

## Design and Validation of a Low-Cost Wireless Pedal Force Measurement System for Biomechanics and Rehabilitation Applications

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### Biyomekanik ve Rehabilitasyon Uygulamaları için Düşük Maliyetli Kablosuz Pedal Kuvveti Ölçüm Sisteminin Tasarımı ve Validasyonu

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#### Abstract

Lower extremity force distribution and pedalling symmetry play a critical role in both optimizing athletic performance and preventing injuries during rehabilitation. Existing pedal force measurement systems are often expensive and limited to controlled laboratory environments. This study presents the design, development, and validation of a low-cost, portable, and wireless pedal force measurement system. The system includes two 50 kg-capacity load cells per pedal, an ESP32 microcontroller for data acquisition and Bluetooth transmission, and a custom C# software for real-time visualization and data logging. In static load tests conducted with calibrated reference weights (21.1 kg, 42.3 kg, and 63.7 kg), the system demonstrated high linearity with the reference loads ( $r = 0.9999$ ). Additionally, an average difference of only 0.72% between the left and right pedals at 42.3 kg confirmed high symmetry and repeatability. One-way ANOVA results p-values (left: 0.640; right: 0.878) exceeded 0.05, indicating that the position of the applied load did not significantly affect measurement accuracy, reflecting consistent sensitivity and structural integrity. Overall, the validated system offers a reliable, non-invasive, and cost-effective platform applicable to sports science, performance monitoring, and physical rehabilitation contexts.

**Keywords:** Biomechanics; Lower-limb rehabilitation; Pedal force symmetry; Real-time monitoring; Kinetic assessment.

#### 1. Introduction

The precise measurement of lower extremity force provides critical information about an individual's level of neuromuscular coordination, balance control, and overall functional capacity. The utilisation of such data has been demonstrated to enhance athletic performance and facilitate the planning of targeted interventions within rehabilitation processes. The distribution of force generated during repetitive lower extremity activities, such as pedalling, is a significant metric for objectively assessing motor control in both healthy and pathological individuals. However, such measurements are typically

#### Öz

Alt ekstremité kuvvet dağılımı ve pedal çevirme simetrisi hem atletik performansın optimize edilmesinde hem de rehabilitasyon sürecinde yaralanmaların önlenmesinde kritik rol oynamaktadır. Mevcut pedal kuvveti ölçüm sistemleri genellikle yüksek maliyetli olup laboratuvar ortamlarıyla sınırlıdır. Bu çalışma, düşük maliyetli, taşınabilir ve kablosuz bir pedal kuvveti ölçüm sisteminin tasarımını, üretimini ve doğrulamasını sunmaktadır. Sistem, her pedal üzerinde iki adet 50 kg kapasiteli yük hücresi, veri toplama ve Bluetooth iletimi için ESP32 mikrodenetleyici ve gerçek zamanlı görselleştirme ve kayıt için C# tabanlı özel bir yazılım içermektedir. Statik yük testlerinde sistem, kalibre edilmiş referans ağırlıklarla (21,1 kg, 42,3 kg ve 63,7 kg) test edilmiştir. Elde edilen sonuçlar, referans yüklerle ölçümler arasında yüksek doğrusal korelasyon değerleri ( $r = 0,9999$ ) göstermiştir. Ayrıca, 42,3 kg'da pedallar arası ortalama farkın sadece %0,72 altında olması yüksek simetriyi ve tekrarlanabilirliği ortaya koymuştur. Tek yönlü ANOVA analizinde p-değerleri (sol: 0,640; sağ: 0,878) > 0.05 bulunmuş, bu da konumsal yük farklarının ölçüm doğruluğunu anlamlı biçimde etkilemediğini göstermektedir. Sonuç olarak sistem, güvenilir, non-invaziv ve ekonomik bir çözüm olarak spor bilimleri, performans takibi ve klinik rehabilitasyon alanlarında uygulanabilir çok yönlü bir platform sunmaktadır.

**Anahtar Kelimeler:** Biyomekanik; Alt ekstremité rehabilitasyonu; Pedal kuvveti simetrisi; Gerçek zamanlı izleme; Kinetik değerlendirme.

performed using laboratory-specific, expensive, and limited-portability equipment. Gold-standard methods, including optical motion capture systems and multi-axis force platforms, offer high levels of accuracy; however, they are only operational under strictly controlled conditions and necessitate highly specialised personnel (Zhu et al., 2025). This severely limits both field-based research and widespread clinical applications (Ahmadi et al., 2024). In recent years, there has been an increasing interest in systems that meet criteria such as portability, low cost, and user-friendly design. The development of microcontroller-based hardware development kits,

affordable force sensors, and wireless communication technologies such as Bluetooth has enabled the creation of systems capable of monitoring pedal forces in real time. However, the majority of extant low-cost solutions offer limited metrics and fail to achieve sufficient accuracy or detail levels when compared to laboratory systems. This deficit gives rise to a substantial lacuna, especially within the domain of neurological rehabilitation. Lower extremity force symmetry is a fundamental parameter in monitoring the recovery process in conditions such as stroke, traumatic brain injury, or multiple sclerosis. The necessity for "early objective assessment," a concept that is being emphasised more and more in clinical diagnostic guidelines, is driving demand for portable systems that can provide time-sensitive and repeatable measurements (Montalban et al. 2025). Furthermore, in the context of enhancing athletic performance, the identification of intra-pedal (front-back) and inter-pedal (left-right) force imbalances provides a scientific foundation for targeted strength training (Farrell and Neira 2023, Worn et al. 2024). The present study has developed a low-cost, portable, wireless pedal force measurement system capable of detailed analysis of lower extremity force distribution and real-time data transmission (Bao et al., 2024). The objective of this study is to contribute to the field by providing an accessible and reliable assessment tool for both research and clinical applications.

## 2. Materials and Methods

The pedal force measurement system developed in this study is designed to meet the criteria of high accuracy, low cost, and portability when evaluating lower extremity biomechanics. Also, one of the major perks of the system is to provide reliable force data in a variety of usage scenarios, including but not limited to rehabilitation, sports science, and performance analysis. Hence, Eliminating the need for additional complex measurement hardware.

### 2.1 System Architecture and General Design Principles

The system's architecture is characterized by an integrated structure comprising load sensing, data collection, wireless transmission, visualization, and energy management components. The system's fundamental operational logic entails the conversion of force data obtained from load cells affixed to the pedals into a digital format through the use of a microcontroller. This data is subsequently transmitted to a computer via Bluetooth communication. A total of four load cells, two installed on each pedal, are employed to meticulously gauge the front-to-back force distribution. This

configuration facilitates comprehensive analysis of both intra-pedal and inter-pedal force symmetry. This structure offers an advanced data framework that goes beyond total force measurement to also examine the regional distribution of force. The system's wireless communication capability enables its utilization in external settings, such as rehabilitation clinics, athletic performance centers, and field tests. The utilization of real-time data transmission and software-based visualization support enables the user to receive immediate feedback while pedaling, thereby facilitating the optimization of their performance. Furthermore, the integration of all system components (i.e., sensors, data collectors, and power source) onto individual pedals, as illustrated in Figure 1, provides a fully independent solution that eliminates the need for external hardware.

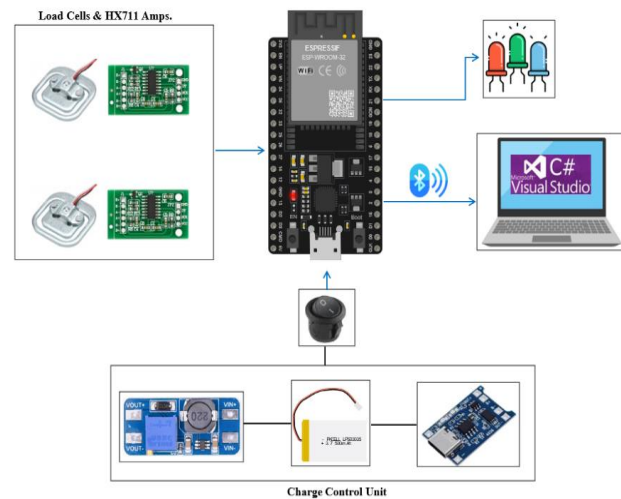


Figure 1. System General Block Diagram

### 2.2 Pedal Structure and Mechanical Design

The mechanical body is composed of a three-layer structure: the bottom layer consists of a rigid metal base plate that provides support for all load cells; the middle layer is a structural support layer made of aluminum; and the top layer is a wooden platform covered with non-slip tape to enhance user comfort and ensure foot stability. This layered configuration guarantees that force is transmitted to the sensors with minimal deformation, while concurrently facilitating vibration absorption. The load cells are affixed to the pedal body via a bolted connection, with each sensor aligned parallel to the direction of the force. This configuration enhances measurement precision and mitigates the impact of cross-talk. The mounting positions of the sensors are selected to be as close as possible to the contact points where the force is directly transmitted. This design ensures the effective detection of loads applied to the front, middle (center), and rear areas of the pedal. The

system is engineered to withstand the torsional, bending, and compressive forces that may occur during the pedal cycle. It is encased in a compact box structure (see Figure 2). The dimensions of the structure are designed to align with the measurements of a standard bicycle pedal, thereby facilitating its integration into existing exercise bikes for clinical or sports applications.



**Figure 2.** Housing Case Designed with SolidWorks



**Figure 3.** Calibration Weight Set

### **2.3 Force Sensing Unit**

The analog voltage outputs from the load cells are amplified with low noise via the HX711 integrated circuit before being digitized. The HX711 is a high-resolution (24-bit Analog to Digital Converter -ADC) signal converter that has been developed specifically for load cell applications. It is individually configured for each load cell in this system. This configuration enables autonomous data acquisition from each sensor, thereby mitigating cross-interference.

The system calibration was performed by matching the load cell outputs with reference values obtained with precisely known calibration masses (Figure 3). The calibration process enhanced the system's accuracy and ensured the synchronized and uniform operation of the load cells on each pedal. High correlation coefficients ( $r \approx 0.9999$ ) were obtained in the static load tests applied for calibration verification, confirming the linearity and accuracy of the system.

### **2.4 Data Acquisition and Control Unit**

The collection of data and the control of the system are executed by ESP32 microcontroller units that have been integrated into each pedal. The ESP32 provides an optimal foundation for mobile biomechanical systems, exhibiting characteristics such as low power consumption, high processor speed, and integrated Bluetooth communication. Each microcontroller is responsible for processing, storing, and wirelessly transmitting digitized force data from two load cells per pedal to the user interface in real time. Each ESP32 concurrently acquires data from both the front and rear sensors via two distinct HX711 channels. The microcontroller maintains a constant sampling frequency of 80 Hz and transmits each data packet instantaneously via Bluetooth with a timestamp. The embedded software running on the ESP32 is responsible for managing data sampling, filtering, packaging, and error checking. Energy management constitutes a vital component of the system with regard to mobility and uninterrupted operation. Each pedal unit is powered by an independent 3.7V 1200 mAh Li-Po battery. The battery is charged using the TP4056 integrated circuit, while the MT3608 booster circuit provides the system's required 5V constant output. This configuration enhances the system's portability and ensures sufficient energy for extended test sessions.

In order to provide the user with instantaneous feedback regarding the system's status, each pedal unit is equipped with three LED indicators: a red LED that indicates the power status, a green LED that signals the Bluetooth connection status, and a blue LED that denotes the current state of data transfer activity. These visual indicators swiftly inform the operator of the system's readiness, thereby facilitating the management of the test process.

Pedal rotation frequency, or cadence (one pulse per complete pedal revolution), is a critical metric for assessing lower extremity performance and efficiency. In this study, cadence measurement was performed using a hall-effect sensor (A3144) sensitive to magnetic field changes (see Figure 4). The sensor was affixed to the pedal body rotating with the pedal, and a small magnet was positioned in close proximity on a stationary location on the bicycle. The sensor passes once during each pedal cycle. With each complete revolution of the pedal, the sensor detects the change in the magnetic field, producing a digital pulse and thereby determining the number of cycles.

The ESP32 microcontroller detects these pulses via a timer-based counter module and determines the cadence

(RPM – Revolutions Per Minute) by calculating the number of revolutions that occur per unit of time. The obtained data is transferred to the software via Bluetooth in real time, and it is both visually presented on the user interface and included in the data recording.

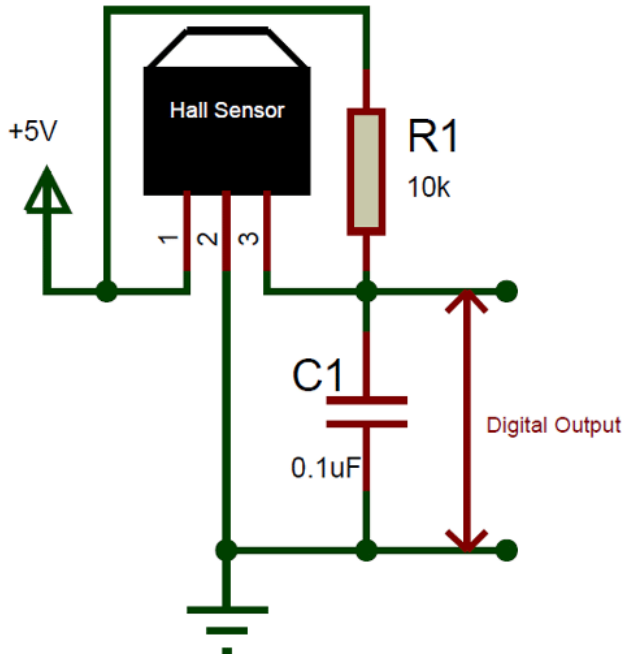


Figure 4. Hall-Effect Sensor's Auxiliary Circuit

This configuration facilitates the immediate monitoring of participants' achievement of their target pedal speed, thereby ensuring measurement consistency. This hall-effect-based approach is a reliable cadence monitoring method that has been widely adopted in bicycle biomechanics research (Hollaus et al., 2022). In comparison to alternative optical or acceleration-based systems, it has been selected due to its reduced sensitivity to mechanical interference, cost-effectiveness, and compatibility with the system's overall portability.

### 2.5 Cost Analysis

The proposed system demonstrates notable economic merit, primarily due to its low material cost and streamlined design architecture. Its capacity for seamless integration into larger and typically high-cost system configurations enables a substantial reduction in overall expenditures without diminishing operational performance. These characteristic positions the subsystem as a strategically valuable component, capable of lowering system-level financial requirements when compared with existing alternatives. Consequently, the design offers a cost-efficient (Table 1) and economically advantageous solution that enhances the feasibility and competitiveness of complex system implementations. The approximate total cost based on the materials used is given in Table 1.

Table 1 System's Estimated Materials Cost

Element	Quantity Used	Cost in Turkish Lira Per Element
ESP32 Microcontroller	1	~ 250
50 Kg loadcell	4	~ 46
HX711 ADC	4	~ 35
DC boost converter	1	~ 90
Charge unit	1	~ 25
Lipo Battery	1	~ 240
<b>Total Cost</b>		<b>~ 690</b>

### 2.6 Experimental Design

#### 2.6.1 Stati Load Test Protocol

To evaluate the accuracy, reliability, and repeatability of the developed pedal force measurement system, controlled static load tests were conducted. The primary objective of these tests was to verify the calibration accuracy and structural consistency by comparing the system's responses under known masses with reference measurement devices. Three distinct reference mass values were utilized during the course of the tests: 21.1 kg, 42.3 kg, and 63.7 kg. These masses facilitated the assessment of the system's performance at varying load levels and established the foundation for linearity analyses. Each test involved the application of load to three specific areas on a pedal, as illustrated in Figure 5 front, middle, and rear—and measurements were recorded 30 times at each position. These repetitions enabled the meticulous calculation of the mean deviation values and standard deviations of the system.



Figure 5. Local Measurement Locations on the Pedal

The Geratech SH-2000 digital force gauge was used as the reference measurement device (see Figure 6). The device operates with an accuracy of  $\pm 0.1$  kg, thereby enabling a comparative assessment of the accuracy of the measurement data obtained from the pedal system's sensors. The measurements were obtained by methodically positioning the loads without perturbing the system's equilibrium, and the data collected from the sensors for each position was meticulously documented.

To ensure uniform load distribution across the pedal surface, a total of six distinct local measurement points

were defined: left front, left center, left rear, right front, right center, and right rear.



**Figure 6.** Reference Load and Reference Measurement Device

The measurements obtained at these points facilitated the analysis of not only the overall accuracy but also the changes in sensor sensitivity across different areas of the pedal structure. This protocol is compatible with a method that is frequently employed in validity tests for low-cost biomechanical measurement systems (Mohamed et al., 2024). The measurements facilitated the numerical evaluation of the system's sensitivity, symmetry, and positional stability characteristics, thereby establishing the reference data set for subsequent statistical analyses.

### **2.6.2 Test Conditions and Controls**

In order to circumvent any potential disruption to the system's balance during the execution of load applications, each mass has been meticulously centered and positioned, thereby ensuring that the mechanical limits of the pedals are not compromised. The same test procedure has been applied with a standardized flow for all measurement points and all reference load levels. In each instance of the load application, measurements were obtained subsequent to the stabilization of the sensor data, thereby ensuring that transient fluctuations did not compromise the integrity of the results. Operator intervention was minimized during the data collection process, and operations were automated by the software to the greatest extent possible. The signals from the pedal sensors were meticulously recorded with time stamps corresponding to the sampling frequency, thereby eliminating the possibility of human error. The system was restarted between sessions to equalize the starting conditions for each test group. The data obtained enabled statistical analyses, which will be presented in detail in subsequent sections, to be built on solid foundations.

### **2.7 Data Analysis**

To ensure the statistical significance of the data sets and to evaluate the consistency of the sensors, 30 repetitions

were performed at each test point, and separate averages were taken for each repetition. The stability of the sensor response was analyzed by calculating the standard deviation, range (min–max), and absolute deviation ratios based on these average values. In addition, the repeatability of the system's measurements was examined by evaluating data from sensors located in the same position on both pedals. The data were stored in a time series format, with each row containing the following information: timestamp, pedal position (left/right), sensor region (front/rear), force value (in kg), and test number. This configuration enabled independent analysis of each sensor channel within the system, calculation of intra-channel and inter-channel correlations, and execution of position-based accuracy analyses. The raw data processing stage is a critical preliminary step for the reliability of all subsequent statistical analyses. The cleaned and organized data set obtained during this process formed the basis for extracting force balance metrics and performing intra-pedal/inter-pedal symmetry analyses. Subsequent to the processing of raw force data, various force balance metrics were calculated to quantitatively assess the system's performance criteria related to lower extremity symmetry and muscle activation balance. These metrics provide detailed information about neuromuscular control and load sharing by analyzing both intra-pedal (front-rear) and inter-pedal (left-right) force distributions separately. The fundamental metrics calculated are enumerated below:

**Front-Rear Force Balance (FRFB):** Front–Rear Force Balance (FRFB) quantifies the relative loading between the front (toe-side) and rear (heel-side) regions of the pedal by calculating the ratio of the average forces measured from the corresponding load cells. This ratio reflects how the applied force is distributed along the anteroposterior axis of the foot during pedaling.

A higher front-dominant value generally indicates a more dorsiflexed, toe-loaded pedaling pattern, whereas a rear-dominant value suggests greater heel loading associated with plantar flexor engagement. Although FRFB does not directly measure muscle activity, it provides a useful mechanical indicator of the functional contributions of dorsiflexor and plantar flexor muscle groups during the pedal stroke.

**Force Symmetry Between Pedals (FSP):** The percentage difference is calculated by comparing the total force values obtained from the left and right pedals. The symmetry index (SI) is generally defined by the following formula:

$$SI = \frac{|F_{right} - F_{left}|}{\left(\frac{F_{right} + F_{left}}{2}\right)} \times 100 \quad (1)$$

This metric is indicative of inter-limb force imbalance and is of particular importance in the detection of unilateral functional impairments.

**Total Force Output (TFO):** The force value per pedal was determined by taking the averages of the two load cells on each pedal. Then, the sum of both pedals was recorded as the overall force production. This value was then compared with reference loads and according to pedal positions. This comparison was used to evaluate the overall accuracy and load application performance of the system.

**Force Distribution Stability (FDS):** The variance was calculated over 30 repetitions at each test point to demonstrate the system's short-term measurement stability. This metric is employed to statistically express the degree of repeatability of the device.

The metrics in question were automatically calculated by the software interface and reported at the conclusion of each test, accompanied by visual graphs. Additionally, the system is configured to evaluate changes under dynamic conditions by filtering these metrics at different pedal speeds (cadence). The calculation of force balance metrics enables the analysis of not only total force production but also force orientation and distribution patterns. This allows the system to provide multidimensional data for both performance monitoring and clinical evaluation purposes.

### 3. Results and Discussions

In the context of static calibration tests, a series of thirty repeated measurements were conducted for each reference load level (21.1 kg, 42.3 kg, and 63.7 kg). This number of repetitions ensured statistical reliability in the system's accuracy and repeatability analyses. Conversely, in positional sensitivity tests—which entail local measurements in the front, middle, and rear regions—20 repetitions were executed for each position and load combination. This distinction enables the independent evaluation of static accuracy and positional sensitivity. A total of 540 measurements were obtained across two pedals, and this data set formed the basis for both accuracy and positional stability analyses.

#### 3.1 System Performance Under Static Load

The study evaluates the fundamental metrological characteristics of the developed pedal force measurement system under static conditions. The system's performance is examined under three main

headings. First, in the Descriptive Statistics subsection, the basic statistical distributions of the measurements obtained under different reference loads are presented. These statistics include the mean, standard deviation, and error margin, revealing the system's overall accuracy and stability profile. In the subsequent section an analysis is conducted to assess the force balance (symmetry) between the left and right pedals, as well as the consistency (repeatability) of the measurements conducted under identical conditions. The reliability of the system is subsequently reported in quantitative terms. Finally, the Correlation and Linearity Analysis examines the relationship between the system's measurement outputs and the applied reference loads. The linearity and sensitivity of the load-response curve are statistically evaluated. This three-pronged analysis approach aims to provide a comprehensive picture of the system's performance under static loads. Each reference load was subjected to 30 repetitions, and 20 local measurements were used in the sub-analyses performed at the sensor locations. The mean ( $\mu$ ), standard deviation (SD), minimum–maximum range, and mean error (ME) were calculated for each sensor location based on these data. Table 2 presents the results obtained under a 42.3 kg load applied to the front region of the right pedal, serving as an illustrative example.

**Table 2.** Sample results measured at 42.3 kg on the right pedal front part

Parameter	Value (kg)
Applied reference load	42.3
Measured mean value ( $\mu$ )	41.7
Standard deviation (SD)	$\pm 0.44$
Minimum value	40.9
Maximum value	42.4
Absolute Error	1.4%

In consideration of the results obtained, the system has exhibited a high degree of accuracy, with an error margin of  $\pm 1.5\%$  in medium-load applications. Specifically, the observation that the standard deviation values remain below 0.5 kg at all positions suggests that the system exhibits high measurement consistency. While the margin of error is up to 2.5% for light loads (21.1 kg), this value is considered reasonable within the limits of low force measurement sensitivity. In addition, the system's consistent performance across all sensor points suggests that structural integrity and calibration are preserved irrespective of position. These data support the system's applicability in applied biomechanical assessment environments. When assessing system performance, it is imperative to consider not only absolute accuracy but also the continuity (repeatability) of measurements and

the analysis of force balance (symmetry) exhibited by sensors on both extremities. Therefore, 30 repetitions were performed under each reference load, and symmetry indices and repeatability consistency were calculated based on the total force values obtained for the right and left pedals.

The test results indicate that the symmetry index values measured by the system remained within the range of 2–5%, exhibiting minimal deviation and no discernible deterioration depending on the load level. For instance, when a load of 42.3 kg was applied, the average forces exerted on the right and left pedals were measured to be 41.7 kg and 42.0 kg, respectively. The symmetry difference was calculated to be 0.72%. This value is substantially lower than the typical left–right pedal force asymmetry reported in healthy athletes (approximately 11–21% for resultant forces) (Bini & Hume, 2015). indicating that the system can detect even very small asymmetry levels with high sensitivity. Additionally, asymmetry has been documented in three-dimensional force components (Martín-Sosa et al., 2023) and neuromuscular/strength tests (Iglesias-Caamaño et al., 2025). Furthermore, asymmetry may fluctuate with exercise intensity (Farrell et al., 2021; Farrell and Neira, 2023). The repeatability analysis was conducted by calculating the standard deviations of the 30 measurements taken at each position and subsequently obtaining the %CV (coefficient of variation) values.

The observation that the percentage of correct values (%CV) ratios persist below 1.5% at all sensor locations suggests that the system exhibits high short-term measurement reliability. Specifically, the proximity of the values obtained in repeated loadings at the same location is associated with the mechanical stability of the system and the precision of the sensor readings. Furthermore, variations in front-to-back force balance were found to be minimal; the system's dual-sensor design enables it to reliably distinguish between pedal-internal force distribution. This enhancement facilitates the analysis of load shifts induced by foot placement in biomechanical assessments.

Consequently, the system exhibited a high degree of symmetry and repeatability in both intra-pedal and inter-pedal measurements, thereby substantiating its reliability as a platform for sports science and rehabilitation applications. To conduct a more in-depth evaluation of the system's measurement accuracy, the relationship between the applied reference loads and the force values measured by the system was examined, and a linear regression analysis was performed. The objective of this

study was to ascertain whether the system exhibited sensitivity to varying load levels, that is, to determine if the load-response relationship followed a linear trajectory. In the analyses performed separately for each sensor position, the reference load (kg) was designated as the independent variable, and the average force value measured by the system was designated as the dependent variable. The regression model applied was formulated as follows:

$$F_{measured} = a.F_{reference} + b \quad (2)$$

In this context, "a" is designated as the slope, also referred to as the sensitivity coefficient, while "b" is the constant term indicating systematic deviation. The correlation coefficients (Pearson r) obtained for all positions were found to be highly significant at the 99% confidence interval ( $r > 0.998$ ,  $p < 0.001$ ). The regression result for the right pedal rear sensor is illustrated below:

- The slope (a) is determined to be 0.985.
- The constant term (b) is a constant term. +0.74 kg
- $R^2$ , also known as the coefficient of determination, has a value of 0.996.

This value indicates a high degree of correspondence between the system's measurements and the reference loads, suggesting a near-perfect match between the two sets of data. In a similar vein,  $R^2 > 0.99$  was observed for all other positions, thereby confirming the system's high linear performance across all measurement regions. This analysis revealed that, despite the utilization of low-cost sensor components, the system performs at a level comparable to commercial laboratory-grade systems in terms of both sensitivity and consistency. In scenarios where data from multiple sensor channels were evaluated concurrently, the measurement error remained minimal. The findings of strong correlation demonstrate the system's high validity, not only in terms of static accuracy, but also in terms of the stability of its responses to load changes. This advantage is particularly salient in clinical and sports applications, as it significantly increases the reliability of measurements.

### **3.2 Position Sensitivity Analysis (Measurement Point Test)**

The measurement response to static loads applied to different positions on the pedals is critical for evaluating both the effectiveness of the sensor placement architecture and the homogeneity of structural sensitivity. To this end, the reference loads (21.1 kg, 42.3 kg, 63.7 kg) were applied individually to the front, middle, and rear regions of each pedal. The resulting force values were recorded by the sensors. Twenty repetitions were

performed at each position, enabling the establishment of a statistically reliable framework for the comparison of positions. To illustrate, the application of a 42.3 kg load to the front region of the right pedal resulted in the following outcomes:

- The mean force registered by the front sensor was 41.7 kg.
- It has been determined that the measurement from the middle sensor is precisely 0.0 kg and the rear sensor indicated a reading of 0.0 kg.

The findings indicate that the sensors exhibit a high degree of responsiveness to localized forces. Furthermore, analogous distribution profiles were observed in the forces applied to the same load position on both sides of the pedals (left and right), indicating that mechanical symmetry between the two pedals of the system was maintained. This outcome suggests that the load is detected exclusively in a localized manner by the target sensor, indicating negligible cross-talk between sensors. The unresponsiveness of neighboring sensors during measurements serves to confirm that mechanical isolation within the pedal body is effectively achieved and that the structure possesses high rigidity.

A one-way ANOVA was performed to evaluate whether the applied loads produced different measurement outputs across the front, middle, and rear regions of each pedal. The results in table 3 showed no statistically significant positional effect for either pedal (all  $p > 0.05$ ), and the effect sizes were negligible ( $\eta^2 < 0.02$ ). These findings indicate that the system perceives the applied load consistently across different regions, confirming the adequacy of the pedal's structural rigidity and sensor placement design.

**Table 3.** ANOVA results according to pedal positions

Pedal	F value	p-value	$\eta^2$ (Effect size)	Comment
Left Pedal	0.45	0.640	0.016	There is no significant difference
Right Pedal	0.13	0.878	0.005	There is no significant difference

These findings suggest that the system perceives the applied load in a consistent manner across different positions, indicating that the positional difference does not exert a statistically significant influence on the measurement outputs. The effect size ( $\eta^2$ ) values are less than 0.02, indicating that there is a minimal level of positional effect. This outcome validates the sensors' capacity to provide a balanced response to the load distribution on the pedal surface, thereby ensuring the system's ability to produce consistent measurements irrespective of position. However, in applications requiring advanced accuracy, especially when sensor placement or pedal surface rigidity exhibits heterogeneity, the integration of local calibration tables or software validation algorithms can further enhance measurement accuracy.

In order to assess the impact of loads applied to different regions of the pedal surface on sensor performance, a local correlation analysis was performed between sensors. This analysis was conducted to determine whether loads affecting specific regions of the pedal surface also impact neighboring regions. The relationships between three regions (front, middle, rear) for each pedal were examined using the Pearson correlation coefficient ( $r$ ) (see Table 4).

**Table 4.** Local correlation coefficients (Pearson  $r$ ) and significance levels ( $p$ ) between sensors

Pedal	Position 1	Position 2	$r$	$P$	Statistical interpretation
Left	Left Front	Left Center	-0.03	0.895	Not statistically significant ( $p > 0.05$ )
Left	Left Front	Left Rear	0.09	0.703	Not statistically significant ( $p > 0.05$ )
Left	Left Rear	Left Center	0.22	0.344	Not statistically significant ( $p > 0.05$ )
Right	Right Rear	Right Center	0.39	0.090	Not statistically significant ( $p > 0.05$ )
Right	Right Front	Right Rear	-0.01	0.965	Not statistically significant ( $p > 0.05$ )

In the analyses conducted for the left pedal, the inter-regional correlation coefficients were found to be quite low. The correlation coefficients between "Left Front-Left Center," "Left Front-Left Rear," and "Left Center-Left Rear" were -0.03 ( $p = 0.895$ ), 0.09 ( $p = 0.703$ ), and 0.22 ( $p = 0.344$ ), respectively. However, subsequent analysis revealed that none of these values were statistically significant ( $p > 0.05$ ). Consequently, it can be posited that the loads applied to the left pedal surface were measured in a predominantly localized manner, and the interaction

between sensors was found to be negligible. For the right pedal, a moderately weak correlation was identified between the "Right Front-Right Center" regions at  $r = 0.39$  ( $p = 0.090$ ). However, this relationship did not attain statistical significance ( $p > 0.05$ ). The relationship between "Right Front-Right Rear" is negligible ( $r = -0.01$ ,  $p = 0.965$ ). Additionally, the measurement variance in the "Right Center" sensor was found to be minimal ( $\sigma^2 \approx 0.018$  kg<sup>2</sup>). This phenomenon led to the production of relatively constant values by the relevant sensor during loadings,

thereby resulting in a statistically limited meaning of the correlation calculation in certain region pairs. The findings indicate that the structural isolation of the system is predominantly effective and that signal transmission between proximate regions remains negligible. Consequently, low-level correlations were observed between the sensors for both the right and left pedals. This finding suggests that the mechanically provided discrete support points and the rigid support layer beneath the pedals effectively limit load transfer between sensors. Consequently, the system demonstrates a configuration in which loads are predominantly identified by local sensors, thereby enhancing the reliability of force distribution analyses.

To comprehensively evaluate system performance, the differences between the reference loads applied to each pedal region and the values measured by the system were examined. These differences were calculated as both absolute deviation ( $|\Delta|$ ) and percentage deviation ( $|\Delta|\%$ ). This analysis is critical for ascertaining whether positional sensitivity engenders systematic errors. The deviation value was obtained using the following formula:

$$|\Delta| = F_{measured} - F_{reference} \tag{3}$$

The mean absolute deviation in left pedal measurements was determined to be 0.35 kg, and the mean percentage deviation was 1.09%. For the right pedal, the mean absolute deviation was calculated to be 0.16 kg, and the mean percentage deviation was 0.39%. The maximum percentage deviation was found to be 2.83%, and the minimum deviation was 0.00%.

**Table 5.** The mean absolute and percentage deviation values were calculated based on the reference load in the pedal regions.

Pedal	Mean $ \Delta $ (kg)	Mean $ \Delta \%$	Max $ \Delta \%$	Min $ \Delta \%$
Left Pedal	0.35	1.09	2.83	0.21
Right Pedal	0.16	0.39	1.18	0.00

These values demonstrate that the system can measure reference loads on both the left and right pedal sides with a very low margin of error. The absence of a substantial increase in measurement errors with increasing load magnitude suggests that the system exhibits a stable response across varying force levels and that non-linear effects are minimal. The percentage error profile indicates that the system operates in a configuration within acceptable error limits for clinical and sports applications ( $\pm 3\%$ ) despite the incorporation of low-cost sensors. In summary, the deviation analysis indicates that the system demonstrates high measurement accuracy when compared to reference loads and that the pedal

structure exhibits consistent performance independent of positional effects. Percentage error analyses demonstrate that the system maintains measurement accuracy despite the use of low-cost sensors and operates within acceptable error limits for clinical or sports applications.

#### 4. Conclusions

In this study, the measurement accuracy, repeatability, and positional sensitivity of a wireless pedal force measurement system developed using low-cost components and a microcontroller-based infrastructure were evaluated in detail. The static load tests and position-dependent analyses performed revealed that the system operates with high accuracy, particularly under stable conditions, and can produce reliable measurements with low variance. Research has demonstrated that such portable systems exhibit reliability and validity that approach the gold standard of laboratory testing (Collings et al., 2024; Mylonas et al., 2023). The findings indicate that the system can be effectively used both in field applications and clinical settings, with deviations in the range of 1–2% from reference loads and high correlation coefficients ( $R^2 > 0.99$ ). When evaluated in terms of measurement reliability, the fact that the %CV values remain below 1.5% in all sensor channels indicates that the system provides stable outputs even in short-term measurements. In a similar vein, portable measurement devices exhibiting high test-retest reliability have been documented in the extant literature (Plakoutsis et al., 2023). This enhancement in functionality broadens the system's applicability in domains that demand the handling of biomechanically sensitive measurements, such as rehabilitation and sports performance monitoring. Comparisons with analogous systems in the extant literature also support the competitiveness of the developed system in terms of measurement accuracy. A one-way analysis of variance (ANOVA) was performed, and the results indicated that there was no statistically significant difference between locations, as evidenced by location sensitivity analyses with p-values above 0.05 for both the left and right pedals (left: 0.640; right: 0.878). However, the observation of very low-level positional variations in the measurement values is related to the mechanical rigidity of the pedal structure and the natural tolerances of the sensor placement. This finding suggests that the system is capable of producing position-independent consistent measurements and that the overall structural integrity is maintained. The absence of cross-sensor effects and the observation of low-level variations in the variance analyses that are not

statistically significant on measurement accuracy confirm the system's structural isolation success. This feature enhances the system's functionality, particularly in advanced biomechanical assessments such as pedal force distribution, foot positioning, and imbalance analysis. Furthermore, research on the impact of lower extremity strength asymmetries and load distributions on performance and injury risk underscores the significance of symmetry and positional awareness (Jiang et al., 2023). The developed system is not only intended for research purposes but also suitable for application in clinical rehabilitation processes and sports training programs. This technology facilitates the reliable monitoring of inter-limb strength symmetry in neuromuscular conditions, including post-stroke hemiparesis, multiple sclerosis, and lower extremity strength imbalances. The documentation of lower extremity strength asymmetries is substantial, with evidence indicating their potential to enhance sports performance and increase the risk of injury (Espada et al., 2023; Jiang et al., 2023). In this context, the system offers a practical solution that could be an alternative to existing commercial systems with its economical and portable design. However, the study is not without its limitations. It is important to note that the measurements were only performed under static conditions; the system's performance during dynamic pedaling, at different cadence levels, and at variable speeds has not yet been evaluated. Despite the recent validation studies on portable force platforms demonstrating satisfactory results even under dynamic conditions (Badby et al., 2023; Collings et al., 2024), dynamic validation for pedal force measurement remains limited due to the lack of standardized protocols and the mechanical variability introduced during high-cadence pedaling. Moreover, the scope of the tests has been confined to healthy individuals. Thus, the present validation represents a healthy population-based classification, and the applicability to clinical groups (e.g., post-stroke, MS, orthopedic rehabilitation) remains to be verified. In the context of future research endeavors, two key issues require further investigation: mechanical durability and long-term calibration stability. In subsequent studies, conducting dynamic accuracy analyses, testing data stability across variable cadences, and integrating bio-signal sources such as electromyography will enhance the system's multidimensional biomechanical analysis capabilities. Furthermore, the development of mobile-application-based user interfaces, in addition to the provision of user-friendly solutions for field applications, will result in a significant expansion of the system's accessibility and its range of application areas.

In summary, the developed wireless pedal force measurement system offers a cost-effective platform with high usability for both scientific research and clinical/sports applications with its high measurement accuracy, sensitivity to force symmetry, and position-dependent reliability. The system's modular configuration lends itself to augmentation with sophisticated analyses and biosignal integrations. In this regard, the system offers a significant contribution as a real-time, portable, and versatile assessment tool, serving as an alternative to expensive laboratory equipment.

#### **Declaration of Ethical Standards**

The authors declare that they comply with all ethical standards.

#### **Credit Authorship Contribution Statement**

Author-1: Conceptualization, investigation, methodology, software, visualization, writing – original draft.

Author-2: Conceptualization, investigation, methodology, software, supervision, writing – review and editing.

#### **Declaration of Competing Interest**

The authors have no conflicts of interest to declare regarding the content of this article.

#### **Data Availability Statement**

Datasets are available on request. The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

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