Direct Brake Force Measurement in Cycling: Development of a strain gauge based sensor

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***Abstract*—This paper discusses the design, development, and implementation of a novel brake force measurement sensor for bicycles. The sensor was designed to gain insights into the dynamic nature of braking forces in cycling, ultimately leading to valuable insights for performance optimization. A adapter was developed and manufactured, engineered to withstand expected mechanical loads, and provide sufficient deformation to be measured by strain gauges. The mechanical strength was validated through finite element analysis ensuring mechanical integrity under field testing scenarios. Utilizing a power-efficient microcontroller (nrf52840, ESP32), the sensor data was read and transmitted wirelessly to a cross-platform mobile application developed programmed with Flutter. The application facilitated sensor calibration, real-time data visualization and provides recording options for future development. Research on the physics of braking, physical requirements of the sport and feedback mechanisms in training was also incorporated, with downhill mountainbiking in mind. The sensor was fully operational and a test run was conducted. The obtained data were analyzed and visualized with a Python Script.**

I. Introduction

DOWNHILL mountain biking, a subset of off-road cycling, has gained widespread popularity as both a recreational activity and a competitive sport. This trend has led to a marked increase in competitive downhill events from 23 in 2000 to 474 in 2013, accommodating approximately 67,000 competitors annually. This sport involves an individual descending a trail in a time trial format, negotiating a multitude of natural and man-made obstacles such as rocks, jumps, sprint sections, corners, and coasting sections. Courses greatly vary in length, but the fastest competitors typically finish races within two to five minutes. [1]

While other mountain biking disciplines, such as cross-country, place a substantial emphasis on the aerobic fitness of the rider, downhill mountain biking primarily focuses on the technical skill and the ability of the rider to handle the bike under varying terrain conditions. Courses can utilize either natural terrain (NT), using the pre-existing landscape topography, or man-made (MM) courses, specifically sculpted with diggers for a smoother, flowing riding experience, each of which may influence the activity profile of the sport. [2]

The physiological and psychological requirements of downhill mountain biking have not been comprehensively studied. Aerobic capacity, anaerobic power, dynamic skill, upper body muscular function, and anxiety control have been identified as necessary elements for success in related disciplines. However, the differences in event duration, self-propulsion requirements, used terrain, and objective risk between these disciplines make it challenging to draw firm conclusions for downhill mountain biking. [1]

Moreover, conventional methods such as heart rate monitoring, power output, and gas analyses that have been utilized to understand the sport's activity profiles have shown limitations, necessitating the exploration of alternative methods. Technological advancements in the form of Global Positioning Systems (GPS) and triaxial accelerometers now offer potential improvements in activity profiling, promising real-time, quick, and accurate analysis that is not limited by the requirement of a clear view of the sporting area. [2]

By combining established technologies like strain gauges with new applications in sports, this study aims to compensate the lack of brake force measurements in downhill mountain biking. It is hoped that by understanding the interaction between the rider, the brake system, and the terrain, a performance boost can be obtained. This study focuses on developing such a system and deploying it in field testing.

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II. Methods and Literature

A. Physiological Demands in Mountainbike Downhill Sport

To better understand the physical requirements and improvement potentials in downhill mountainbiking a literature review about this particular field was conducted. The physiological requirements of downhill (DH) mountain biking are complex and multi-faceted. Chidley et al. hypothesised several variables of importance to DH performance including rider skills, psychological factors, and aerobic capacity. These variables were confirmed by both an expert panel and a survey of DH riders. Particularly, the skill, self-confidence, aerobic capacity, lower body anaerobic power, handgrip endurance, bike set up, and past experience were recognised as vital for DH performance. [1]

Notably, the skill and handgrip endurance accounted for 73% of variance in downhill ride time at a DH competition, and laboratory studies confirmed the substantial role of aerobic components in DH events. Conversely, lower body anaerobic power and self-confidence did not explain DH performance in primary analyses. The potential correlation between better handgrip endurance and improved performance could be attributed to the superior upper body muscular endurance of the skilled riders or to more efficient terrain tackling and relaxed grip due to increased confidence. [1]

The study identified a high aerobic demand of the sport, and during the simulated DH competition, oxygen uptake was 86% of the participants' maximal aerobic capacity. Interestingly, despite mean power output at the crank being only 9% of peak values in DH and pedalling periods making up only 55% of total ride time, 90% of DH ride time was completed above the first ventilatory threshold and 43% above the second ventilatory threshold. [1]

Self-confidence was not directly related to performance, but a re-specified analysis model showed that skill influenced self-confidence which in turn affected performance. Aerobic capacity was also found to significantly relate to performance in this post hoc analysis. [1]

Miller et al. investigated the performance and physiological demand of either pedalling or coasting while navigating a cross-country mountain bike (XCO-MTB) descent. They found that the addition of propulsive work to off-road descending significantly increased oxygen uptake, despite there being no change in downhill performance through the absence of propulsive work. They also discovered that the mechanical and soft tissue damping associated with road descents resulted in significantly decreased oxygen uptake and heart rate. [3]

The findings of both Chidley et al. and Miller et al. highlight the complex interplay of physiological and psychological variables in determining performance in downhill mountain biking. Further research is needed to fully understand these relationships and to develop training and strategies that can maximise performance in this demanding sport. [1] [3]

B. Feedback Mechanisms in Elite Sports

In the highly competitive arena of elite sports, minor differences often dictate the outcomes. Coaches and athletes increasingly rely on integrated approaches that meld sports science, engineering, and computer science to fine-tune performance. A. Baca from the Department of Biomechanics, Kinesiology and Applied Computer Science at the University of Vienna conducted research about feedback mechanisms training. Feedback systems, which provide either 'Knowledge of Results' (KR) related to overall performance measures or 'Knowledge of Performance' (KP) concerning the specific nuances of how a movement is performed, play a critical role. Advanced technology, including artificial intelligence (AI), facilitates real-time feedback, make these systems more available for both athletes and coaches. [4]

Technological advancements have particularly enabled the development of user-friendly systems and affordable that are designed with the end-user in mind. The rapid availability and comprehensible presentation of feedback information are crucial for these systems to be effective. Specialized tools in data mining also aid in uncovering subtle patterns from vast data sets, which are often impossible for coaches to manually sift through. However, while the motivational effects of such systems are usually evident, there remains a gap in empirical evidence regarding their sustained effectiveness. [4]

In cycling, the continuous measurement of work rate, particularly power output, provides a wealth of data that can be crucial for training and performance. Methods such as sRPE, TRIMP, and HR-based EPOC are used alongside more sophisticated power output metrics, allowing for a nuanced quantification of individual training and competition sessions. This granularity in data enables cycling to be one of the few sports that can deeply benefit from various mathematical models aimed at understanding the relationship between training impulse and performance. [5]

C. Need for a Brake Force Measurement Device in Professional Downhill Mountainbiking

In the competitive sphere of professional downhill mountainbiking, factors such as rider skill and efficient use of brakes play a significant role in determining race outcomes. Downhill sections in particular demand strategic use of brakes to maintain control and speed while negotiating challenging terrain. Interestingly, the propulsive work performed by the rider, primarily influenced by gravity rather than rider output, becomes a less significant factor in these sections. [6]

Power meters have provided valuable insights into the propulsive work in cycling. However, they only capture propulsive measurements, failing to shed light on the critical interaction between the rider and the terrain, especially regarding braking [6]. A brake force measurement device could offer a deeper understanding of a rider's skill and efficiency. By measuring torque and angular velocity at the brakes, it could quantify the energy removed from the bicycle-rider system during braking. This data could contribute to better strategic planning and optimization of downhill racing performance, where excessive or unnecessary braking could be identified and minimized to save metabolic energy. [6]

Braking efficiency also impacts the pacing strategy of a rider in XCO-MTB. While necessary braking ensures safety and control, excess braking requires additional propulsive work to regain speed, potentially exacerbating glycogen depletion and reducing recovery post high-intensity pedalling efforts [7]. Furthermore, the study of braking data could provide valuable insights into lap performance, with potential correlations between braking variables (like brake work, brake time, and resultant brake power) and lap times [7].

To sum up, a brake force measurement device is a much-needed tool in professional downhill mountainbiking. It offers a potential avenue for a more comprehensive understanding of rider skill, braking efficiency, and performance, thereby enabling more effective training regimes and racing strategies.

D. Requirements for Effective Feedback Systems in Sports

According to existing research, feedback systems are particularly advantageous for athletes when they provide immediate and objective insights during training. However, the design and construction of such systems come with a set of requirements that must be carefully considered. Firstly, precise parameters and accurate measurement systems must be established. This ensures that the data collected is both reliable and actionable. Secondly, the technique parameters should be made as specific as possible to the sport in question. This allows for targeted performance diagnosis and technique analysis. [8]

Another crucial factor is minimization of interference with the athlete's performance. The measurement system should be unobtrusive, allowing athletes to focus on their training rather than the data collection process. Furthermore, the system should provide results that are both fast and easily comprehensible, featuring an easily decipherable graphical user interface (GUI). Importantly, the system should also be mobile and available at the actual training location; otherwise, its applicability is limited to laboratory environments. [8]

E. Physics of Braking

The physics of braking is a fundamental concept that must be understood in order to measure key variables and make further calculations with them. [9].

The brake power P_B, measured in W, is calculated as the product of brake torque and the bicycle's velocity:

$$P_B = \omega_f(\tau_f + \tau_r) \tag{1}$$

In this equation, ω_f represents the angular velocity of the front wheel, while τ_f and τ_r are the brake torques at the front and rear wheels, respectively (Miller et al., 2019).

The brake work W_B, measured in J, is calculated by integrating the product of front and rear brake power over time:

$$W_B = \int_0^t (P_{Bf} + P_{Br})\, dt \tag{2}$$

The brake work completed by a rider slowing down on flat ground equates to the change in kinetic energy when considering aerodynamic drag and rolling resistance:

$$W_B + E_{rr} + E_d = \Delta E_K \tag{3}$$

In this equation, E_{rr} represents the energy lost due to rolling resistance, E_d signifies the energy lost to aerodynamic drag, and ΔE_K is the change in kinetic energy (Miller et al., 2017).

The change in kinetic energy of the bicycle-rider system is given by:

$$\Delta E_K = \left[\frac{1}{2}mv_2^2 - \frac{1}{2}mv_1^2\right] + \left[\frac{1}{2}I\omega_2^2 - \frac{1}{2}I\omega_1^2\right] \tag{4}$$

In this equation, m is the combined mass of the bike and the rider wearing cycling gear, v is the velocity, I is the moment of inertia, and ω is the angular velocity of the front wheel.

The instantaneous kinetic energy can be calculated as:

$$E_K = \frac{1}{2}mv^2 + \frac{1}{2}I\omega^2 \tag{5}$$

In Eq. 5, m and v are crucial. If we consider two riders of different mass, their kinetic energy at any given time is not equal, and therefore the brake work required to slow these two masses will not be equal. More importantly, two riders of the same mass but travelling at different velocities will have different kinetic energy because the kinetic energy of each rider is proportional to the square of their velocity. For example, a rider traveling twice as fast will require four times the brake work to come to a complete stop.

Given the variety of variables, understanding the physics of braking is fundamental in measuring, calculating, and comparing brake power meter measurements, which in turn, have potential utility for training.

1) Calculation of Maximum Braking Moment for a Bicycle: To analyze the braking dynamics of a bicycle, it is crucial to understand the forces and moments acting upon the system. This subsection aims to calculate the maximum moment exerted by the bicycle's braking system, under the constraint that the rear wheel is on the verge of lifting off the ground. The results of these calculations are forwarded in the design stage to ensure the safety of the whole brake system.

Assumptions The following assumptions are made for simplification:

1) The bicycle and the rider are treated as a single system.
2) Static friction is considered, implying the wheel does not skid during braking.
3) Aerodynamic drag and rolling resistance are neglected.
4) The bicycle is moving on a flat surface and in a straight line.
5) The mass distribution of the bicycle and rider is known.

Governing Equations Firstly, the force of gravity F_g acting on the system (bicycle + rider) is calculated as:

$$F_g = m \cdot g \tag{6}$$

where m is the total mass and $g = 9.81\,\mathrm{m\,s^{-2}}$ is the acceleration due to gravity.

The normal forces N_f at the front wheel and N_r at the rear wheel counterbalance the gravitational force:

$$N_f + N_r = F_g \tag{7}$$

At the point of impending rear wheel lift-off, the normal force at the rear wheel becomes zero ($N_r = 0\,\mathrm{N}$) and all weight is supported by the front wheel ($N_f = F_g$). Therefore, the maximum braking force $F_{\text{b,max}}$ is given by:

$$F_{\text{b,max}} = \mu \cdot N_f \tag{8}$$

where μ is the coefficient of static friction between the tire and the road surface.

Finally, the maximum moment or torque T exerted about the front wheel is calculated as:

$$T = F_{\text{b,max}} \cdot h \tag{9}$$

where h is the vertical distance from the ground to the axle height (radius of wheel).

Calculations Given:

- Rider weight $= 100\,\mathrm{kg}$
- Bike weight $= 20\,\mathrm{kg}$
- Axle height $= 351\,\mathrm{mm} = 0.351\,\mathrm{m}$
- Coefficient of static friction $\mu = 0.9$ [10]

The total mass m of the system (bicycle + rider) is:

$$m = 100\,\mathrm{kg} + 20\,\mathrm{kg} = 120\,\mathrm{kg} \tag{10}$$

The force of gravity F_g is then:

$$F_g = 120\,\mathrm{kg} \times 9.81\,\mathrm{m\,s^{-2}} = 1177.2\,\mathrm{N} \tag{11}$$

At the point of impending rear wheel lift-off, the normal force N_f at the front wheel becomes equal to F_g:

$$N_f = F_g = 1177.2\,\mathrm{N} \tag{12}$$

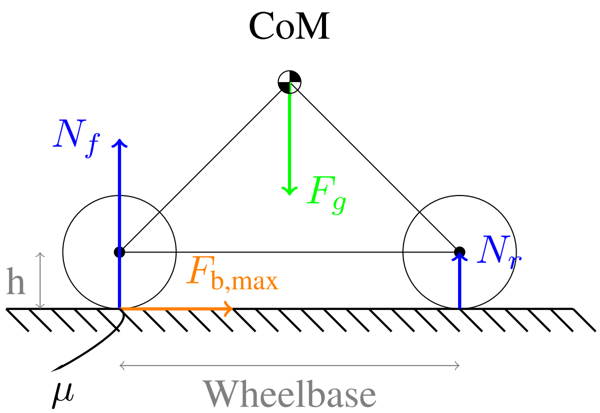

Fig. 1. Diagram illustrating the braking dynamics of a bicycle.

The maximum braking force $F_{\text{b,max}}$ can now be calculated as:

$$F_{\text{b,max}} = 0.9 \times 1177.2\,\text{N} = 1059.48\,\text{N} \tag{13}$$

Finally, the maximum torque T exerted about the front wheel is:

$$T = 1059.48\,\text{N} \times 0.351\,\text{m} = 371.875\,\text{N m} \tag{14}$$

2) Empirical Brake Force Measurements: Recent research has been conducted to empirically measure the achievable brake forces and moments, using two different methods for data collection.

Method 1: Accelerometer-Based Measurements A three-dimensional acceleration sensor (MMA7260Q) with a measurement range set to $\pm 1.5\ g$ was placed on the top tube of the main frame of a mountain bike. The rider was advised to shift back his center of mass and brake as hard as possible without losing rear wheel ground contact. The maximum deceleration measured was $6.62\,\text{m}\,\text{s}^{-2}$. Using Equation (1) from the previous section and a system weight of $120\,\text{kg}$, an actual brake force of $F_{\text{b,actual}} = 794\,\text{N}$ was calculated. [11]

Method 2: Pressure Sensor Measurements Fuji Prescale measurement films were used to measure the contact pressure between the brake pads and the brake disc. A force of $F_{\text{H}} = 100\,\text{N}$ was applied at the brake lever. The measured pressure was $12\,\text{N}\,\text{mm}^{-2}$. The calculated contact force $F_{\text{R}} = 5040\,\text{N}$ and with a friction coefficient $\mu = 0.5$, the brake force $F_{\text{B}} = 775\,\text{N}$ was determined. [11]

Implications for further development The empirical measurements yielded actual brake forces of $F_{\text{b,actual}} = 794\,\text{N}$ and $F_{\text{B}} = 775\,\text{N}$, which are in proximity to the theoretically calculated maximum brake force of $F_{\text{b,max}} = 1059.48\,\text{N}$. This information is fed forward for the dynamic stability assessments in the development stage, although these forces are rarely reached in real-world scenarios due to dynamic effects. Since there is the inherent risk of the rider going over the front wheel, the calculated maximum and empirically measured brake forces are seldom reached in real-life scenarios. Theoretically the are approached only when coming to a full stop in the last moments of braking.

3) A Sidenote on Braking Dynamics During Skidding: In the previous chapters only brake force and power correlations during static friction were considered. In real world riding conditions also slipping occurs, mainly when the back wheel locks up by exerting too much brake force. The tire starts slipping over the ground and the energy is not dissipated at the brake system, but at the contact point between tire and ground. Assessing the dynamics of skidding during braking events in biking are vital for correctly estimating energy losses.

Miller et al. describe that using a brake power meters measuring the torque and angular velocity at each wheel fails to reflect the energy loss during rear wheel skidding. The authors of the study validate an alternative approach: calculating rear brake power by using the angular velocity of the front wheel and the torque of the rear brake. Results show that this method provides accurate estimations on paved surfaces, displaying strong correlations between estimated energy removed and the change in kinetic energy. However, on gravel surfaces, measuring skidding becomes challenging due to factors such as tire deformation, uneven terrain, and lateral skidding. While the results show the significance of energy lost to skidding the study also underscores the need for improved methods to precisely determine the bicycle's linear velocity during skidding events, particularly on gravel. [12]

While in theory brake power has to be obtained from both wheels for accurate estimation of total brake power, this thesis is more focused on the development of the sensor and therefore will focus on only wheel.

F. System Installation

The brake force sensor was mounted on an XCO-MTB (Canyon, Koblenz; Model Exceed 2019 Size M) at the fork, positioned between an adapter and the brake caliper. This adapted from the PM Standard 160, a fork prerequisite, to a 200mm sized disc. This specific positioning is critical for the accurate functioning of the sensor. Potential complications arising from improper installation include the risk of the brake caliper being positioned incorrectly or loosely. Such challenges can lead to calibration and testing problems, such as rubbing brakes or even a complete loss of braking capabilities.

Prior to the sensor's installation, the brake caliper and wheel were disassembled from the bike. There was no additional cleaning before the procedure. To ensure proper accommodation of the sensor housing, the brake disc size was transitioned from its initial 180 mm to 200 mm, creating more space in the fork region.

For the installation, a standard 5mm hex wrench is needed. In addition, a torque wrench was utilized to ensure the bolts were tightened to the recommended torque of 9.5 Nm, as specified by the manufacturer for the brake caliper. Before tightening the screws to recommended torque, correct alignment of the brake caliper was ensured to avoid disc rub. This was meticulously resolved by adhering to the manufacturer's installation guidelines.

The sensor's placement is right between an adapter on the fork and the brake caliper. Using M6 screws, the sensor was firmly bolted onto the adapter with the specified torque.

Simultaneously, the brake caliper was attached to the sensor array using M6 screws of the same torque. It was ensured that besides from the specified contact points at the screws no additional contact between sensor and adapter or brake caliper were established to ensure force distribution as intended. Also clearance of the disc brake was checked.

The sensor's connection to the microcontroller is established with protected wires. To protect them from getting in contact with rotating parts such as the disc brake or spokes they are held in place with electrical tape. As a note, due to the lack of moisture resistance, it is imperative to conduct tests in dry conditions only.

The installation can be done in about one hour by an individual. A bike stand is recommended for ease of installation. Once installed, a post-installation check was conducted ensuring no wires interact with any rotating components of the bike, and all screws are installed and tightened correctly.

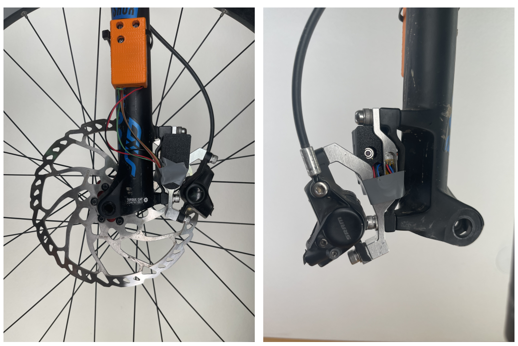

Fig. 2. Left (left) and right (right) views of the installed brake force sensor system, with and without wheel installed.

The images in 2 show the installed sensor with the microcontroller and wiring. The housing of the microcontroller mounted with a zip tie as proposed in the design.

G. Calibration Procedure

The calibration of the strain gauge aimed to relate its readings to a reference torque with known values. This procedure establishes a correlation, ensuring that the gauge provides accurate and consistent readings when subjected to different torques.

To execute the calibration, a weight of 5.04 kg in form of dumbbell weights was selected. This weight was suspended at a specific distance (0,285 m) from the wheel axle at a spoke with a carabiner and a textile sling. It is noteworthy to mention that the weight was verified using a kitchen scale to maintain the calibration's integrity.

The calibration was conducted right before the test ride at ambient temperature. A total of 10 data points are collected during this procedure.

The calibration process involved the use of code written in the Arduino programming environment. This code was tasked with automating a significant portion of the calibration process. Upon providing the reference torque value, the code takes ten measurement points. Calibration can be started either by Bluetooth connection with the accompanying app or with commands transmitted over the serial monitor included in the Arduino IDE. It then calculates the average of these readings and adjusts the scaling factor to align with the known and transmitted reference value. The underlying assumption guiding this calibration code is the linear behavior of the strain gauge. This calibration process was conducted right before data collection and power supply must not be interrupted after calibration. Only this way subsequent measurements taken using the strain gauge are accurate and reflective of the actual physical quantities.

H. Real-World Data Collection

The real-world testing phase took place on a hill situated in Innsbruck, specifically on Herrmann Gmeiner Straße. The selected road section is paved terrain and was chosen to minimize the sensor's exposure to shocks and vibrations that might result from a rougher surface. The runout of the testtrack was flat to ensure a rollout zone in case of brake failure. In this case also the rearbrake existed as fallback solution. The tests were conducted during daylight to ensure optimal visibility and safety. Weather conditions were kept dry, both to protect the sensor from potential moisture damage and to maintain consistent traction during the rides. The test drive included a short approach to the hill, then a 5 times repetition of driving uphill, turning around and rolling downhill. The braking was done gently and evenly over a distance of about 15 metres at the end of the downhill run in the flat runout zone. Braking was done until to a full stop and only with the front brake.

The only vehicular traffic present during the testing did not pose a challenge or influence the braking. The key focus was on the defined braking point, which was initiated next to a road sign as a visual marker. In addition to the brake force sensor, a Garmin 830 device was used to record GPS data for the whole test ride. Preparations for the bicycle involved fitting the previously described and calibrated sensor. The test ride included five consecutive rides up and down the hill, with no pedalling during the downhill section. This ensured higher consistency in terms of speed and approach by using comparable starting conditions (same speed) at the same spot for each trial.

Throughout the rides, data was continually recorded on both the microcontroller and the Garmin 830. There wasn't a need for manual triggering of the recording as the systems were set to capture data throughout the test duration. Once completed, the data was procured from the Garmin platform in GPX format, while the microcontroller provided it in CSV format, both of which would be used in subsequent statistical analyses.

During the rides, standard protective gear, such as a helmet, was donned in line with the recommendations from the ethical assessment. There weren't any special measures needed apart from the precautions typical for mountain biking.

I. Data Preparation

Post the tests, the data sets from the GPX and CSV files were prepared with a Python Script for further detailed analysis to visualize patterns in the braking force over the trials. The process of data preparation was divided into several stages to ensure accurate and meaningful analysis. The Python Code is also available in the GitHub.

Data Loading: Data from the two primary sources was loaded into the environment. The first source was the braking data captured by the sensor, stored as a CSV file. The second was the GPX data from the Garmin 830 device, which provided the geographic and time-based information of the test ride.

Initial Processing: The GPX data was parsed to extract relevant information, including the time, latitude, longitude, and elevation for each data point. This information was then structured into a pandas DataFrame construct to enable manipulation and analysis.

Timezone Synchronization: A crucial aspect of our data involved aligning the timestamps from both the braking data and the GPX data. All timestamps were localized to the 'UTC' timezone and then converted to 'Europe/Berlin'. This ensured that there were no discrepancies due to time zone differences when merging the two data sets.

Data Resampling and Interpolation: To ensure uniformity and to fill any potential gaps in the braking data, it was resampled at a 1-second frequency. The data was then interpolated to address any missing or incomplete data points, ensuring that the dataset remained continuous and consistent.

Data Merging: The processed brake data and GPX data were then combined based on their timestamps to produce a unified dataset. This combined data facilitated the calculation of various derived metrics, such as force and speed.

Calculation of Derived Metrics: Several derived metrics were calculated for further analysis. The force exerted during braking was calculated using torque values and the wheel's radius. Speed was computed by determining the distance traveled between subsequent GPS coordinates, using the Haversine formula, and dividing it by the time interval. Brake power was then determined in two ways: using torque and RPM, and using force and the calculated speed.

In conclusion, this meticulous data preparation process ensured a reliable and robust dataset, paving the way for in-depth analysis and insights.

III. Data Analysis and Visualization

Data visualization plays a pivotal role in understanding and interpreting complex relationships present in the data. In this section, we provide a comprehensive analysis of various parameters related to the braking system through a series of meticulously curated plots.

1) Overview over Data: The analyzed data consist of a total of 373 data points taken during the ride spanning approximately 9 minutes and 41 seconds. Over this duration, the rider covered a distance of approximately 2.93 kilometers (2932.50 m).

On average, the rider's speed was approximately 4.81 m/s with the speed ranging from a complete standstill (0 m/s) to a maximum of 11.09 m/s. The median speed was 4.44 m/s.

Regarding the braking system, the brake's power had a mean value of 50.03 W. The braking power varied considerably throughout the ride, from no braking activity (0 W) to 559.28 W during certain instances. The median brake power was observed to be 23.76 W.

The elevation during the ride varied according to the ride profile, with a total change in elevation of approximately 12.8 meters. The lowest point was at 589.80 m above sea level and the highest at 602.60 m.

Torque averaged at 3.88 Nm. It ranged from a minimum of 0.26 Nm to a maximum of 19.79 Nm, with a median of 2.05 Nm.

2) Spatial Visualization of Brake Power: To grasp an overview of the distance covered and observe the correlation of brake power over the distance, a heatmap was created. The map overlay visualizes the brake power against the geographical coordinates (latitude and longitude). This visualization works with a gradient of green (indicating low brake power) transitioning from yellow to red (indicating high brake power). The map, centered on the mean location, offers insights into the ride profile, including braking and turning points.

Fig. 3. Spatial Visualization of Brake Power.

3) Time-Resolved Visualization of Raw Values: The timely evolution of raw values, specifically speed and torque, is depicted in Figure 4. By plotting torque against speed, it becomes feasible to analyze periods of intense braking in conjunction with the vehicle's speed.

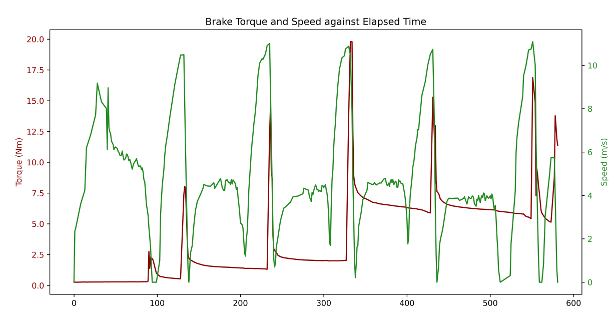

Fig. 4. Brake Torque and Speed against Elapsed Time.

4) Time-Resolved Visualization of Calculated Values: Understanding the relationship between brake power and speed over time is vital. In Figure 5, the brake power (in W) is showcased alongside the speed (in m/s) against elapsed time.

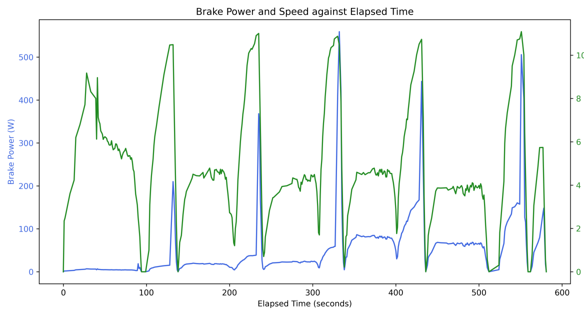

Fig. 5. Brake Power and Speed against Elapsed Time.

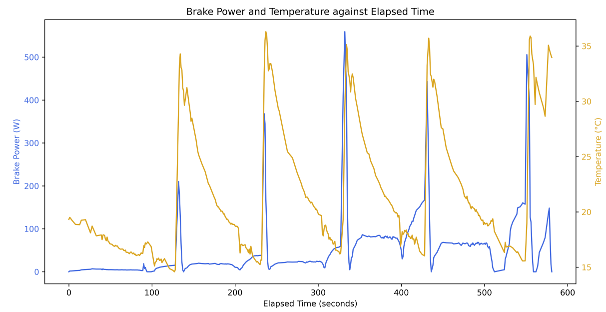

Fig. 7. Brake Power and Temperature against Elapsed Time.

5) Graphical Representation of Correlations: To assess the interrelationships between key parameters, namely brake power (in W), torque, speed, elevation, and temperature, a correlation matrix was employed. The heatmap, presented in Figure 6, effectively illustrates both the strength and direction of the relationships between these variables. The choice of colors, transitioning from cool to warm tones, intuitively suggests the range of correlation from negative through neutral to positive.

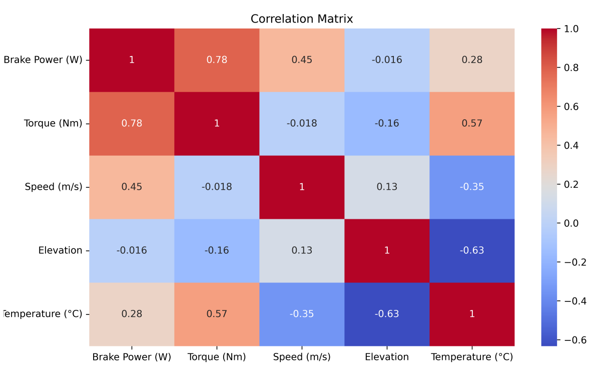

Fig. 6. Correlation Matrix of Selected Parameters.

6) Analysis of Highly Correlated Values: Finally, to show the correlation between brake power and temperature, both parameters were visualized against elapsed time. As shown in Figure 7, periods of high brake power typically corresponded with a sharp rise in disc brake temperature.

The visualization of the data provide a detailed insight into the braking dynamics of the test ride.

7) Interpretation of Results: The torque readings acquired throughout the course of this research were in a expected range, showing the reliability of the calibration and measurement process. However, they cannot be verified, since no reference system was used. Nevertheless, the range of calculated brake power values seems quite realistic. An interesting finding was the detection of torque values above zero even during non-braking times, post the initial braking event. This "baseline" torque showed a trend of increasing after each braking event. One hypothesis to account for this phenomenon is the potential deformation of the disc brake due to temperature increase while and after braking. This deformation might induce disc brake rub, resulting in an unnoticeable brake force even during non-braking intervals. Another consideration is the possible influence of the disc brake temperature on the strain gauge readings. Heat radiation could influence the electrical resistance of the highly sensitive strain gauges. Although there is an inherent temperature compensation in the Wheatstone Bridge, due to the arrangement of one half of the bridge located closer to the disc brake this might still influence the readings negatively.

IV. Conclusion and Future Outlook

The effort of developing a sensor for measuring brake power turned out to be mostly successful. Despite some features not working as intended, and with some features still to be developed to be a market ready product, the prototype was able to measure valuable data. A worthful insight into the dynamics of braking could be gained.

Valuable insights into working with technologies like rapid prototyping, strain gauges and microcontrollers and their applications in product development, especially in sports sensorics, were gained.

An extensive data analyis with data resulting from a test ride was conducted to demonstrate the functionalities of the developed sensor. It was notable that the derived power readings were comparable to existing literature and in the expected range. Interestingly, even during non-braking phases, small torque values were evident, especially subsequent to initial braking incidents. A possible reason, rooted in potential disc brake deformation resulting from temperature increase, was identified but could not be validated.

Furthermore, the research showed a strong interplay between temperature and brake power. The disc brake temperature was surprisingly responsive to brake actions. This suggests that the disc brake temperature might be a reliable relative indicator for brake power in the future, but further reasearch has to be done in this field. An algorithm for disc brake temperature and related brake power has to be developed and paramaters like brake dimensions and rider's weight must be factored in. Using it as an absolute power gauge might not yield accurate results.

V. Appendix

All code was uploaded to GitHub. The code development until submission of this thesis can be found with this link:

https://github.com/Eternoxy/OpenBrakes/commit/\protect\penalty\z@a8b12c36d4fe419bee93b64228db35a49018e26e

The project may be continued and enriched with more files after the submission of this thesis and can be found on the main tree:

https://github.com/Eternoxy/OpenBrakes

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