrected with skier body weight
- Power (calculated with treadmill velocity times corrected force)

One of the main challenges was ensuring the correct treatment of body weight in the force signal. This is because body weight contributes to both vertical loading and propulsion through weight transfer.

Therefore, it was critical to determine the proportion of the force that was the skier's weight, in order to avoid overestimating the power output. Several scenarios were tested.

- Subtracting the full body weight from the force value
- Subtracting only a percentage of body weight
- Identifying a residual baseline force between cycles and removing only this component
- Use the highest 20 force values instead of the mean force
- Combining these approaches

Unfortunately, no clear solution emerged. From observation, it was found that a small amount of force may be lost and not measured. Subtracting the total body weight resulted in a force value of 0 for more than 50 percent of the tests. The residual baseline showed only a small amount of unused weight, making it unusable. The top 20 force values did not accurately represent the effort of the skier.

In order to continue and compare values between tests, an empirical calibration was adopted, leading to the use of an 80 percent body weight correction factor. An effective propulsion force of 18 percent was retained for power computations. Further testing is required to develop a robust protocol for this critical step and to ensure that the calculated values accurately reflect the propulsion forces.

4.1.5 Presentation of the results

4.1.5.1 Design

The final stages of development led to the design in figure 4.9. The measurement system is housed inside the light gray component that fits into the binding parts (in black and light blue).

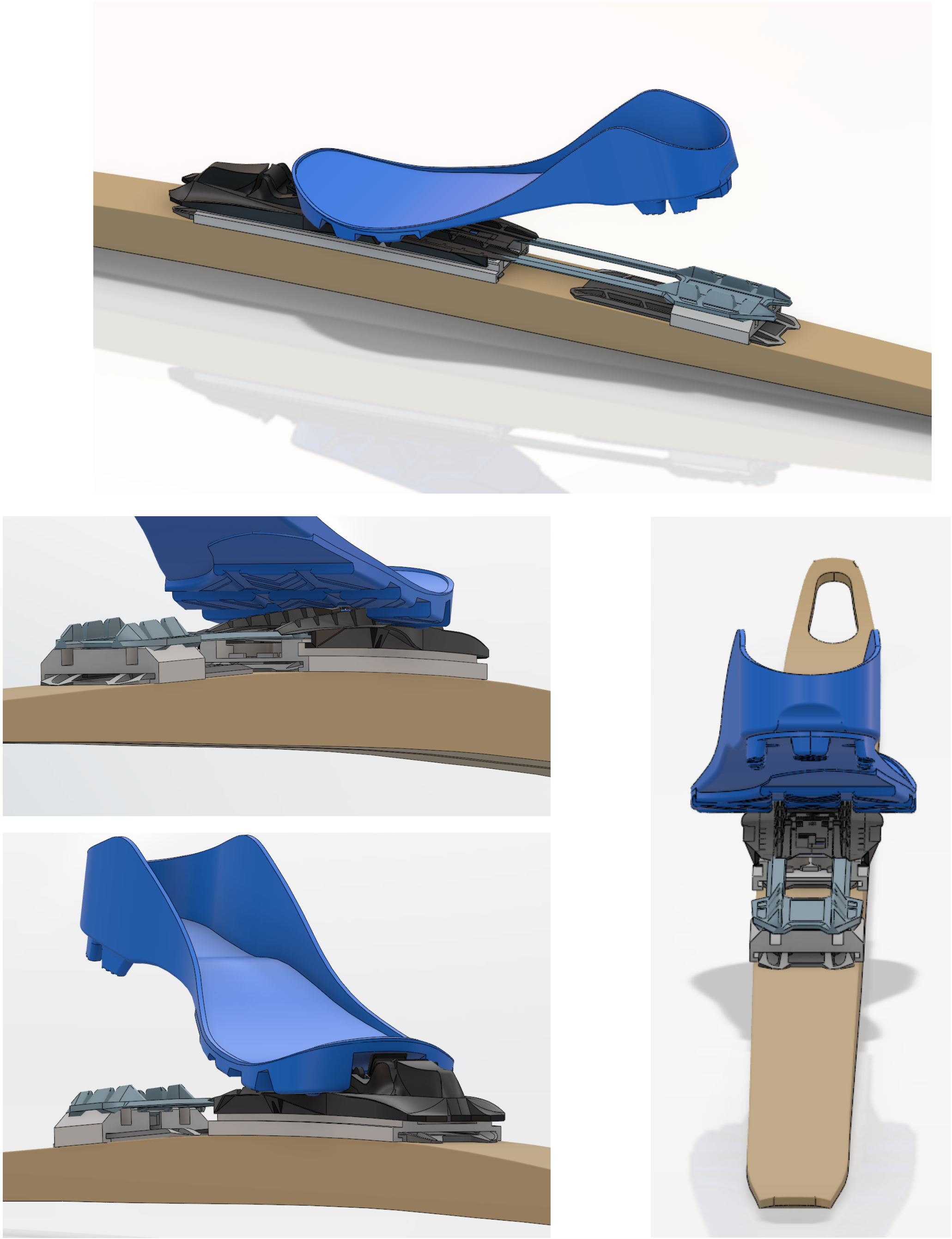


Figure 4.9: Concept picture of the measuring system assembled in a full ski binding.

4.1.5.2 Values from the tests

The tests carried out demonstrated a strong correlation between the signals measured by the Skisens sensors mounted on the binding and those measured by the reference force plate. A correlation coefficient of 74-86 percent was observed. The MAPE was between 24.76 and 29.80 percent with a RMSE of 108.1 - 126.1 N.
The visual impression of the results is shown in figure 4.10, in three different tests. The reference measurement is shown in red and the measurement in the binding system is shown in blue.

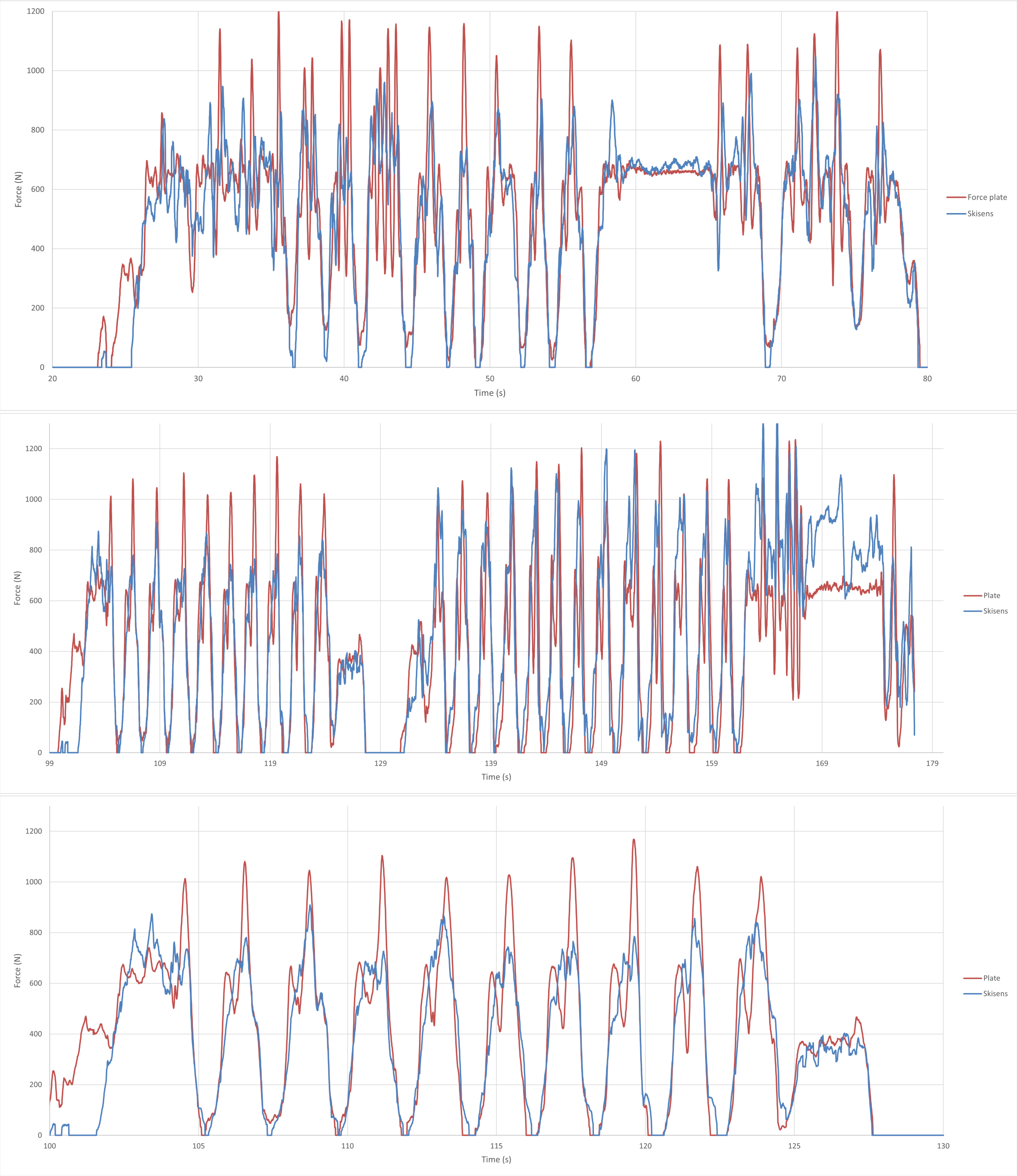


Figure 4.10: Comparison of the force measured by the prototype and the force measured by the reference force plate

These results confirm the robustness of the measuring prototype for direct force measurement. The best correlation was obtained when the binding was placed directly on the force plate. When the bindings were placed on the roller ski, slightly larger deviations (around a R^2 of 3 percent) occurred, likely due to the higher elasticity of the wheels and the entire system.
The cycle detection algorithm proved highly effective in isolating the propulsion phases and filtering out the part of the signal not used for propulsion. An example of cycle segmentation is presented in Figure 4.11.

Based on these identified cycles, the impulse was computed by numerical integration of the corrected force signal:

$$I = \int_0^T F_z(t)\, dt \tag{4.1}$$

where T is the thrust duration, F_z the vertical force.

From this formulation, the following variables were derived:

- Impulse

$$I = \sum_{i=0}^{N} k \cdot F_z(i) \cdot \Delta T, \quad \Delta T = 0.01\, s \tag{4.2}$$

- Average force per cycle

$$F_{\text{avg}} = \frac{I}{T} \tag{4.3}$$

- Average power per impulse

$$P = \frac{v \cdot k}{T} \cdot \sum_{i=0}^{N} F_z(i) \cdot \Delta T \tag{4.4}$$

where v is the displacement speed.

The computed values demonstrate good consistency and follow the expected trends with velocity and slope.
Figure 4.12 shows an example of a roller ski session on a treadmill at 10 km/h and a 2 % slope.

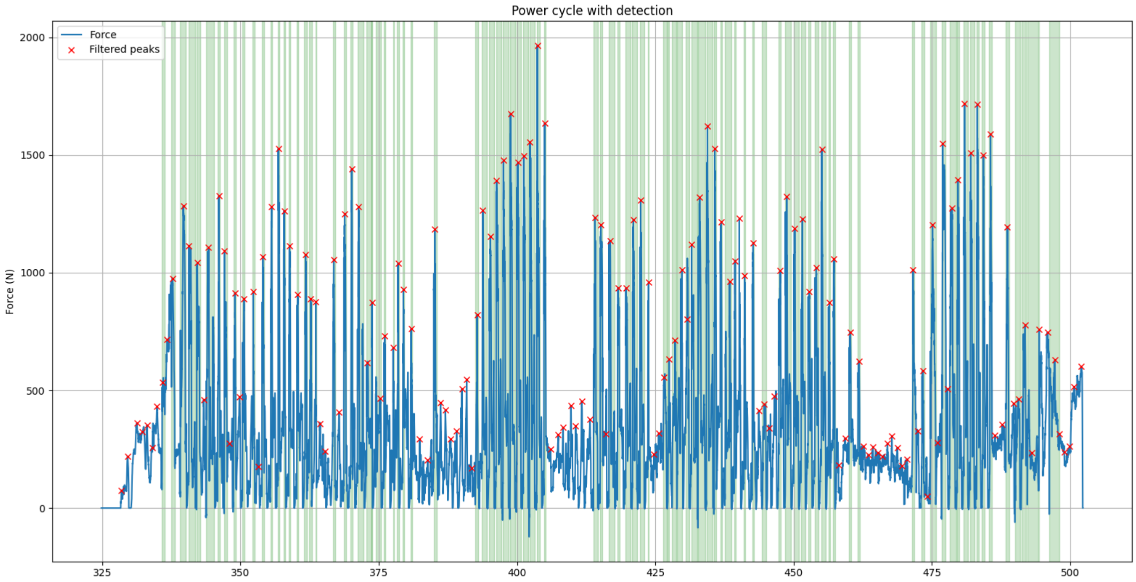


Figure 4.11: Force in a function of time during roller ski session on treadmill, with cycle segmentation highlighted in green

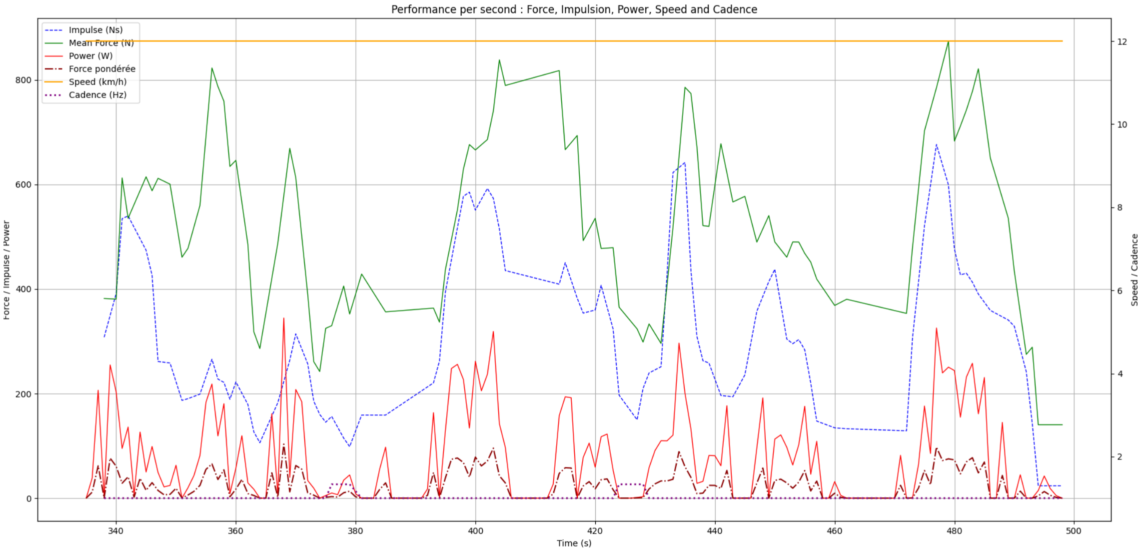


Figure 4.12: Evolution of the speed, cadence, mean force, impulse and power for a roller ski session on treadmill

4.1.5.3 Comparison with reference

In order to verify the treadmill test data, the theoretical power required to overcome the speed and incline of the treadmill was calculated. This theoretical power value is given by:

$$P = M \cdot g \cdot v \cdot \left(\sin\left(\arctan\left(\frac{\text{slope}}{100} \right) \right) + \cos\left(\arctan\left(\frac{\text{slope}}{100} \right) \right) \cdot C_{rr} \right) + C_{loc} \cdot M \cdot v \quad (4.5)$$

Where:

- M is the skier's body mass
- $g = 9.80665\,m/s^2$
- v is the treadmill velocity
- slope is the treadmill inclination (%)
- C_{rr} is the rolling resistance coefficient
- C_{loc} represents the additional locomotion cost term in W/kg

The resistance coefficient of the wheels was not measured. The manufacturer's information gives values between 0.02 and 0.035. A median value of 0.025 was used. Similarly, the locomotion factor is described as a value between 0.7 and 0.95 W/kg depending on the individuals in the studies, [16, 17]. A value of 0.85 W/kg was chosen, the objective was simply to obtain an order of magnitude for the expected values rather than to make a precise comparison.

This calculation allowed to check if the measured value corresponded to the expected power. During roller-ski tests, the propulsion phases reached power values of around 200 W (Figure 4.12), which is slightly lower than the theoretical moving power of 251 W.

4.2 Force plate system

4.2.1 Requirements

The objective here is to see whether Skisens force sensors can be adapted to static plates. The following requirements have been defined:

- Reliable and accurate measurements
- Portability
- Ease of connection and data processing, through the existing Skisens ecosystem
- User-friendly setup, for rapid installation and versatility across different sports contexts

4.2.2 Design and sensor placement

To meet portability and manufacturability requirements, a modular design was proposed. The system consists of four interlocking plate segments that can be assembled into a single platform. This modular approach facilitates transport and makes manufacturing easier while ensuring structural stability during use. The sensing elements are embedded between the four 3D printed components and a stainless steel cover plate, which serves as the direct interface with the athlete. This upper layer guarantees uniform load transfer and protects the sensors against mechanical damage. The sensors were arranged in a 'dice five' pattern, with four sensors at the corners and one at the center. This configuration minimizes the maximum distance between any applied load and a measurement point, while keeping the number of sensors limited. The central sensor plays a key role in preventing underestimation of forces applied near the middle of the plate due to deformation. With this configuration, the system is capable of recording total vertical ground reaction forces and their spatial distribution across the platform. This information could be used to:

- Quantify the symmetry of the force between the left and right legs.
- Identify the center of pressure trajectories that are relevant for jumps or landings.
- Monitor load patterns in strength training, such as squats or deadlifts.

The proposed system is shown in Figure 4.13.

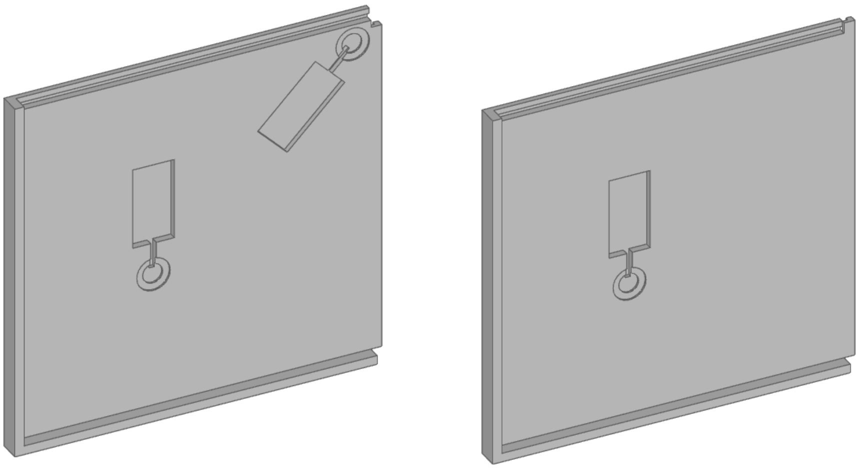


Figure 4.13: Structural parts of the measuring plate, the right part is use tree time to form a square, completing the left part

4.2.3 Test data

To verify the reliability of the measurements, the plate was tested on the force plate. Different weights of known value are tested and the measured values have a good correlation. Weightlifting and jumping movements were also performed. The correlation coefficient is 0.953 for the tests performed. The comparison of force values can be seen in Figure 4.14. This plate prototype shows a wide range of applications and seems promising for many sports. Skisens technology can be well adapted for this type of application. However, strong data processing needs to be developed to help coach and enable real-time feedback.

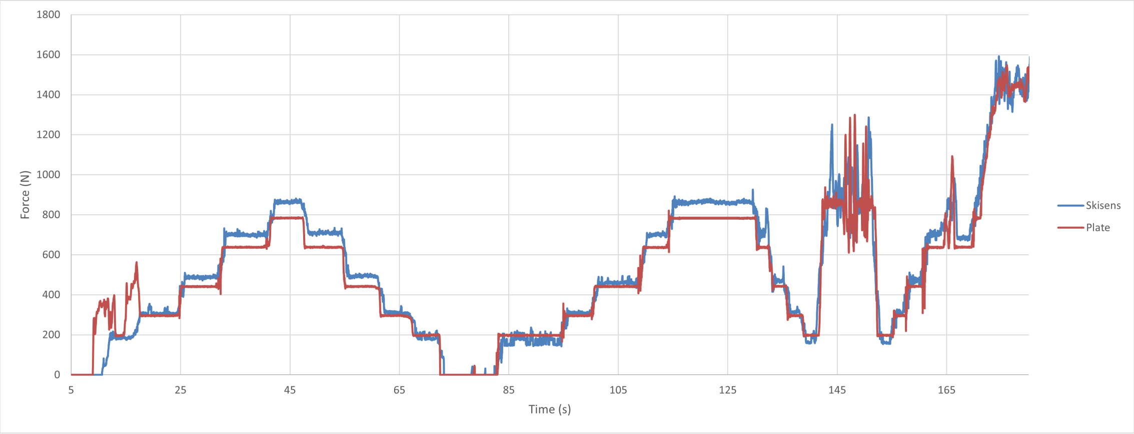


Figure 4.14: Weight test on the modular plate, with the reference force shown in red and the measurements shown in blue.

4.3 Traction force sensor

4.3.1 Use cases

In addition to ski bindings and force plates, a feasibility study was conducted and a feedback algorithm developed on a traction force sensor. The main application envisaged lies in strength training, where the device can be attached to pull cable strength machines. This allows training sessions to be tracked by directly recording load and repetitions while also providing advanced insights into movement execution. By analyzing not only the applied force but also the velocity profile of the movement, the system can identify eccentric and concentric phases as well as the shape of force movement. Provides direct insight into how movements are performed and highlights potential technical flaws. This type of feedback is particularly valuable for athletes and coaches, contributing to the growing demand for digital coaching tools in sports and strength training.

4.3.2 Design principles

The prototype in figure 4.15 is a compact inline force sensor, capable of measuring forces up to 2000 N. The structural body is manufactured from stainless steel to ensure durability under repeated dynamic loads.
The sensor is seamlessly integrated into the existing Skisens ecosystem. To facilitate straightforward use, the design includes two threaded steel rings mounted on either side of the sensor. These enable rapid connection to training equipment with only two carabiners.
As with other Skisens products, the device connects wirelessly to the application to provide real-time visualization of the measured force signal.

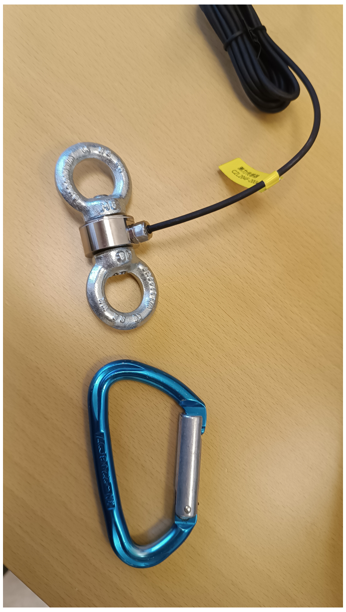


Figure 4.15: Drag sensor coupled with 2 traction rings

4.3.3 Results and algorithm development

As the sensor uses only a single connection channel, the traction force device measurements were visible directly in the Skisens application. To improve post-processing, a dedicated Python script was developed to enable the calculation and visualization of derived performance metrics.

The initial section of a recording is used to determine the load on the machine. The script identifies a stable 5-second period during which the user must maintain the load without moving. Then training can begin, and all repetitions are detected. The following variables were calculated:

- Duration of each repetition.
- Amplitude of eccentric, concentric, and total displacement.
- Average velocity of movement and concentric phase.
- Power output.
- Maximum velocity during a repetition.

To validate the precision of these outputs, the results were compared with two independent reference methods:

- Known weight stacks from gym equipment, used to verify absolute force measurement.
- High-speed video analysis, coupled with distance tracking, is used to independently calculate the displacement, velocity, and timing of repetitions.

The comparison shows no major differences in measured force relative to known loads (less than 2%). However, video analysis shows a deviation of approximately 10 percent for the time calculation value. The amplitude estimation showed a larger error of around 35 percent. However, this deviation was consistent (ranging from 30–45 percent), suggesting that it could be partially corrected through a calibration factor.

Figure 4.16 shows an example of the visualization of the resulting data, with the detected cycles highlighted in yellow, the force (blue), the speed (red), and the power (green) being displayed over time.

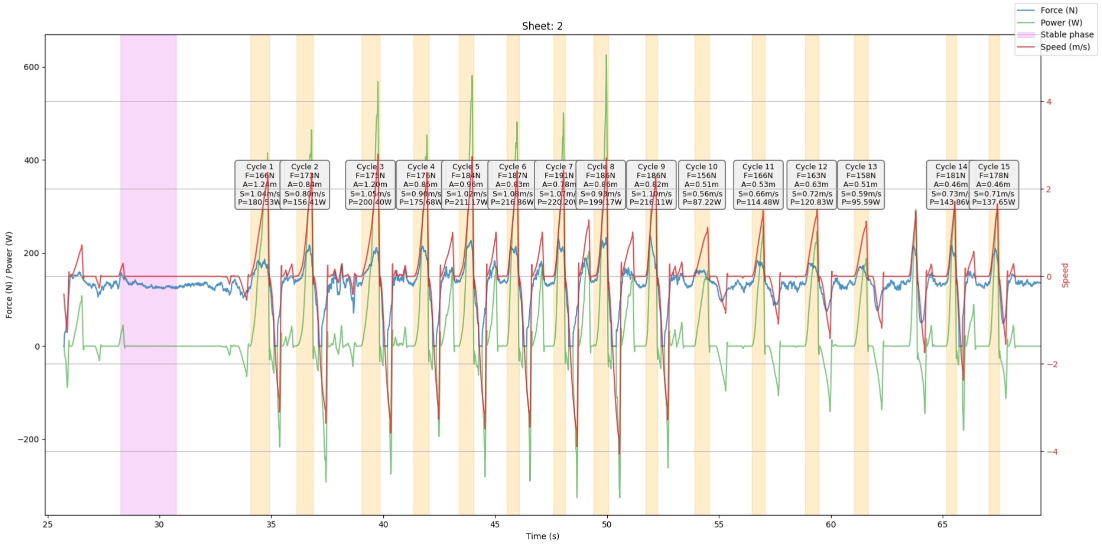


Figure 4.16: Traction sensor analysis graphic display

4.3.4 Performance indicators and training recommendations

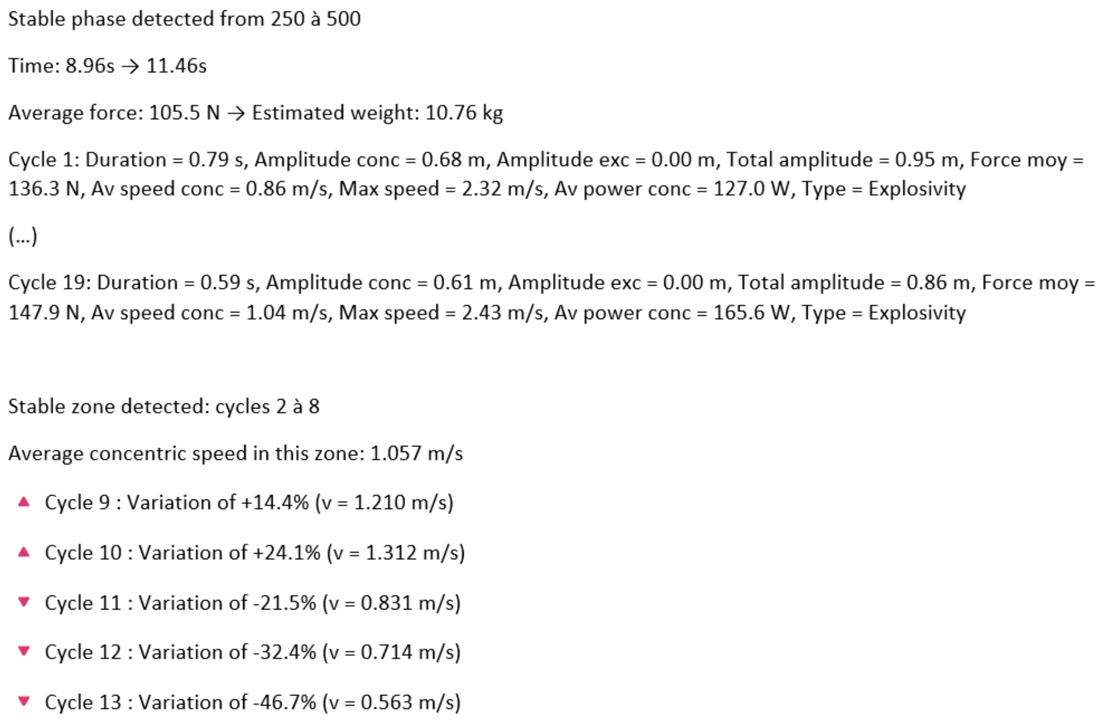
The objective is to provide clear and actionable metrics without overwhelming the user with too much information. The sensor may therefore deliver a small set of key indicators and synthesize values. To do that, one option is to directly inform the user if their movement is within the correct speed range.

The coaches and theory use three training categories in strength training: maximal strength, hypertrophy, and explosiveness [18]. By comparing the measured number with the theoretical value, it is possible to display direct feedback in the Python script.

Training objective	Load (%1MR)	Concentric speed	Loss tolerated
Maximal Strength	85–100 %	0.15 – 0.35 (m/s)	20–25 %
Hypertrophy	65–85 %	0.50 – 0.75 (m/s)	30–40 %
Explosiveness	30–60 %	1.00 – 1.50 (m/s)	10–15 %

Table 4.1: Table summarizing the working force and speed range, with the speed loss that can be tolerated

Stable phase detection of repetition speed is performed, and feedback on reduction or increase is provided in addition to the type of exercise being performed. This feedback on speed changes during repetitions can provide a good indication of whether the workload is sufficient or too high. An example of analysis is shown in figure 4.17.



```
Stable phase detected from 250 à 500

Time: 8.96s → 11.46s

Average force: 105.5 N → Estimated weight: 10.76 kg

Cycle 1: Duration = 0.79 s, Amplitude conc = 0.68 m, Amplitude exc = 0.00 m, Total amplitude = 0.95 m, Force moy =
136.3 N, Av speed conc = 0.86 m/s, Max speed = 2.32 m/s, Av power conc = 127.0 W, Type = Explosivity

(...)

Cycle 19: Duration = 0.59 s, Amplitude conc = 0.61 m, Amplitude exc = 0.00 m, Total amplitude = 0.86 m, Force moy =
147.9 N, Av speed conc = 1.04 m/s, Max speed = 2.43 m/s, Av power conc = 165.6 W, Type = Explosivity


Stable zone detected: cycles 2 à 8

Average concentric speed in this zone: 1.057 m/s

 ▲ Cycle 9 : Variation of +14.4% (v = 1.210 m/s)

 ▲ Cycle 10 : Variation of +24.1% (v = 1.312 m/s)

 ▼ Cycle 11 : Variation of -21.5% (v = 0.831 m/s)

 ▼ Cycle 12 : Variation of -32.4% (v = 0.714 m/s)

 ▼ Cycle 13 : Variation of -46.7% (v = 0.563 m/s)
```

Figure 4.17: Example of feedback from the algorithm for the traction sensor.

5

Discussion

5.1 Prototype performance

One of the main limitations during this project was the robustness of the sensors and the software stability of the application software. Sensors are particularly fragile at the solder joints that connect cables to the PCB and battery. Additionally, the application, which is regularly updated and improved, had difficulty reconnecting the sensors after disconnection, as well as experiencing issues such as memory leaks, where the accumulated data made the interface extremely slow. These issues greatly complicated the testing process and made it difficult to use the system for long periods under real outdoor conditions.

These problems were largely due to the integration of the four sensors into the 3D-printed frame. It was not possible to design a single PCB that combines all of the signals from the four sensors and transmits a combined flow to the application. The lack of space required a dispersed architecture with independent sensors, each of which required its own power supply and cables of different lengths. Unlike Skisens ski poles, where the fragile part is encapsulated in epoxy resin, it was not possible to implement this protection strategy for this prototype, even though it would have been necessary.

Finally, force measurements could not be processed quantitatively or scientifically on skis to determine thrust power. Although theoretical calculations allow certain factors to be calibrated, the results were consistent overall but not yet usable as reference metrics in an in-depth research setting.

5.2 Prototype limitations

Although the current design is functional for roller ski testing on treadmills, it is not really suitable for outdoor use. Sensors, PCBs, and batteries are not protected against external stresses such as snow, dust, humidity, and gravel, and the material is sensitive.

Additionally, the 3D-printed plastic parts lack the rigidity and mechanical strength required for long-term or intensive use. Engineering polymers similar to those used in industrial cross-country ski bindings, such as POM plastic, would be a much stronger alternative that would offer greater resistance to mechanical and environmental stresses.

Furthermore, using four sensors to generate independent signals requires complex logistics: two phones are needed to record the signals from one binding, meaning

five phones are required in total, one for the poles and four for the bindings.
This fragmentation of the measurement process considerably complicates the practical deployment of the system. It also introduces challenges in terms of synchronizing the different data flows.
The development of a dedicated PCB connecting the four load cells of the binding is entirely feasible. It was not implemented in this project due to time constraints. Such a PCB could integrate a micro controller with multiple ADC channels to acquire the four sensor signals, powered by a larger battery. The design could either sum the four signals before transmission, or transmit them individually via Bluetooth. This approach would reduce the space required, improve integration, and enable real-time data display.

5.3 Challenges in data processing

Once the force had been measured, the approach taken was to calculate the impulse to extract characteristic values and detect thrust cycles. Although this strategy is effective in post-processing, it remains difficult to implement in real time.
Currently, the application cannot provide an instantaneous and stable estimate of power, which restricts its potential as a tool for providing immediate feedback to athletes or coaches.
However, Python scripts can be integrated into the application, so significant progress is possible.

5.4 Reproducibility and consistency

The results obtained from the various tests demonstrated a high degree of reproducibility. All tests were performed under the same protocols, and the sensors consistently produced stable and reliable measurements when working. Comparison of multiple sensors confirmed that the measured values were independent of the sensor and its placement inside the prototype. Similarly, the assembly of the prototype with the binding did not introduce any variability.
The results of the various tests showed satisfactory reproducibility, provided that the sensors were working correctly. All tests were performed according to identical protocols, and the measured values remained stable from one test to the next. Comparisons between sensors confirmed that there was no significant influence from their positioning or the part in which they were integrated. Similarly, the assembly of the instrumented fixture did not introduce any additional bias or variability.

5.5 Generalization potential of concepts

The potential applications extend far beyond cross-country skiing. For example, the principle of measuring force in bindings could be applied to speed skating or recreational ice skating where bindings and supports have an exact similar design. It was tested by mounting the prototype on it, as shown in figure 5.1. Only a wedge

to block forward and backward movement needs to be added.
The technology could also be adapted for downhill skiing, ski touring, and even snowboarding, where the forces transmitted by the binding significantly impact performance.
The work carried out on the modular force plate opens up prospects for many sports, particularly athletics and weight training, where the understanding of support and movement dynamics is limited. This solution is lightweight, portable, and connected, and would provide field metrics that were previously only available in laboratories.

Similarly, the traction sensor has proven its value in weight training rooms by quantifying not only the load moved, but also the execution speed and power developed. By connecting directly to the Skisens ecosystem, the traction sensor is a natural extension of the system, paving the way for a true digital coach capable of providing athletes with personalized feedback on their movements.

Figure 5.1: Binding prototype mounted on recreational ice skate

5.6 Collaboration and industrial relevance

These developments suggest potential for direct collaboration with ski and binding manufacturers. Upstream integration, starting with the binding design, would enable for more robust and ergonomic instrumentation.
In indoor sports, applications in strength training and physical preparation are particularly promising. The vast majority of professional athletes use strength training to improve their own sport. The addition of objective monitoring of strength, speed, and power represents clear added value. Strength training and gym are a large market, and numerous integrations are possible on existing strength machines to enable access to these new data.

6

Conclusion

The aim of this thesis was to explore the integration of force measurement technologies into cross-country ski bindings, as well as the conceptual design of modular force plates and traction force devices for use in other sports. The primary focus was on the ski binding prototype, which was developed through CAD modeling, additive manufacturing, and experimental validation. The tests performed on the force plate showed a good correlation, up to 85%. With a tendency to underestimate the most extreme peak force values.
These results confirm the system's ability to measure the force used by a skier on their skis. Push-off cycles were consistently detected and biomechanical parameters such as impulse, average force, and cadence could be derived.
Calculating power proved to be more complicated. Although a reasonable approximation, undoubtedly close to reality, was found, more research is needed to transfer the measured force more directly into power.
The created system meets the requirements of lightness and versatility and allows for measurements in the field. This validates the feasibility of directly embedding force sensors in ski equipment.

In general, this work offers prospects for Skisens and the sports industry to supplement upper limb force measurement with lower limb measurement. This offers the potential to provide skiers and coaches with richer real-time performance metrics.
Similarly, the traction sensor and the modular force plate showed good correlations compared to the reference values. These correlations are not yet sufficient for a marketable product, but can be an improvement.
These systems have also shown an ability to provide very rich and useful information for coaches and athletes in terms of biomechanics. Skisens has been a pioneer in the implementation of power sensors in the field of winter sports. This thesis illustrates that force sensors can be used in other areas or placed in other parts of the equipment, to create a broader ecosystem of performance tools given advanced feedback to the athletes.

Several steps are still required to turn these prototypes into commercial products. Improvements in sensor integration, robustness, and environmental resistance are necessary for field deployment. In terms of software, real-time signal processing and simple feedback are important, in order to provide athletes with actionable insights without overwhelming them with data.
Future studies should therefore focus on optimizing power estimation algorithms and

validating the devices with elite athletes in real training and competition conditions on the snow.

Overcoming these challenges could lead to further progress towards a new generation of integrated force measurement systems in sport. These systems would offer precise, portable, and practical tools for performance analysis.

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A

Appendix

A.1 Python scripts

Listing A.1: Drag force sensor analysis algorithm

```
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
from scipy.signal import savgol_filter, find_peaks

# --- PARAMETERS ---
g = 9.80665
seuil_variation_N = 25  #35 N
seuil_duree_s = 2.5   # 4 seconds
sampling_rate = 100  # 100 Hz
seuil_depart_force = 20  # 20N
seuil_fin_force = 20     # [20-50]N

xlsx = pd.ExcelFile('2025-05-13 Gym test.xlsx')

for sheet_name in xlsx.sheet_names:
    print(f'\n--- Traitement de la feuille : {sheet_name} ---')
    df = xlsx.parse(sheet_name)
    lower_cols = {col.lower(): col for col in df.columns}
    try:
        col_time = lower_cols[[c for c in lower_cols if 'time' in c][0]]
        col_force = lower_cols[[c for c in lower_cols if 'force' in c][0]]
    except IndexError:
        print(f'Columns 'time' or 'force' not found in the sheet {sheet_name}')
        continue
    df = df[[col_time, col_force]]
    df.columns = ['time', 'force']
    # --- 2. DISPLACED WEIGHT  ---
    rolling_window = int(seuil_duree_s * sampling_rate)
    rolling_std = df['force'].rolling(rolling_window).std()
    idx_force_start = None
```

```
for i in range(len(rolling_std) - rolling_window):
    window_force = df['force'].iloc[i:i+rolling_window]
    if rolling_std.iloc[i:i+rolling_window].max() <
       seuil_variation_N and window_force.mean() > 20:
        idx_force_start = i
        idx_force_end = i + rolling_window
        break
if idx_force_start is not None:
    force_moyenne_stable = df['force'][idx_force_start:
       idx_force_end].mean()
    masse = force_moyenne_stable / g
    print(f'Stable phase detected from {idx_force_start}
       to {idx_force_end}')
    print(f'Time : {df['time'].iloc[idx_force_start]:.2f}
       s -> {df['time'].iloc[idx_force_end]:.2f}s')
    print(f'Average force : {force_moyenne_stable:.1f} N
       -> Estimated weight : {masse:.2f} kg')
    phase_stable_t0 = df['time'].iloc[idx_force_start]
    phase_stable_t1 = df['time'].iloc[idx_force_end]
else:
    raise ValueError('No stable phase detected to
       estimate weight')
# --- 3. ACCELERATION / SPEED / POWER ---
df['acceleration'] = (df['force'] / masse) - g
df['acceleration'] = savgol_filter(df['acceleration'],
   11, 3)
dt = df['time'].diff().fillna(1 / sampling_rate)
vitesse = [0]
max_force = df['force'].max()
seuil_pic = 0.60 * max_force
min_distance_pts = int(0.5 * sampling_rate)
peaks, _ = find_peaks(df['force'], height=seuil_pic,
   distance=min_distance_pts)
if len(peaks) < 2:
    raise ValueError('Not enough peaks detected to
       estimate the optimum window.')
intervals_s = np.diff(df['time'].iloc[peaks].values)
duree_moy = intervals_s.mean()
intervals_trop_courts = intervals_s[intervals_s < 0.3 *
   duree_moy]
if len(intervals_trop_courts) > 0:
    fenetre_opt_s = min(intervals_trop_courts) * 1.2
else:
    fenetre_opt_s = min(intervals_s) * 0.9
fenetre_future = int(fenetre_opt_s * sampling_rate)
seuil_variation_force_locale = 15
for i in range(1, len(df)):
    if i + fenetre_future < len(df):
        force_future = df['force'].iloc[i:i +
```

```
           fenetre_future]
        variation_future = force_future.max() -
           force_future.min()
    else:
        variation_future = 100
    if abs(df[’force’].iloc[i] - force_moyenne_stable) <
       10 or variation_future <
       seuil_variation_force_locale:
        vitesse.append(0)
    else:
        dv = df[’acceleration’].iloc[i] * dt.iloc[i]
        vitesse_actuelle = vitesse[-1] + dv
        if vitesse_actuelle < -5:
            vitesse_actuelle = 0
        vitesse.append(vitesse_actuelle)
vitesse_lisse = savgol_filter(vitesse, 11, 3)
df[’speed’] = np.roll(vitesse_lisse, -5)
df.loc[df.index[-5]:, ’speed’] = 0
df[’power’] = df[’speed’] * df[’force’]
# --- 4. MOVEMENT DETECTION ---
inv_force = -df[’force’]
min_peaks, _ = find_peaks(inv_force, distance=int(1 *
   sampling_rate), prominence=40)
selected_mins = [i for i in min_peaks if df[’time’].iloc[
   i] > df[’time’].iloc[idx_force_end]]
peaks_vitesse, _ = find_peaks(df[’speed’], distance=int
   (1.9 * sampling_rate), height=1)
mouvements = []
stats = []
for i in range(len(selected_mins) - 1):
    idx_min = selected_mins[i]
    idx_max = selected_mins[i + 1]
    peaks_in_cycle = [p for p in peaks_vitesse if idx_min
        <= p < idx_max]
    if not peaks_in_cycle:
        continue
    idx_peak_vitesse = peaks_in_cycle[0]
    vitesse_segment = df[’speed’].iloc[idx_min:
       idx_peak_vitesse]
    index_segment = df[’speed’].iloc[idx_min:
       idx_peak_vitesse].index
    start_idx = None
    for j in range(len(vitesse_segment)):
        if vitesse_segment.iloc[j] > 0:
            future = vitesse_segment.iloc[j:
               idx_peak_vitesse - idx_min]
            if (future <= 0).any():
                continue
            else:
```

```
                    start_idx = index_segment[j]
                    break
        if start_idx is None:
            continue
        speed_after_peak = df['speed'].iloc[idx_peak_vitesse:
           idx_max]
        fin_candidates = speed_after_peak[speed_after_peak <=
            0]
        if not fin_candidates.empty:
            end_idx = fin_candidates.index[0]
        else:
            end_idx = idx_max
        interval_force = df['force'].iloc[start_idx:end_idx]
        if interval_force.empty:
            continue
        max_force = interval_force.max()
        min_force = interval_force.min()
        if (max_force - min_force) < 5:
            continue
        mouvements.append((start_idx, end_idx))
        f = df['force'].iloc[start_idx:end_idx]
        v = df['speed'].iloc[start_idx:end_idx]
        p = df['power'].iloc[start_idx:end_idx]
        t_mvt = df['time'].iloc[end_idx] - df['time'].iloc[
           start_idx]
        v_concentrique = v[v > 0].sum() / sampling_rate
        v_excentrique = abs(v[v < 0].sum()) / sampling_rate
        amplitude_totale = 1.4 * (v_concentrique +
           v_excentrique)
        mask_concentrique = v > 0
        f_conc = f[mask_concentrique]
        v_conc = v[mask_concentrique]
        p_conc = p[mask_concentrique]
        stats.append({
            'Av_force_conc': f_conc.mean() if not f_conc.
               empty else 0,
            'Av_speed_conc': v_conc.mean() if not v_conc.
               empty else 0,
            'Max_speed': v.max(),
            'Av_power_conc': p_conc.mean() if not p_conc.
               empty else 0,
            'Duration': t_mvt,
            'ampli_conc': v_concentrique,
            'ampli_excent': v_excentrique,
            'total_ampli': amplitude_totale
        })
        training_obj = []
        for s in stats:
            v_conc = s['ampli_conc'] / s['Duration']
```

```
        if 0.20 <= v.max() <= 0.40:
            training_obj.append('Max Force')
        elif 0.50 <= v.max() <= 0.80:
            training_obj.append('Hypertrophy')
        elif v.max() > 1.0:
            training_obj.append('Explosivity')
        else:
            training_obj.append('Other')
# --- 5. DISPLAY STATS ---
for i, s in enumerate(stats):
    print(f'Cycle {i+1} : '
        f'Duration = {s['Duration']:.2f} s, '
        f'Amplitude conc = {s['ampli_conc']:.2f} m, '
        f'Amplitude exc = {s['ampli_excent']:.2f} m, '
        f'Total amplitude = {s['total_ampli']:.2f} m, '
        f'Force moy = {s['Av_force_conc']:.1f} N, '
        f'Av speed conc = {s['Av_speed_conc']:.2f} m/s, '
        f'Max speed = {s['Max_speed']:.2f} m/s, '
        f'Av power conc = {s['Av_power_conc']:.1f} W, '
        f'Type = {training_obj[i]}')
# --- 6. CONCENTRIC SPEED STABILITY ANALYSIS ---
v_conc_moyennes = [s['Av_speed_conc'] for s in stats]
n_cycles = len(v_conc_moyennes)
seuil_stabilite = 0.15
seuil_variation_pct = 10
taille_min_fenetre = 3
indice_stable_debut = None
indice_stable_fin = 0
for window_size in range(n_cycles, taille_min_fenetre -
   1, -1):
    for i in range(n_cycles - window_size + 1):
        fenetre = v_conc_moyennes[i:i + window_size]
        if max(fenetre) - min(fenetre) <= seuil_stabilite
           :
            indice_stable_debut = i
            indice_stable_fin = i + window_size
            break
    if indice_stable_debut is not None:
        break
if indice_stable_debut is None:
    print('No stable zones found')
    v_moy_stable = 0
else:
    zone_stable = v_conc_moyennes[indice_stable_debut:
       indice_stable_fin]
    v_moy_stable = np.mean(zone_stable)
    print(f'Stable zone detected: cycles {
       indice_stable_debut + 1} to {indice_stable_fin}')
    print(f'Average concentric speed in this zone: {
```

```
           v_moy_stable:.3f} m/s')
    for i in range(indice_stable_fin, n_cycles):
        v_i = v_conc_moyennes[i]
        variation_pct = 100 * (v_i - v_moy_stable) /
           v_moy_stable
        if variation_pct > seuil_variation_pct or
           variation_pct < -seuil_variation_pct:
            signe = 'Up' if variation_pct > 0 else 'Down'
            print(f'{signe} Cycle {i + 1} : Variation of {
               variation_pct:+.1f}% (v = {v_i:.3f} m/s)')
    # --- 7. GRAPHIC DISPLAY ---
    fig, ax1 = plt.subplots(figsize=(12, 6))
    ax1.plot(df['time'], df['force'], label='Force (N)',
       color='tab:blue', alpha=0.8)
    ax1.plot(df['time'], df['power'], label='Power (W)',
       color='tab:green', alpha=0.6)
    ax1.set_xlabel('Time (s)')
    ax1.set_ylabel('Force (N) / Power (W)', color='black')
    ax1.tick_params(axis='y', labelcolor='black')
    if 'phase_stable_t0' in locals() and 'phase_stable_t1' in
        locals():
        ax1.axvspan(phase_stable_t0, phase_stable_t1, color='
           violet', alpha=0.3, label='Stable phase')
    for i, (start, end) in enumerate(mouvements):
        t0 = df['time'].iloc[start]
        t1 = df['time'].iloc[end]
        ax1.axvspan(t0, t1, color='orange', alpha=0.2)
        t_milieu = (t0 + t1) / 2
        f_moy = stats[i]['Av_force_conc']
        amplitude = stats[i]['total_ampli']
        v_moy = stats[i]['Av_speed_conc']
        power = stats[i]['Av_power_conc']
        texte = (f'Cycle {i+1}\n'
                f'F={f_moy:.0f}N\n'
                f'A={amplitude:.2f}m\n'
                f'S={v_moy:.2f}m/s\n'
                f'P={power:.2f}W')
        ax1.text(t_milieu, 300, texte,
                fontsize=9,
                ha='center',
                va='bottom',
                bbox=dict(boxstyle='round,pad=0.4',
                        facecolor='#f0f0f0',
                        edgecolor='#666666',
                        linewidth=1.2,
                        alpha=0.95))
    ax2 = ax1.twinx()
    ax2.plot(df['time'], df['speed'], label='Speed (m/s)',
       color='tab:red', alpha=0.8)
```

```
    ax2.set_ylabel('Speed', color='tab:red')
    ax2.tick_params(axis='y', labelcolor='tab:red')
    lines1, labels1 = ax1.get_legend_handles_labels()
    lines2, labels2 = ax2.get_legend_handles_labels()
    fig.legend(lines1 + lines2, labels1 + labels2, loc='upper
        right')
    plt.title(f'Sheet: {sheet_name}')
    from matplotlib.ticker import AutoLocator
    ylim1 = ax1.get_ylim()
    ylim2 = ax2.get_ylim()
    ratio1 = abs(ylim1[1] / ylim1[0]) if ylim1[0] != 0 else 1
    ratio2 = abs(ylim2[1] / ylim2[0]) if ylim2[0] != 0 else 1
    if ratio1 > ratio2:
        range2 = abs(ylim2[1]) + abs(ylim2[0])
        center = 0
        half_range = max(abs(ylim2[1]), abs(ylim2[0])) *
           ratio1 / ratio2
        ax2.set_ylim(center - half_range / 2, center +
           half_range / 2)
    else:
        range1 = abs(ylim1[1]) + abs(ylim1[0])
        center = 0
        half_range = max(abs(ylim1[1]), abs(ylim1[0])) *
           ratio2 / ratio1
        ax1.set_ylim(center - half_range / 2, center +
           half_range / 2)
    plt.grid(True)
    plt.tight_layout()
    plt.show()
```

Listing A.2: Drag force sensor analysis algorithm

```
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
from scipy.signal import find_peaks, savgol_filter

# ------------------ Parameters ------------------
MIN_PEAK_DISTANCE_SEC = 0.8
MIN_FORCE_DIFF = 350  # Between 300 and 400
TIME_WINDOW_SEC = 0.2
SKIER_MASS_KG = 70.0

df = pd.read_excel("2025-06-27 Snow test cleaned.xlsx")
time = df['time'].values.astype(float)
force = df['force x1,4'].values.astype(float)
dt = np.median(np.diff(time))
time_window_pts = int(TIME_WINDOW_SEC / 0.01)
min_peak_distance_pts = int(MIN_PEAK_DISTANCE_SEC / 0.01)
```

```
# ------------------ Peaks detection ------------------
peaks, _ = find_peaks(force, distance=min_peak_distance_pts)

filtered_peaks = []
for i in range(len(peaks)):
    if filtered_peaks and time[peaks[i]] - time[
       filtered_peaks[-1]] < MIN_PEAK_DISTANCE_SEC:
        if force[peaks[i]] > force[filtered_peaks[-1]]:
            filtered_peaks[-1] = peaks[i]
    else:
        filtered_peaks.append(peaks[i])
filtered_peaks = np.array(filtered_peaks)
force_smoothed = savgol_filter(force, window_length=20,
   polyorder=8)

# ------------------ Cycles detection -----------------
cycles = []

for i in range(len(filtered_peaks) - 1):
    prev_peak_idx = filtered_peaks[i]
    peak_idx = filtered_peaks[i + 1]
    segment = force[prev_peak_idx:peak_idx]
    if len(segment) == 0:
        continue
    min_idx_local = np.argmin(segment)
    min_idx = prev_peak_idx + min_idx_local
    if i + 2 < len(filtered_peaks):
        next_segment = force[peak_idx:filtered_peaks[i + 2]]
        if len(next_segment) > 0:
            next_min_idx_local = np.argmin(next_segment)
            next_min_idx = peak_idx + next_min_idx_local
        else:
            next_min_idx = peak_idx + 20
    else:
        next_min_idx = peak_idx + 20

    start_idx = None
    for j in range(min_idx, peak_idx):
        for k in range(1, min(time_window_pts, j - min_idx +
           1)):
            delta = force[j] - force[j - k]
            if delta >= MIN_FORCE_DIFF:
                start_idx = j - k
                break
        if start_idx is not None:
            break

    end_idx = None
    for j in range(peak_idx, next_min_idx - time_window_pts):
```

```
        for k in range(1, time_window_pts):
            if force[j] - force[j + k] >= MIN_FORCE_DIFF:
                end_idx = j + k
                break

    if end_idx is None:
        end_idx = next_min_idx

    if start_idx is not None and end_idx is not None and
       start_idx < end_idx:
        ref_duration = 0.1
        ref_window_pts = int(ref_duration / dt) if not np.
           isnan(dt) else 10
        ref_start = max(0, start_idx - ref_window_pts)
        ref_end = start_idx
        ref_weight = np.mean(force[ref_start:ref_end])
        corrected_force = (force[start_idx:end_idx + 1] -
           ref_weight)
        corrected_force[corrected_force < 0] = 0
        force_cycle = force[start_idx:end_idx + 1]
        mean_force_raw = np.mean(force_cycle)
        mean_force_net = np.mean(corrected_force)
        top_n = 20
        top_force_values = np.sort(force_cycle)[-top_n:] if
           len(force_cycle) >= top_n else force_cycle
        peak_force_mean20 = np.mean(top_force_values)
        impulse_corrected = np.trapz(corrected_force, time[
           start_idx:end_idx + 1])
        cycles.append({
            'start_time': time[start_idx],
            'end_time': time[end_idx],
            'duration': time[end_idx] - time[start_idx],
            'max_force': force[peak_idx],
            'mean_force_raw': mean_force_raw,
            'mean_force_net': mean_force_net,
            'peak_force_mean20': peak_force_mean20,
            'mean_force_per_kg': np.mean(force[start_idx:
               end_idx + 1]) / SKIER_MASS_KG,
            'impulse': impulse_corrected,
        })

cycle_df = pd.DataFrame(cycles)
print(cycle_df)

for i, cycle in enumerate(cycles):
    print(f"Cycle {i + 1}: Impulsion = {cycle['impulse']:.2f}
       Ns, Duration = {cycle['duration']:.2f} s")

def save_force_and_power_per_second(cycles, treadmill_file="
```

```
Speed.xlsx", speed_start_row=2):
 import pandas as pd
 import numpy as np

 df_cycles = pd.DataFrame({
     ’start_time’: [c[’start_time’] for c in cycles],
     ’end_time’: [c[’end_time’] for c in cycles],
     ’impulse’: [c[’impulse’] for c in cycles],
     ’net_force’: [c[’mean_force_net’] for c in cycles],
     ’mean_force_raw’: [c[’mean_force_raw’] for c in
        cycles],
     ’peak_force_mean20’: [c[’peak_force_mean20’] for c in
         cycles],
 })
 df_cycles[’time_center’] = (df_cycles[’start_time’] +
    df_cycles[’end_time’]) / 2
 t_min = int(df_cycles[’start_time’].min())
 t_max = int(df_cycles[’end_time’].max()) + 1
 df_uniform = pd.DataFrame({’Time (s)’: np.arange(t_min,
    t_max)})
 df_cycles = df_cycles.dropna(subset=[’time_center’])
 df_cycles[’Time (s)’] = df_cycles[’time_center’].round().
    astype(int)
 df_grouped = df_cycles.groupby(’Time (s)’).mean().
    reset_index()
 df_rolling = df_grouped.rolling(window=3, center=True).
    mean()
 df_rolling[’Time (s)’] = df_grouped[’Time (s)’]
 df_cycles[’rounded_time’] = df_cycles[’time_center’].
    round().astype(int)
 df_counts = df_cycles.groupby(’rounded_time’).size().
    reset_index(name=’Cadence’)
 df_counts.rename(columns={’rounded_time’: ’Time (s)’},
    inplace=True)
 df_counts[’Cadence (Hz)’] = df_counts[’Cadence’].rolling
    (3, center=True).mean()
 df_final = df_uniform.merge(df_rolling, on=’Time (s)’,
    how=’left’)
 df_final = df_final.merge(df_counts[[’Time (s)’, ’Cadence
     (Hz)’]], on=’Time (s)’, how=’left’)
 df_final.interpolate(method=’linear’, inplace=True)
 df_speed = pd.read_excel(treadmill_file)
 if ’speed_kmph’ not in df_speed.columns:
     raise ValueError("No speed in treadmill file")
 speed_values = df_speed[’speed_kmph’].iloc[
    speed_start_row - 1:].reset_index(drop=True)
 min_length = min(len(df_final), len(speed_values))
 df_final = df_final.iloc[:min_length]
 df_final[’Speed (km/h)’] = speed_values.iloc[:min_length
```

```
        ].values
    df_final['mean_force'] = (df_final['net_force'] ).clip(
        lower=0)
    df_weighted_force = compute_weighted_force_per_second(
        time, force)
    df_final = df_final.merge(df_weighted_force, on='Time (s)
        ', how='left')
    df_final['weighted_force_net'] = (df_final['
        Weighted_Force_Mean']).clip(lower=0)
    df_final['Speed (m/s)'] = df_final['Speed (km/h)'] / 3.6
    df_final['Power (W)'] = df_final['weighted_force_net'] *
        df_final['Speed (m/s)']
    df_final['mean_force_per_kg'] = df_final['mean_force'] /
        SKIER_MASS_KG
    df_final['net_force_per_kg'] = df_final['net_force'] /
        SKIER_MASS_KG
    df_final['Power_per_kg'] = df_final['Power (W)'] /
        SKIER_MASS_KG

    print('Export succesfull')
    return df_final

def compute_weighted_force_per_second(time, force):
    df_force = pd.DataFrame({'Time': time, 'Force': force})
    df_force['Time (s)'] = df_force['Time'].astype(int)

    def weight_function(f):
        if f < 200:
            return 0
        elif f < 600:
            return 0.7 + (f - 200) * (1.0 - 0.7) / (600 -
                200)
        elif f <= 1200:
            return 1.0 + (f - 600) * (1.2 - 1.0) / (1200 -
                600)
        else:
            return 1.2
    df_force['Weight'] = df_force['Force'].apply(
        weight_function)
    df_force['Weighted_Force'] = (df_force['Force'] *
        df_force['Weight'] - SKIER_MASS_KG * 9.81 *0.8 ) *
        0.18
    df_force['Weighted_Force'] = df_force['Weighted_Force'].
        clip(lower=0)
    grouped = df_force.groupby('Time (s)').agg({
        'Weighted_Force': 'sum',
        'Weight': 'sum'
    }).reset_index()
    grouped['Weighted_Force_Mean'] = grouped['Weighted_Force'
```

```
        ] / grouped['Weight']
    grouped.replace([np.inf, -np.inf], np.nan, inplace=True)
    return grouped[['Time (s)', 'Weighted_Force_Mean']]

# --------------------- Graphic display --------------------
plt.figure(figsize=(12, 6))
plt.plot(time, force, label='Force')
plt.plot(time[filtered_peaks], force[filtered_peaks], 'rx',
   label='Filtered peaks')
for c in cycles:
    plt.axvspan(c['start_time'], c['end_time'], color='green'
       , alpha=0.2)
plt.xlabel('Temps (s)')
plt.ylabel('Force (N)')
plt.title("Power cycle with detection")
plt.grid()
plt.legend()
plt.show()

def plot_performance_graph(df_final):
    fig, ax1 = plt.subplots(figsize=(14, 6))
    ax1.plot(df_final['Time (s)'], df_final['impulse'], label
       ='Impulse (Ns)', color='blue', linestyle='--',
       linewidth=1)
    ax1.plot(df_final['Time (s)'], df_final['mean_force'],
       label='Mean Force (N)', color='green', linewidth=1)
    ax1.plot(df_final['Time (s)'], df_final['Power (W)'],
       label='Power (W)', color='red', linewidth=1)
    if 'Weighted_Force_Mean' in df_final.columns:
        ax1.plot(df_final['Time (s)'], df_final['
           Weighted_Force_Mean'], label='Weighted force',
           color='darkred', linestyle='-.', linewidth=1.5)
    ax1.set_xlabel('Time (s)')
    ax1.set_ylabel('Force / Impulse / Power')
    ax1.grid(True)
    ax2 = ax1.twinx()
    ax2.plot(df_final['Time (s)'], df_final['Speed (km/h)'],
       label='Speed (km/h)', color='orange', linewidth=1.5)
    ax2.plot(df_final['Time (s)'], df_final['Cadence (Hz)'],
       label='Cadence (Hz)', color='purple', linestyle=':',
       linewidth=2)
    ax2.set_ylabel('Speed / Cadence')
    lines_1, labels_1 = ax1.get_legend_handles_labels()
    lines_2, labels_2 = ax2.get_legend_handles_labels()
    ax1.legend(lines_1 + lines_2, labels_1 + labels_2, loc='
       upper left')

    plt.title('Performance per second : Force, Impulsion,
       Power, Speed and Cadence')
```

```
    plt.tight_layout()
    plt.show()

df_final = save_force_and_power_per_second(cycles)
plot_performance_graph(df_final)
```

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