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Functional Design Employing Miniaturized Electronics with Wireless Signal Provision to a Smartphone for a Strain-Based Measuring System for Ski Poles

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Abstract: The individual monitoring of cross-country skiers' technique-related parameters is crucial to identifying possible athlete-individual deficits that need to be corrected in order to optimize the athlete's performance in competition. To be able to record relevant biomechanical parameters during training in the field, the development of measuring systems exploiting the athlete's full potential is the key. Known mobile monitoring systems for measuring forces on ski poles use comparably heavy uniaxial load cells mounted on the pole with a data logger also attached to the pole or carried by the athlete. Measurements that are more accurate can be acquired using wire-based systems. However, wire-based systems are highly immobile and only usable when the athletes undergo a stationary test, e.g., on a treadmill. This paper focuses on the functional design of a measuring system using specialized, miniaturized electronics for acquiring data from strain sensors. These data are then used to determine the technique-related parameters pole force and angle of bend. The functional design is also capable of transmitting the acquired data wirelessly via Bluetooth to a smartphone that runs a proprietary app. This approach is advantageous regarding mass, dynamic behavior, analyzing functionality, and signal processing compared to the state of the art.

Keywords: competitive sports; winter sports; cross-country skiing; skiing technique; pole force; miniaturization; Bluetooth Low Energy; Android; strain gauge

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1. Introduction

The individual monitoring of cross-country skiers' technique-related parameters is crucial to identifying possible athlete-individual deficits that need to be corrected in order to optimise the athlete's performance in competition. To be able to record relevant biomechanical parameters during training in the field, the development of measuring systems exploiting the full potential of digitalised sports is the key. Many different approaches for measuring forces acting on ski poles are already known and well described in the literature [1–13]. In general, two approaches to measurement systems can be distinguished: (i) force measuring plate on the track ground [1–3] and (ii) force transducer at the pole [4–13].

The use of a force measuring plate makes it possible to detect the forces transmitted by the pole to the track ground in all spatial directions. However, a force platform is a stationary system and only few poling phases can be measured, even if several platforms are connected in series. Additionally, it is an expensive system which is accessible only to a few groups.

Due to these restrictions, the use of force transducers at the pole has been established. In previous investigations a force transducer with a weight of approximately 45 g was positioned next to the pole tip [4]. In this configuration, the additional mass significantly changes the moment of inertia and, thus, the swing behavior of the pole. For this reason, the force transducer is positioned next to the pole grip in the majority of the developed measurement systems [5–13]. Most of the systems use strain gauge-based force transducers, which add an additional mass of 5 g to 60 g to the pole. The cited references differ in terms of the measurement frequency by an order of magnitude, ranging from 100 Hz to 2000 Hz.

The measuring system developed in [13] is viewed as the most advanced system in the state of the art, regarding the aspects of mobility, weight, influence on the athlete, and recorded information content. Apart from the uniaxial force, accelerations and angular rates can also be measured using an inertial measurement unit (IMU).

Hejda et al. mention a system with strain gauges applied to the ski pole. However, there are no details on the usage of these strain gauges and the mass of the needed measuring electronics [14].

The following limitations are identified based on the state of the art of measurement systems mounted to the pole:

- Uniaxial force measurement: Force transducers for uniaxial force measurement in the longitudinal direction of the pole have been reported in all known investigations. In addition to the longitudinal force, the athlete also introduces other loads, i.e., forces and moments, into the pole due to the complex motions. A recording of all the loads introduced by the athlete into the pole has not been reported. In particular, the moments which have no effect on the propulsion but are decisive for the deflection of the pole could not yet be measured. The relation of introduced moments and the efficiency of the running technique is an open sport-scientific question and cannot be solved using current systems. However, the answer to the aforementioned question becomes more relevant since modern poles have higher bending stiffness than older poles. Thus, they can absorb higher non-propulsion bending loads without great deformation.
- Weight of measurement unit: In the case of uniaxial, strain-based force transducers, transverse forces on the transducer must be avoided. Otherwise, the signal is distorted by cross-talk due to inevitable bending moments. The housing of the transducer typically features a shear force decoupling, in order to correctly measure the uniaxial force. Despite the effort to use adapted designs and lightweight materials, the transducer housing or specific external sleeves, e.g., as developed in [13], add most of the weight to the measurement unit. It should be noted that the need for a transverse force decoupling hinders a further decrease in the weight in case of the common measurement solutions for pole forces. Therefore, a solution without the need for a shear force decoupling has to be developed.
- Signal provision: The mobile measurement systems allow for an online recording of the force data on the track. However, a visualisation and analysis of the measurement data can only be carried out after the investigations, for the time being. Wireless data transmission on computers or smartphones has not yet been reported in the literature. This would offer the possibility of live-feedback training and enable the design of a smart pole, which can be applied also for mass sports application, e.g., as self-tracking device.

At this point, the present investigations for the development of alternative measuring methods are initiated. Such alternatives can be found in other, cutting-edge industries such as the aviation or aerospace industry. These industries drive forward the interdisciplinary development of function-integrated components in order to increase safety, efficiency, and value of their products. The function integration approach implies the combination of several functions in one component, e.g., load-carrying functionality and in operando measurement for structural health management or active damping by using integrated sensors, actuators, and electronics [15–20]. Since typical requirements in the field of function integration and mobile measuring systems are reflected in sports technology, for instance, in terms of mass, functionality and reaction-free measurement technology, the findings of the aforementioned research and development works at the Technische Universität Dresden, Institute of Lightweight Engineering and Polymer Technology (TUD-ILK) can be advantageously adapted.

For the development of the measuring system presented in this paper, the function integration approach is used in order to monitor ski pole loads. Initial investigations on the subject made at the TUD-ILK are described in [21]. These investigations featured the development of a measuring system where the pole itself is considered as part of the measuring element using its mechanical behavior for the load measurement. The function of the ski pole is thus integrated into a measuring system. This approach supersedes the use of additional equipment such as force transducers by integrating two functions into one device. Additionally, the stiffness and strength of the ski pole remain unaffected since the pole is not cut or drilled in any way.

In the context of the initial investigations [21], strain gauges were adhesively bonded onto the pole and the pole loads could be calculated based on prior calibration data. The developed measuring system used four strain gauges per ski pole, two active strain gauges measuring the actual strain induced by axial forces and two strain gauges for temperature compensation. Furthermore, the measuring system used a measuring module directly bonded to the pole next to the strain gauges and a signal processing module which was positioned in the drink belt of the athlete. The basic characteristics of the electronic modules developed in [21] are shown in Table 1.

Table 1. Basic characteristics of the electronic modules developed in [21].

Characteristic	Measuring Module	Signal Processing Module
Basic electronic devices	2 Wheatstone Bridges; Bi-Level Signal Amplifier; 2D-Accelerometer	Microcontroller Arduino Nano Board; Serial Bluetooth Link Bluefruit EZ-Link; Li-Ion Battery, 3.7 V, 1950 mAh; Mini USB Connector for Charging and Data Transfer; Charge Display
Weight	10 g	100 g
Dimensions	34 mm × 25 mm × 15 mm	80 mm × 45 mm × 28 mm (with housing)
Positioning	Pole	Drink belt

The measuring system developed in [21] is the basis for the measurement system first described in [22] and detailed in this paper.

The paper is organized as follows. The second section discusses the results of the paper. Here, particular attention is paid to how the specific parameters of pole force and bending are obtained from the parameters measured on the ski pole and how they are presented to the user. The third section describes the functional design of the system. In Sections 4 and 5, the hardware and software structure of the two implemented subsystems is described in detail. The last section briefly summarizes the contributions of the work presented with respect to their relevance for sports medicine.

2. Results

The measuring system was developed and investigated with the focus on measuring three strain measurements per ski pole in order to determine the axial force and bending or deflection experienced by the ski pole [22]. In sports science, it is assumed that the bending of the ski pole caused by the athlete significantly reduces the poling efficiency. Using the developed measuring system enables new evaluation methods in the field of cross-country skiing sports science.

Figure 1 illustrates the different states of a ski pole that the measuring system is able to show up. In Figure 1a, the green load condition is an idealized state where the ski pole is only loaded axially. This state cannot be achieved in a realistic environment. The orange load condition is a condition with high axial force and relatively low bending which can be achieved by a highly skilled professional. The red load condition shows low axial force combined with high bending of the ski pole which might be achieved by an amateur. In this example, the y-direction corresponds to the running direction of the athlete.

The measuring system is able to measure the strain resulting from these load conditions in three locations around the circumference of the ski pole. The strain signals are used to determine the axial force and the angle of bend which is assumed to be an indicator for the athlete's efficiency while poling. Details on the general concept of the measuring system and the calculation of forces and bending angles were described in [22]. The axial force and angle of bend can be displayed like in Figure 1b. Here, the arrows correspond to the load conditions in Figure 1a. Every arrow shows the respective axial force and angle of bend over the course of half a poling cycle from a minimum of axial force to the maximum.

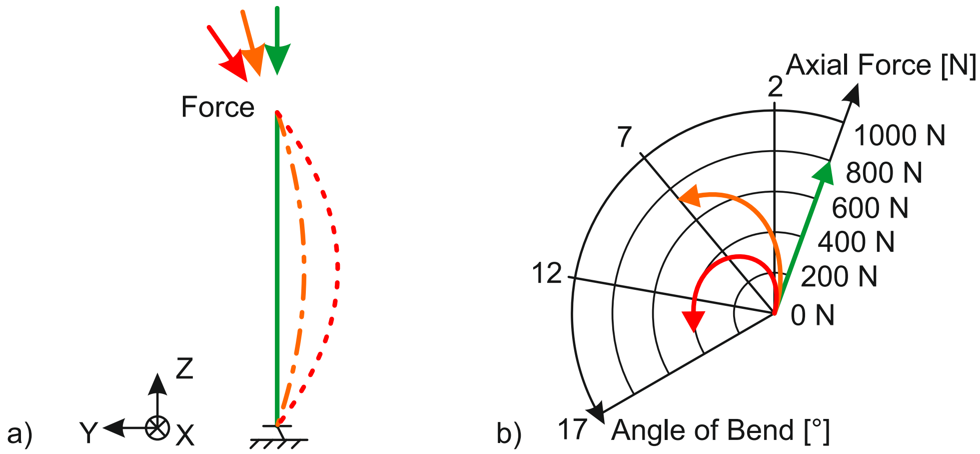

Figure 1. (**a**) Different load conditions and corresponding deflection of a ski pole: ideal poling (green), professional poling (orange), and amateur poling (red) and (**b**) calculated axial forces and angles of bend using strain signals measured by the developed measuring system for the load conditions in (**a**) over the course of half a poling cycle.

The axial forces and angles of bend are calculated from strain signals which are measured, saved, and displayed using a specialized measuring system. Additionally, the acceleration due to gravity in three dimensions acting on the ski pole to determine the position of the pole in space is measured.

The development of the electronics and the programming work made for the specialized measuring system are described in the upcoming sections. These works resulted in a measuring system with the following highlights:

- High-performance specialized and miniaturized lightweight electronic system for data acquisition and amplification;
- Wireless transmission of the acquired data via a Bluetooth connection;
- Individualized software solution for the signal provision including a method for transmitting vast amounts of data through Bluetooth Low Energy (BLE);
- Android app for receiving acquired data from the specialized measuring system.

3. Functional Design

The following subtasks can be derived from the basic task of the system to record the handling of the ski poles by the athlete during the run and to draw conclusions about the motion sequences:

- Measurement of the strain that the ski pole undergoes at its outer circumference to determine the force acting on the pole and its bend;
- Measurement of the acceleration due to gravity in three dimensions acting on the ski pole to determine the position of the pole in space;
- Transmission and storage of the recorded measured values for further processing;
- Calculation of the required information for the athlete's training from the stored measured values;
- Display of training information in a clear, understandable and easy-to-use format.

The first two subtasks have to be carried out by a measuring system in the ski pole itself. The data transmission should be wireless in order to achieve maximum flexibility in the use of the system. A computer with a sufficiently large display should be used to calculate and display the training information. This in turn results in new subtasks:

- Configuration, calibration and monitoring of the measuring system;
- Formatting, compression and protection of data before and during transfer;
- Safe and permanent storage of the data.

Other tasks usually associated with electronic data capturing and processing, such as protecting the system against external and internal attacks or authenticating and authorizing users, are not considered further here because this is a prototype development used only in a well-known and very small user community.

The concept of the overall system includes three devices: the ski pole with an embedded measurement system; a smartphone for intermediate storage of the measurement data; a computer for analyzing the measurement data and displaying the results. This allows the system to be used on the treadmill indoors and outdoors on a training parkour.

Data transmission between the ski pole and the smartphone takes place continuously via Bluetooth. This is a simple and widely used interface, but it only allows relatively short transmission distances. However, this does not affect its use in this project, since the athlete can carry the smartphone on their body due to its low weight. Between the smartphone and the computer, the data of complete training sessions are transferred. This transfer can be done using common device interfaces, such as USB or WLAN.

The ski pole requires a mobile power supply with low weight, e.g., a rechargeable battery. To ensure several hours of operation, components with low power consumption were chosen for the embedded system. For this reason, also for the Bluetooth interface the low-energy (BLE) operation was chosen. Furthermore, the ski pole offers little space for mounting the measurement system and shields higher frequency signals due to the carbon fiber reinforcement. For this reason, the package sizes for the components of the embedded system were chosen to be as small as possible and a high packing density of the components was striven for. The Bluetooth module had to be placed in the handle of the stick above the carbon fiber reinforcement. Since the strain gauges had to be mounted on the outside of the ski pole, it was unavoidable to lead the connection cable of the sensors alongside the Bluetooth module. Despite the use of a shielded cable, this leads to interference with the measurement signals during operation. To eliminate such interference pulses, the measurement signal of the strain gauges is smoothed with a first-order low-pass filter before it is amplified. In addition, measures are also taken in the software to reduce interference pulses.

Originally, the measurement data in the ski pole was to be recorded 512 times per second. From the point of view of data acquisition in a microcontroller (MC), this is not a great challenge. However, it turned out that there was still a bottleneck in the system—the Bluetooth interface. Since older phones do not yet support the length extension of the data packets introduced with revision 4.2 of the Bluetooth core specification [23] and this is also an optional feature for newer phones, the default packet length was used for the transmission of the data. For an application based on the attribute protocol, this means that the payload can have a size of up to 20 octets.

To test the Bluetooth communication, we had smartphones of the following types at our disposal:

- Huawei Mate 20 Pro;
- Huawei P-20;
- Samsung Galaxy A3 (2016);
- Samsung Galaxy S10;
- Xiaomi Mi 8;
- Xiaomi Redmi 4.

The phones allowed transmission of about 50 to 168 data packets per second. This leads to a usable data rate on application level between 8 kbit/s and 26.88 kbit/s. Regarding the amount of data, this means that between 1000 and 3360 octets per second could be transmitted. To be compatible with as many phones as possible, the acquisition of the measured values was adapted to a transmission rate of 50 packets per second. This leads to the fact that, despite compression of the measured values, a maximum of 400 measurements per strain gauge and second can be transmitted.

Each ski pole transmits an average of 1399.61 data values per second to the smartphone. This number results from 3072 strain readings, 381 accelerometer readings, one temperature and one battery voltage reading each, as well as 128 packet numbers, which are transmitted within 128 data packets. The smartphone stores each measured value with a width of 16 bits. This results in an average data volume of around 22.4 kbit/s per ski pole, which has to be processed and stored by the phone.

The smartphone exports the data of the recorded training sessions to text files as comma-separated values (csv). This format is widely used and allows flexible import possibilities into various applications on the computer. Such a file contains the data of the training session, such as start and end, the name of the athlete, the data of the ski poles used, such as MAC address, name and configuration data, and a list of the recorded measurement data. The phones also record how many and which data packets were not received correctly from the ski poles and were, therefore, discarded. Since the Bluetooth data transmission leaves no room for timestamps, the time values exported in the text file are calculated during the export from the database using the stored numbers of the measurements. It is assumed that the first data packet arrived exactly at the beginning of the training session and that each subsequent packet has a fixed time interval of 20 ms from the previously transmitted packet. Any discarded data packets are also taken into account. Within the data packets, the measurement times are calculated under the assumption that the measurements were recorded with a temporal distance of 2.5 ms. The time stamps of two ski poles calculated in this way can therefore have a maximum deviation of 20 ms from each other.

4. Embedded System

4.1. Mechanical Design

The carbon fiber-reinforced part of the ski pole has a diameter of 15 mm on the inside at the upper end and 16.5 mm on the outside. For the printed circuit boards (PCBs) a width of 12 mm was selected. This allows them to be installed inside the ski pole with a narrow round sleeve. An exception is the place where the Bluetooth module is equipped. Here, a PCB width of 15 mm was necessary. This part has a length of 25 mm and, after assembly, is located outside the carbon fiber-reinforced part of the ski pole but inside the attached handle. Figure 2 shows the two mounted PCBs and the mounting sleeve. The measuring board has a length of 75 mm; the signal processing board is 100 mm long.

The embedded system—fully assembled circuit boards, strain gauges, battery, cables and mounting aids—increases the weight of the ski pole by about 32 g. The battery accounts for about 10 g of this.

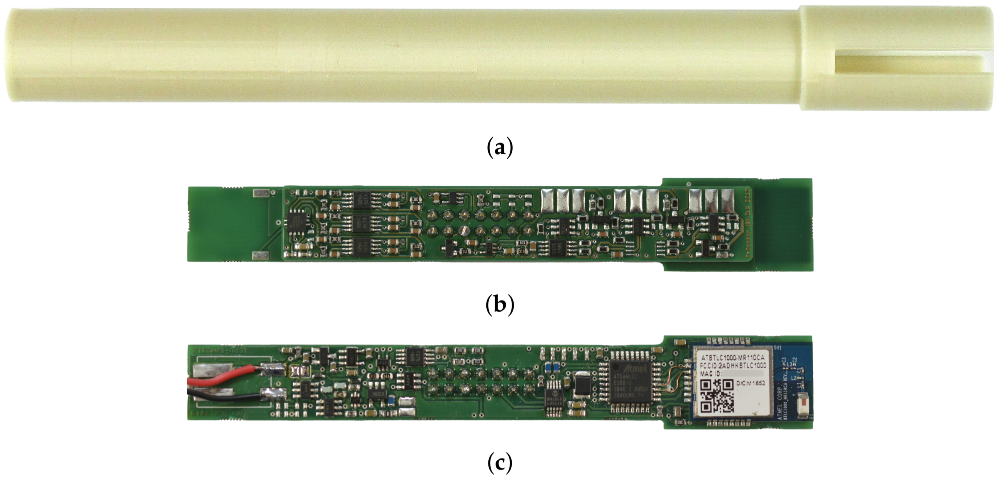

Figure 2. Printed circuit boards and mounting sleeve. (**a**) Mounting sleeve; (**b**) Measuring board; (**c**) Signal processing board.

4.2. Hardware Design

The embedded system shall operate self-sufficiently. Therefore, it is powered by a Li-ion rechargeable battery with a nominal voltage of 3.7 V and a capacity of 350 mAh. The constant charging current of the battery is set to approximately 210 mA. To save energy and to extend the time between two battery charging cycles, the battery can be disconnected from the rest of the system. Voltage regulators are used to set the operating voltage of 3.3 V for the system and the reference voltage of 2.048 V for the analog-digital converter (ADC) and digital-analog converter (DAC).

As shown in Figure 3, the central component of the embedded system is the microcontroller (MC). The ATSAML21E18B-AUT from Microchip was chosen because of the available small package that could be semi-automatically soldered, the amount of memory and the balanced mix of peripherals that provide assistance to the processing unit (CPU). Table 2 gives an overview to some of the features of the MC. The MC is mainly responsible for the measurements und the communication. The clock frequency was set to 16 MHz in order to not increase the power loss of the chip beyond what is technically necessary.

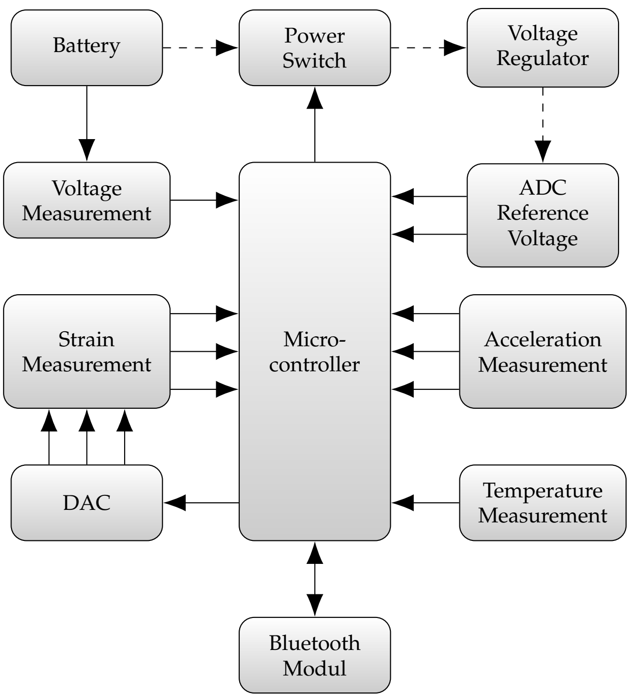

Figure 3. Hardware structure of the embedded system—energy flow (dashed), signal flow (solid).

Table 2. Main features of the MC ATSAML21E18B-AUT [24].

Characteristic	Property
Package	TQFP32 (nominal size: 9 mm × 9 mm)
CPU	ARM Cortex-M0+
Memory	256 kB Flash (programm memory); 32 kB SRAM (main memory); 8 kB SRAM (low power memory); 8 kB EEPROM
Peripherals	12-bit, 1 Msps ADC with up to 10 channels; Up to three 16-bit timer/counter; 32-bit real time counter; 16-channel DMAC; 12-channel event system; Up to six serial communication interfaces

The MC measures three analog strain signals in order to calculate the forces on the ski pole and its bending. The three acceleration signals—one for each space coordinate—are measured to identify the position of the ski pole in space. The temperature and the battery voltage are measured to provide information about the battery state to the user and to protect the battery from deep discharge. From the reference voltage, two signals are derived to calibrate the ADC measurement.

The strain signals are obtained from a resistance bridge that operates as half bridge for temperature influences to the strain gauges and as quarter bridge for the forces on the ski pole. The measuring bridges use the same voltage as operating voltage as the ADC as reference. The output signals of the measuring bridges are filtered with a first-order low-pass filter with a time constant of 844 µs and then amplified by a factor of 100. The amplifier circuit enables the setting of the output voltage reference. This option is used for the zero adjustment of the measurement chains. Since the MC provides only two internal DAC channels, an external DAC is used to adjust the three measurement chains independently. For the communication between MC and DAC an I^2C interface is used. The interface is configured for fast mode with a data rate of 400 kbit/s.

Each of the measuring chains for strain measurement is calibrated by means of a resistor connected in parallel to the measuring strip. By connecting a 20 kΩ resistor in parallel to a strain gauge with a nominal resistance of 350 Ω, a compression of 1.72 % is simulated. This leads to an increase in the output voltage of the measuring bridge of 8.88 mV.

All analog signals are provided as single-ended signals and measured using the internal ADC of the MC. The ADC makes it possible to convert multiple signal inputs within one sequence. In addition, the oversampling option is used that accumulates the measurement results from 16 consecutive conversions and extends thereby the resolution to 16 bits. The measurements are fully controlled by hardware. All measurements are automatically started by an overflow event of one of the three internal 16-bit timers of the MC. The timer has a cycle period of 2.5 ms. After a measurement is completed the internal direct memory access controller (DMAC) moves the result into memory and after completing a measurement sequence the DMAC interrupt is used to trigger the software for further activities.

To compensate for possible offset and gain errors of the ADC, a two-point calibration is performed [25]. The required partial voltages are derived from the reference voltage of the ADC with the help of two voltage dividers, each consisting of two resistors with the values 2 kΩ and 30 kΩ. Both resistor values have a tolerance of ±0.05 %. With a resolution of the ADC of 12 bits, this results in the digital values 256 and 3840 with a tolerance of ±0.24 digits each.

The data transfer to the smartphone is done via Bluetooth. Due to its small dimensions and low current consumption, modules of the type ATBTLC1000-MR110CA were used.

The module supports Bluetooth Low Energy (BLE) operation. The main features are shown in Table 3.

Table 3. Main features of the Bluetooth module ATBTLC1000-MR110CA [26].

Characteristic	Property
Dimensions	12.700 mm × 20.152 mm
Transmit power	−55 dBm to 3.5 dBm
Power supply voltage	1.8 V to 4.3 V (power management unit); 1.62 V to 4.3 V (general purpose input/output)

For the data transfer between MC and Bluetooth module, two UARTs (Universal Asynchronous Receiver/Transmitter) are used. In the so-called 6-wire mode, one UART with hardware flow control lines (four wires) and one UART without hardware flow control (two wires) are used. Both UARTs are configured with the following parameters: no parity, 8 data bits, 1 stop bit and 115.2 kbit/s data rate.

All of the 25 pins of the MC available for general input/output purposes are used. Since one of the ten inputs of the ADC is needed for the external reference voltage, only nine inputs are available for the ten analog measurement signals. Therefore, the control signal for switching the calibration resistors to the resistance measuring bridges is also used for switching between two of the analog signals.

4.3. Software Design

The software running on the embedded system basically consists of two parts—the application software and the BluSDK, a software development kit and programming interface for BLE applications offered by Microchip for the Bluetooth module. The architecture and the general application flow of the the BluSDK software is shown in Figure 4. The application is implemented in C.

During initialization and device configuration, the following steps are performed in the specified order:

- Basic initialization of the MC;
- Initialization of components relevant for the application (common control signals, timer, ADC, communication interfaces for Bluetooth module and external DAC, event system);
- Hardware calibration (ADC, strain measurement chains);
- Start monitoring the battery voltage;
- Initialization of the Bluetooth module;
- Initialization of the BLE-services (device information service, configuration data service, measurement data service);
- Start of Bluetooth advertising information transmission.

When calibrating the ADC, the deviation of the measurements from an ideal straight-line characteristic is determined on the basis of two fixed measuring points and stored in the form of correction values for the offset error and the gain error in the registers provided for this purpose in the MC. These correction values are then used automatically for each individual measurement.

When calibrating the strain measurement chains, on the one hand, a mean output value of the amplifier is set which corresponds to a measurement without an external force, the zero point of the measurement chain, and on the other hand, the sensitivity of the measurement chain for a simulated compression of the strain gauges is calculated by means of a calibration resistor. These values are used within the embedded system for the processing of the raw measurement data and are also transmitted to the smartphone as part of the configuration data service.

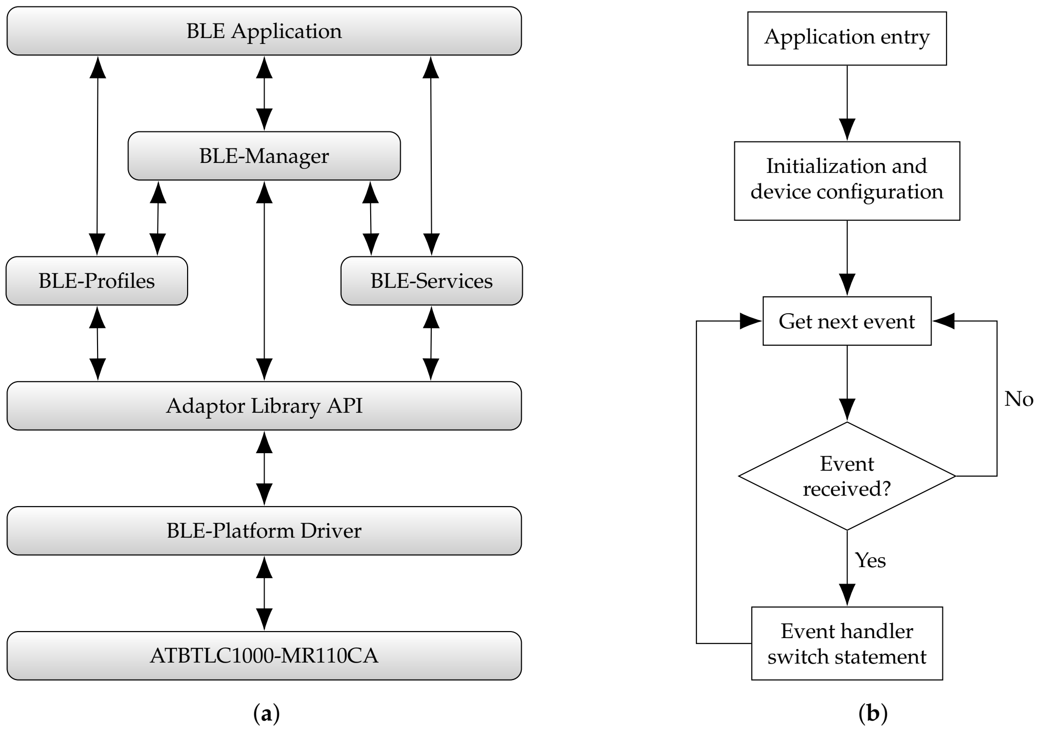

Figure 4. BluSDK software architecture and general application flow. (**a**) Software architecture [27]; (**b**) General application flow [28].

After initialization and device configuration is completed, the application handles only Bluetooth events and hardware interrupt requests. Interrupts are requested by the hardware when a measurement sequence of the ADC has been completed or when the software timer has expired.

In the case of an interrupt request from the DMAC, two situations must be distinguished. If no data is currently being collected for a strain measurement, the measurement sequence of the ADC only contains the current value of the battery voltage. Otherwise, the current values of the three strain measurement chains, the current values of the acceleration sensor and the current temperature are also recorded in each measurement sequence. For each of these two cases, a different callback function is stored for the DMAC.

The unipolar raw data from the strain, acceleration, and temperature measurements are shifted by their mean value and temporarily stored as bipolar values. The raw data of the strain measurements contain sporadically occurring spurious peaks due to the close proximity of the connection lines of the strain gauges and the Bluetooth module. Therefore, they are filtered and smoothed in a two-step procedure. In the first step, the median is determined from eight consecutive measurements. In the second step, each measured value is compared with a limit value, which is calculated based on the median and the maximum transferable difference values. If a measured value exceeds this limit, it is replaced by the limit value. In this way, disturbances can be filtered out that are not wider than three consecutive measured values or 7.5 ms. After completion of eight measurement sequences, a new data packet is assembled with the measured values from the strain gauges and the acceleration sensor and transmitted to the smartphone via Bluetooth. In each 128th data packet, a temperature measurement value and a battery voltage value are transmitted instead of the accelerometer data.

In this way, 24,000 strain readings from each measurement chain, approximately 2977 accelerometer readings, and about 23 temperature and battery voltage readings, respectively, are transmitted per minute. Due to the limited space in the data packets, the eight strain measurement values per measurement chain are not transmitted as independent values, but as one 10-bit wide base value and seven 4-bit wide difference values. This means that 14.25 octets per data packet are occupied by the strain measurements, 4 octets by accelerometer data or temperature and battery voltage data, and 1 octet for the numbering of the packets. The remaining 6 bits within each data packet are not used.

The example in Figure 5 shows a section of measurement data measured with an early test system. This system captures 512 values per second, uses an operating voltage of 5 V for the measuring bridges and amplifies the signals from the strain gauges by a factor of 200. In the marked area, the measured curve of strain gauge 3 has its maximum rise when viewed over several measured values. This range includes 10 time steps in which the measurement signal changes by 96.272 mV.

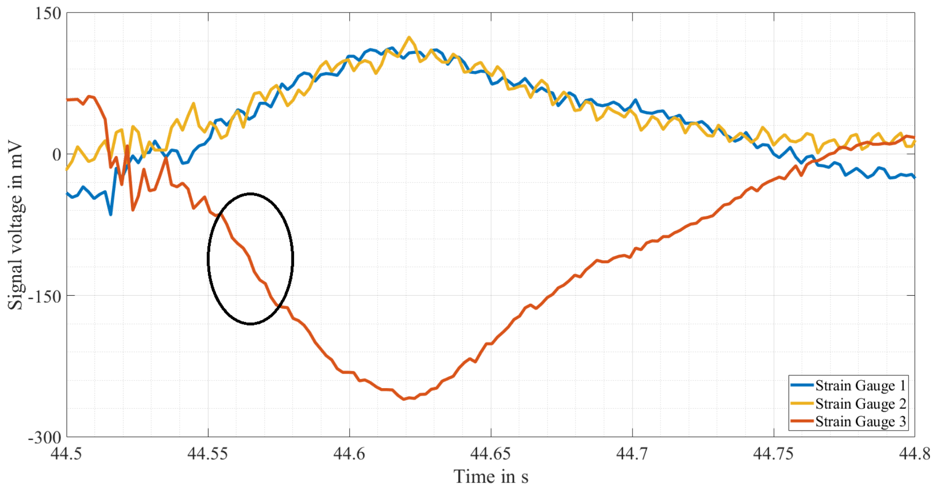

Figure 5. Example of measured strain gauge signals using an early test system.

In the system described here, the same strain gauges and the same circuit structure are used. The marked area would have a width of 7.8125 time steps and with the same external load the measurement signal would change by around 19.72 mV after the amplifier. This corresponds to an average signal change of 2.524 mV per time step. With a reference voltage of 2.048 V and a resolution of 10 bits, this corresponds to a change in the digital measured value of 1.26 digits per time step. The selected compression method allows maximum changes between two successive measured values of $+7$ and -8 digits, respectively, and should thus work well for the strain measurements.

The voltage of the battery is continuously monitored. If ten consecutive readings are below the limit of 3.4 V, the battery is disconnected from the rest of the system to prevent deep discharge.

The software timer interrupts the normal program flow when one of the following situations occurs:

- The Bluetooth advertising information is broadcast for five minutes without establishing a Bluetooth connection.
- After establishing a Bluetooth connection, the measurement data service is not activated within one minute.
- The application initiates the Bluetooth disconnection but does not receive a confirmation event from the BluSDK within one minute.

If the measurement data service is not activated, the application terminates the Bluetooth connection. In the other two cases, the application turns off the operating voltage of the MC.

5. Smartphone

5.1. Software Design

For the mobile application, smartphones are used as hardware platform, running the Android operating system. The application was created with the following settings:

- compileSDKVersion 29

- targetSDKVersion 26
- minSDKVersion 23

This means the application has been compiled on Android version 10, released at the end of Q3 2019, is intended for use with version 8.0 (Oreo), released in Q3 2017, and should be usable from version 6.0 (Marshmallow), released in Q4 2015.

The generic attribute profile (GATT) [23], which is based on the attribute protocol (ATT), is used to transmit the data between smartphone and embedded system. The embedded system acts as GATT server and the smartphone as client. The software flow of this application is shown in Figure 6. The software was implemented in Java. Therefore, an object-oriented approach was pursued.

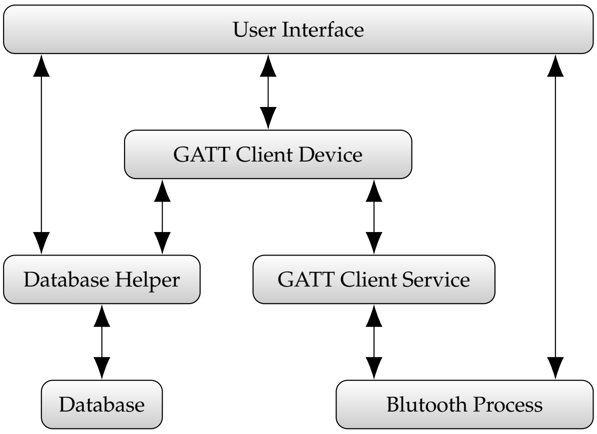

Figure 6. Software flow architecture of the smartphone application.

The device scan is started manually by the user from an instance of the dedicated "BleDeviceScanActivity" class. This class was derived from the "AppCompatActivity" class. For each device that is found, an instance of the "BleSimpleDevice" class is created. The MAC (media access control) address of the device, the name and the current RSSI (receive signal strength indicator) value are handed over to the constructor. The instances of this class are added to the device list that is displayed to the user. The two main tasks of this class are to test if the device is a ski pole and to store the device data. If it is a ski pole, a designation is retrieved from the database, which currently consists of the abbreviation of the project designation and a two-digit number. This is to simplify the user's work with the application, since the MAC address cannot really be used intuitively as a device identifier. Regarding the storage function for the device data, the class implements a callback function that is executed when parameter values of the device change.

If a ski pole is selected for further use from the device list, an instance of the "SkiPole" class is created for it, which inherits from the "BleGattClientDevice" class. If the user activates the connection to the ski pole, an instance of the "BleGattClientService" class is used to establish the connection, request the device information and the configuration data, and start the transmission of the measurement data. The user is informed about the status of the Bluetooth connection. During the transmission of the measurement data, the user also sees the charge status of the battery in the ski pole and a continuous visualization of the force measured on the ski pole.

Once the user has selected an athlete and at least one ski pole for the current training session, it is possible to record the data in an SQLite database. For this purpose, an instance of the "DatabaseHelper" class is used, which implements the mediator pattern [29].

If one or more training sessions have been recorded, they will be displayed to the user in a list when he switches to the database management view. The user can select training sessions in this list and save the corresponding data in a csv-file. The name of this file is generated automatically and contains the name of the athlete as well as the start and the end of the training session.

5.2. User Interface

The application was developed for German-speaking users and contains five views. Each of these views inherits from the class "AppCompatActivity". The view that is used to launch the application has no controls or displays. It is used to initialize the application. This includes the following steps:

- Get the handle of the Bluetooth system service (BluetoothManager);
- Test if the smartphone supports BLE;
- Get a handle for the Bluetooth adapter;
- Test if Bluetooth is available for the application;
- Test if the application has been granted the required access rights and request them from the user if necessary;
- Connect to the database;
- Display the training session view.

The training session view (Figure 7) is the central view of the application. It offers the user the possibility to select an athlete and up to two ski poles, control the data recording, switch to the database management view and exit the application. The last two options are accessible via the options menu. In addition, this view provides displays to visualize the status of the Bluetooth connection to the ski poles, the charging status of the batteries in the ski poles and the currently transmitted measurement data.

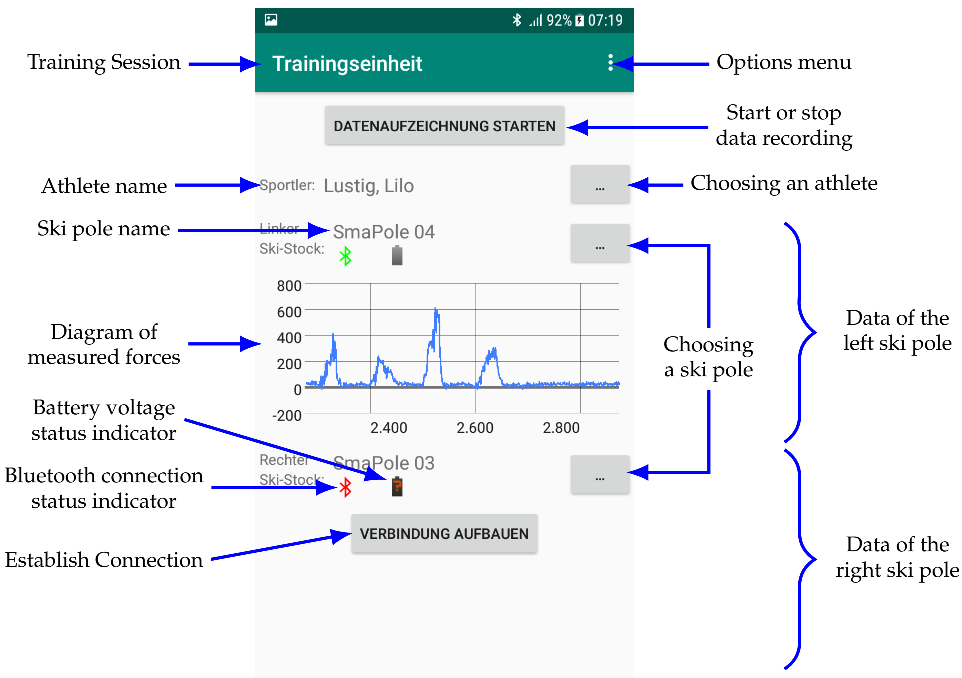

Figure 7. Training session view.

The view for entering the name of an athlete (Figure 8) is shown when the user presses the corresponding button in the training session. Here, it is possible to type in a name or select a name that is already known and stored in the database. From this view is only the way back to the training session possible.

The Bluetooth device search view (Figure 9) opens when the user presses the corresponding button for one of the two ski poles. At the same time, pressing this button deletes any information that may have already been stored for that ski pole during the training session. Pressing another button starts the scan. While the device search is running, a bar shows the progress. All devices found by the smartphone are presented to the user in the form of a list. The devices are sorted in ascending order by MAC address, but the ski poles are placed at the top of the list. Furthermore, from this view, the user can only go back to the current training session.

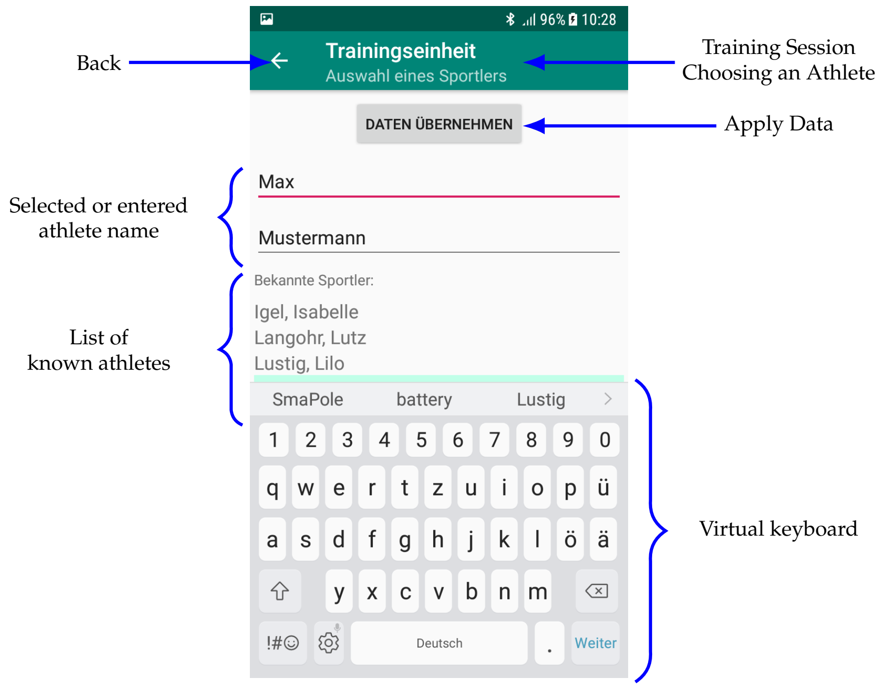

Figure 8. Input of the athlete name.

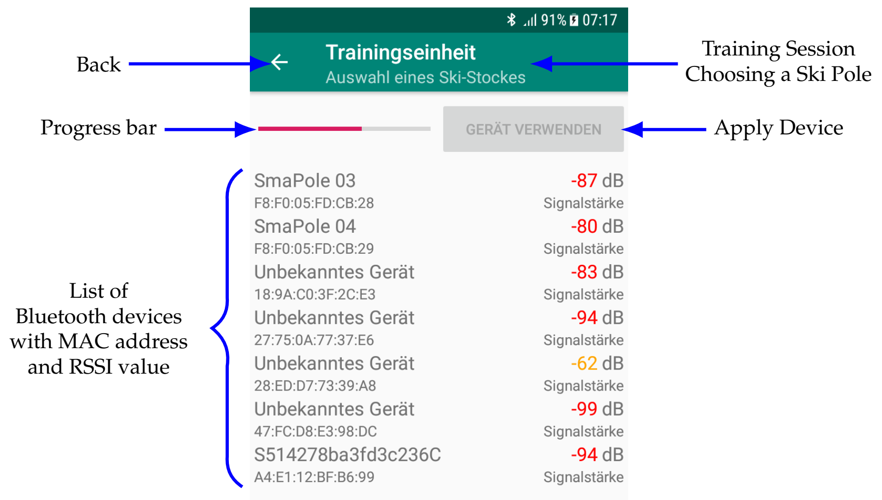

Figure 9. Bluetooth device scan view.

The database management view (Figure 10) lists all the training sessions stored in the database and allows the user to select and export them to a text file. The training sessions are sorted alphabetically by the athlete's name and in ascending order by date. The options menu can be used to switch to a new training session or to exit the application.

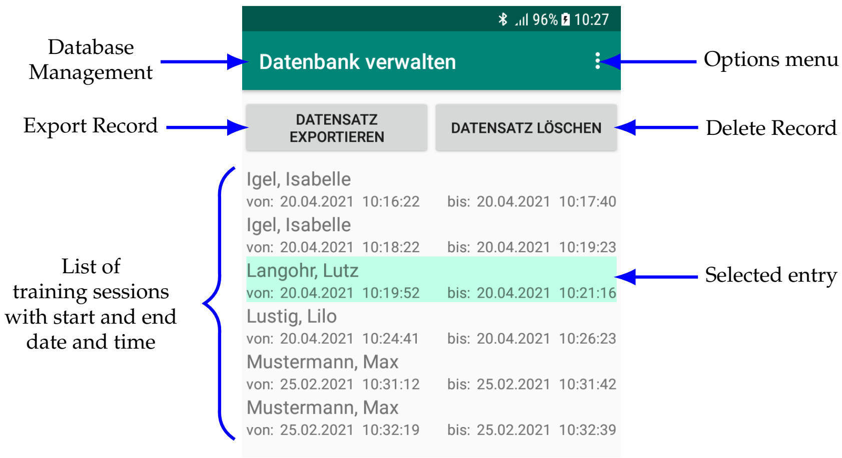

Figure 10. Database management view.

6. Conclusions

The special practical benefit of the presented measuring system is the non-reactive applicability in diagnostics and training. The described construction features, the small weight, and the positioning of the measuring system on the top end of the ski pole contribute to a operational feeling that is comparable to any other ski pole used in cross-country skiing. When running, the athlete virtually does not feel a difference between a conventional ski pole and a ski pole equipped with the described measuring system. From the perspective of sports science, the presented measuring system offers completely new ways of looking at things. The measurement approach chosen here using the deformation of the pole to infer the forces acting on it makes it possible to understand the characteristics of the bending as an efficiency parameter. This means that depending on how the pole is used by the athlete, statements can be made about optimising the execution of the movement. The recording of relevant movement parameters as well as the individual monitoring of their progress offers an optimal possibility to check interventions in technique training or, for example, to shed light on the influence of endurance training and the associated fatigue on the quality of the movement technique. The presented measuring system is a very suitable instrument for technique diagnostics and at the same time enables live feedback training. It should also be noted that the additional recording of the position of the ski pole in space at any time during the measurement allows the use of the measuring system in various sub-techniques of cross-country skiing to precisely describe events in a biomechanic context. The measurement system can thus contribute to the understanding of optimal pole use in cross-country skiing.

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References

1. Vähäsöyrinki, P.; Komi, P.; Seppälä, S.; Ishikawa, M.; Kolehmainen, V.; Salmi, J.; Linnamo, V. Effect of Skiing Speed on Ski and Pole Forces in Cross-Country Skiing. *Med. Sci. Sport Exerc.* **2008**, *40*, 1111–1116. [CrossRef] [PubMed]
2. Nilsson, J.; Jakobsen, V.; Tveit, P.; Eikrehagen, O. Pole length and ground reaction forces during maximal double poling in skiing. *Sport. Biomech.* **2003**, *2*, 227–236. [CrossRef] [PubMed]
3. Clauß, M.; Herrmann, H. Angewandte Biomechanik im Leistungssport am Beispiel des Skatens im Biathlon. In *Biomechanik als Anwendungsforschung-Transfer Zwischen Theorie und Praxis*; Czwalina: Hamburg, Germany, 2004; pp. 50–57.
4. Millet, G.; Hoffman, M.; Candau, R.; Clifford, P. Poling forces during roller skiing: Effects of technique and speed. *Med. Sci. Sport Exerc.* **1998**, *30*, 1645–1653. [CrossRef] [PubMed]
5. Holmberg, H.; Lindinger, S.; Stöggl, T.; Eitzlmair, E.; Müller, E. Biomechanical analysis of double poling in elite cross-country skiers. *Med. Sci. Sport Exerc.* **2005**, *37*, 807–818. [CrossRef] [PubMed]
6. Stöggl, T.; Kampel, W.; Müller, E.; Lindinger, S. Double-push skating versus V2 and V1skating on uphill terrain in cross-country skiing. *Med. Sci. Sport Exerc.* **2010**, *42*, 187–196. [CrossRef] [PubMed]
7. Stöggl, E.; Holmberg, H. Three-dimensional Force and Kinematic Interactions in V1 Skating at High Speeds. *Med. Sci. Sport Exerc.* **2014**, *47*, 1232–1242. [CrossRef] [PubMed]
8. Göpfert, C.; Holmberg, H.; Stöggl, T.; Müller, E.; Lindinger, S. Biomechanical characteristics and speed adaptation during kick double poling on roller skis in elite cross-country skiers. *Sport. Biomech.* **2013**, *12*, 154–174. [CrossRef] [PubMed]
9. Pellegrini, B.; Bortolan, L.; Schena, F. Poling force analysis in diagonal stride at different grades in cross country skiing. *Scand. J. Med. Sci. Sport.* **2011**, *21*, 589–597. [CrossRef] [PubMed]
10. Wank, V.; Heger, H.; Schwarz, M.; Rapp, W.; Blab, F.; Schwarz, O. Entwicklung von leistungsdiagnostischen Methoden im Langlauf der Sitzschlittenfahrerinnen und -fahrer (AZ 080402/11). In *BISp-Jahrbuch Forschungsförderung 2011/12*; Sportverlag Strauß: Cologne, Germany, 2012; pp. 101–106.
11. Hladnik, J.; Supej, M.; Jerman, B. Force Measurement System for Roller-Ski Skating. *Tehnički Vjesnik* **2018**, *25*, 1291–1297.
12. Nikkola, A.; Särkkä, O.; Suuriniemi, S.; Kettunen, L. Pole force and inertial measurements to analyze cross-country skiing performance in field conditions. *Proc. Inst. Mech. Eng. Part P J. Sport. Eng. Technol.* **2018**, *232*, 323–333. [CrossRef]
13. Wank, V.; Heger, H.; Rapp, W. Optimierung der Lauftechnik entsprechend den individuellen Voraussetzungen der Athleten im Sitzschlitten-Skilanglauf (AZ IIA1-070403/13). In *BISp-Jahrbuch 2012/13*; Sportverlag Strauß: Cologne, Germany, 2014; pp. 141–146.
14. Hejda, J.; Volf, P.; Mejstřík, J.; Hýbl, J.; Tvrzník, A.; Gerych, D.; Michálek, T.; Oberman, Č.; Bolek, E.; Kutílek, P. Design of Device for Measuring the Load of Cross-Country Ski Poles. In Proceedings of the XV Mediterranean Conference on Medical and Biological Engineering and Computing–MEDICON 2019, Coimbra, Portugal, 26–28 September 2019; Henriques, J., Neves, N., de Carvalho, P., Eds.; Springer International Publishing: Cham, Switzerland, 2020; pp. 640–649.
15. Modler, N.; Winkler, A.; Filippatos, A.; Weck, D.; Dannemann, M. Function–integrative Lightweight Engineering–Design Methods and Applications. *Chemie Ingenieur Technik* **2020**, *92*, 949–959. [CrossRef]
16. Filippatos, A.; Höhne, R.; Maron, B.; Holeczek, K.; Kostka, P.; Modler, N. Development of a composite, load-adaptive leaf spring: A multi-domain approach. In Proceedings of the 6th International Conference on Experiments/Process/System Modeling/Simulation/Optimization (6th IC-EpsMsO), Athens, Greece, 8–11 July 2015.
17. Filippatos, A.; Höhne, R.; Kliem, M.; Gude, M. A composite-appropriate integration method of thick functional components in fibre-reinforced plastics. *Smart Mater. Struct.* **2016**, *25*, 35026. [CrossRef]
18. Weck, D.; Sauer, S.; Adam, F.; Starke, E.; Böhm, R.; Modler, N. Embedded Sensor Networks for Textile-Reinforced Thermoplastics: Sensor Network Design and Mechanical Composite Performance. *Adv. Eng. Mater.* **2016**, *18*, 444–451. [CrossRef]
19. Steinbild, P.; Höhne, R.; Füßel, R.; Modler, N. A sensor detecting kissing bonds in adhesively bonded joints using electric time domain reflectometry. *NDT E Int.* **2019**, *102*, 114–119. [CrossRef]
20. Hohlfeld, K.; Eßlinger, S.; Eydam, A.; Winkler, A.; Weber, T.; Gude, M.; Modler, N.; Gerlach, G.; Michaelis, A.; Schönecker, A.; et al. Integration of Piezoceramic Composites into Structural Components: Effect on the Polarisation State and Polarisability. *J. Ceram. Sci. Technol.* **2019**, *10*, 19–26.
21. Höhne, R.; Filippatos, A.; Pärschke, R.; Modler, N.; Schürer, A.; Wilhelm, A. Evaluation eines innovativen Monitoringsystems zur uniaxialen Stockkraftmessung mittels applizierter Dehnmessstreifen–EviS. In *BISp-Jahrbuch Forschungsförderung 2016/17*, 1st ed.; Jahrbücher des Bundesinstituts für Sportwissenschaft, Sportverlag Strauß: Hellenthal, Germany, 2018; pp. 297–301.
22. Steinbild, P.J.; Hentschel, U.; Schwaar, A.; Dannemann, M.; Modler, N.; Schürer, A.; Wilhelm, A. Strain-based monitoring system for ski poles with low impact on their total mass and inertia. *Procedia Manuf.* **2020**, *52*, 187–192. [CrossRef]
23. Bluetooth SIG. *Bluetooth Core Specification*; Version 5.2; Bluetooth SIG: San Jose, CA, USA, 31 December 2019.
24. Microchip Technology Inc. *SAM L21 Family Data Sheet*; Microchip Technology, Inc.: Chandler, AZ, USA, 2019.
25. Microchip Technology Inc. *TB3185–ADC Gain and Offset Error Calibration on ARM® Cortex®-M0+ Based MCUs*; Microchip Technology, Inc.: Chandler, AZ, USA, 2018.
26. Microchip Technology Inc. *ATBTLC1000-MR110CA Ultra-Low Power BLE Module*; Microchip Technology, Inc.: Chandler, AZ, USA, 2019.
27. Microchip Technology Inc. *ATBTLC1000 BluSDK v6.2 Release Notes*; Microchip Technology, Inc.: Chandler, AZ, USA, 2018.

28. Microchip Technology Inc. *ATBTLC1000 BluSDK BLE API Software Development Guide*; Microchip Technology, Inc.: Chandler, AZ, USA, 2018.
29. Gamma, E.; Helm, R.; Johnson, R.; Vlissides, J. *Design Patterns: Elements of Reusable Object-Oriented Software*, 1st ed.; Addison-Wesley Professional Computing Series; Addison-Wesley Professional: Boston, MA, USA, 1995.