Force Orientation Measurement: Evaluating Ski Sport Dynamics

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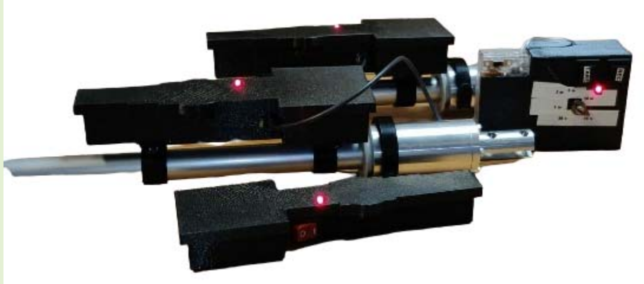

***Abstract*—A modular sensor application for measuring athlete performance in skiing sports was developed. Using inertial measurement units (IMUs) and load cells in a modular system, a force orientation measurement system, FOMS, was developed. A functioning prototype capable of measuring ski sports dynamics was created. Data processing using the system, a validation of the prototype in terms of angle measurement IMU accuracy, example data from in-field athlete testing, and visualization by animations are described. The system developed contains four subsystems: a controller, two pole measuring modules, and a terrain-measuring module. The system structure also allows for additional modules, making the system applicable to different sports. The IMUs use orientation-sensing components to measure pole orientations, which are used to calculate decomposed forces relative to the terrain. Data from different modules are synchronized using wireless communication and saved on SD cards with time stamps. A validation experiment was conducted in which the angles from the modules were compared with the Oqus motion capture system from Qualisys. Examples for athlete testing in both cross country and alpine skiing were calculated from the matrix provided by the different modules and are presented in graphs to evaluate the athlete. In addition, the relative pole/terrain coordinates are visualized in 2D and 3D animations for analyzing the movement pattern in connection with the applied forces, opening up a whole new level of sports analysis.**

***Index Terms*—Dynamics, kinetics, kinematics, ski poles.**

I. INTRODUCTION

IN SPORTS science, the ability to describe sports accurately and objectively is key to further improvements. To complement traditional measurements, such as speed, time, heart rate, and lactate, understanding pole dynamics using force and movements would greatly benefit athletes, coaches, and researchers in performance analysis and product development. In ski sports, one solution is to use a mobile system that can describe pole dynamics to complement existing methods and technology. Ski sports manufacturers have made considerable attempts to make watt and force measuring ski poles. However, prototypes available to coaches and athletes have not provided accuracy or functionality for measuring top-level athletes. The forces exerted by the skier [1] relative to the skiing direction and terrain are of considerable interest to the skiing sports community. A patent from Fisher [2] describes pole forces and angles relative to the ground using force sensors and the inertial measurement units (IMUs); however, this method provides no physical way to present data. In other sports, sensors integrated into sports equipment have captured movements [3] with high accuracy and recognized specific movements [4], [5]; integrating sensors for smart sports equipment [6] makes research and understanding of technique possible and creates the foundation for product development.

In this study, a mobile sensor system for measuring forces and orientation in poles relative to terrain, evaluated with high accuracy, was developed and tested with sit-ski athletes. The system is called the force and orientation measuring system (FOMS), and it can be used to analyze pole usage and athlete performance accurately in different ski sports.

In mobile systems used outside a laboratory, it is insufficient only to measure pole forces and orientation because this would only lead to crude approximations of the terrain. Even GPS is insufficient for snow conditions, and track preparations may alter the terrain. In such situations, GPS may find it difficult to determine the altitude and, in turn, the slope between two data points [7]–[9]. Therefore, when working with professional Olympic and Paralympic top-level athletes, the system must measure the terrain in real time.

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This work involved human subjects or animals in its research. The authors confirm that all human/animal subject research procedures and protocols are exempt from review board approval.

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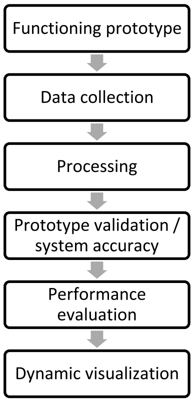

Fig. 1. Experimental work presented in this study describing FOMS.

In different sports, such as cycling, such sensors as power meters are used for in-depth athlete and equipment analysis [10]–[12].

Heart rate is a commonly used parameter in cross-country skiing, but the heart rate of an athlete can behave differently from day to day and change during equipment testing as time progresses [13], [14]. In addition, snow and weather conditions can also vary, making performance evaluation challenging. The athletes and coaches must interpret the parameter to assess the effort exerted.

Another standard measure is blood lactate, for which continuous measurement is in development [15]. Whereas force and watts are real-time effort measurements, blood lactate and heart rate are parameters with inertia [16], [17].

In ski sports, and in cross-country skiing in particular, scientists have attempted to analyze sports using technological tools to measure forces and the orientation of the force relative to the body [18]–[28]. Load cells usually mounted in the handle [18]–[20], [26], [28] are most commonly used to measure ski pole forces. There is also the option of mounting strain gauges directly on the pole [21], [27]. Another method that is only suitable for laboratory environments is the force measuring track of multiple force plates [22]. Goniometers can be used to determine joint angles [18], [20], and a chain of goniometers would determine the pole orientation. Cameras are more commonly used to determine pole orientation [19], [23], [25], but they are challenging to implement outside of laboratory environments. IMUs are a third alternative [23], [29]. They are commonly used to generate input for flight controllers in drones and can accurately measure 3D movement and acceleration.

The FOMS provides the ability to describe ski sports accurately and objectively. The sensor design is applicable for capturing dynamics in ski sports and provides a foundation for evaluating technique and equipment for professional athletes. Data acquired by measuring both the magnitude and direction of the force can be used to analyze the technique, efficiency, and other parameters of interest. The system is modular and, with proper adjustment, can be adapted to measure body movements, providing an opportunity to analyze such sports as running, cycling, and tennis.

II. METHOD

The flow chart in Fig. 1 illustrates the work performed in this study to measure skiing technique accurately.

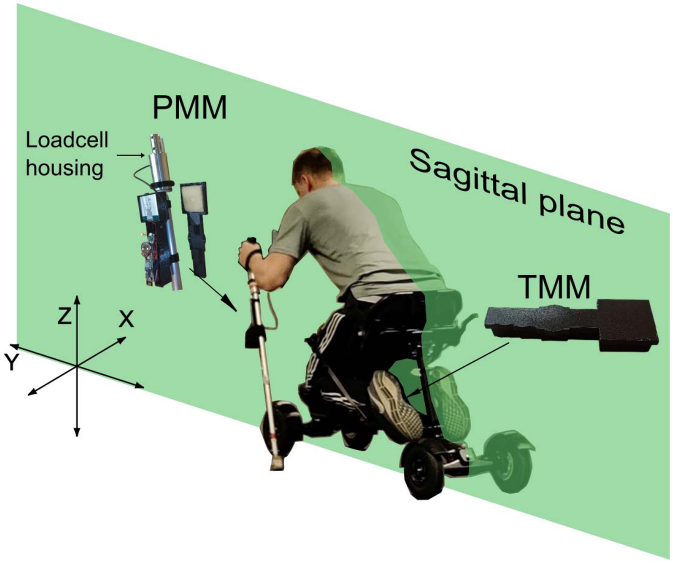

Fig. 2. PMM measures the scale and direction of the normal force in the poles, while the TMM measures the orientation of the roller sit-ski. Forces acting on the skier parallel to the sagittal plane are of particular interest.

The prototype records data with an 80-Hz sampling rate from all sources, synchronized by Bluetooth and time stamps. The activity data are postprocessed in Python, and the accuracy is benchmarked against the Oqus motion capture system from Qualisys.

A. Hardware

The FOMS consists of four subsystems: a controller, a module that senses the travel direction and surface slope (terrain measuring module, TMM), and two modules that measure the orientation of and normal force within a pole (pole measuring module, PMM) (Fig. 2). The controller transmits an integer defining the mode, either "tare" or "record," and an integer that tells the modules how many data to record. All subsystems consist of the same hardware.

1) Microcontroller Unit: A microcontroller unit (MCU) connects all sensors and breakouts. This prototype uses Teensy 4.1 because it covers multiple project needs. It has a large amount of memory (7936K Flash, 1024K RAM) and comes with an integrated real-time clock (RTC) and micro-SD card slot, marking the data with time stamps.

2) Orientation Sensing Component: The FOMS uses BNO085 IMUs to capture 3D motions in both the TMM and PMM modules, providing linear and angular accelerations in all three dimensions with a magnetometer to correct long-term drift. BNO085 operates with an augmented-reality/virtual-reality stabilized rotation vector setting and Serial Peripheral Interface communication. It requires the following start-up calibration:

1) Calibrating the gyro by leaving the sensors on a table for 4–5 s;
2) Calibrating the accelerometers, pointing each side of the module toward the ground while still holding for 3 s;
3) Rotating the module 180° and back around each axis in a motion that takes 4 s per axis;
4) Moving the modules randomly for 1–2 min to allow the calibration to settle.

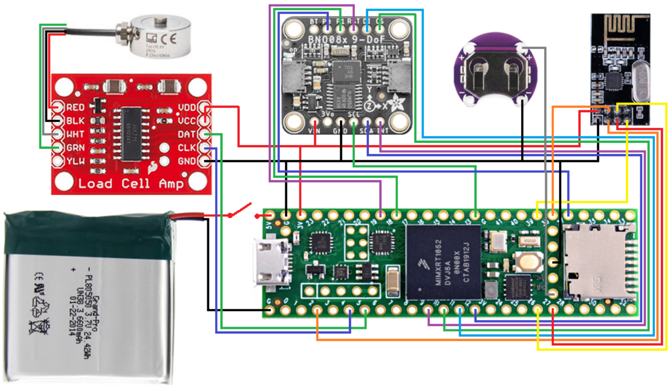

Fig. 3. All components of a PMM in a wiring schematic. Top row from left: load cell and amplifier, orientation sensing component, RTC 3-V battery holder, and wireless communication component. Bottom row from left: power supply and MCU. The TMM is identical, except it has no load cell and amplifier.

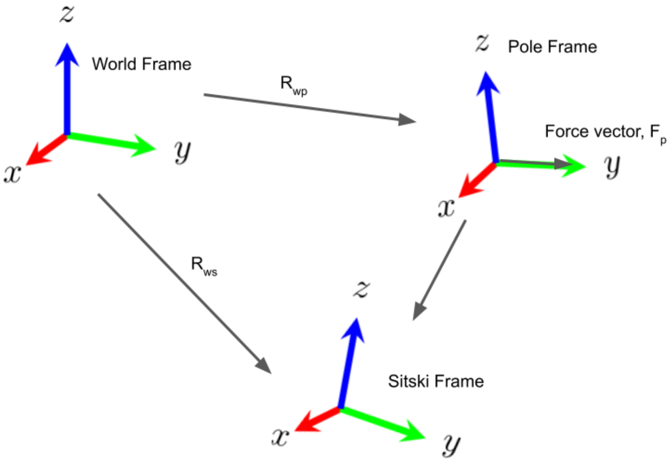

Fig. 4. Illustrated relationships between the different coordinate systems: "world coordinate system" refers to Earth's magnetic field and gravitation.

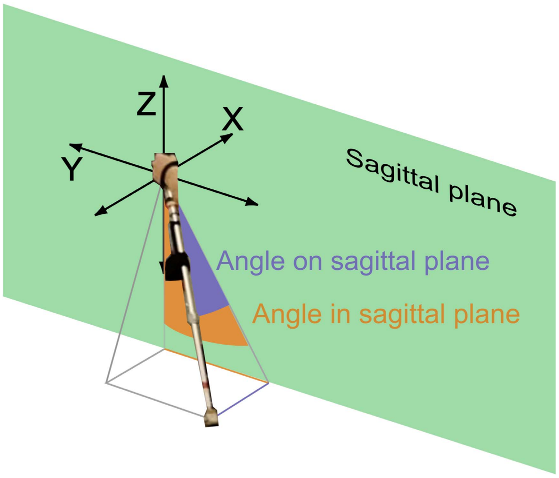

Fig. 5. Illustration of the different angles of interest: the pole angle in the sagittal plane relates to the propulsive force, and the angle on the plane relates to the wasted sideways forces.

3) Wireless Communication Component: Wireless communication is critical for synchronizing multiple sensor modules. An NRF24l01 breakout enables the system to expand with more modules and is adaptable for more-complex techniques and other sports.

4) Power Supply: A LiPo battery, model PL805050, by Grand-Pro functions as a power supply, delivering 3.7 V with 8.14-Wh or 2200-mAh capacity. All power consumed by the other modules runs through the MCU, which steps it down to 3.3 V. This type of power supply is easy to recharge and carries sufficient power for an entire day of testing.

The complete wiring schematics of the PMM module are shown in Fig. 3.

B. Data Processing

Data are stored as.txt files on the SD cards in each module. Each row of data contains a time stamp, a scalar force measurement, four quaternion components, the estimated accuracy of the sensor, and calibration status. The IMUs are calibrated to provide an identical output when oriented in identical directions. The individual rotation matrices for the coordinate system of each module relative to the world coordinate system are calculated from the quaternions. From these matrices (Fig. 4), the rotation matrix is calculated using Equation (1), transforming a vector from a pole coordinate system to the terrain measuring module coordinate system (TCS). A force unit vector (FUV) of length one is parallel to the pole. If the FUV is transformed to the TCS and multiplied by the scalar force, one obtains the forces acting on the body from the pole, as in Equation (2). Plots are generated using Python and Matplotlib.

$$R_{ps} = R_{wp}^{-1} R_{ws} \tag{1}$$

$$F_s = F_p F_{ps} \tag{2}$$

C. Validation Experiment

An experiment was conducted to validate the accuracy of the proposed system. The FOMS was tested on a treadmill by roller sit-skiing with the TMM mounted in a level position on the Spike sit-ski (Exero) and PMMs mounted on aluminum poles. An Oqus camera system (Qualisys) captured the 3D motion of the skier with a 100-Hz sample rate and provided a benchmark for the FOMS. First, a validation experiment was performed on a flat treadmill at 5, 10, and 15 km/h. Second, a longer run with varying inclinations was performed to validate the TMM output. Fig. 5 shows the angles used to validate the PMM modules, in addition to the accuracy of the terrain measured by the TMM.

III. RESULTS

The following figures present the results from the accuracy benchmark and example data from the cross-country and Paralympic alpine sit-skiing with a world-class professional athlete.

A. Validation Data

In Fig. 6, the right pole angles in the sagittal plane, as measured by Oqus and the FOMS, are compared. The sagittal

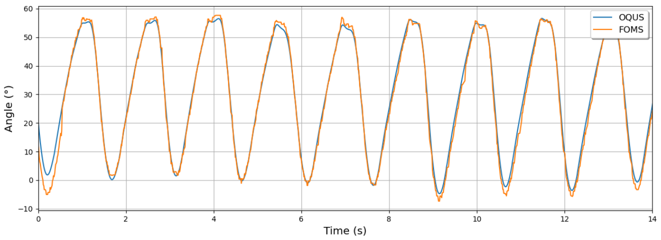

Fig. 6. Validation data for the right pole at 5 km/h, angle in the sagittal plane.

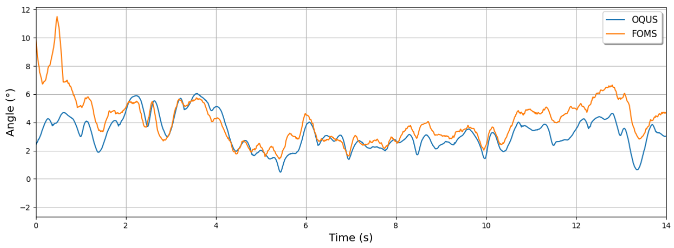

Fig. 7. Validation data for the right pole at 5 km/h, angle on the sagittal plane.

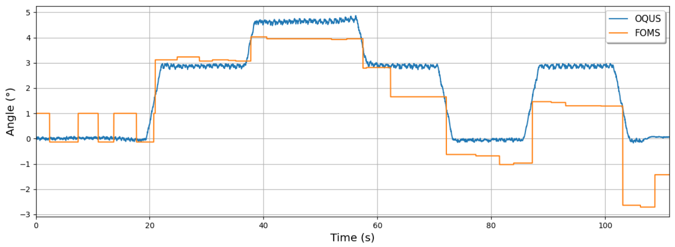

Fig. 8. Validation data for the sit-ski TMM at 0°, 3°, and 5° inclinations.

plane angle was used to calculate the propulsive and static force components of a pole stroke.

The sagittal plane root mean square error (RMSE) (Fig. 6), for poling at 5 km/h, was 2.1°. The RMSE values were 8.0° and 8.3° at 10 and 15 km/h, respectively.

Fig. 7 shows a comparison of the measured angles of the two systems on the sagittal plane.

The RMSE on the sagittal plane in Fig. 7 at 5 km/h was 1.6°. For 10 and 15 km/h, the RMSE values were 10.8° and 5.3°, respectively.

Fig. 8 shows the measurements by the two systems of the inclination of the treadmill. The RMSE was 1.1°.

B. Example of Analysis Data

A force plot is one of many outputs. Fig. 9 shows the force plot of the right pole at 5 km/h. The propulsive force is calculated using the angles of the pole PMM relative to the sit-ski TMM.

In Fig. 9, the bounces from the pole plant created by the rubber tips used for roller skiing on treadmills are visible, as well as the negative force that occurs when the poles are lifted after a stroke. A fast Fourier transformation is used to find the frequency (in this example, 0.74 Hz). The efficiency is the propulsive fraction of the total force, 43.91%, during the 14-s window.

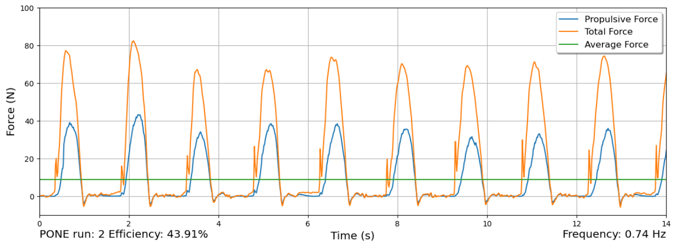

Fig. 9. Force outputs from right pole at 5 km/h.

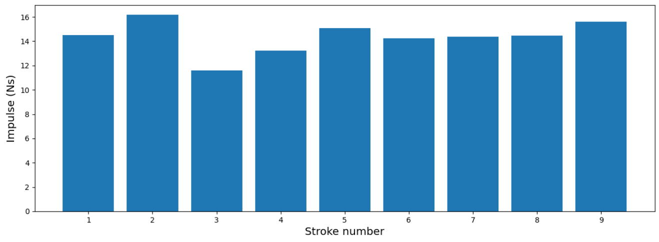

Fig. 10. Impulse per stroke at 5 km/h.

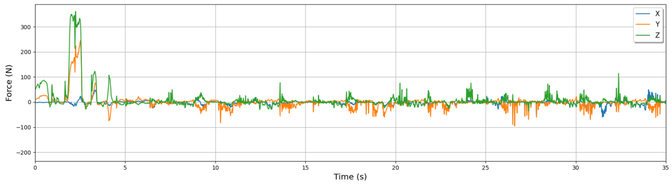

Fig. 11. Example sample of decomposed forces in alpine sit-skiing.

Fig. 10 shows the impulse generated from the right pole at 5 km/h.

Impulse can capture the effort exerted by athletes in sports where large fractions of the forces are static and are found for each stroke by integrating the interpolated force and time between the data points.

Fig. 11 shows the data from a run performed with a Paralympic alpine sit-skier. Sit-skiers use their poles (outriggers) for support in turns and maintain their balance.

The forces shown in Fig. 11 are the decomposed forces relative to sit-ski. All negative forces in the Y-direction were pure loss, breaking the athlete.

C. Example of Data Visualization

Multidimensional data can be difficult to understand in 2D plots. Therefore, multidimensional plots can be used to visualize the data better. Fig. 12 shows a 2D animation of orientation and forces simultaneously. In addition, the athlete motion is animated in 3D in Fig. 13, creating a visual presentation for a more in-depth understanding of the data.

IV. DISCUSSION

In this article, multiple sensors have been presented for measuring force and orientation in ski poles relative to the

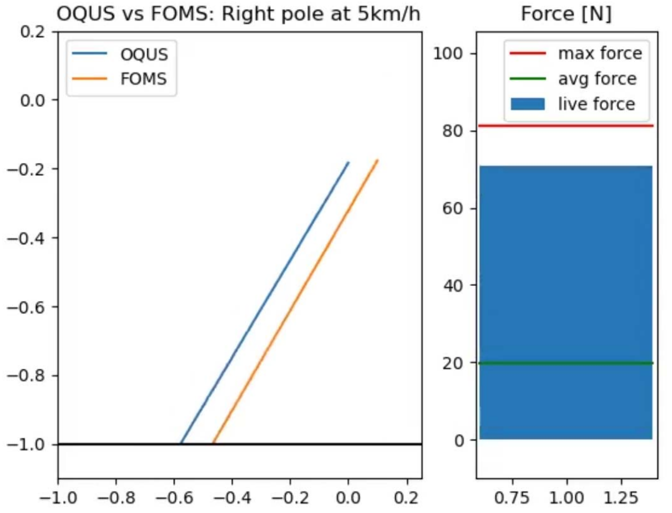

Fig. 12. 2D animated visualization of the validation data.

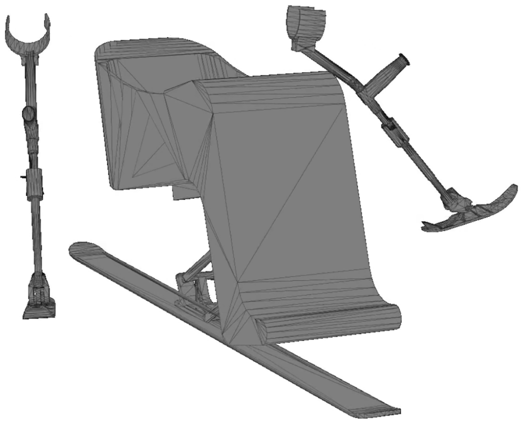

Fig. 13. 3D animated visualization of movements during Paralympic sit-ski alpine.

body and terrain. Using the FOMS in addition to GPS, heart rate, lactate, and VO2 provides a thorough understanding of ski sports. Furthermore, because a large part of the forces during a stroke is static and watts are calculated from both force and distance, not including the static forces, the FOMS provides an accurate understanding of ski sports kinetics and dynamics.

A validation test was performed to determine the accuracy of the FOMS orientation benchmarked against the motion capture system Oqus. Different analytical graphs generated by the data from the system have been obtained for use during athlete and equipment testing.

The results show that the FOMS can determine the pole orientation with good accuracy. At low speeds (5 km/h), the PMM RMSE was only 2.1° in the sagittal plane. As the speed and pole acceleration/frequency increased, the RMSE increased to 8.3°. At the start of the run, the BNO085 auto-calibrating feature increased the accuracy of the system during testing.

The TMM measured the terrain incline mounted on the sit-ski, providing an RMSE of 1.1°, a significant error relative to the inclination. Because all modules continuously record the calibration status and estimated accuracy, the data from the TMM provided a low calibration status during the validation test. Before testing, all sensors showed excellent calibration status, but it dropped as the test progressed. Magnetometers are sensitive to changes in the magnetic field, and the treadmill may have provided sufficient noise to affect the module. All sensors showed a continuous excellent calibration status during outdoor athlete testing.

The FOMS was first designed to gather data on Paralympic alpine sit-skiing [30], where the TMM was mounted on the sit-ski, and the PMMs on poles called “outriggers.” However, the system can be implemented on all ski poles and skis outside the laboratory. Examples of parameters to analyze in cross-country skiing are technique, efficiency, maximum and average effort, and poling frequency. In alpine skiing, the system can be used to analyze how the athlete skis out of the starting ramp and how the skier uses the poles in relation to the body, as well as loss resulting from friction when using the poles for support.

The FOMS is a modular system, and it can easily be expanded to tailor data capture for more-complex techniques. For example, by adding another TMM, the dynamics can be tracked in techniques where the legs move independently. Building on the modular nature of FOMS, it is possible to adapt the system to unrelated sports, where other sensors are used to measure ground contact forces.

The FOMS opens new opportunities for technique and equipment analysis. This can help coaches, athletes, researchers, and equipment manufacturers acquire objective feedback in their quest for improvement. The prototype presented is made of highly accessible components using Python code to extract data and animate 2D/3D videos. The TMM and PMM sensors presented are the first-stage prototype and can easily be made lighter and smaller, fitted into existing equipment, such as ski-pole handles and ski-binding.

V. CONCLUSION

A multisensor system was presented for measuring the forces and orientation of the poles and terrain used in different ski sports. The system accuracy was determined through a validation experiment with a roller sit-ski on a treadmill, with a maximum RMSE of 8.3°. This system makes it possible to analyze athlete and equipment performance in multiple ski sports by measuring the relative motion between the sensor modules. Examples using athletes in cross-country and alpine skiing provide a thorough understanding of how propulsion is created and animated together with data for analysis. In addition, the applicability of the force orientation measurement system to analyzing athlete performance was demonstrated, making research on equipment and technique possible.

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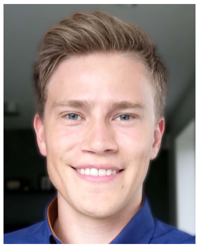

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