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Master's Thesis

Development and Implementation of a Proof-of-Concept for a Skier-triggered Automatic Binding Release Mechanism to Prevent Common Skiing Injuries

Entwicklung und Implementierung eines Proof-of-Concepts für einen Skifahrer-gesteuerten automatischen Bindungsauslösemechanismus zur Verhinderung häufiger Skiverletzungen

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Abstract

Ski bindings provide a firm connection between the skier's boots and the skis. Most bindings release the ski boot when the forces at the bindings become so large that they could harm the skier. The conventional ski binding, which is most commonly used in alpine skiing, can effectively prevent lower leg injuries, but knee injuries are still very common among skiers. Multiple scenarios exist where the ski induces dangerously large forces on the knee, but the binding does not release, often tearing the anterior cruciate ligament. An improved binding system is needed to prevent these injuries. In the scope of this thesis, a prototype was developed consisting of a sensor glove and a mechatronic binding. The sensor glove uses flex sensors to measure the abduction of the fingers. If the fingers are spread far and quickly enough, the glove triggers the release of the binding by sending a radio signal. For the mechatronic binding, a conventional adjustable ski binding is modified in such a way that it can be opened with a servomotor. Once it receives the release signal, this mechanism opens the binding automatically and releases the boot. Provided the skier is familiar with the injury mechanisms and reacts quickly, this system should be able to prevent common skiing injuries.

Keywords: Mechatronic ski binding, Sports injuries, Anterior cruciate ligament, Sensor glove, Flex sensor

Zusammenfassung

Skibindungen stellen eine starre Verbindung zwischen dem Skischuh und dem Ski her. Die meisten Bindungen geben den Skischuh frei, sobald die Kräfte an der Bindung so groß werden, dass sie den Skifahrer verletzen könnten. Die konventionelle Skibindung, die im Abfahrtsski vornehmlich zum Einsatz kommt, verhindert die meisten Verletzungen im unteren Bein. Knieverletzungen sind unter Skifahrern jedoch nach wie vor verbreitet. In einigen Unfallszenarien übt der Ski gefährlich hohe Belastungen auf das Knie aus, ohne ein Auslösen der Bindung zu verursachen, was häufig zu einem Kreuzbandriss führt. Ein verbessertes Bindungssystem ist erforderlich, um solche Verletzungen zu vermeiden. Im Rahmen dieser Arbeit wurde ein Prototyp eines Sensorhandschuhs gepaart mit einer mechatronischen Bindung entwickelt. Der Sensorhandschuh misst die Spreizung der Finger mit Biegesensoren. Werden die Finger schnell und weit genug gespreizt, so wird ein Auslösesignal mit einem Funksender übertragen. Für die mechatronische Bindung wurde eine konventionelle, verstellbare Skibindung so modifiziert, dass diese mit einem Servomotor geöffnet werden kann. Sobald das Auslösesignal empfangen wird, öffnet der Mechanismus die Bindung und gibt den Skischuh frei. Sofern der Skifahrer mit dem System sowie den Verletzungsmechanismen vertraut ist und schnell genug reagiert, sollte dieses System in der Lage sein, typische Verletzungen beim Skifahren zu verhindern.

Stichwörter: Mechatronische Skibindung, Sportverletzungen, Kreuzband, Sensorhandschuh, Biegesensor

Contents

List of Abbreviations

Abbreviations	**Definition**
Anatomy	
ACL	Anterior cruciate ligament
MCL	Medial collateral ligament
Pin Names (some of those are only used in the schematics)	
GND	Ground
VCC/V_{CC}	Supply voltage / Voltage at the common collector
CHG	Charge / Charging
PWR	Power
RX	Receiver
DATA	Signal / Data
D9,D10,D11	Digital Pin 11,12,13
A1,A2,A3	Analog Pin 1,2,3
Technical	
DoF(s)	Degree(s) of Freedom
LiPo/ LIPO	Lithium-Polymer
ADC	Analog-to-digital converter
PWM	Pulse-width-modulation
RSS	Resistive strain sensors

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1. Introduction

Alpine skiing is a popular winter sport performed by 135 million people across the globe [1, p. 17]. In the year 2019, about 380 million individual daily ski resort visits have been recorded [1, p. 18]. Similar to athletes in other sports that involve moving at high speeds, skiers are prone to getting injured if they lose control or collide with other skiers or objects. A meta-analysis performed in 2020 involving statistics from the previous 15 years estimates 3.49 injuries to occur for every 1000 days a skier spends on the slope [2]. Combining those numbers, more than 1.3 million people are predicted to be injured while skiing annually.

A yearly report on accidents and injuries of German skiers estimates that in the 2022/23 skiing season, 26.3 % of accidents resulted in a knee injury [3, p. 6, 7]. Using this ratio, more than 300,000 skiers are estimated to suffer from knee injuries each year. Female skiers are especially prone to this type of injury, with 37.2 % of accidents affecting the knee, while for men this number is 18.2 % [3, p. 7].

The reason for the knee being this vulnerable while skiing is apparent when looking at a skier and the gear. Skis are usually about as long as the skier is tall, and thus act as a lever which can exert large forces at the point where the ski is attached. Since the ankle is fixed in the stiff ski boot, the knee becomes the most vulnerable part of the leg.

To protect the skiers from these harmful forces, every ski is equipped with a binding that connects the ski boot to the ski and releases the boot in case of an accident. The force required for the release can be adjusted according to parameters such as the weight and skill of the skier.

Ski bindings work well in most cases, releasing reliably in heavy crashes, but they have a central problem that was already recognized in a patent published in 1981 [4]: When an experienced skier adjusts the binding so it doesn't release during the most forceful turns, the binding is too firm to release in low-speed crashes or when the skier tumbles down the hill after a crash. If the body of the skier turns but the ski does not while still being connected, the forces exerted on the knee often result

in a rupture of the anterior cruciate ligament (ACL).
Although various solutions for releasing the binding on demand of the skier or when the knee is in danger have been proposed and invented [4–9], not a single one has fully established itself on the consumer market to this date. Many knee injuries still occur every season, even though they could be avoided if there was a better binding system. The goal of this thesis is to develop and implement an automatic binding release system triggered with a sensor glove worn by the skier, which is also developed for this purpose. At least a portion of all knee injuries could potentially be prevented when the skier has control over the release of their bindings.
Based on the fact that skiers keep their hands clenched into fists around the ski poles for the majority of time, spreading the fingers can be used as a trigger for opening the binding on demand at any time. The ski glove is equipped with sensors which can detect when the fingers are spread. If that's the case, a release signal is sent to an automatic binding. This automatic binding is a common ski binding modified with a servomotor and electronic components so it can release the ski boot immediately when it receives the release signal. This system should act as a proof-of-concept which could be refined to a market-ready product by a ski or binding company to prevent injuries in the future.
The thesis is structured as follows. First, an overview of the history and different types of bindings is given and the theory for the necessary components such as flex sensors and microcontrollers is explained. In the state of the art chapter, solutions of improved binding concepts are outlined and methods for measuring finger abduction are introduced. The development and implementation of the sensor glove and subsequently the automatic binding are described in detail in their individual chapters. Advantages and disadvantages of the two systems are pointed out in the discussion. Lastly, a brief summary and an outlook is given.

2. Theory

This chapter details why ski bindings are needed, their historical development, the different types of bindings available and why the conventional binding can't prevent certain injuries. Moreover, the basics of flex sensors, voltage divider circuits and microcontrollers are explained since these are needed for the development of the prototype.

2.1. History of Ski Bindings

When skiing began to become a sport at the end of the 19th century, leather shoes were fastened to the ski with straps at the toe, leaving the heel free to move up and down. For downhill skiing, this setup did not provide enough rigidity and control over the ski. It was improved by adding a metal bracket for holding the toe, as well as another strap attached near the heel and passing over the foot of the skier [10].
Various similar binding concepts were developed and implemented around this time until the year 1929 when Guido Reuge proposed a spring-tensioned cable binding, called *Kandahar* binding, which was then largely adopted [10]. As in previous bindings, the *Kandahar* binding featured toe straps or a toe cup for holding the front of the boot. The new addition was a cable with springs that ran from the front of the binding all the way around the heel. This cable could be fixed down besides the toe, pulling the heel down on the ski and enhancing rigidity.
Up to this point, the bindings had no means to self-release. In the event of a crash where the body moves and turns in a different way than the ski, the fixed connection often led to a broken leg, as was the case for Hjalmar Hvam. He was known as a successful ski racer and the first inventor of a releasable ski binding [11]. After his injury, he came up with an idea for a binding, which he patented in 1941 [12]. As shown in the original patent drawings in Figure 1, his binding consists of a spring cable that fixates the heel, just like the *Kandahar* binding, and a toe plate on which the skiers boot is placed and attached with a strap. The entire toe plate can rotate

around either one of two screws placed in a slot at the rear of the plate, which opens toward the back. These slots can be seen in the top view of the drawing in Figure 1(b). Usually, the toe plate is locked in place by the weight of the skier pressing down on it. However, in the case of a crash where the skier's weight no longer rests on the foot, the toe plate is able to release sideways and fully detach from the ski together with the boot.

(a)

(b)

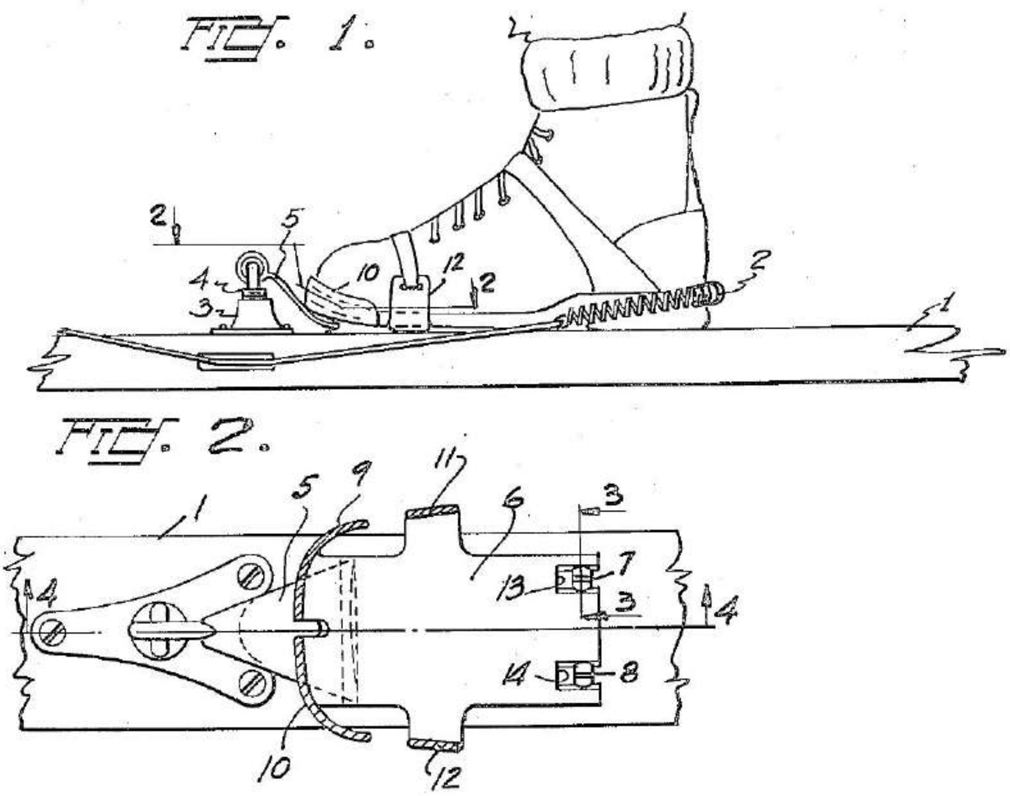


Figure 1.: Patent drawings of Hjalmar Hvam's releasable ski binding [12]. (a) Top view of the complete setup. (b) Side view of the toe plate and the retention mechanism. See the original patent for a description of the different components.

Mitch Cubberly was among the first to design a step-in binding [13] which does not require any straps or cables to be fastened when attaching the ski. Instead, the binding closes itself when the skier steps into it. His *Cubco* binding consisted of a toe piece that could release in all directions, as well as a heel piece releasing upwards. The binding parts snapped into metal plates which needed to be screwed into the sole of the shoe. Cubberly also invented a ski break for stopping the ski from sliding down the hill in the case of a release.

Another important development concerning ski bindings was the ski boot. Leather boots were varying in shape and form, thus worked differently on each binding. Moreover, their sole transforms as they wear down, which influences the retention characteristics of the binding. The metal pieces that Cubberly used or other metal plates on which the whole boot was fixed [14] solved these problems, but were not convenient for normal walking.

By the end of the 1970s, the first modern plastic ski boots with metal buckles for precise closing were introduced by the company *Lange* [15] and quickly replaced the leather boots due to its stiffness, enhancing control over the ski, and easier compatibility with the bindings. The main advantages were also that these boots were waterproof and more durable than leather boots. For snapping into the heel and toe binding pieces, plastic boots feature sturdy plastic lips in the front and back of the boot, eliminating the need for metal brackets.

Modern bindings with lateral toe and vertical heel release were introduced in the 1970s, among others, by the companies *Look* and *Marker* [14, 16]. Tibia fractures and other lower leg injuries could be almost completely prevented with this design, and injury numbers decreased significantly [17]. Although materials and design of the bindings changed over time, the general release mechanism remained mostly unaltered until today. We call this type of binding the conventional (alpine ski) binding.

2.2. The Conventional Ski Binding

The conventional and most widely used ski binding is a two Degree of Freedom (DoF) binding with lateral toe and vertical heel release.

The toe release mechanism of this binding is shown in Figure 2. A twist of the boot can cause the toe to release sideways if the torque between the boot and ski is sufficient to overcome the preset retention force set by adjusting the compression of the retention spring.

Secondly, the heel piece can release vertically if the upward force of the boot or the downward force on the ski is large enough to overcome the heel retention force. This is illustrated in Figure 3.

The toe of the binding is in its closed state when the boot is not engaged. In contrast, once opened, the heel remains in its open state. The skier can simply step into the binding, closing it with its weight pressing down on the heel. To manually open the binding, the rear of the heel piece serves as a lever that is operated with the ski pole, a hand, or occasionally also the underside of the other ski. The latter is not recommended as it may damage the ski's surface.

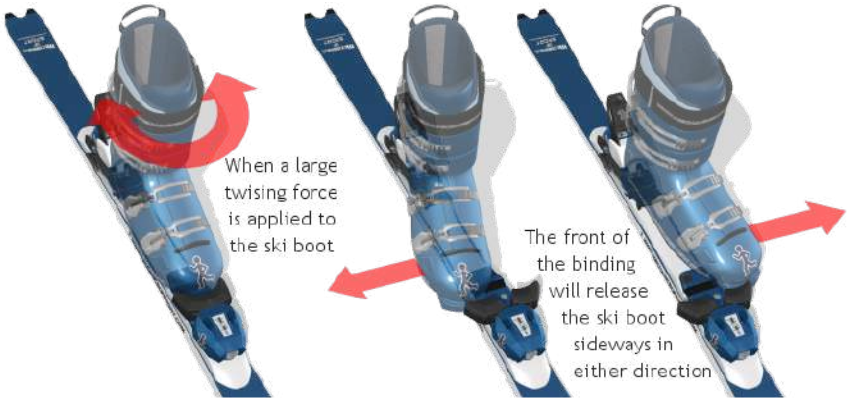


Figure 2.: Toe release mechanism of a conventional ski binding [18]. A sufficiently strong torque applied to the ski boot causes the toe of the binding to release the ski boot sideways. Reprinted with permission from the author.

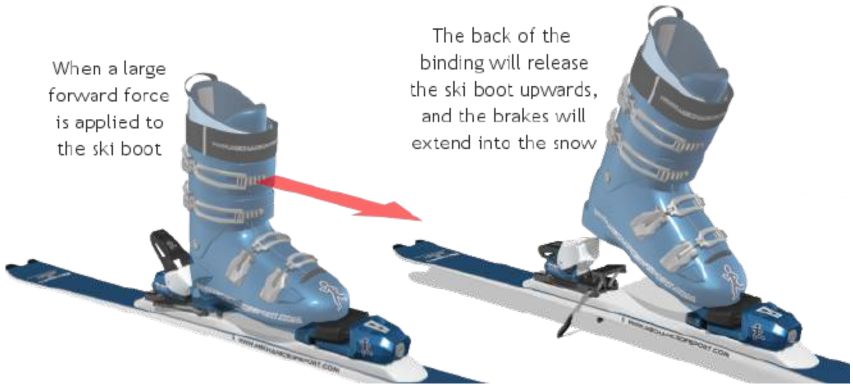


Figure 3.: Heel release mechanism of a conventional ski binding [18]. A sufficiently strong forward or upward force applied to the boot releases the heel upwards. Reprinted with permission from the author.

2.3. Types of Bindings

There are various types of ski bindings on the market. Different kinds of skiing like alpine skiing, ski touring or Nordic skiing all have different requirements that the binding needs to fulfill. The focus of this thesis will be on alpine skiing, but some of the concepts are also applicable for the other disciplines.

Within alpine ski bindings, there are two main categories: drill mounted and track mounted bindings [19]. Drill mounted bindings consist of a toe and a heel piece which are individually drilled and glued into the ski. Usually, the toe piece is fixed while the heel piece can be adjusted in a narrow range. These types of bindings are particularly lightweight and offer the best feedback from the ski, enhancing control over the ski at all times [20].

Figure 4.: Side view of a ski with a track mounted *Head PR11* binding and engaged ski boot.

The track mounted system requires a third component, which is a track or a plate fixed onto the ski by the manufacturer of the ski. The toe and heel piece then slide onto this track and can easily be adjusted and fixated on a wide range of positions. This type is commonly used in rental skis as it can accommodate a large variety of different ski boots and can quickly be set to the required length. Having both the front and rear part adjustable ensures that the boot is always in the desired position relative to the ski, which is important for the ski's behavior. The additional plate increases the weight of the ski but also improves stability, making the ski easier to control at high speeds [20]. An example of such a binding with an attached ski boot is depicted in Figure 4. In the scope of this thesis, this *Head PR11* binding will be modified to allow for an automatic release.
Ski bindings and boots are monitored by different organizations such as the German

Institute for Standardization (ger: Deutsches Institut für Normierung - DIN) as well as the International Organization for Standardization (ISO). Both of these institutions provide, often in cooperation, standards for various aspects of the skiing sport to ensure safety and compatibility. Since most ski boots and bindings follow these norms, an alpine ski boot is usually compatible with any alpine binding that can be found on the market.

In addition to design standards for alpine ski boots defined in DIN ISO 5355 and alpine ski bindings given in DIN ISO 9462, a unified table for selecting the tension of the release system is described in DIN ISO 11088. Depending on the skier's weight, height, age, skill level and boot sole length, a DIN-value (ger: Z-Wert) is determined using this table. All accredited bindings include an adjustment mechanism as well as a scale for reading the currently set DIN-value at both the heel and the toe piece. Usually by the means of a large flat-head or Phillips Screwdriver, the skier or the renting agency can adjust the binding to the skier's profile.

A study performed from 1974 to 2004 in the Vermont ski area identified incorrectly adjusted bindings and poorly maintained gear as a reason for many lower leg injuries in skiing [21]. Interestingly, knee injury statistics do not correlate with the quality and condition of the binding, pointing to the fact ski bindings were not developed with knee safety in mind [22].

2.4. Knee Injury Mechanisms in Alpine Skiing

As already mentioned in the Introduction 1, the knee is the most commonly injured body part in modern alpine skiing. In contrast to other body parts, knee injuries are directly related to the binding system because it transmits forces from the ski to the leg of the skier.

Different researchers have identified four main injury mechanisms that result in knee damage in recreational skiing [17, 22–24]. Conflicting evidence on the frequency of these processes has been found, so it was decided to focus on the most recent study of those, performed by Shea et al. [23], representing the most up-to-date ski equipment and practices. Their six-year study involving 541 injured patients found the valgus-external rotation to be the most common mechanism making up 32.9 % of knee injuries, followed by the phantom foot with 22.5 %, hyperextension with 19.0 % and finally the boot-induced anterior drawer causing 7.8 % of knee injuries. The remaining 17.8 % of patients observed a different injury mechanism, or they

were unsure about the exact course of events. For understanding the role of the ski binding in injuries, these four mechanisms will now be explained in detail.
The valgus-external rotation, also commonly called forward twisting fall, is shown in Figure 5(a). The main problem is that one ski tip digs into the snow, rapidly slowing down while the skier keeps moving [25, 26] In more detail, the skier usually loses balance, shifting the center of gravity forward. As a consequence, the weight of the skier transfers from the tail to the front of the skis, making it difficult to keep the skis under control. One ski tip digs into the snow and rapidly slows down while the skier still has plenty of momentum. The back of this ski violently jerks upward and begins to rotate towards the other ski. This causes a valgus movement in the knee (the knee is bent inward towards the other knee) and an external rotation of the tibia (the toes are turned outward, away from the other toes), which is the reason for this mechanism's name. This combination of external rotation and valgus movement can tear the medial collateral ligament (MCL) and sometimes also damage the ACL [17, 24].

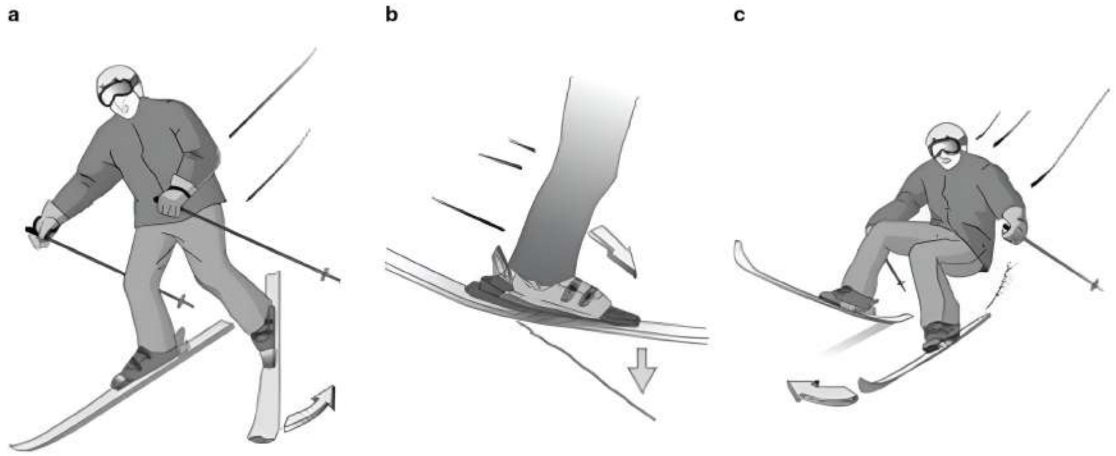


Figure 5.: Common ACL injury mechanisms in skiing. (a) valgus-external rotation (b) boot-induced anterior drawer (c) phantom foot [24]. Reprinted with permission from Springer Nature.

The second most common cause for knee injuries is the phantom foot mechanism, also commonly named backwards twisting fall. The conditions for this type are depicted in Figure 5(c). Again, the skier loses balance, but now falls towards the rear of the skis. The hips are positioned below the knees, bending them by more than 90°. While the skier naturally shifts the upper body in the downhill direction, pressure is taken from the uphill ski onto the tail of the downhill ski, causing this

ski to dig into the snow and turn inwards. The turning of the ski paired with the stiff ski boot creates an internal rotation of the tibia (the toes are turned inward, towards the other toes) as well as a valgus movement, eventually tearing the ACL or the MCL [22, 25, 26]. The name 'phantom foot' comes from the fact that the tail of the downhill ski acts as a lever equal to a human foot, which points in the opposite direction as the actual foot because of the inward turning that the ski performs [22].
The hyperextension injury mechanism occurs when a skier traveling at high velocity transitions from a low-friction surface such as ice to a surface with higher friction [17, 26] such as deep snow or wet snow produced by a snow machine. The skis together with the binding and lower leg are rapidly slowed down while the body of the skier keeps moving. The skier falls forwards, extending the joints and rupturing the ACL. While the skis slow down, they also often rotate inward until the tips cross in the front, putting further strain on the knees. This type of accident is then called hyperextension with internal rotation.
Another injury mechanism is the boot-induced anterior drawer, illustrated in Figure 5(b). It occurs when a skier lands back-weighted from a jump with the knee fully extended [22, 26]. The tail of the ski comes in contact with the ground first, and the ski bends under the skier's weight. As the ski rebounds to its natural state, the tip of the ski is pulled towards the ground while the skier's weight remains shifted backwards. The rigid ski boot restricts ankle movement and transfers the force directly to the tibia, driving it forward away from the femur. Additionally, the skier intuitively tries to avoid falling backwards and strongly tenses the quadriceps, further increasing the anterior pull on the tibia [23]. This combined excessive anterior translation tears the ACL.
When injuring their ACL, the majority of skiers report that the binding did not release during the accident [27]. This is because in the mechanisms described above, the involved forces and torques cannot trigger the release of a conventional binding [24]. The lateral forces at the toe and the vertical forces at the heel are simply not large enough to overcome the retention force and release the binding. Instead, the binding paired with the rigid boot play a key role in transmitting the forces from the ski to the skier's knee. Thus, this problem can be addressed by changing the workings of the binding [28]. Ideally, it should release in all the cases presented above before a dangerous rotation or translation can reach the knee.

2.5. Flex Sensors

A resistive flex sensor or bend sensor is a resistor which changes its electrical resistance depending on how strongly it is bent. There are multiple different types of flex sensors. Here we will only focus on conductive ink-based sensors because of their low cost and robustness.
As presented in Figure 6, the sensor consists of conductive ink that adheres to a substrate. Importantly, the ink does not break or detach from the substrate upon bending of the sensor. Multiple segmental conductors are placed on top of the conductive ink in a regular pattern. A coating is added on top for protection.

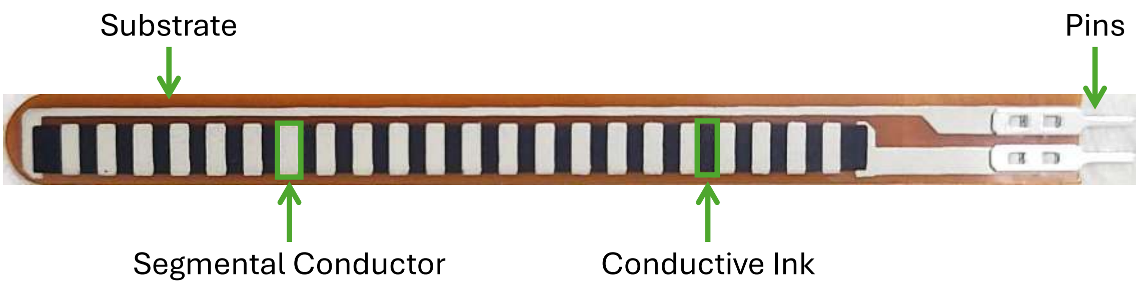


Figure 6.: Photograph of a *Spectra Symbol* 5.5 cm flex sensor with conductive ink, segmental conductors, substrate and two connection pins.

Usually, the conductive ink is made of carbon elements in a binder [29]. While bending the sensor, the ink is stretched and forms more and more microscopic cracks of increasing width. The number and size of these micro-cracks influence the electrical resistance of the ink. Once the sensor is bent back to its original state, the cracks tighten again and the resistance decreases to its previous value.
The segmental conductors are necessary to reduce the sensitivity of the sensor and to ensure a reproducible behavior of the resistance with bending [30]. The dependence of the resistance against the bending radius is different for every manufacturer, but it is usually nonlinear [29].
Although one might assume that the cracks could damage the sensor over time, these sensors are capable of enduring numerous bends. In the example of the *Spectra Symbol* flex sensors, the manufacturer specifies a life cycle of more than one million bends [31].

2.6. Voltage divider

A voltage divider circuit reduces the input voltage V_{in} to a lower output voltage V_{out} using two resistors with resistance R_1 and R_2. A schematic of this circuit is shown in Figure 7.

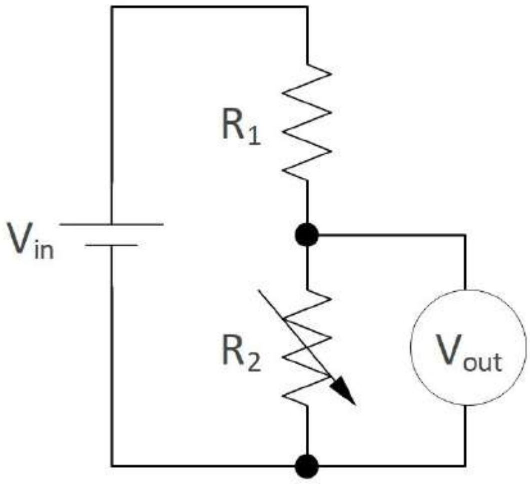


Figure 7.: Voltage divider circuit with voltage supply V_{in}, resistor R_1, variable resistor R_2 and voltage meter V_{out}. Created with Wondershare EdrawMax.

The output voltage depends on the input voltage as well as the two resistors. An expression can be derived from Ohm's Law $V = I \cdot R$ where I is the current and using the fact that resistors connected in series need to be added up yields

$$V_{\text{in}} = I \cdot (R_1 + R_2) \quad \Leftrightarrow \quad I = \frac{V_{\text{in}}}{R_1 + R_2}$$
$$V_{\text{out}} = I \cdot R_2 = \frac{V_{\text{in}}}{R_1 + R_2} \cdot R_2 \,.$$

Using this equation and $R_2 < (R_1 + R_2)$ it follows that $V_{\text{out}} < V_{\text{in}}$. In the special case of two equal resistances $R_1 = R_2$, the output voltage is exactly half the input voltage.

If V_{in} and R_1 are fixed, the voltage divider can also be used to determine the value of R_2 by measuring V_{out}. Solving the equation for R_2 gives

$$R_2 = \frac{R_1 \cdot V_{\text{out}}}{V_{\text{in}} - V_{\text{out}}} \,.$$

If the measurement of the output voltage increases, this means the resistance R_2

has increased as well, since R_1 is fixed.
If the voltage divider is used as a measurement device for a variable resistor R_2, the value of the fixed resistor influences the measurement accuracy. The variable resistor can obtain values between R_{min} and R_{max} with corresponding output voltages of V_{min} and V_{max}. The optimal value for R_1 is the one that maximizes the voltage difference between the two limit states:

$$\begin{aligned}
\Delta V = V_{\text{max}} - V_{\text{min}} = V_{\text{in}}(\frac{R_{\text{max}}}{R_1 + R_{\text{max}}} - \frac{R_{\text{min}}}{R_1 + R_{\text{min}}}) \\
\frac{\partial(\Delta V)}{\partial R_1} = V_{in}\left(\frac{R_{\text{min}}}{(R_1 + R_{\text{min}})^2} - \frac{R_{\text{max}}}{(R_1 + R_{\text{max}})^2}\right) \overset{!}{=} 0 \\
\frac{R_{\text{min}}}{(R_1 + R_{\text{min}})^2} = \frac{R_{\text{max}}}{(R_1 + R_{\text{max}})^2}
\end{aligned}$$

Using $R_{\text{max}} = n \cdot R_{\text{min}}$ with $n \,\epsilon\, \mathbb{R}$, $n > 1$, this simplifies to:

$$\begin{aligned}
\frac{R_{\text{min}}}{(R_1 + R_{\text{min}})^2} &= \frac{nR_{\text{min}}}{(R_1 + nR_{\text{min}})^2} \\
R_1^2 + 2R_1R_{\text{min}} + R_{\text{min}}^2 &= \frac{R_1^2 + 2nR_1R_{\text{min}} + n^2R_{\text{min}}^2}{n} \\
R_1^2 + 2R_1R_{\text{min}} + R_{\text{min}}^2 &= \frac{1}{n}R_1^2 + 2R_1R_{\text{min}} + nR_{\text{min}}^2 \\
R_1^2\left(1 - \frac{1}{n}\right) + (1-n)R_{\text{min}}^2 &= 0
\end{aligned}$$

Dividing through $\left(1 - \frac{1}{n}\right) = \frac{n-1}{n}$ gives:

$$\begin{aligned}
R_1^2 - nR_{\text{min}}^2 = 0 \\
\Rightarrow R_1 = \sqrt{n} \cdot R_{\text{min}} \quad \text{since} \quad R_1 > 0
\end{aligned}$$

This value of R_1 maximizes the range of output voltages for a given R_{min} and R_{max}. The optimal value of R_1 is in between the minimum and maximum values of the variable resistor since $R_{\text{min}} > \sqrt{n} \cdot R_{\text{min}} > n \cdot R_{\text{min}} = R_{\text{max}}$

2.7. Microcontroller Basics

A microcontroller is a small computer embedded on an integrated chip that can measure sensor values and control actuators [32, p. 7]. A common microcontroller platform is called “Arduino”providing multiple different microcontroller boards as well as the Arduino integrated development environment (IDE) as a programming interface. Due to its compact size and versatility, it is widely used in electronic projects and prototypes.

Microcontrollers have two general types of data pins: analog and digital pins. Both are capable of outputting signals or measuring input, but in distinct manners. Digital pins can only distinguish between off (`LOW`) and on (`HIGH`) states when used as input. Alternatively, these pins can power certain actuators with these two states when used as output [33, p. 17].

Some digital pins also feature pulse-width-modulation (PWM) capability, which allows them to simulate a desired output voltage by repeatedly switching on and off quickly with precise timings [32, p. 41]. Another type of digital pin is an interrupt pin. When its input signal changes, such as when a button is pressed, other active processes are interrupted to prioritize a specific function [32, p. 52]. A pin can have both PWM and interrupt characteristics.

Analog pins have the same basic functionality as digital pins [33, p. 79] but additionally allow analog measurements of input voltages [33, p. 66]. An analog input is converted into a digital signal, which the microcontroller can process using an analog-to-digital converter (ADC) [32, p. 42]. Depending on the choice of the ADC, the digital signal can contain different numbers of bits, influencing the resolution of the conversion. A microcontroller with a 10-bit ADC divides its 5 V voltage range into $2^{10} = 1024$ equally large segments of around $\frac{5\,\mathrm{V}}{1024} \approx 5\,\mathrm{mV}$. ADC’s with fewer bits have a lower resolution, more bits correspond to a higher resolution.

Arduino code is based on the `C++` programming language. It is commonly structured in a `void setup` and a `void loop`, which is continuously repeated after the setup [33, p. 31]. Variables, additional functions and external packages required for the loop are defined in the beginning before these two parts.

The setup is executed once when the microcontroller is started. Here, the pins of the board are assigned to their input and output tasks, like reading a pin’s value or controlling a motor. In the loop, the actual process is implemented, always in such a way that the loop can be repeated endlessly [33, p. 32].

3. State of the Art

This chapter gives an overview of existing binding concepts and products that improve the conventional ski binding. Additionally, current methods of hand tracking with a focus on measuring finger abduction are presented.

3.1. Improved Binding Concepts

The conventional binding system introduced in Section 2.2 can successfully prevent most injuries. However, there are multiple different scenarios where it does not release despite the body being exposed to harmful movements and forces as described in Section 2.4. There are two main strategies for solving this problem: a purely **mechanical** solution or a **mechatronic** approach. Both of them rely on the established conventional two DoF binding but extend its functionality in different ways to enhance safety.

The **mechanical** approach usually adds one or multiple additional DoFs to the existing two DoF to allow for a release in more scenarios. While a mechanical binding system cannot be aware of when an injury might occur, analyzing injury and accident patterns can provide insights on the direction and magnitude of forces on the binding which should trigger a release to prevent the skier from being harmed. The main challenge when designing these bindings is avoiding unwanted releases in situations where the skier is still in control and not in danger. If the binding were to release in a high speed turn or when going over a bump, the consequences can be fatal and quickly diminish the skier's trust in the binding.

Multiple examples of three DoF bindings are already sold on the market. *Howell Bindings* [34], *Kneebindings* [35] and the *Tyrolia/Head Protector* series [36], a successor of the *Head PR11* binding used in this project, all implement a *lateral heel release* mechanism. This mechanism allows the heel piece of the binding to twist slightly, enabling the heel of the boot to release sideways in addition to the conventional upwards release.

Mechatronic bindings allow releasing the boot with an electric signal paired with a mechanical or sometimes even a pyrotechnical mechanism. They rely on sensors to detect a potentially dangerous situation or the skier can trigger them manually, for example by pressing a button. Although various patents, publications and dissertations already describe such a system [4–9], none has yet reached the consumer market. There is little information on why this is the case. It is likely that these systems are too complex to be manufactured and sold at a price consumers would accept. Since a binding of this type is developed in the scope of this thesis, an overview of some existing concepts will be given.
A detailed investigation into mechatronic ski bindings is presented by Aljoscha Hermann in his dissertation "Knee Injuries in Alpine Skiing - Why and How Mechatronic Ski Bindings Can Help" [5] and a corresponding article by Hermann et al.[6]. These works include a detailed analysis of the injury mechanisms of the knee. Furthermore, a system is developed that constantly monitors the knee angle, thigh muscle activity, skiing speed and load at the foot by means of different sensors. By combining these variables with information about the skier, an algorithm determines the likelihood of an imminent injury. Based on this value, a mechatronic binding could automatically release or adjust its retention strength. In the following, this system will be referred to as the *fully automatic* binding. Their work does not include the binding mechanism itself, but variations of these can be found in the patents outlined in this section.
The idea of adjusting the retention strength based on muscle activity for protecting the knee was already used by Eseltine and Hull in 1991 [7]. Based on the finding that the vulnerability of the knee depends on the contraction in the muscles crossing the knee joint, they developed a binding which could switch between two retention settings. If the muscle activity is high, the knee is stronger than when the muscles are relaxed. In their system, surface electrodes measure the activity of the quadriceps. An electronic system can enable or disable an additional spring that increases the retention strength of the toe binding piece by means of a solenoid. When only one of the springs is activated, the retention setting is low enough to avoid damage to the knee in its weakest state.
The patent "Electrical ski boot release", published in 1981 and filed in 1974 by D'Antonio et al. [4] was among the first to describe a mechatronic ski binding. They noticed most bindings at the time had unreliable release characteristics influenced by ice and dirt buildup, varying the friction that needs to be overcome in the case

of a release. To mitigate this issue, they proposed a device for measuring the forces and torques acting on the binding. Once these values surpass certain thresholds which could be harmful to the skier, the system would automatically separate the boot from the ski.

In contrast to purely mechanical bindings, their system also takes the duration of the acting forces into consideration. During certain controlled skiing maneuvers like sharp high-speed turns or jumps, large forces might occur for very short periods of time without harming the skier. Only if such forces are exhibited over a longer time span do they become dangerous and a release should be initiated. The authors also proposed multiple release mechanisms for different bindings, like the *Spademan* binding or cable bindings. Since these are outdated by now, they will not be further elaborated here.

In the 2006 patent “Backwards release ski binding” [8], spring and gas powered mechanisms are presented which can be activated by an electric signal and then pull the rear binding piece backwards. This opens the binding far enough for the boot to be no longer secured. This patent also discusses additional advantages of such a system besides injury prevention. Beginner skiers having problems standing back up after a fall could simply open the binding with a push of a button. Standing up is easier when the skis are not attached. In deep ungroomed snow conditions, skiers sometimes get trapped in underground holes in the snow near trees or small streams. When the ski is still connected to the boot, it may prohibit the skier from climbing out of the hole. If the skier is surrounded by snow, it might not be possible to release the binding manually. A skier-triggered mechatronic binding system would allow the skier to open the bindings and escape a possibly life-threatening situation.

A more recent patent called “Remote release ski binding” [9] introduces a release system for drill mounted bindings. The toe piece of the binding is placed on top of two plates, of which the lower one is mounted on the ski. A mechanism contained in the lower plate locks the upper plate where the binding is attached in place. When the system is triggered, the locking mechanism opens and a spring accelerates the upper plate with the toe piece forward, releasing the ski boot. The *Rossland Binding Company*, which filed this patent, provides two videos demonstrating a prototype [37].

3.2. Hand Tracking and Finger Abduction

Measuring finger abduction is only one part of the more broad topic of hand tracking. The latter typically aims to track movements of all finger joints across every DoF to provide a representation that mirrors the real human hand as closely as possible. Hand tracking is useful for interacting with robots or computers and can also be used to engage with virtual environments. In recent years, different techniques were developed and improved in accuracy as well as robustness.

In their recent survey on hand tracking, Heo et al. differentiate seven sensor categories: “vision, soft wearable, encoder, magnetic, inertial measurement unit, electromyography and a fusion of sensor modalities”[38]. Most of these are not suitable for this project for different reasons, such as their cost, accuracy, size or the impossibility of using them remotely in the context of skiing. Skiers already use soft wearable devices in the form of gloves to protect their hands from the cold temperature and snow. Therefore, the focus will be on this category, where a sensor can simply be integrated into the glove instead of requiring an external device.

Soft wearable hand tracking devices are also commonly called sensor gloves or data gloves. Different sensor types can be used for creating such devices. The least expensive of those are flex sensors and resistive strain sensors (RSS). Flex sensors are limited to one direction and are not stretchable, which means measuring joints with multiple DoFs is difficult to implement and requires multiple of these sensors. While being more stretchable, RSS are susceptible to changes in temperature and humidity [38]. Capacitive strain sensors, fiber Bragg grating sensors and piezoresistive fabric also belong to this category but will not be considered due to their higher cost.

Based on their properties, flex sensors appear to be the most suitable option for the problem at hand. A wealth of flex sensor gloves exists that can record the extension and flexion of a single [39], multiple [40] or all fingers [41]. Simpler ones measure the flexion of each finger as a whole [42], or of a single joint of all fingers [43]. More advanced gloves use segmented sensors to measure flexion of the individual joints [44]. Additional examples can be found in a review paper about resistive flex sensors and their use cases [29] and in a review paper about data gloves in general [45].

Apart from extension and flexion, fingers have an additional degree of freedom. They can perform abduction and adduction, which describes the sideways rotation away from and towards the adjacent finger. Sensor gloves which can measure this type of motion are scarce in the literature but as finger spread will be used as a trigger in this project, the existing solutions are outlined here. The positioning of the sensors for recording this type of movement is more complex than when measuring finger flexion, where the sensors are simply placed on top of the fingers or individual joints. Therefore, the different solutions are presented according to their placement on the hand, as compared in Figure 8.

The concept of using a flex sensor for measuring abduction of two fingers was introduced by Blanco et al. who developed a sensor glove to allow patients with spinal cord injuries to mechanically control their extremities [46]. In addition to sensors measuring flexion of the fingers, sensors were placed on top of the fingers to identify when the fingers are spread. Two sensors were used for this purpose, and one end of each sensor was fixed on the middle finger. The other ends curve out to the index and to the ring finger. The placement on the middle and index finger is shown in Figure 8(a) for the hand in rest and spread positions.

The sensors can also be placed perpendicular to the fingers, pointing away from the top of the hand, as shown in Figure 8(b). This type of placement is used by Saggio et al. [47]. A large variation in the bending radius between the rest and spread position is achieved. Since this maximizes the obtainable resistance range of the sensor, this is beneficial for the measurement accuracy. However, the sensor sticks out far from the hand. Because it forms half a loop, it could easily get caught on other objects and be damaged or even torn off. Gentner et al. mitigated this issue by placing the sensors closer to the base of the fingers and by using shorter flex sensors with a length of 5 cm [48].

Because the thumb can be abducted much further than the other fingers, the perpendicular positioning is not applicable for this finger. Instead, Gentner et al. placed one sensor in between the thumb and the index finger. This is similar to the setup shown in Figure 8(c), and can be applied to all the other fingers as well, not exclusively to the thumb. In this setup, it is possible to use a very short sensor, but the sensor might be pinched at a single point when the hand is in the rest position or when it forms a fist. This sharp pinching could permanently deform and damage the sensor. O'Flynn et al. avoided this problem by shifting the sensors upwards and out of the space between the fingers so they can bend without being pinched [49].

When it is possible to place the sensor in between two fingers, the most obvious alternative to this is placing the sensor on two adjacent fingers but on the outside edges of the fingers. This setup could not be found in any publications but is still demonstrated in Figure 8(d) as it minimizes the sensor's protrusion from the hand.

(a)

(b)

(c)

(d)

Figure 8.: Different possible placements for the flex sensor in rest (left images) and spread (right images) position of the hand. (a) The sensor is placed on top of the fingers. (b) The sensor is placed in between the fingers and is angled perpendicular to the hand. (c) The sensor is placed in between the fingers. (d) The sensor is placed around the fingers. The flex sensor is represented by a cardboard strip. Setting (d) required the use of some double-sided tape so the strip remains in the correct position when taking the photos.

4. Sensor Glove

In this chapter, the development of a sensor glove for measuring finger abduction is described. Firstly, the concept of this glove and the initial tests are outlined. Next, the prototype is explained with respect to its electrical components, their arrangement on the circuit board and the algorithm. Finally, the system's power consumption is evaluated.

4.1. Concept

Plenty of intricate release mechanisms for different types of bindings have been developed, as described in Section 3.1. However, many of the existing solutions rely on a simple button in the ski pole to trigger the release. This is the most straightforward solution, but it is questionable if the skier remembers to push the button quickly enough in the case of a crash. The surprise of an accident could cause the skier to let go of the ski poles, leaving the skier with no way of activating the release mechanism.

This problem asks for a solution attached to the body or integrated into the gear of the skier. An option would be to measure activity of some muscle or joint in the skier's body. However, the challenge lies in the fact that skiing engages nearly all muscles in the human body, with various body parts continuously adjusting to maintain balance and control. Therefore, the regular muscle activity is difficult to distinguish from an event of a necessary or desired binding release in the case of an accident.

The skier needs to keep the balance forwards and backwards as well as sideways with the legs, core and arms. The arms and wrists also operate the ski poles to initiate turns or to push the skier forward. The neck is tilted and rotated so the eyes can evaluate the upcoming section of the piste and observe the positions of other skiers. The knees compensate for bumps and unevenness in the surface. The legs and ankles adjust the exact angle and position of the skis for controlling the

direction and regulating the speed.
The fingers are one of the few body parts not actively engaged during skiing. For most of the time they are holding the ski poles and are wrapped around their handles, clenched into a fist. The natural reflex of humans when they are falling is to stop their fall as quickly as possible with their hands [50]. Any object held in the hands before a fall is released, and the fingers are spread to achieve maximum contact with the ground. For this reason, a suitable trigger for releasing a mechatronic binding is detecting finger spread. Measuring finger flexion instead of abduction would be simpler, but since the fingers are spread less frequently than they are flexed, using finger spread is less prone to triggering false releases of the system.
During a normal skiing day, one does not hold the ski pole for the entirety of the day. While riding the ski lift, both poles are often held in one hand so the other hand is free to do other things like drinking some water stored in a backpack. Because the skis are still attached in chairlifts, it would be highly impractical or even dangerous if the automatic binding opened unintentionally. Therefore, it would also not be sufficient to only use spreading of the fingers as a trigger. Instead, the fingers have to be spread *quickly*, which is not a regularly performed movement but requires an intention or happens in reaction to an abrupt event.
As mentioned in Section 3.2, there are various ways of tracking finger movement. This project does not require a sophisticated hand tracking system with fine resolution. The sensor only needs to differentiate between the two states where the hand forms a fist and the one where the fingers are spread. It should also be able to recognize how quickly the transition between these two positions is obtained. Slightly limiting the glove's range of motion is in this case not a problem, since the hands don't need to handle complex tasks or perform intricate movements during skiing. Considering these factors, flex sensors appear to be the most suitable sensors. Additional advantages supporting this choice are their affordability, lightweight design, temperature resistance, ease of electronic integration and their low power consumption.

4.2. Initial tests

Before developing a fully functional prototype, a testing setup was constructed. Two flex sensors were attached to an existing ski glove and a circuit board was manufactured. This board integrates two voltage divider circuits for measuring the resistance of two flex sensors with an "Arduino Nano Every" microcontroller, which features a 10-bit ADC. One red and one green LED have also been included for visually indicating the state of the flex sensors. For supplying the board with power and data acquisition, it needs to be connected to a computer with a USB continuously.

The positions of the flex sensors on the hand are critical for this setup to work. They should be placed in a way that maximizes the difference in the bending radius between the rest and the spread position of the fingers. Still, the hand and finger movement should remain unrestricted, and the sensors should not protrude too far from the hand to allow integration into a glove. Of all the possible positions for the flex sensors that were described in Section 3.2, option (d) was found to be most convenient for this project. In this arrangement, the bend radius never becomes small enough to damage the sensors, and they do not protrude far from the hand. Compared to option (a), it is also easier to fixate the sensors on the glove since they are tangential to the fingers instead of standing on top of them.

This type of setup requires a long flex sensor, which can span the distance between two fingers while still providing a sufficient attachment space for the sensor ends. Resistive flex sensors with an active length of 9.5 cm are therefore used. Having larger segmental conductors, these look a bit different from the sensor presented in Section 2.5, but the working principle is similar. The length is the same as the dummy sensor used in Figure 8.

To facilitate a seamless integration into the glove and avoid overlap, one sensor has been placed along the index and middle finger and will be referred to as the left sensor. Another one has been placed along the ring finger and the pinkie and will be referred to as the right sensor. Holes have been drilled in the two ends of the flex sensors and these points were sewed to the sides of glove fingers. This arrangement along with the initial testing board is shown in Figure 9. Next to where the flex sensors are connected, the board also includes pins which allow for an oscilloscope to be connected. This allows to measure the output voltage with higher accuracy and better time-resolution compared to the Arduino.

The purpose of this setup is to conduct experiments with the flex sensors to determine if they can reliably detect when the fingers are spread. The flex sensors only undergo a slight change in their bent radius from the fist or rest state to the spread finger state. This test should determine if this slight change in the bend radius is sufficient to be reliably detected by the Arduino in combination with a voltage divider. The noise of the system should be small when compared to the range of values the flex sensor reaches during the finger movement. This is required for the different positions to be identified reliably.

Figure 9.: First test setup of the flex sensor glove. Sewed onto the glove are two flex sensors and a circuit board housing an Arduino, two LEDs and voltage divider circuits for the flex sensors.

According to the data sheet of the flex sensors [31], the flat resistance is $10 \pm 3\,\mathrm{k\Omega}$ and increases as it is bent to more than two times the flat resistance. Since these numbers are not highly accurate, the resistance has been measured in the bend state when the sensors were fixed to the glove and values between 9 and $29\,\mathrm{k\Omega}$ have been recorded, depending on the abduction of the fingers. As derived in Section 2.6, the resistance of R_1 should be in between the minimum and maximum values of the variable resistor for the best accuracy. Therefore, a resistor of $20\,\mathrm{k\Omega}$ has been

chosen as the fixed resistor R_1 in the voltage divider circuits.
Figure 10 shows an oscilloscope measurement of the output voltage of the two flex sensor voltage divider circuits. For the duration of the measurement, the flex sensors have not been bent but remained static. The voltage curves both span over two to three vertical segments, corresponding to a noise of 10 to 15 mV. The microcontroller uses a 10-bit ADC, so as mentioned in Section 2.7, it can record values in the range of 0 to 1023 with a resolution of about 5 mV. Therefore, this noise spans over two to three of the ADC measurement intervals, which will now be referred to as ADC-units.
The ADC-units are proportional to the output voltage of the voltage divider, which depends on the resistance of the flex sensor, as seen in section 2.6. For detecting the different states of the sensors, only relative changes in the sensor values are important, so a conversion to the voltage is not necessary.

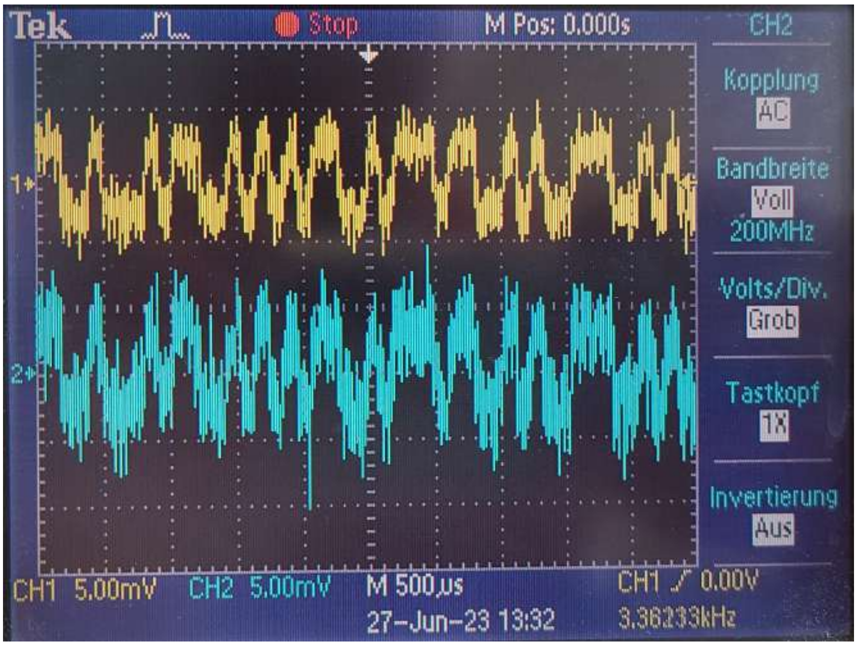


Figure 10.: Oscilloscope measurement of the sensor noise. The output voltage of one divider circuit is shown in yellow, the other one in blue. One box in the plot corresponds to 5 mV on the y-axis and 500 µs on the x-axis.

To examine the range of sensor values and how quickly they can change, a test has been performed. The glove is moved from the clenched fist to the spread finger state repeatedly. The measured sensor signal during this test is plotted in Figure 11 for each 0.05 s time step. The difference in the sensor signal compared to the previous time step is shown in the lower subplot and is now called signal change.

The right sensor reaches values between 585 and 715 ADC-units and the left sensor values range from about 505 to 640 ADC-units. These scales are clearly larger than the noise, which has just been estimated at about three ADC-units. Most importantly, this plot shows a clear distinction between the fist and the spread finger state based on the sensor signal.

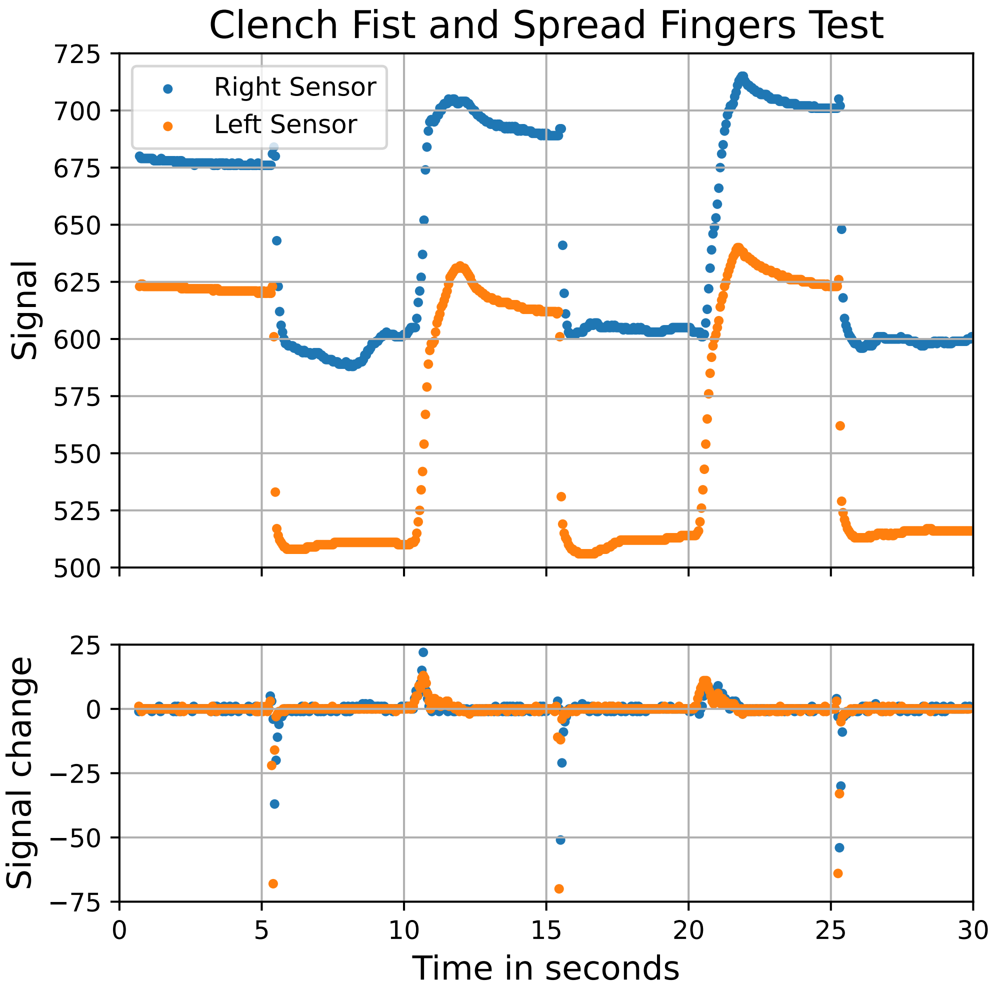


Figure 11.: The sensor signal and the change in the signal compared to the previous time step recorded by the microcontroller in ADC-units are plotted against the time. The glove is clenched into a fist and after five seconds, the fingers are spread rapidly. This position is kept for five seconds until the glove is slowly brought back to the fist position and the procedure is repeated another two times.

The signal change is minimal except for the transitions between the two states. Rapidly spreading the fingers induces a negative signal change of up to -50 or -70 depending on the sensor. This large negative change in the signal can serve as an additional identifier of a quick finger spread movement. The slow transition to the clenched fist leads to smaller positive changes of up to 15 to 25 ADC-units.
The previously mentioned value ranges for the two sensors are offset. This can also be observed in the shift of the two curves along the y-axis of the plot in Figure 11. The main reason for this is that individual finger movement and sensor placement result in different bending radii and thus different resistances. The ring finger and pinkie are closer together than the other two fingers, and therefore the right sensor has a smaller bend radius. This causes a higher resistance of the flex sensor and thus a higher sensor value. Additionally, two sensors are not manufactured perfectly similar but can have different resistances within a significantly large tolerance mentioned at the beginning of this section.
The initial tests confirm that a voltage divider circuit, paired with a microcontroller featuring a 10-bit ADC, is an adequate setup for detecting finger spread. The selected sensor placements offer enough variation in the bend radius between the clenched fist and spread finger positions. Additionally, the sensor noise is small compared to these ranges and is not expected to impact a correct classification of the hand positions.
Based on these results, the configuration of the flex sensors remained unchanged in the final sensor glove prototype. The other placement options presented in section 3.2 have not been tested, but are expected to yield slightly different sensor ranges and accuracies because of the different bend radii. For integration into the glove, the selected positions are thought to be the most ideal option.
The circuit board was revised extensively to offer more functionality and have minimal dimensions. These changes are explained in detail in the upcoming sections.

4.3. Electrical Components and Schematic

The circuit board on the glove has the task of measuring the sensor's positions and detecting when the fingers have been spread far and quickly enough to trigger the release mechanism. As soon as this occurs, it has to send a radio signal to the mechatronic binding. These tasks require the use of a microcontroller. A "DFROBOT Beetle" microcontroller was chosen because of its small dimensions. The space on

the glove is limited, so the board should be as small as possible.
To supply the board with power, a small battery measuring only 20 by 25 cm is used. It is a 3.7 V, 555 mWh Lithium-Polymer (LiPo) battery. This capacity is sufficient since only the flex sensors need to be continuously measured and the release signal needs to be transmitted just once. More details on the power consumption can be found in the next chapter. For recharging the battery, a USB LiPo charger is included on the board as well.
The schematic of the glove in Figure 12 shows how the different components are connected. The LiPo battery is wired to the battery terminals of the LiPo charger. The positive terminal of the battery passes through a power switch on the way to the charger.

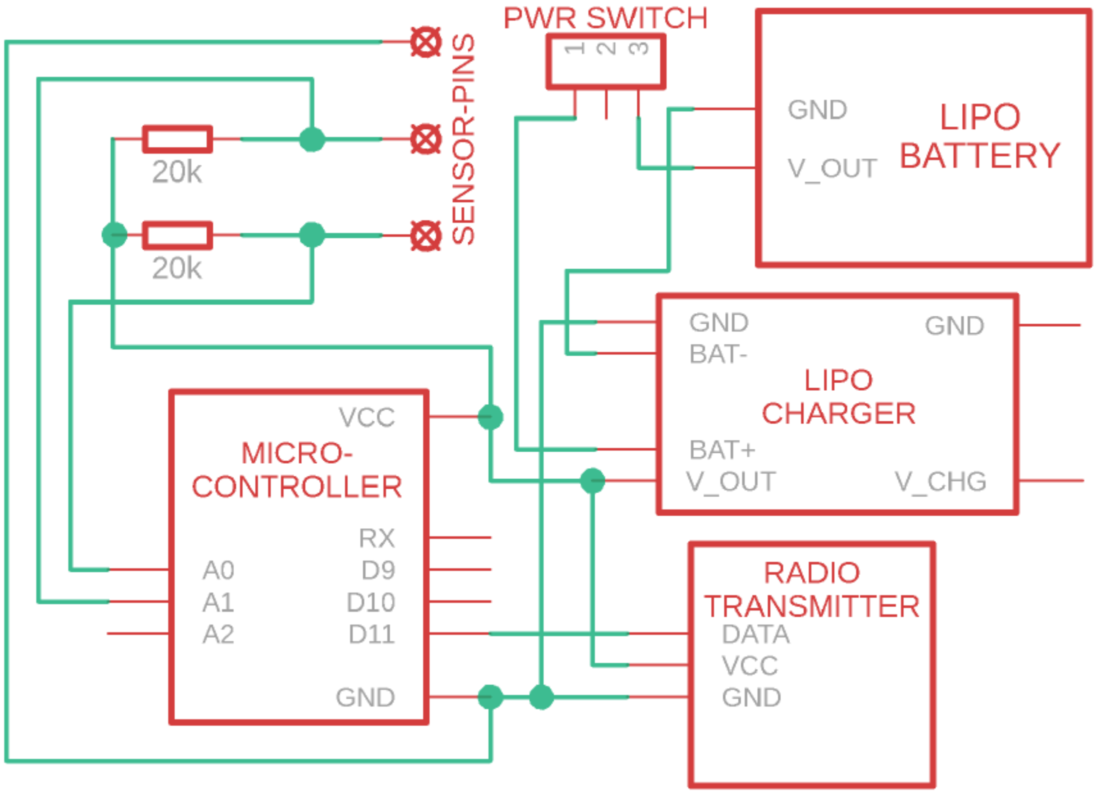


Figure 12.: Schematic of the glove circuit board created with Autodesk Eagle. Over a power (PWR) switch, the inbuilt LiPo battery is connected to a LiPo charger and powers the microcontroller. The microcontroller operates the radio transmitter and evaluates the flex sensors connected to the sensor-pins with two voltage divider circuits.

The LiPo charger powers the microcontroller, the radio transmitter as well as the voltage divider circuits through the supply voltage (VCC) and ground (GND) pins. The radio transmitter is controlled by the microcontroller over the digital D11 pin. The analog pins A0 and A1 are used to measure the output voltage of the two voltage divider circuits with 20 kΩ resistors. As in the initial tests, the microcontroller includes a 10-bit ADC for this purpose, maintaining the same resolution.
Note that the microcontroller has more pins than necessary for this circuit board. Some of its pins are also not shown in the schematic, since they are not needed in the whole project.
All the components used for the glove are listed with their exact name and price in Table B.1. Excluding the costs for manufacturing the circuit board as well as the glove itself, the components add up to a price of around 40 €.

4.4. Circuit Board

The Layout of the circuit board for the glove is shown in Figure 13. Because the space on the hand is limited, the main goal was to keep the board as small as possible while still providing all the functionality and including all the components described in the previous section. The final board now measures 49 by 54 mm which should fit on the back of the hand of most adults.
The blue lines in the figure are the conducting paths which are manufactured into the bottom side of the board by etching away the surrounding copper. The components are soldered on with pins which pass through holes drilled into the circuit board at the respective pin locations of the components. Only the two resistors are attached on the bottom side of the board since they don't have any pins.
When arranging the components on the board, the USB ports of the microcontroller as well as the LiPo charger need to point in order to remain accessible. The sensor pins are placed near the edge of the board to simplify the connection to the sensor cables.
Figure 14 presents a top view of the real board, annotated with labels for the components. This image has the same orientation as the circuit board rendering. The radio transmitter has been upgraded with a helical antenna that suits the 433 MHz frequency to improve the signal transmission.

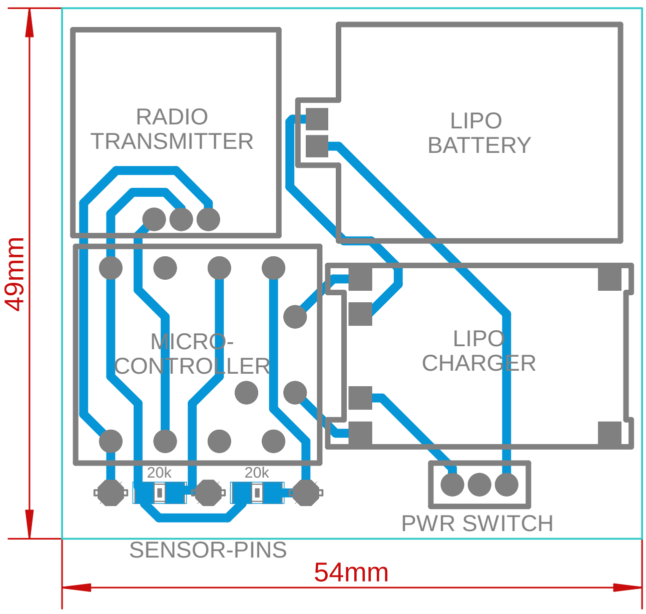


Figure 13.: Glove circuit board rendering created with Autodesk Eagle. The pins of the microcontroller, radio transmitter, LiPo battery, LiPo charger, power (PWR) switch, sensor pins and resistor are connected as shown in Schematic 12. The outlines of the components, as well as the solder pads, are shown in gray, the connections between them in blue. The outline of the board is light-blue and its dimensions are shown in red.

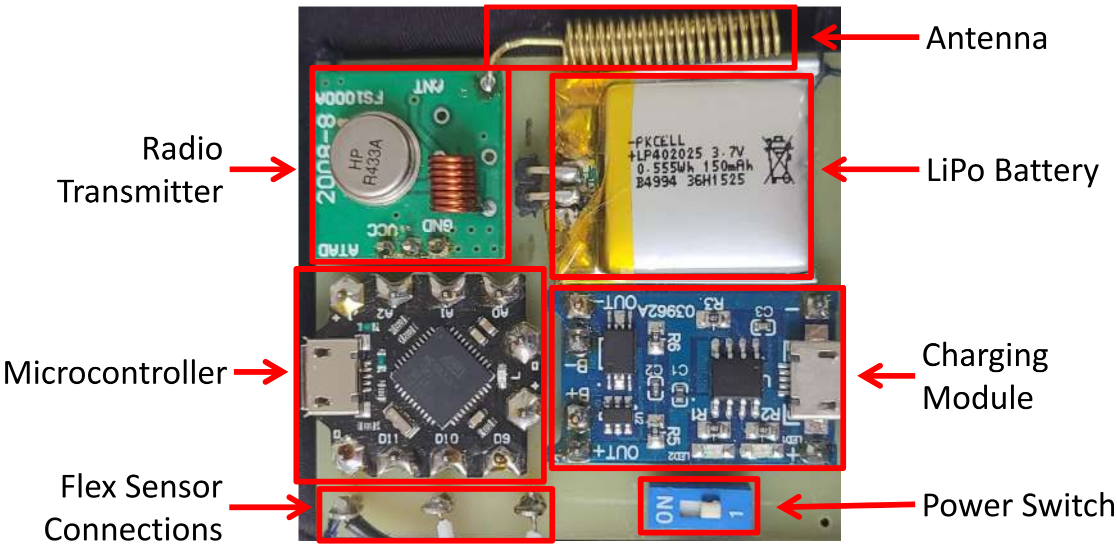


Figure 14.: The circuit board of the glove is made up of a Radio Transmitter with Antenna, a Microcontroller, Flex Sensor Connections, a Power Switch, a Charging Module and a LiPo Battery.

4.5. Algorithm and Calibration

The used microcontroller is based on the Arduino framework, so it is also programmed with the Arduino version of `C++`. The code is attached in the Appendix A.1.

For controlling the transmitter, the `RCSwitch` library [51] is needed. The setup defines which pins should measure the flex sensor values and which one controls the transmitter. Additionally, it activates the internal LED for use. At the beginning of each step of the loop, the sensor values are measured. In the following, the system goes through a calibration sequence. Once the calibration is finished, it is evaluated if a quick finger spread is detected. If that's the case, the release mechanism is triggered by sending the release signal via the transmitter. If not, the step finishes and starts anew. In between each step, a delay of 0.05 s is included to achieve a fixed sampling rate of 20 Hz. Furthermore, the previous sensor values are overwritten with the current ones.

Since the microcontroller has no internal storage for permanently storing variables when the controller is powered off, the system needs to be calibrated on every startup in order to be able to correctly detect a quick finger spread.

(a) (b) (c)

Figure 15.: The glove is shown in different positions. In the rest position (a), the flex sensors are bent more than in the spread position (b). In the fist position (c), the sensors have almost the same bend radius as in the rest position, but they are angled away from the glove.

Figure 15 shows the final sensor glove in the rest, spread and fist positions required for the calibration. The circuit board shown in the previous section has been fastened on the glove with thread. The flex sensors remained in the same position as in the initial tests and were soldered to the connection points of the circuit board.
The user needs to move the hand according to the protocol presented in Table 2. The time steps are indicated with the integrated LED of the microcontroller. During the clench fist time frame, the maximum measured values b_{fist} of both flex sensors are saved individually, corresponding to the position where the flex sensors are bent the most. Consequently, when the fingers are in the spread position, the minimum values b_{spread} are saved. This is the position where the flex sensors are bent the least.

Event	Time in s	LED status
Preparation	0 - 2	ON
Clench Fist/ Hold Pole	2 - 4	OFF
Pause, Hand in Rest Position	4 - 6	ON
Spread Fingers	6 - 8	OFF

Table 2.: Calibration protocol and LED status after startup of the system. The event column lists the required user hand movement.

To determine at which point the finger position is defined as spread, a threshold of

$$T_{\text{spread}} = b_{\text{spread}} + \frac{1}{3}(b_{\text{fist}} - b_{\text{spread}})$$

is calculated. The range between the maximum spread position and the fist position is divided into three equal sections. Sensor values within the section closest to the maximum spread are classified as spread fingers. Depending on the desired sensitivity of the system, this threshold can be varied to make it easier or more difficult to trigger the release. The user can also influence the sensitivity by spreading the fingers more or less during calibration.
An example of the calibration measurement is plotted in Figure 16. The sensor values are recorded to illustrate how the thresholds are determined. Between seconds two and four, the fingers are moved into a clenched fist state. In this interval, the sensors encounter the largest signal, we can estimate $b_{\text{fist}} \approx 700$ ADC-units for the right sensor, shown in blue. Between seconds six and eight, the fingers are spread and the sensor values are minimal, $b_{\text{spread}} \approx 550$ ADC-units for the left sensor. According to the formula above, T_{spread} is approximately 600 ADC-units, which

agrees with the value found by the system. This value is shown in the plot by the blue line beginning at second 8. The same calculation could be performed for the right sensor.
It is also visible in this plot that the sensor values in the rest position (before second two and between seconds four and six) are in between those of the fist and the spread positions. The sensors are bent less than in the fist position. This is the reason why a spread threshold closer to the spread than to the fist position should be selected. This strategy reduces false detection of other finger movements.
As already mentioned in Section 4.1, simply detecting if the fingers are *spread* is not sufficient. It needs to be determined if the spread occurred *quickly*. This requires an additional threshold, called Δ_{quick_change}. For a spread movement to be classified as quick, the sensor value needs to decrease by more than Δ_{quick_change} in one 0.05 s time step.

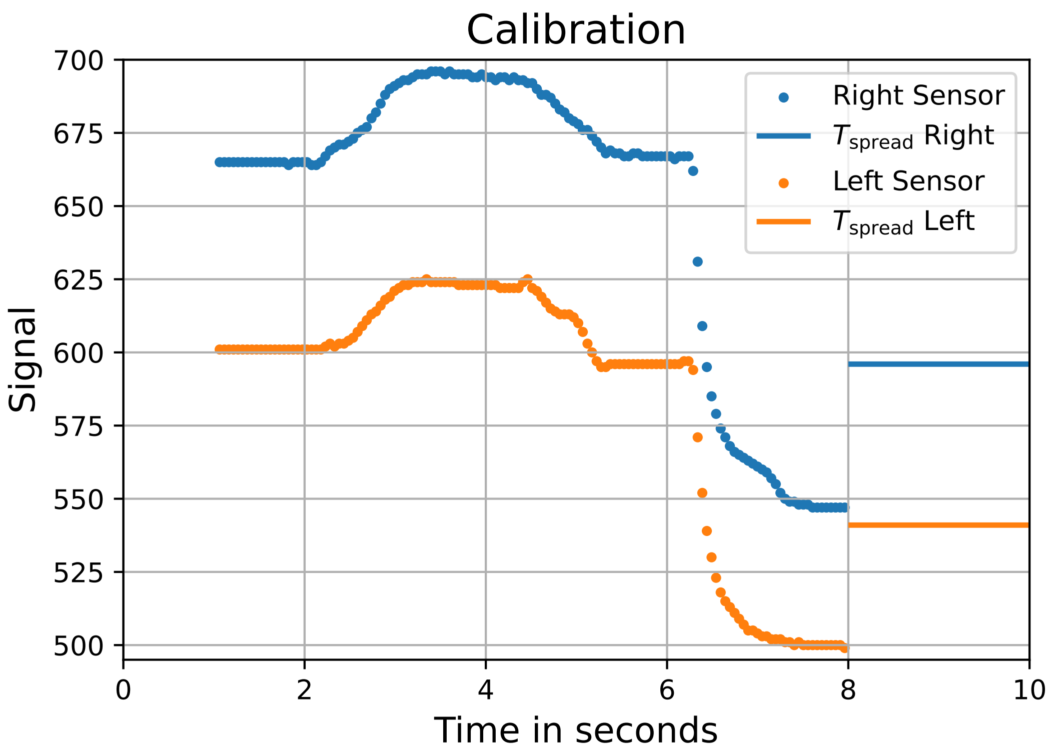


Figure 16.: Example of a calibration measurement of the sensor signals in ADC-units plotted against time. The fingers are moved according to the protocol in Table 2. After eight seconds, the calibration is finished and the thresholds for both sensors are determined. These are also shown in the plot as horizontal lines.

In contrast to the other thresholds, this one is always fixed to a value of $\Delta_{\text{quick\_change}} = -10$ for both sensors. This specific value was selected because it is large enough to prevent the triggering when the fingers are moved at a normal speed, for example when handling objects. If instead the fingers are spread quickly with intention or out of reflex, the sensor values change at a significantly larger rate, which can be seen in the bottom part of Figure 11. Therefore, the selected value does not prevent the system from being triggered when desired.
Once the calibration is finished, the system transitions to the active phase where it can send the release signal at any point. This part consists of an if-condition that checks if the *spread* and the *quick* conditions are satisfied for both sensors. If this is the case, the release signal is sent via the radio receiver and the LED blinks to indicate the detection of the signal. The radio signal can contain 16 bits of information, so for example a number ranging from $-2^{15} = -32768$ to $+2^{15} - 1 = +32767$. A specific number is selected to be transmitted, e.g. 42. The binding should only release when it detects this specific number and not any signal to protect the system from being triggered by other radio signals.

4.6. Power Consumption

To estimate the battery life of the board, the current needs to be measured. This is done with an Ampere meter that bypasses the power switch. When the fingers are spread, a current of $(21.1 \pm 0.5)\,\text{mA}$ is measured. In the clenched fist state, the current is $(20.8 \pm 0.5)\,\text{mA}$. Since the fingers are held at this state for most of the time while skiing, this value is used for estimating the power consumption. With a nominal battery voltage of $3.7\,\text{V}$, this corresponds to a power of

$$P = V \cdot I = 3.7\,\text{V} \cdot (20.8 \pm 0.5)\,\text{mA} = (77 \pm 2)\,\text{mW}\,.$$

Comparing this to the battery's capacity of $555\,\text{mWh}$ shows that it could power the system for a little over seven hours. This could be just enough for a typical skiing day, on which the ski lifts operate from 9:00 AM to 4:00 PM.
In a separate measurement of the radio transmitter, a current of $(0.40 \pm 0.02)\,\text{mA}$ was recorded when the transmitter idles and does not send a signal. This is less than 2% of the total current, and therefore a negligible contribution.
The power consumption of the voltage divider circuits can be estimated without a

measurement of the electric current because the resistance is known. It is assumed that the hands are in the fist state for most of the time, with an average flex sensor resistance close to the maximum resistance at $\overline{R_2} = 25\,\mathrm{k\Omega}$. Using Ohm's Law $V = R \cdot I$, the power is

$$P = V \cdot I = \frac{V^2}{R} = \frac{V^2}{R_1 + \overline{R_2}} = \frac{(3.7\,\mathrm{V})^2}{20\,\mathrm{k\Omega} + 25\,\mathrm{k\Omega}} \approx 0.3\,\mathrm{mW}\,.$$

Since two voltage divider circuits are used, this number needs to be multiplied by a factor of two for finding the combined power. The choice of a larger fixed resistor could reduce the power consumption of the voltage dividers. This comes at the cost of a reduced resolution of the sensor values since a larger resistor does not provide the biggest difference of the minimal and maximal voltages as shown in Section 2.6. These measurements and estimations show that the microcontroller itself consumes most of the power. Contributions from the radio transmitter and the voltage dividers are negligible. Most likely, the ADC consumes a large part of the power when converting the analog measurements of the voltage dividers into digital values.

5. Automatic Binding

This chapter describes the automatic binding release mechanism. Firstly, its working principles, as well as the required mechanical and electrical components are explained. Next, the schematic, as well as the circuit board, are presented to illustrate the interaction of the electrical components. Lastly, the system's power consumption is evaluated.
A video demonstrating a glove triggered release of the prototype binding is provided on the project's website [1].

5.1. Binding platform

It would exceed the scope of this thesis to develop a complete mechatronic ski binding from scratch. Instead, a conventional binding is modified in such a way that it can release automatically on an electronic signal but also still in the conventional mechanical way. Inspiration for this was drawn from the concepts presented in Section 3.1, but the developed mechanism differs notably from those solutions.
The specific type of binding used for this project, a *Head PR 11* from 2012, is a track mounted binding. It uses a so-called *Powerrail* as the track which is mounted on the ski and where the heel and toe parts of the binding can slide onto. Figure 17(a) shows only the track without the heel and toe pieces. Here, the eight screws that fix the track to the ski can best be seen. Additionally, the two arrays of teeth for the adjustment mechanisms are visible in this view.
Figure 17(b), (c) and (d) show the binding in different positions from the smallest boot setting of 257 mm over a medium setting of 314 mm and finally the setting for the largest possible boot soles of 380 mm length. The heel and toe piece can obtain 16 different states by interlocking with different teeth of the track. The scales on the track indicate the position that the pieces are currently adjusted to.

[1] `https://alexandria.physik3.uni-goettingen.de/triggerbind/`

The lever used to unlock the front binding is located on the plate where the boot stands while skiing, and is therefore inaccessible when the ski is used. For the rear part, the lever is positioned at the very back of the binding and is easy to reach, even when the boot is engaged with the binding. This is the reason why the heel piece will be modified for the release mechanism.

(a) (b) (c) (d)

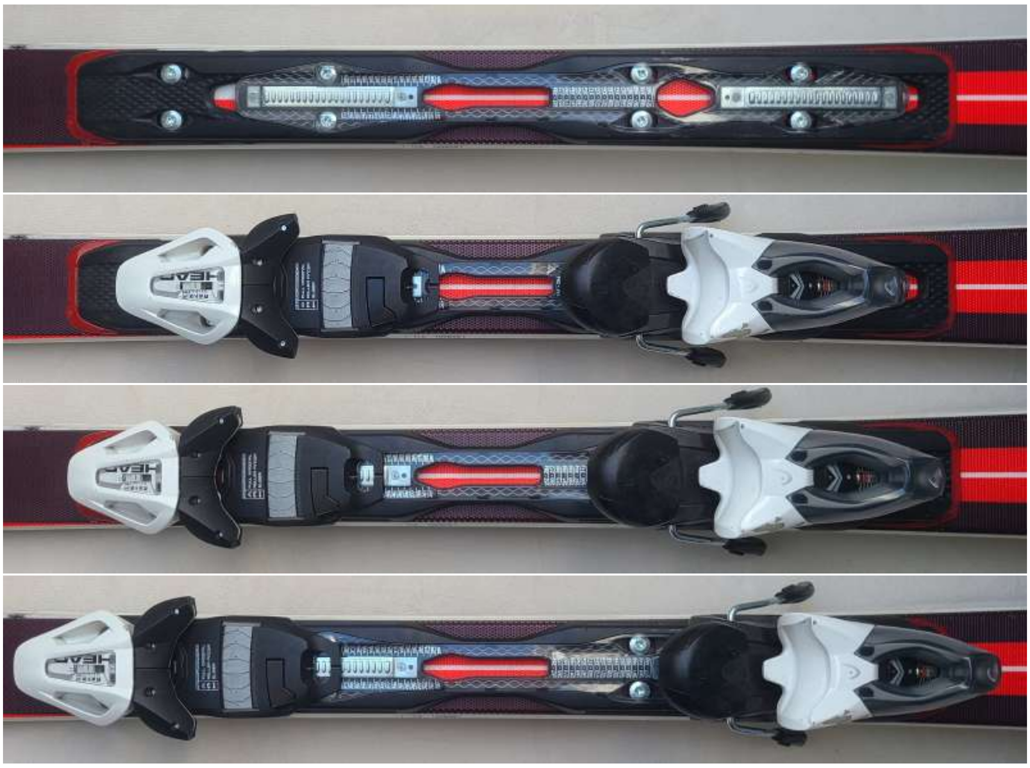
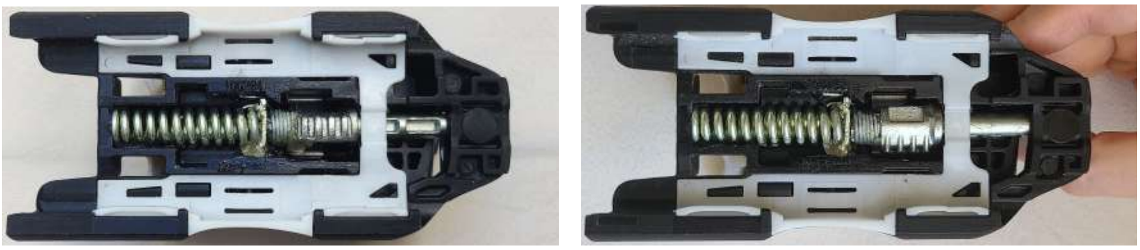


Figure 17.: Binding System in different settings: (a) disassembled, (b) shortest setting (257 mm), (c) example boot setting (314 mm), (d) longest setting (380 mm).

Figure 18 shows the heel piece from underneath where it interfaces with the rail in the closed and the open states. The sides of the heel piece hold on to the rail, which only allows forward and backward movement along the ski. The array of teeth seen in Figure 17(a) partially interlocks with the rotatable teeth of the binding piece and allows for securing the piece in different positions. The mechanism of the toe piece works similarly. Combined, this allows to adjust the binding to different shoe sizes while always keeping the center of the shoe in the same position.
The axis of the rotatable teeth and the lever is loaded by a torsional spring, which keeps the teeth in the locked position when no force is applied to the lever. This prevents the system from unlocking on its own.



(a) (b)

Figure 18.: Underside of the heel piece of the binding when detached from the track. The left image (a) shows the locked state. In (b) the lever is turned to open the interlocking teeth, so the heel piece can move back and forth along the rail.

The binding heel piece also features a compression spring. Once the boot engages with the binding, it pushes back on the heel piece, putting this large compression spring seen in Figure 18 under tension. This elasticity in the system also helps to keep the binding at the correct length when the ski flexes. Because the teeth of the adjustment lever are engaged with those on the track, the lever stays in place relative to the ski. When the heel piece is pushed back against the spring, the lever can partly disappear into a slit of the heel piece.

5.2. Mechanical Setup

When developing the mechanical setup of the automatic binding, various requirements of the system need to be addressed. Most importantly, the system should be able to reliably release the binding when desired and never release accidentally. It should be reusable, to enable the skier to continue after a release and even release multiple times a day if necessary. Since the system is based on an adjustable conventional ski binding, the mechanism should not restrict the adjustment capabilities and the conventional release modes of the binding need to remain unaffected. It should be able to operate in freezing and snowy conditions. Finally, the properties of the ski, its weight and its flexibility, should not be altered significantly.
As explained in Section 2.2, a conventional binding releases the boot by allowing parts of the binding pieces to rotate against the tension of loaded springs. In contrast, for the mechatronic binding implemented in this project, the entire rear piece of the binding is moved backwards. If this movement is far enough, the boot can no longer be held in place by the front part of the binding, and it is released from

the ski. This concept is presented in Figure 19 along with the developed release mechanism, which will now be explained in detail.

(a)
(b)

Figure 19.: The automatic binding release system together with the ski boot. In (a) the system is closed and the ski boot is attached. The system after release is shown in (b). The toe and heel piece are now too far apart to hold the boot in place.

The desired functionality can be achieved by automating the adjustment mechanism of the rear part of the binding. The release system needs to be able to operate the adjustment lever and also pull back on the rear piece with enough force to release the boot. A close-up view of a system integrating this concept is presented with labeled components in Figure 20. In the following, all of these components and their functions are explained in detail by proceeding from the left to the right in this figure.

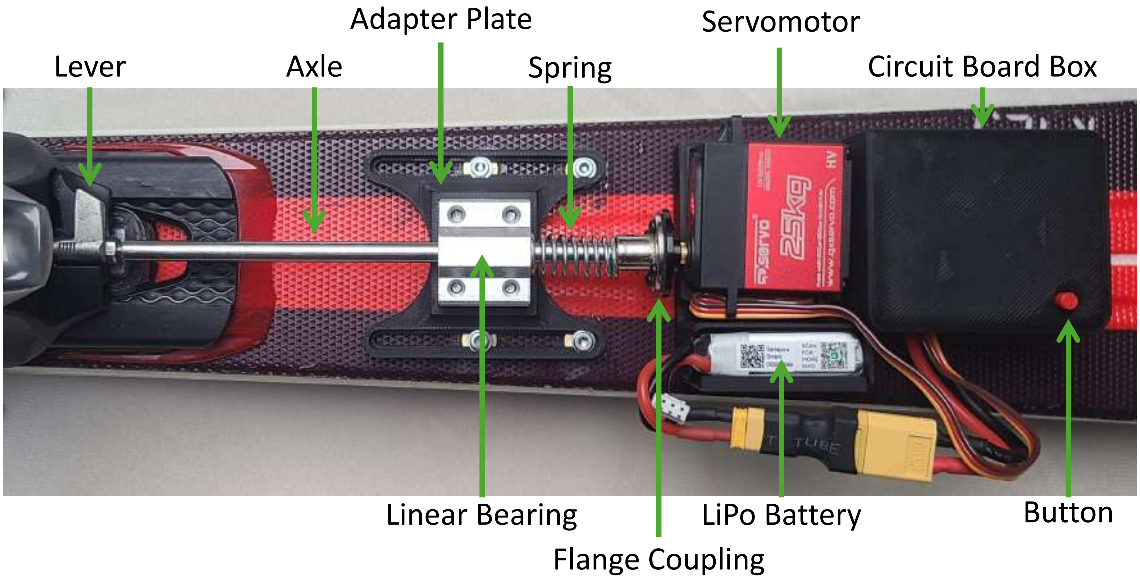


Figure 20.: The automatic release system consists of a Lever, an Axle, an Adapter Plate with Linear Bearing, a Spring, a Flange Coupling, a Servomotor, a LiPo Battery, and a Circuit Board Box with a Button.

For operating the adjustment lever, a servomotor is attached to an axle screwed into the original lever axle. A mechanism that simply pushes against the lever similar to a finger could open the mechanism as well. However, since it cannot pull the rear piece backwards, this would not be sufficient for releasing the binding. By using a screwing connection, it is possible to also pull on the axle and move the binding far enough backward.

Implementing this screwing connection turned out to be difficult for multiple reasons. The original lever is sloped on the back, prohibiting drilling a hole aligned with the axle. Therefore, it was necessary to create a flat surface perpendicular to the axle with a milling machine. Moreover, the axle is not solid but has multiple pockets near the lever, which can be seen in Figure 18(a). In these pockets, there is no material for the thread to be cut into. To solve this problem, a metal piece was glued into the pocket with two-component glue. The lever had to be removed from the binding to make the pocket accessible. Since the lever is held in place by a strong spring, a screw clamp is needed to disassemble the locking mechanism.

As the binding is pressed backwards when the boot is engaged and the ski flexes, a section of the lever usually slides into a slit in the binding and prevents it from rotating. While the lever was disassembled, material was also removed from this

section of the lever. This allows the lever to always be turned, which is necessary for a reliable release mechanism.
Once the additional axle is screwed into the threaded hole of the lever, it is held in place with an additional lock nut so it does not unscrew once the motor turns. Thread glue has also been used in order to further secure the connection.
A linear bearing guides the axle and allows it to turn as well as slide forwards and backwards freely. It needs to be in alignment with the original adjustment axle. To reach the correct height, a 3D-printed adapter plate secures the linear bearing to the ski. The adapter plate is attached to the ski with four screws that interface with custom-made threaded bushings in the ski. These bushings were glued into four precisely drilled holes, which can be seen in Figure 21. The adapter plate features slotted holes which allow for the position of the linear bearing to be adjusted.

Figure 21.: Threaded bushings are glued into the ski for mounting the automatic release system.

Continuing further to the right in Figure 20, two flange couplings connect the axle to the servomotor. The one facing the axle is clamped down with two grub screws. The end of the axle near the motor is flattened on two opposite sides for screwing the axle into the lever and to ensure that the grub screws can transmit the rotational motion without slipping. The flanges are connected with four screws passing through aligned holes. The coupling on the motor interlocks with teeth on the motor's shaft and is secured in place by a screw going into the shaft.
The servomotor rests on a spacer plate, but neither of these parts are directly attached to the ski. Instead, the carefully chosen height of the spacer plate allows the axle to press the motor and the plate down on the ski. This prevents the motor housing from rotating when it opens the lever. Additionally, this setup allows the motor to move back and forth together with the axle and the binding heel piece.

Between the linear bearing and the flange couplings, a spring is placed. The adjustment mechanism of the linear bearing allows setting the correct spring tension for different positions of the rear binding piece. While the current adapter plate cannot be moved far enough to support all possible settings of the heel piece, it could easily be replaced to fit the desired range. Once the locking mechanism is opened by the motor, this spring pulls the rear binding backwards, releasing the boot from the binding.

A box housing the circuit board and another one housing the battery are joint with the spacer plate of the motor. The whole assembly is 3D printed as a single part. The battery box is open at the top and one of the four sides is detached from the others, allowing it to bend slightly for inserting the battery. Once the battery is inside, the bendable side returns to its original state, making the opening too small for the battery to fit through, so it stays inside the box. The circuit board and its enclosure will be explained in more detail in Section 5.5.

The mechanical components used for modifying the binding are listed with their exact name and price in Table B.1. This table does not state the costs for manufacturing the thread in the lever and the one on the axle, as well the bushings that were glued into the ski. The 3D-printed parts are also not mentioned there, but their costs are negligibly small.

5.3. Electrical Components

The circuit board of the binding needs to activate the release mechanism with the servomotor once the correct radio signal is received. Operating a radio receiver and a servomotor requires a microcontroller, for which the same "DFRBOTO Beetle" as for the glove is used.

To ensure that the torque of the torsional closing spring as well as any ice buildup that might jam the system can always be overcome, a servomotor with a torque of $25\,\mathrm{kg\,cm} \approx 2.5\,\mathrm{N\,m}$ is used. The original adjustment lever of the binding is approximately $1\,\mathrm{cm}$ long and is operated with one finger. If one were to exert the same torque as this servomotor is able to, it would be like lifting a weight of $25\,\mathrm{kg}$ with a single finger.

Because this motor reaches its peak torque at a voltage of $7.4\,\mathrm{V}$, a two cell LiPo battery with this voltage is used as the power supply. The microcontroller is limited to an input voltage of $5\,\mathrm{V}$, any higher voltage could damage it. Therefore, a voltage

regulator must be included which reduces the battery voltage to 5 V for powering the microcontroller. In contrast to the glove board power supply, this battery needs to be charged externally with a LiPo balance charger, which ensures that the voltages of the individual cells stay in balance.
A push button is included for operating the release mechanism independently of the glove. This is necessary for three main reasons. Firstly, since the servomotor is directly connected to the adjustment mechanism, manual adjustment of the binding is no longer possible. Because of the high gear ratio used in the servomotor, turning it by hand requires a high torque and could even destroy the gears within the motor. The button is used to open and close the mechanism for adjusting the binding position, making a manual operation of the lever obsolete.
Secondly, in the case of an accident where the release mechanism is triggered successfully, and the skier is unharmed, the skier will likely want to continue skiing, at least to the bottom of the slope. Because the heel piece has been moved backwards for the release, the binding will not be set to the correct boot size anymore. The skier then needs to move the heel piece to the correct position and close the system by pushing the button. Afterward, the skiing can continue as usual.
Lastly, it can sometimes be difficult to open a binding in the conventional way by pressing the back of the binding with a ski pole or other means. Instead, the skier can simply press the button to open the binding. This requires the ski to be lifted up because the weight of the skier pressing down on the binding could hinder the system from opening. This scenario could also be controlled with the glove instead of the button. However, if the glove is deactivated, opening the binding with the button can still be useful.
The electrical components used for the binding with their exact name and price are also listed in Table B.1. In total, the costs of this mechatronic binding system add up to about 60 €.

5.4. Schematic

The schematic for the binding circuit board is shown in Figure 22 and illustrates how the different components mentioned in the previous section need to be connected.
The battery (not shown in the schematic) is attached to a screw terminal, and the positive pin is protected by a fuse. From there it powers the motor as well as the voltage regulator. The signal (DATA) pin of the motor is connected to the digital pin

D10 of the microcontroller for controlling the motor position. The voltage regulator connects to the VCC and GND pins of the microcontroller, supplying it with 5 V. The radio receiver also needs a 5 V input, which is provided by the microcontroller. One of the DATA pins is connected to the receive (RX) pin of the microcontroller. This pin offers interrupt functionality, explained in Section 2.7, which is necessary for operating the radio receiver.
The button is attached to the VCC pin and the digital D9 pin of the microcontroller. Over a 10 kΩ pull-down resistor, the digital pin is additionally connected to GND which sets the pin to its `LOW` state when the button is not pressed. Once the button is pressed, the pin gets connected to VCC and thus obtains the `HIGH` state. In this case, the pull-down resistor also prevents a direct connection between GND and VCC.
Again, not all pins of the microcontroller are occupied. The analog pins are not needed for this board at all.

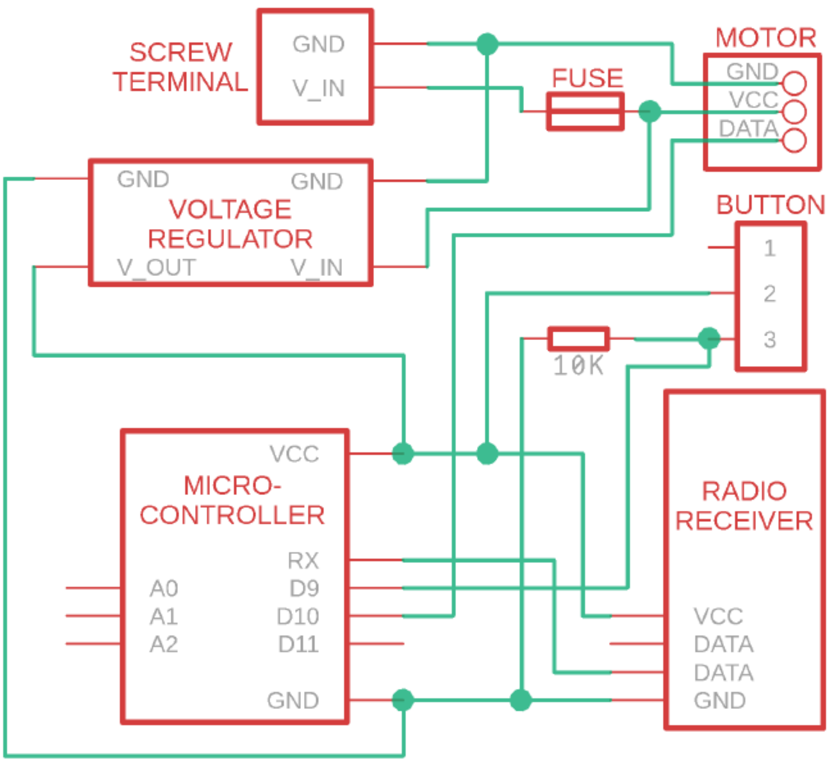


Figure 22.: Schematic of the binding circuit board created with Autodesk Eagle. A battery (not shown) can be connected to the screw terminal and powers the motor as well as the voltage regulator while being protected by a fuse. The voltage regulator supplies the microcontroller which operates the radio receiver, reads the button state and controls the motor.

5.5. Circuit Board and Enclosure

The circuit board rendering for the binding can be found in Figure 23. The board measures 45 by 55 mm. For comparison, the ski widens behind the binding towards the rear tip from about 75 to 110 mm, so this board easily fits on the ski. Because the fuse has only been added later, it extends past the board by a few millimeters.

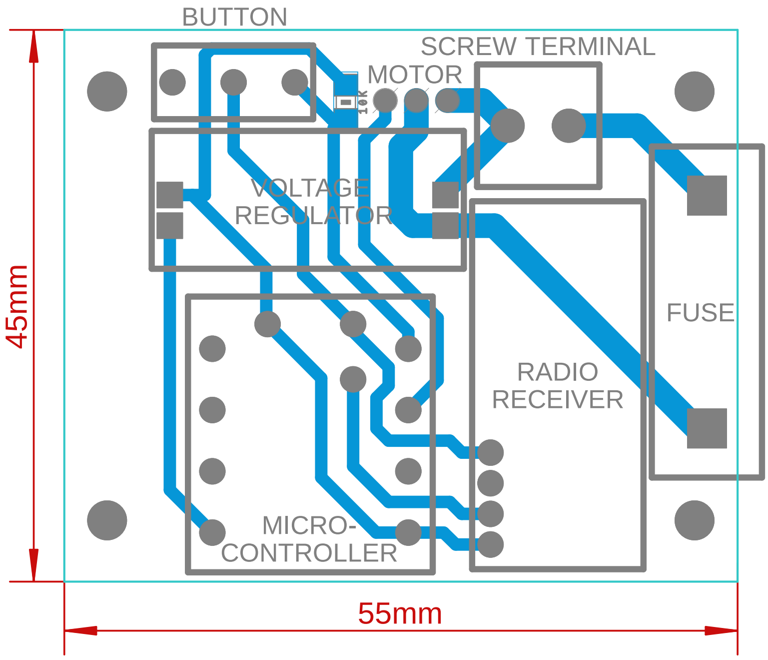


Figure 23.: Binding circuit board rendering created with Autodesk Eagle. The pins of the microcontroller, voltage regulator, radio receiver, fuse, button, motor, screw terminal and resistors are connected as shown in Schematic 22. The edges of the components, as well as the solder pads, are shown in gray, the connections between them in blue. The outline of the board is light-blue, and its dimensions are shown in red.

The LiPo battery is connected to the screw terminal. The conductive paths to the motor and the voltage regulator are wider than the others to ensure sufficient current flow. Again, the components are arranged in such a way that the USB as well as motor and battery connectors are pointed outwards for easy accessibility. The four points in the corners of the board are not solder pads, but holes which allow the board to be held in place with screws. These screws can be seen in Figure 24 which shows the real board with annotated components. Note that in this picture, the board is rotated 90° counterclockwise compared to the board rendering.

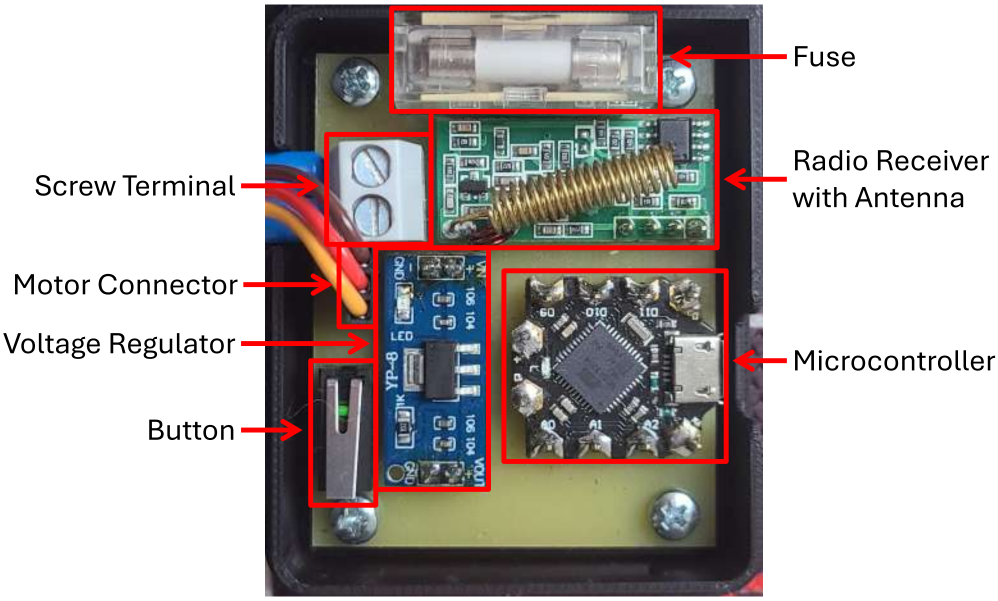


Figure 24.: The circuit board of the Binding is made up of a Screw Terminal, a Motor Connector, a Voltage Regulator, a Button, a Microcontroller, a Radio Receiver with Antenna and a Fuse.

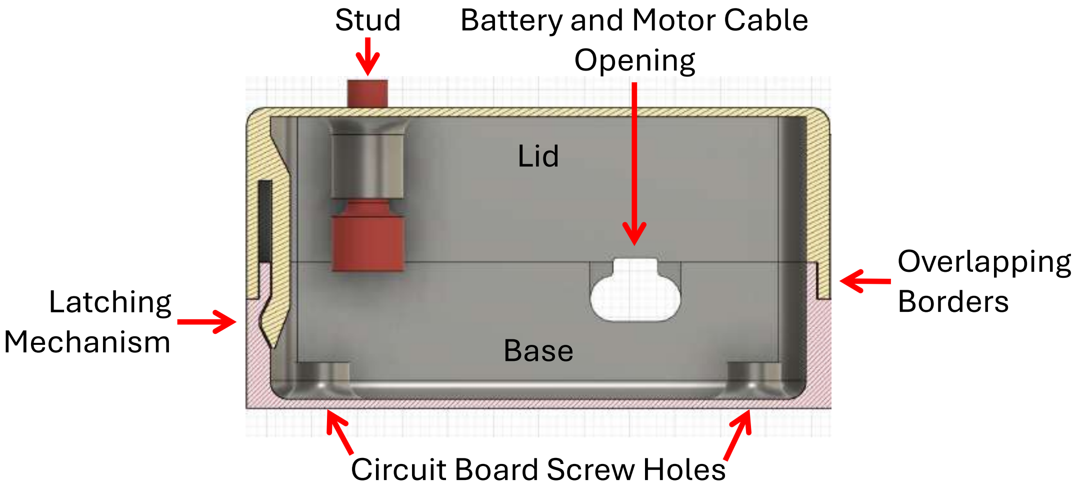


Figure 25.: Cross-section of the box housing the binding circuit board created with Autodesk Fusion 360. The box consists of a base and a removable lid. The stud, battery and motor cable opening, overlapping borders, circuit board screw holes and latching mechanism are highlighted.

The board is screwed into a closable box for protecting the electronics from the elements. When opened, the microcontroller can be connected to a computer for programming. A cross-section of this box is shown in Figure 25. On one side of the box, the lid features a latch that snaps into a notch of the base when the box is closed, keeping the lid in place. The lid also has a hole above the push button in which a red stud is inserted, allowing the button to be activated from the outside. The border of the box is split into overlapping sections at the interface of the bottom piece and the lid to further secure the connection. While the design is not fully waterproof, this could be achieved with little effort by adding a seal around the outgoing cables and some rubber along the top and bottom interface.

5.6. Algorithm

The algorithm of the mechatronic binding should ensure that the binding always opens when the transmitter receives the correct signal. It also needs to react to a push of the button. The code of the `C++` algorithm implementing this functionality is attached in the Appendix A.2.

Like for the glove, the `RCSwitch` library [51] is required to operate the radio receiver. This library uses functions that interrupt all other processes to focus on receiving a signal. Additionally, the `Servo` library [52] provides functions to control the servomotor. In the setup, the pins for the transmitter, the servomotor and the push button are assigned.

The position of the servomotor can't be measured with the microcontroller, but it is necessary to know the current state of the system to determine how the servomotor needs to turn. A workaround for this problem is setting the servomotor to the closed position when the program is started and keeping track of all state changes performed during runtime.

The loop of the program continuously checks if either the receiver detects a signal or if the button is pressed. If a signal is detected, it is first confirmed whether the signal contains the correct number transmitted by the glove. If this is the case, the servomotor will open the mechanism and release the binding immediately. If the signal is detected while the system is in the open state, nothing happens. The glove is only used for opening the binding, not for closing or adjusting it.

Depending on the state of the system, the button can either open or close the binding. In both cases, a pause is included before the movement. If the system is to be opened, the delay is one second long, enough time to remove the hand and avoid that the rapidly opening parts of the mechanism harm the user. A longer pause of three seconds is provided for pushing the binding against the spring into the desired position before the system is closed.

5.7. Power Consumption

The binding features a 450 mAh, 7.4 V LiPo battery. It was measured that the system draws a current of (48 ± 1) mA from the battery when it is trying to receive signals and the motor is not turning. With this discharge rate, the system can be powered for roughly nine hours, a little more than one typical skiing day. Since both the battery capacity and the measured current are based on the same voltage, the additional step of calculating the power consumption in watts is not necessary to calculate the battery life.
The servomotor generates a holding torque to maintain the desired position when an external torque is applied to the shaft. Increasing this external torque also increases the holding current of the motor up to a few hundred mA. If the motor angle and the lever position are not perfectly aligned, this can lead to an unnecessary high power consumption in the closed state of the binding. In the open state, the motor balances the torque from the torsional spring, which normally closes the lever. This requires a large holding torque, so the current increases to at least (0.26 ± 0.3) A, draining the battery in less than hours. Interestingly, the system remains in the open state even when the battery is disconnected. The torsional spring does not have enough torque to turn the gears of the servomotor by itself.
Measurements of the motor current indicate that the motor requires (7.3 ± 0.3) mA when no external torque is applied. The remaining current of (40.7 ± 1.3) mA passes through the voltage regulator. The voltage regulator lowers the voltage by simply converting the excess energy into heat. This heat loss can be calculated with

$$P_{\text{heat}} = (V_{\text{in}} - V_{\text{out}}) \cdot I = (7.4\,\text{V} - 5\,\text{V}) \cdot (40.7 \pm 1.3)\,\text{mA} \approx (97.7 \pm 3.1)\,\text{mW}\,.$$

More than a quarter of the total $P = 7.4\,\text{V} \cdot (48 \pm 1)\,\text{mA} \approx (355 \pm 8)\,\text{mW}$ consumption is turned into heat.

6. Discussion

This chapter provides an in-depth analysis of the developed prototype. It begins by outlining the general limitations for understanding the system's constraints. Specific implementation problems of both the sensor glove and the automatic binding are then examined in detail. The security of the system is evaluated and considerations about its battery are presented. Special attention is given to assessing the effectiveness in injury prevention, the system's main goal. Finally, the prototype's costs are reviewed, along with an investigation into the market feasibility of this system and alternative solutions.

6.1. Limitations of the Prototype

The main aim of this Thesis was to develop a *proof-of-concept* skier-triggered automatic binding release mechanism. A *proof-of-concept* aims to demonstrate that the concept is generally possible, but does not aspire to be a fully market-ready product. Therefore, it has limitations, which are listed here. If this concept will be brought to the market, this can act as a guideline showing which additional steps are necessary.

The most obvious problem with the sensor glove is that the flex sensors as well as the circuit board have not been integrated into the glove but are exposed to the elements. The sensors, as well as the circuit board, need to be sewn into the glove or wrapped in fabric and fixed to the glove. The electrical components also need to be waterproofed to avoid malfunction in snowy or wet conditions.

For the mechatronic binding, the main disadvantage is similar. The mechanism is not integrated into the binding, but is an external add-on to the system. This is not optimal since the long axle paired with the linear bearing restrict the natural flexibility of the ski, negatively influencing its skiing behavior. Although the circuit board of the binding is enclosed in a box, it is also not fully waterproof.

Developing and testing of the system was only performed indoors. It remains unclear how effectively the system can prevent injuries, since gathering injury data would require a fully working system to be tested by many skiers. Even though knee injuries are the most common injuries among skiers, injuries in general are rare with 3.49 per 1000 skier days as seen in the Introduction 1. Raising meaningful statistics on injury prevention would thus require at least hundreds, or better thousands of participants who are all equipped with the novel binding system. A theoretical discussion about injury prevention with the developed system will follow in Section 6.5.

Perhaps the number of participants required is also why no peer-reviewed studies for the available *lateral heel release* bindings exist yet. On their website, the *KneeBinding* company provides statistics indicating a significant reduction in knee injuries when using their bindings [35]. While these are claimed to be “independent”, they were published by the company itself rather than in a peer-reviewed journal and should therefore be viewed with caution.

The lack of tests of the developed system in real skiing conditions also means it is unclear if all components can withstand freezing temperatures. However, the flex sensors which are the central components of the system are rated for temperatures as low as -35 °C, according to their datasheet [31]. Apart from the batteries, most other components should not be sensitive to cold temperatures.

Additionally, ice buildup could clog the binding from opening. Unlocking the system should not be a problem since the locking mechanism itself is placed between the track and the heel piece and is therefore not directly exposed to the elements. Moreover, the servomotor has plenty of torque, which ensures reliable opening at all times. In the case that the spring is not strong enough to move the heel piece of binding because it is frozen stuck, it can easily be replaced by a stronger one.

The boards were manufactured in a prototype manner with components that are simple to solder manually because they are included on circuit boards with standard connection pins. This is great for prototyping, but for a product, one would instead only use the main component included on these circuit boards. In this way, the size of the final circuit board can be reduced significantly, but more advanced manufacturing techniques are required.

One example of this is the microcontroller. Instead of the whole board, only the main processing unit of the microcontroller should be used. In the picture of the glove circuit board in Figure 14, this is the black square placed in the middle of the microcontroller board and oriented at 45°.

6.2. Implementation Problems of the Prototype

In addition to these general limitations, there are some minor problems with the prototype. These are specific to this implementation and were only noticed during testing after the prototype was completed. These problems and suggested improvements are discussed in this section, split into aspects of the sensor glove and the automatic binding.

6.2.1. Sensor Glove

As mentioned in Section 4.3, the power switch of the sensor glove is wired between the positive lead of the battery and the battery charger. This ensures that the battery cannot be discharged when the power is switched off. However, when no load is connected, the charger does not consume any power. The charging module even has an over-discharge protection which automatically interrupts the output once the battery voltage drops below 2.5 V . It would be better to place the switch between the charger's output lead and the microcontroller. This would allow for charging the battery without the rest of the system being powered.
Another problem is that the flex sensor resistances used for selecting the fixed resistor of the voltage divider were measured before the sensors were attached to the gloves. Hence, the fixed resistance is not optimal for the actual range of resistance values that can be obtained with the possible finger movements. In the calibration plot shown in Figure 16, both sensor signals are always larger than 500 ADC-units. This indicates that the resistances of the sensors are always larger than the ones of the fixed resistors[1]. A higher value of the fixed resistor could increase the range of sensor values, thereby improving the measurement resolution.
The two sensors have different resistance ranges, as already noticed in Section 4.2. Therefore, the best resolution can only be achieved by using two different fixed resistors, specifically selected for each sensor individually. However, since the non-optimal resistances used for this prototype were sufficient for detecting the finger spread, it should first be determined which resolution is required and if a perfect optimization is absolutely necessary. As long as the fixed resistance is in the same order of magnitude as the variable resistance, finding exactly the optimal value does not appear to be critical.

[1] For $R_2 = R_1$, the equations presented in Section 2.6 yield an output voltage of half the input voltage, which corresponds to a sensor value of about 500 ADC-units.

Another important factor influencing the measurement accuracy is the number of bits that the ADC provides when converting the voltage to a digital number. One additional bit already increases the resolution by a factor of two. However, a more accurate ADC is only beneficial if the noise can be reduced as well. For this prototype, a 10-bit ADC was suitable, since the noise only spanned two to three ADC-units. With an 8-bit ADC, the noise would have been less than 1 unit, wasting potential for a more accurate measurement.
While testing the glove, the cables of the sensor broke off and had to be soldered back on multiple times. This points to the fact that the current fixation of the cables, as can be seen in Figures 14 and 15, is not ideal and needs to be improved. The solder hardens the ends of the cables which are attached to the connections. In the locations where solder ends, the copper wires are less stiff and not insulated, so the cables are most likely to bend in these places. When this happens repeatedly, the thin cables can easily tear.
A better solution would be to reinforce the connection with heat shrink tubing to protect the cables and prevent sharp bending. Instead of pointing outward, the cables can also be soldered on to stick upwards, parallel to the flex sensor connectors. This allows the heat shrink tubing to reinforce the interface between the connectors and the cables by surrounding both components at once. The downside is that the cables would extend further upwards. To address this, connectors angled at 90° could be used instead.
The calibration procedure is not very intuitive. It requires the user to memorize the correct sequence and quickly react to the LED state with the correct finger movements. Alternatively, it should also be possible to determine the necessary spread thresholds when the user simply performs one quick finger spread without any interruption. As could be seen in Figure 16, the fist state is the position with the smallest possible bend radius and the spread state is the one with the largest. Therefore, it should be possible to design an algorithm that determines adequate thresholds from the two minimal and maximal values.
Avoiding the pause in the calibration and going directly from a clenched fist to spread fingers also allows measuring the change in the sensor values at any given time step during this movement. This would also facilitate an adaptive $\Delta_{\text{quick\_change}}$ threshold. So far, this threshold was only set to a fixed value. Since the speed at which different people can spread their fingers is variable, this could prevent the system from triggering reliably.

In Section 4.6, it was estimated that the system consumes so much power that it would only last for one day of skiing. Since having to charge the battery every day is not convenient, measures for reducing the power consumption have to be implemented. The voltage divider circuits do not require a lot of power for themselves, but the microcontroller draws lots of power for converting the signals to digital values with the ADC and for running the code. Switching to a different microcontroller that requires less power and optimizing the code are possible steps to increase the battery life.

6.2.2. Automatic Binding

A pull-down resistor is included in the circuit board of the binding for reading the state of the switch as explained in Section 5.3. This resistor is redundant, since the microcontroller has built in pull-up resistors. These work similarly to the pull-down resistors, only that the digital pin is connected to VCC instead of GND. Consequently, the other end of the switch needs to be connected to GND instead of VCC.

As measured in Section 5.7, the servomotor constantly draws power from the battery, even during standstill. To save power and extend the battery life, the motor should be supplied over a relay or a transistor to guarantee that it is only powered on the rare occasions when it needs to rotate. The motor is not required to provide any holding torque because the torsional spring of the adjustment mechanism keeps the mechanism closed. In the open state, the gears of the servomotor have enough friction to stop the system from closing on its own without the motor being powered. The voltage divider converts a quarter of the total energy the system requires into heat. This is not ideal for the power consumption either. Selecting components that can handle the higher voltage would be an option to avoid this. Alternatively, it could be tested if the servomotor provides enough torque if it is running on 5 V as well. If that is the case, a 5 V battery could be used and the voltage regulator would be obsolete.

In Section 5.5, the circuit board box was shown. It features a latch that keeps the lid closed. With this design, the lid can still twist open. To prevent this, the lid should be equipped with a second latch on the other side. Since the circuit board is close to the edge of the box, the box needs to be slightly enlarged to provide space for the latch protruding into it. When redesigning this box, it could also be waterproofed at the same time.

6.3. Security

As mentioned before, the glove circuit board includes a radio transmitter and the binding board houses a radio receiver. These components can communicate on a frequency of 433 MHz.
The communication between the transmitter and the receiver as explained in Section 5.6 is very simple, which could make the system vulnerable to attacks. Releasing the binding at an unexpected moment during skiing could harm the skier severely. For this reason, the system needs to be secured against any unwanted triggering from the outside.
Only a limited range of numbers can be transmitted at once. At the end of Section 4.5, it was highlighted that the transmitter can send about 60,000 unique numbers. It is imaginable that an attacker uses a powerful transmitter to send out all possible numbers shortly after one another. Since the correct number is among them, the binding will open.
To prevent one of these attacks, a simple strategy would be to always transmit multiple numbers shortly after one another and only release if the correct combination of consecutive numbers is detected. Even with only two consecutive numbers, this would increase the number of possible combinations to $(2^{16})^2 = 4.3 \cdot 10^9$. An attacker might attempt to record and replicate the release signal. To prevent this, the signal needs to be encrypted.
Transmitting two consecutive numbers would also avoid the release being triggered by another skier who uses a glove triggered ski binding release system. In the biggest ski resorts, there can be over 20,000 skiers per day [2]. This number of skiers is still five orders of magnitude smaller than the number of possible combinations of two consecutive numbers. A false trigger is therefore very unlikely to occur.
Another challenge could be that the 433 MHz frequency is busy with other signals, which could block the receiver from detecting the release signal from the transmitter. Many devices like car keys or other remote controls are using this frequency. Switching to some other less commonly used frequency could solve this problem. Alternatively, the communication system can also be realized with a Bluetooth or Wi-Fi connection.

[2] The second most visited ski resort in the world, Ski Arlberg, has $\approx$ 2.4 million skier days per season [1, p. 16]. Assuming that it is open for 140 days from December to mid-April, this gives an average of 18,000 skiers per day. Considering that there are less and more busy days, this number can easily exceed 20,000.

6.4. Battery Considerations

The sensor glove as well as the automatic binding only work when the batteries are charged. For a system with two gloves and two bindings, four batteries would need to be monitored and always ensured to be fully charged before skiing. With the power consumption that is estimated in Sections 4.6 and 5.7, both systems would need to be charged every day.

For the real product, measures to save battery consumption need to be implemented. It would be ideal if the system could last for a week or maybe even the whole skiing season without requiring a recharge in between. Some ideas for improving the battery life were mentioned in Section 6.2.

Furthermore, the charging process of the batteries needs to be simplified. The glove battery can be charged with a micro USB cable from a laptop or a USB plug. However, the battery used in the binding requires a special LiPo charger with balance charge capabilities because it has two cells. Since this is not something everyone has at home, the system needs to include a charging device. Ideally, it should be capable of charging all four batteries simultaneously.

Even with a simpler charging system, charging these batteries remains an inconvenience that users must accept. However, evidence from other sports indicates that athletes are willing to tolerate this for enhanced functionality of their equipment.

Some modern bicycles use an electronic shifter that transmits the shifting signal from the handlebar to the derailleur via a cable or even wireless. The derailleur is operated by a motor instead of a bowden cable and requires a battery. The battery life depends on the shifting behavior, but it is sufficient for cycling a few hundred to sometimes over a thousand kilometers before it needs to be charged [53]. Customers are not opposed to charging the batteries every once in a while for having an improved shifting performance. While skiing is a different sport than cycling, this fact may still be transferable to skiing: Skiers might not be opposed to charging some batteries occasionally if they get more safety in return.

In fact, there are electronic devices that are widely used in skiing already. So-called avalanche rescue beacons or avalanche transceivers are used for finding a skier caught in an avalanche and buried under the snow. These devices are capable of transmitting signals that penetrate snow, and they can also receive signals sent by a second device. If both the buried skier and the search crew have one of these devices, it points in the direction of the buried skier and helps to locate and rescue

him. These devices are widely used by off-piste and touring skiers skiing in possible avalanche terrain. Most of them use disposable AAA batteries, which avoids the charging problem. As required by the European Telecommunication Standard 300 718 norm, they need to be able to send signals for at least 200 hours when equipped with new batteries.
The sensor glove is not much different from these devices. It also sends out radio signals, only much less frequently, but continuously monitors the sensor state. Since the voltage divider circuits themselves do not require a lot of power, as was seen in Section 4.6, it should also be possible to achieve a similar battery life like these devices. Possibly, this would require switching to single-use batteries, eliminating the need for a charger.

6.5. Effectiveness in Injury Prevention

There is evidence indicating that skiers don't recognize when they are in a dangerous situation right before an injury occurs. The ACL injury study by Ettlinger et al. finds [17]: "In our study, many skiers who sustain this injury believe right up to the moment of the injury that they are only temporarily off balance and fully capable of regaining control. If a release were to occur in these circumstances which prevented injury, the skier may interpret it to be unnecessary"
A skier-triggered release of the binding could fail if the skier is not aware of a potentially dangerous situation and does not trigger the release of the binding. Therefore, this system would need to be accompanied by a training program that teaches the skier how to recognize dangerous situations and in which cases to trigger the release.
In this sense, the mechanical *lateral heel release* solution or the *fully automatic* binding that were both mentioned in Section 3.1 are simpler to use. The skier does not need to be trained, and the systems decide autonomously whether a release is necessary or not. Still, a possible release of the binding might cause confusion if the skier does not understand the harm that could have been caused if no release had occurred. Thus, training and informing the skier about injury mechanisms is also worthwhile for these systems.
Since no test on the ski slope could be performed with the prototype, it is not clear at this point what percentage of injuries this system would be able to prevent. In general, it should be possible to avoid any injuries from accidents where the skier

falls slowly and has enough time to actively let go of the ski poles and spread the fingers. When looking at the injury mechanisms mentioned in Section 2.4, one notices that the majority of them happen rapidly. It is questionable if the skier has enough time to identify the danger of these situations and spread the fingers before the knee reaches critical strain.
The valgus-external rotation and the hyperextension mechanism are both rapid forward falls. Intuitively, the skier might move the hands in front of the body and spread the fingers to stop the fall. If this is the case, the binding could open quickly enough to avoid a severe knee injury.
The phantom foot mechanism is also avoidable with a triggered release, since it happens slower than the other mechanisms and can easily be recognized. As soon as the skier notices a backwards fall, the release could be triggered. The knee would not even get into the vulnerable sharp bend position, and the tail of the downhill ski would not have a chance to dig into the snow.
As presented in Section 2.4, these three mechanisms account for about three quarters of all knee injuries. Even if the skier fails to trigger the release quick enough in some of these cases, it is imaginable that around half of the knee injuries could be prevented. This can be achieved when the system works reliably and when the skier is trained to use it.
By counting the frames in the video provided on the project's website[3], it was estimated that the system requires a little less than 0.3 s to release the boot after the fingers have been spread. Further injury analysis is necessary to determine whether this release time combined with the skier's reaction time is low enough to prevent the different injury types. If not, the release time can be reduced by increasing the sampling rate of the sensors and by using a stronger spring that can accelerate the binding faster.
Training of the skier with regard to injuries is useful in many scenarios and can even prevent injuries when skiing with conventional bindings. It has been scientifically proven that injury awareness training can reduce the risk of an ACL injury [22]. This awareness training teaches the skier how to behave in an accident in order to reduce the risk of injury. One example of this is trying to get back up after a backwards fall, which increases the risk of an injury based on the phantom foot mechanism. It is better to accept the fall and get back up once the sliding has fully stopped.

[3] https://alexandria.physik3.uni-goettingen.de/triggerbind/

6.6. Cost Analysis and Market Feasibility

It is assumed that the numerous mechatronic bindings developed so far, some of which were presented in Section 3.1, never reached the market because they were too expensive. Therefore, one goal of this thesis was to develop a mechatronic binding with inexpensive components.

As seen in Table B.1, the components of the glove cost about 40 € while the components of the binding add up to around 60 €. The combined system thus costs about 100 €. The manufacturing costs of the circuit boards themselves, the 3D-printed parts as well as the mechanical modifications to the ski and binding are not considered here. Moreover, these prices do not include the original glove and binding but only the modifications. A stand-alone system would be more expensive.

The above-mentioned costs only consider a single binding, but bindings always come in a set of two and both knees need to be protected. It is unclear at this point whether two sensor gloves are necessary, or whether a single one can suffice. Using a second one could improve redundancy in case the other one fails, or could prevent false releases by only triggering if both detect the correct signal. Having two binding would increase the costs to 160 €, or 200 € if combined with a second glove.

Various online shops currently offer conventional alpine ski bindings in a price range of about 100 to 400 € [54, 55]. It is imaginable that a skier who is concerned about injuries would pay a premium for the additional safety provided by the system. The existing *lateral heel release* bindings are sold for 300 to 400 € [35, 36] which is less affordable than conventional bindings. This price is still within a reasonable range for ski equipment, since skis and also ski boots cost multiple hundred Euro. When manufacturing a mechatronic binding, it should be aimed for a similar price range in order to be competitive with the mechanical bindings.

The *fully automatic* release system mentioned in Section 3.1 is estimated to be a lot more expensive than this because of the number of required sensors. Even the mechatronic binding without the sensors will be pricier than a conventional binding because of the increased complexity. Since the binding has not been developed yet, it is not expected that this system will reach the consumer market anytime soon.

If working correctly, the *fully automatic* system is believed to be the most effective solution in injury prevention because of the wealth of information it collects and bases its release decision on. However, sensors that measure knee flexion and muscle activity need to be accurately positioned for each skiing day to guarantee a reliable release, which could be inconvenient for customers. The sensor glove triggered system proposes a less expensive and simpler solution to the problem. The skier only needs different gloves, which are already part of the gear.

When both of these systems are more refined and user-friendly, it is also imaginable that they could be combined. This would unite the advantages, releasing the binding when the knee is in danger and on demand of the skier in any other situation.

The release mechanism itself should not be an add-on to an existing binding, but instead it should be fully integrated into a new binding design. Modifying bindings in the way done in this thesis is only an option for a prototype, not for an actual product. The existing bindings are too diverse and the necessary modifications to the bindings, which were described in Section 5.2, are too elaborate to be performed economically.

The approach of the *Rossland Binding Company*, mentioned in Section 3.1, is also considered infeasible. While being compatible with all screw mounted bindings, their adapter plate raises up the binding, changing the handling characteristics of the ski. Furthermore, their system is incompatible with track mounted bindings.

A binding that does not release but only adjusts its retention setting automatically or when triggered might also work, but it is unclear if it releases in all the injury scenarios. It also cannot solve the problem of a skier being stuck in deep snow because the binding can't be released manually.

Concerning the glove, it could be problematic that there is a large variety of different ski gloves available. Every skier has individual preferences when it comes to the type, design and warmth of the glove. It is not possible to develop a single glove that matches the needs of every skier.

Instead, the user could send in his or her own gloves, so the sensors can be integrated into or onto them. This modification could be implemented in the summer months, since most people don't use their gloves during that time. In this way, the production of the glove itself can be avoided, which would make the system less expensive. However, this is only true if adapting the system for every single glove design and size can be achieved cost-efficiently.

The most versatile alternative would be to design a very thin sensor glove that could act as a liner to be worn below the actual glove. This would enable the skiers to keep their preferred gloves, while still being able to use the system. Mittens, which are gloves featuring a combined chamber for all fingers except for the thumb, would also be compatible with these liners.

Developing such a thin sensor glove is challenging since the flex sensors are not allowed to stick out from the liner. Otherwise, they could be ripped off while removing the upper glove. It should be assessed whether finger flexion, instead of abduction, would be sufficient as a trigger. This would greatly simplify the integration into even a thin glove. Alternatively, the other sensor types or hand tracking techniques mentioned in Section 3.2 can be reconsidered as well. Apart from the sensors, the circuit board would also need to be more compact or positioned somewhere else entirely.

7. Summary and Outlook

In the scope of this thesis, a novel concept for triggering mechatronic ski bindings was introduced. A sensor glove that detects when the fingers are spread quickly was developed and is thought to be a suitable trigger for releasing the binding on demand of the skier to prevent injuries. Using flex sensors for the sensor glove is cost-effective, and their accuracy turned out to be more than sufficient for the task at hand when evaluated with a voltage divider and the selected microcontroller.
Secondly, a prototype of a mechatronic ski binding was implemented and forms a complete binding release system when combined with the sensor glove. The binding prototype was realized with inexpensive components and is fully functional. The release modes of the conventional binding it is based on are not impaired, and even the adjustment mechanism for different boot sizes is maintained.
To create a product from the system presented in this thesis, the sensors need to be integrated into the glove or better into a thin liner to be worn below the glove. For the glove and the binding, the circuit boards need to be miniaturized and waterproofed, and the power consumption should be optimized. The communication between the two systems requires encryption to prevent unwanted releases. Manual modification of existing bindings is economically not considered feasible. Instead, a mechatronic binding with the conventional release modes as well as a way to release the binding on an electric signal needs to be developed.
When analyzing knee injury mechanisms, it was presumed that the system developed in this thesis can prevent injuries effectively. However, there is no evidence to support this, as extensive testing with many skiers would be required. This leads to a chicken-or-egg dilemma. If there is no fully functional mechatronic system that can be tested, there is no data on its effectiveness in injury prevention. Without sufficient data, customers do not trust the product, and it is risky to invest all the resources required to develop a fully functional product suitable for testing in the first place. Possibly, this dilemma hindered new concepts from reaching the markets and solidified the status of the now over 40-year-old conventional binding.

The digitalization can be observed in numerous sports and ranges from smartwatches and tracking devices to electronic shifters in bicycles. Because of the limitations of mechanical bindings, it is inevitable that mechatronic bindings will be introduced someday. The challenge is to exceed the already high safety standards of conventional bindings. No false releases are tolerated. Still, mechatronic bindings cannot be considerably pricier than the mechanical bindings in order to be competitive.
The introduction of mechatronic bindings involves multiple different stakeholders. Most important are the binding manufacturers that could use their existing expertise and market share to develop and promote these bindings. Standard organizations are also involved since they regulate the binding market and need to set standards for new binding systems. Overly restrictive standards can be an additional challenge for mechatronic bindings. If the system incorporates sensors as proposed in this thesis, the textile industry also plays a role since they could integrate sensors into gloves or other gear. Universities and researchers can help by quantifying the safety of new bindings, providing evidence on injury reduction, and proposing novel solutions. Lastly, the skiers themselves need to be open-minded about new technology and accept inconveniences that such a system might bring, like charging batteries, for the enhanced safety.
Mechatronic ski bindings can only make their way to the ski slopes if these stakeholders work together effectively. Furthermore, someone or some company needs to be willing to take the initial risk of developing a full product which can be tested, expanded and refined until it is a reliable alternative to conventional bindings.
Realistically, this process will still take multiple years before mechatronic ski bindings can be sold on the market. A skier who is concerned about knee injuries is well advised to switch to *lateral heel release* bindings in the meantime. Furthermore, I would like to draw the attention of every skier reading this to the main points of ACL awareness training [56]:

- “Don’t fully straighten your legs when you fall. Keep your knees flexed.”
- “Don’t try to get up until you’ve stopped sliding. When you’re down–stay down.”
- “Don’t land on your hand. Keep your arms up and forward.”
- “Don’t jump unless you know where and how to land. Land on both skis and keep your knees flexed.”

By sticking to these guidelines, many knee injuries can already be avoided without changing the binding system.

A. Appendix

```
#include <RCSwitch.h>  // library for the Transmitter

// setup for the Radio Transmitter
RCSwitch mySwitch = RCSwitch();
const int transmitter_pin = 11;

// timesteps for the calibration loop in milliseconds
unsigned long time;
unsigned long fist_time = 2 * 1e3;
unsigned long pause_time = 4 * 1e3;
unsigned long spread_time = 6 * 1e3;
unsigned long calibration_time = 8 * 1e3;
bool calibration = false;

// variables that store the flex sensor readings
int left, right;
int prev_left, prev_right;

// variables that store the flex sensor values from the calibration loop
int fist_left, fist_right;
int spread_left, spread_right;

// below the threshold, the position is defined as "spread"
float threshold_factor = 1. / 3.;
int spread_threshold_left, spread_threshold_right;

// how much the sensor value has to change in one step to count as "quick"
int quick_change_delta = -10;

// function that detects when fingers are spread far and quick enough
bool detect_quick_spread(int prev_left, int prev_right, int left, int right) {
  // both sensors need to surpass the spread threshold
  if (left < spread_threshold_left && right < spread_threshold_right) {
    // both sensors have to be bent quickly
    if (left - prev_left < quick_change_delta && right - prev_right <
    quick_change_delta) {
      return true;
```

```
    } else return false;
  } else return false;
}

// function for blinking the LED for a set duration
void blink_LED(unsigned long duration, unsigned long blink_stop) {
  time = millis();
  unsigned long LED_start = time;
  while (time < LED_start + duration) {
    digitalWrite(LED_BUILTIN, LOW);
    delay(blink_stop);
    digitalWrite(LED_BUILTIN, HIGH);
    delay(blink_stop);
    time = millis();
  }
}

// pin assignment
void setup() {
  mySwitch.enableTransmit(transmitter_pin);
  pinMode(A0, INPUT);
  pinMode(A1, INPUT);
  pinMode(LED_BUILTIN, OUTPUT);
}

void loop() {
  // start loop by measuring the flex sensor values
  left = analogRead(A0);
  right = analogRead(A1);
  time = millis();

  // calibration step
  if (time < calibration_time) {
    // startup, LED ON
    if (time < fist_time) {
      digitalWrite(LED_BUILTIN, HIGH);
      fist_left = left;
      fist_right = right;
    }
    // measuring rest position / holding ski pole, LED OFF
    else if (time > fist_time && time < pause_time) {
      digitalWrite(LED_BUILTIN, LOW);
      if (left > fist_left) fist_left = left;
      if (right > fist_right) fist_right = right;
    }
    // break, LED ON
```

```
    else if (time > pause_time && time < spread_time) {
      digitalWrite(LED_BUILTIN, HIGH);
      spread_left = left;
      spread_right = right;
    }
    // measuring spread position, LED OFF
    else if (time > spread_time) {
      digitalWrite(LED_BUILTIN, LOW);
      if (left < spread_left) spread_left = left;
      if (right < spread_right) spread_right = right;
    }
  }
  // calculating the spread threshold from the values that have just been measured
  else if (time > calibration_time && calibration == false) {
    spread_threshold_left = spread_left + threshold_factor * (fist_left - spread_left);
    spread_threshold_right = spread_right + threshold_factor * (fist_right - spread_right);
    calibration = true;
  }
  // once the calibration is finished, keep LED ON and continously check if quick spread can be detected
  else {
    digitalWrite(LED_BUILTIN, HIGH);
    if (detect_quick_spread(prev_left, prev_right, left, right) == true) {
      mySwitch.send(42, 24);  // send release signal via the transmitter
      blink_LED(2000, 250);
    }
  }

  prev_left = left;
  prev_right = right;
  delay(50);  // pause for 0.05sec, this limits the sampling rate to ~20Hz
}
```

Code A.1: Glove

```
#include <RCSwitch.h>  // library for the receiver
#include "Servo.h"     // library for the servomotor

// setup for the receiver
RCSwitch mySwitch = RCSwitch();
Servo Servomotor;
const int transmitter_pin = 2;

// servo connection and open and close angles
const int servo_pin = 10;
const int closed_state = 120;
const int open_state = 50;
int servo_state;

// button configuration
const int button_pin = 9;
int button_state = 0;

// assign pins and assure servo is at the closed position
void setup() {
  mySwitch.enableReceive(transmitter_pin);
  pinMode(button_pin, INPUT);
  Servomotor.attach(servo_pin);
  Servomotor.write(closed_state);
  servo_state = closed_state;
}

void loop() {
  // check if the button is pressed
  button_state = digitalRead(button_pin);

  // check if reciever detects a signal
  if (mySwitch.available()) {
    int value = mySwitch.getReceivedValue();
    // if the signal is the correct one, turn servo to release binding
    if (value == 42) {
      Servomotor.write(open_state);
      servo_state = open_state;
    }
    mySwitch.resetAvailable();
  }
  // if button is pressed, close or open the bindnig depending on the current
     state
  else if (button_state == HIGH) {
    if (servo_state == open_state) {
```

```
      // 3s pause after press so that binding can be pushed in the desired
    position
      delay(3000);
      Servomotor.write(closed_state);
      servo_state = closed_state;
    } else {
      // for opening, only a small pause is required
      delay(1000);
      Servomotor.write(open_state);
      servo_state = open_state;
    }
  }
}
```

Code A.2: Binding

Sensor Glove

Component	Exact Name & Manufacturer Number	Price in €
Microcontroller	DFRobot Beetle Board DFR0282	7.37
Flex sensors	spectrasymbol FL-L-0095-103-ST	2 × 12.66
LiPo Battery	LiPo Battery 3,7V 150mAh	4.40
LiPo Charger	LiPo Battery Charging Module TP4056 XD-58A	1.09
Radio Transmitter	433 MHz Transmitter Module MX-FS-03V	0.83
Switch	Minature Slide Switch	≈ 0.10
	Glove Total	**39.11**

Mechatronic Binding

Mechanical		
Axle	6mm Steel Axle	≈ 1.00
Linear Bearing	Linear Bearing SCS6UU	4.00
Spring	Coil Pressure Spring 1,5x12x40 mm	2.08
Flange Coupler	Steel Flange Coupling for 6 mm axle	2.00
Servo Adapter	Aluminum Servo Disk 25T 4x16.5 M2.5	4.10
Electrical		
Servomotor	GXservo 25kg-GX3225MG Digital Servo	16.99
Microcontroller	DFRobot Beetle Board DFR0282	7.37
LiPo Battery	Tattu LiPo TA-75C-450-2S1P	8.99
Voltage regulator	Mini Step-Down Voltage Regulator AMS1117-5.0	2.52
Radio Receiver	433 MHz Receiver Module MX-05V	0.83
Button	Omron Ultra Subminature Switch D2FS-FL-N	0.79
Battery cable	10cm 14AWG Cable with XT60 Plug	4.29
Battery adapter	RC Adapter XT60 Socket to XT 30 Plug	4.10
Fuse	Fuse Carrier with 1A Microfuse	≈ 1.50
Screw terminal	Screw Terminal Block Connector 5 mm	≈ 0.20
	Binding Total	**60.76**
	Total	**99.87**

Table B.1.: List of the components used for the sensor glove and the mechatronic binding. The exact name of the component and manufacturer number if known is given along with the price of the component at the time of purchase. The circuit boards, machined parts for the binding and 3D printed parts have been custom-made and are not mentioned here.

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