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Design and Statistical Validation of Low-Cost Electrogoniometers for Elbow Orthosis Applications

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Abstract

This study presents the design, implementation, and statistical validation of four low-cost electrogoniometers for elbow joint angle measurement in orthotic applications. The proposed systems are four sensing configurations based on three hardware sensing modalities: IR sensing with two calibration strategies, rotary potentiometry, and slide potentiometer, all integrated into a custom mechanical structure that enables indirect measurement while reducing mechanical stress on sensing components. Experimental validation was performed using a controlled elbow motion simulator and five healthy volunteers for preliminary assessment of device placement and wearable feasibility, with measurements compared against a reference digital goniometer. Performance metrics included mean absolute error (MAE), repeatability, linearity (R^2), and statistical agreement. A one-way ANOVA revealed significant differences among sensing modalities ($p < 0.05$), and Tukey's post hoc analysis confirmed that the IR-based system exhibited significantly higher errors than calibrated IR-based and both potentiometer-based systems. Bland–Altman analysis demonstrated strong agreement for calibrated IR-based and potentiometer-based designs, with minimal bias and narrow limits of agreement. The calibrated IR achieved the highest accuracy (MAE ≈ 2.78°), while the slide potentiometer provided a favorable balance between performance (MAE ≈ 4.72°) and mechanical integration. These results indicate that potentiometer-based electrogoniometers are suitable for wearable rehabilitation systems requiring reliable and real-time joint monitoring. The proposed designs offer cost-effective alternatives for biomechanical instrumentation and support the development of accessible assistive technologies.

1. Introduction

Upper-limb orthotic systems are essential for restoring motor function and improving the quality of life of patients undergoing neurorehabilitation or recovering from musculoskeletal injuries. The integration of electronic sensing modules into orthotic structures enables real-time monitoring and adaptive control, fostering the development of adaptive and intelligent assistive devices.

From a biomechanical perspective, accurate elbow joint angle estimation is essential for quantifying movement quality, assessing rehabilitation progress, and enabling closed-loop control in assistive devices [1]. Measurement errors greater than 5° can lead to misinterpretation of the functional range of motion and may affect clinical decision-making in rehabilitation protocols. Therefore, evaluating both the accuracy and repeatability of wearable sensing systems under realistic motion constraints is crucial. This study explicitly considers these biomechanical requirements by analyzing measurement fidelity across the functional

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range of elbow flexion-extension and assessing the suitability of each sensing approach for integration into assistive orthotic systems.

In the literature, a wide range of sensing approaches has been explored for joint motion tracking, including bioelectrical sensors (e.g., EMG and EEG), biomechanical sensors (e.g., force-sensitive resistors), and electromechanical systems (such as potentiometers). Flexible and optical sensors offer advantages in terms of comfort and low intrusiveness, but they often exhibit nonlinear behavior and long-term performance degradation [2]. However, electromechanical sensors provide a more direct correlation with the performed motion.

Electrogoniometers remain an attractive solution due to their simplicity, low cost, and direct relationship between mechanical displacement and electrical output. These devices must meet several requirements, including measurement accuracy, device cost, and user comfort—particularly in applications involving prolonged use—so as not to interfere with the performance of activities of daily living (ADLs) [3-6].

These devices employ a variety of technologies, including potentiometers, inertial measurement units (IMUs), flexible resistive and capacitive sensors, Hall-effect sensors, and optical systems [2, 7–12]. Each technology involves trade-offs in terms of accuracy, cost, power consumption, and ease of integration. Most commercial electrogoniometers are relatively expensive, which can limit their accessibility for independent researchers [13].

The most common type of electrogoniometer uses a potentiometer as the sensing element, as these components are significantly less expensive than other measurement methods and allow for immediate data acquisition, typically through a microcontroller with an integrated ADC or a data acquisition system [3, 4, 12, 14–17].

A commonly considered solution involves the use of a rotary potentiometer [12]. However, when the potentiometer shaft is used as the pivot point of the mechanism, the entire load is transferred to the sensor, which is not structurally designed to withstand the applied mechanical forces, estimated to be around 50 N for normal unloaded motion [18]. Alternatively, placing the potentiometer adjacent to the pivot significantly increases the system's volume and compromises both functionality and device aesthetics.

Recent research highlights the need for compact, lightweight, and user-adaptable sensors for wearable systems. For instance, systems based on inertial measurement units (IMU) , which integrate gyroscopes, magnetometers, and accelerometers, provide three-dimensional motion tracking [10, 19]; however, they are affected by temperature variations, magnetic fields, and unwanted external accelerations, among other factors [6]. Additionally, they require complex calibration procedures, as their operation relies on acceleration measurements influenced by the Coriolis effect. This dependence introduces a limitation: in the absence of continuous acceleration (particularly along the axis perpendicular to the gravitational vector), consistent and accurate position tracking cannot be achieved [20].

Flexible and fiber-optic sensors offer advantages in terms of low intrusiveness and user comfort, but they may exhibit nonlinearity and performance degradation over time [4, 21]; in the case of optical sensors, material rigidity may also interfere with natural movement [22]. Optocoupler-based sensors are advantageous due to their low weight and relative ease of integration into mechanical systems, like encoders, achieving good measurement linearity [16].

Optical encoders can provide high resolution and accuracy—surpassing magnetic encoders—but they may be costly and susceptible to vibration, impact, and mechanical stress [1]. Potentiometric systems remain widely used due to their linear behavior and mechanical simplicity, although they are prone to wear and electrical noise [23–28].

This study introduces four electromechanical systems designed to adapt to elbow joint motion. The proposed systems— four sensing configurations based on three hardware sensing modalities: IR sensing with two calibration strategies, rotary potentiometry, and slide potentiometer—can be integrated into orthotic devices with relative ease and offer several advantages: measurements are performed indirectly, thereby protecting the sensors from mechanical stress, and displacement data can be acquired independently of the device's spatial orientation.

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The proposed configuration allows real-time data acquisition, and the overall design remains compact, making it suitable for wearable applications. The development and comparison of the four elbow electrogoniometers are intended to support their future integration into an orthotic device.

The proposed electrogoniometers were experimentally evaluated under identical experimental conditions. In addition to conventional performance metrics, statistical analyses are employed to assess differences in accuracy and agreement with a reference device. The analysis includes construction simplicity, response linearity, and measurement reliability, contributing to the development of affordable assistive technology solutions.

Furthermore, this work establishes a systematic framework for the design and evaluation of low-cost electrogoniometers suitable for wearable rehabilitation applications. This work goes beyond a conventional comparison of sensing technologies by introducing a design framework for indirect angular measurement mechanisms that decouple mechanical load from sensing elements. Unlike traditional electrogoniometers, where the sensor is directly subjected to joint forces, the proposed architectures redistribute mechanical stresses through auxiliary linkages, thereby enhancing sensor durability and measurement stability. Furthermore, the study establishes a systematic comparison between optical and potentiometric sensing modalities under identical mechanical and experimental conditions, providing a controlled benchmark that is currently lacking in literature.

2. Materials and methods

2.1. General Design Framework

The design and development process of the electrogoniometers followed a structured approach comprising: (1) the definition of device requirements, (2) the mechanical design of the structure on which the electrogoniometers are mounted, (3) the design and construction of four electrogoniometers using the proposed mechanical structure, and (4) validation testing and comparative performance analysis. The prototypes were evaluated in a controlled laboratory environment using the mounted structure on healthy subjects.

This study was reviewed and approved by the TecNM/Instituto Tecnológico de Morelia Ethics Committee. All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki Declaration and its later amendments. Written informed consent was obtained from all individual participants included in the study prior to data collection. Five subjects, four men and one woman, aged 22 to 28 years, were included in the study. Their arm lengths, measured from the shoulder to the wrist, ranged from 51 to 58 cm, while their arm circumferences ranged from 26 to 35 cm.

To ensure methodological rigor, the experimental protocol was designed to minimize systematic and random errors. Each measurement was repeated five times under identical conditions, and the sensors were recalibrated before data acquisition to reduce drift effects. The device tests were performed in a randomized sequence across the subjects using Python programming language.

Although the present study focuses on quasi-static angular positions, these conditions provide a controlled baseline for evaluating intrinsic sensor performance, independent of dynamic artifacts such as inertial effects or soft tissue motion. This approach enables a clear comparison of sensing principles, which is a necessary step before extending the system to dynamic and real-world rehabilitation scenarios.

2.2. Mechanical Design of Arm Structure

The mechanical structure was constructed using one-inch square aluminum profiles, selected for their high stiffness-to-weight ratio. Segments are incorporated to be positioned along the humerus and forearm, facilitating proper placement.

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Rotary and sliding components replicate elbow flexion–extension with a single degree of freedom, over a functional range from 30° to 170°, without considering hyperflexion or hyperextension. Angular measurements are compared against a commercial digital goniometer (NOENNULL, model PD290), featuring a resolution of 0.05° and an accuracy of ±0.3°, which is used as the reference standard.

For the controlled laboratory validation, the reference angle was established directly between the upper and lower aluminum segments of the elbow simulator using the commercial digital goniometer. The reference goniometer was aligned with the rotational axis of the mechanical structure, and measurements were obtained at discrete angular positions separated by 5°. At each position, the prototype output and reference angle were recorded under quasi-static conditions.

All sensors were interfaced with an ESP32 microcontroller for data acquisition. As calibration models were derived using regression techniques, depending on the sensor characteristics and acquisition settings. Since an interface with an established communication protocol is already available, the sampling frequency is selected at 7,800 Hz to avoid delaying the measurements. According to the literature, this sampling frequency is considerably higher than that required to record elbow motion. Nevertheless, the acquired data is used to calculate the mean of each sample window. This averaging process is performed over every 780 samples, yielding one averaged value every 100 ms. Oversampling and sample averaging help mitigate undesirable variations in sensor measurements, such as those produced by a potentiometer, or the ESP32ADC resulting in a smoother, filtered response.

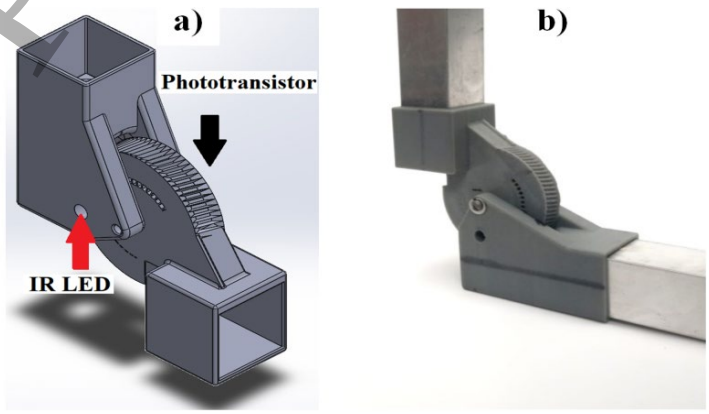
2.2.1. IIR Sensor-Based electrogoniometer

This electrogoniometer is used for both calibrated and uncalibrated sensors, exploiting the variation in light intensity received by an infrared (IR) sensor as a function of joint angle. A variable aperture window (implemented as a light-tight arc) is positioned between the infrared LED and the phototransistor, such that the opening changes with the joint angle. The design considers both the sensor configuration and the mechanical arrangement associated with elbow joint positions. The system includes:

• ***Mechanical configuration***: A fixed infrared LED source and a phototransistor, forming the IR sensor, are mounted at opposite ends of a light-tight arcuate guide, where the light intensity reaching the sensor varies with elbow rotation.

• ***Data acquisition:*** The voltage output of the IR sensor was recorded at known angular positions using an ESP32 mmicrocontroller, with resolution determined by the 12-bit analog-to-digital converter (ADC) generating a characteristic response curve.

• ***Calibration:*** The sensor output was converted into angular displacement using a second-order polynomial calibration model derived from a least-squares fit. Figure 1 shows the 3D design of the mechanism of the elbow joint electrogoniometer and its physical application.



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Figure 1. Mechanism of IR sensor-based electrogoniometer: a) design in 3D, b) physical implementation.

Figure 2 shows the mechanical design of the elbow with the IR sensor and variable windows mounted on an aluminum structure that simulates the arm. The structure is made of one-inch square aluminum tubing, 30 cm long, and 2 inches at its widest point. A 10 cm section of aluminum tubing protrudes from the top, to which an orthopedic shoulder support is attached. This structure will be the same for all proposed electrogoniometer designs. The shape of the mechanism is shown in flexion and extension to demonstrate that it is compatible with the movement of the human arm. The black Velcro straps are used to attach to the arm of the user.

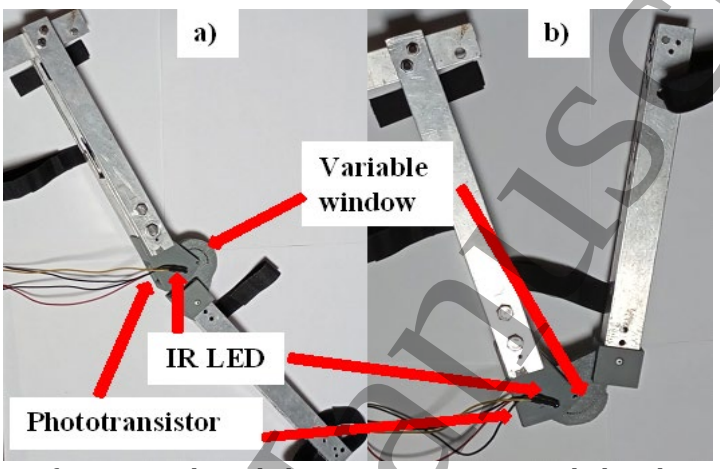


Figure 2. Mechanism of IR sensor-based electrogoniometer coupled in the structure of the arm: a) extended, b) flexed.

2.2.2 Rotary Potentiometer-Based electrogoniometer

The second prototype uses a rotary potentiometer (Vishay 157-11502) placed on the elbow joint axis in an elbow motion simulator. The key components and procedures include:

• ***Mechanical integration***: The potentiometer is mechanically coupled to a sliding linkage, and the angular displacement of the forearm is transmitted to the rotary potentiometer through this linkage.

• ***Data acquisition:*** Voltage outputs were measured using an ESP32 board, with resolution determined by the 12-bit analog-to-digital converter (ADC).

• ***Calibration:*** A regression model was used to convert voltage readings to angular values, leveraging the potentiometer's known linear behavior.

Figure 3 presents a) the 3D design of the proposed electrogoniometer mechanism intended for use with a rotary potentiometer, and b) the mechanism coupled in the elbow simulator with the rotary potentiometer.

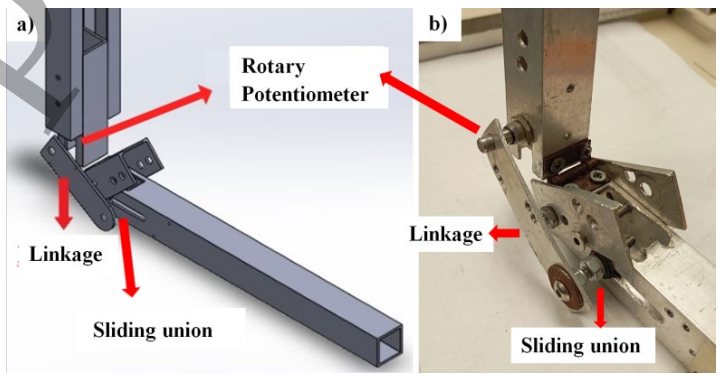


Figure 3. Mechanism of rotary potentiometer-based electrogoniometer: a) Design in 3D, b) Real implementation.

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Figure 4 shows the electrogoniometer mechanism with the rotary potentiometer assembled on the aluminum arm when flexed and extended.

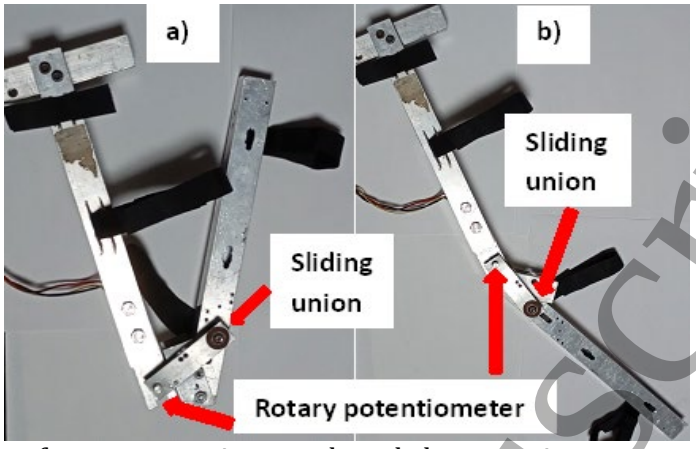


Figure 4. Mechanism of rotary potentiometer-based electrogoniometer assembled on the aluminum arm: a) flexed, b) extended.

2.2.3. Slide Potentiometer-Based electrogoniometer

The third prototype employs a slide potentiometer (Fader B103) featuring a rotary joint positioned proximally above the elbow. The key components and procedures include:

• ***Mechanical integration:*** The potentiometer is mechanically connected to a bearing with a fixed base (housing). The slide potentiometer moves in accordance with the forearm angular displacement. Both the pivot and the housing bearing are positioned such that the stroke of the potentiometer spans the entire range of angular motion.

• ***Data acquisition:*** Voltage outputs were measured using an ESP32 board, with resolution determined by the 12-bit analog-to-digital converter (ADC).

• ***Calibration:*** A linear regression model was used to convert voltage readings to angular values, leveraging the potentiometer's known linear behavior.

Figure 5 shows the prototype with slide potentiometer, a) the front side of the electrogoniometer, and b) the rear side of the device, showing the coupling of the potentiometer and the housing bearing in the forearm.

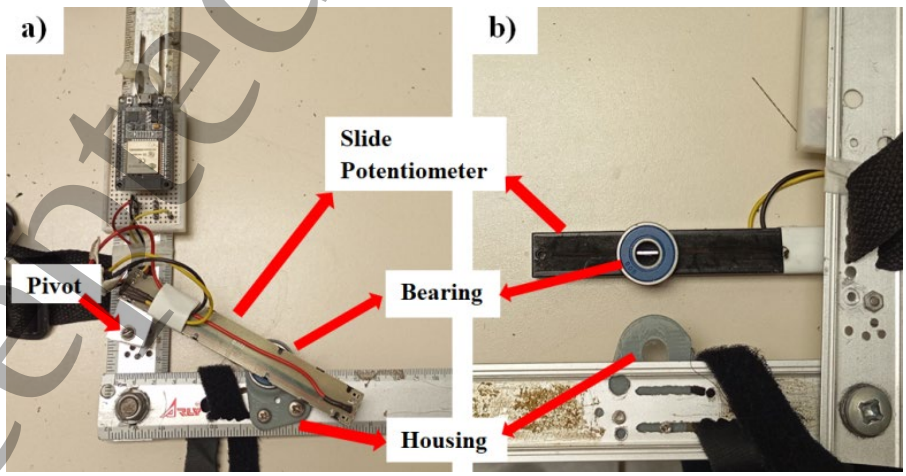


Figure 5. Mechanism of prototype with slide potentiometer using a housing bearing: a) front side, b) rear side.

Figure 6 shows the same design as the prototype, adapted to the structure used in the previous designs, and assembled on the aluminum arm in the positions of flexion and extension.

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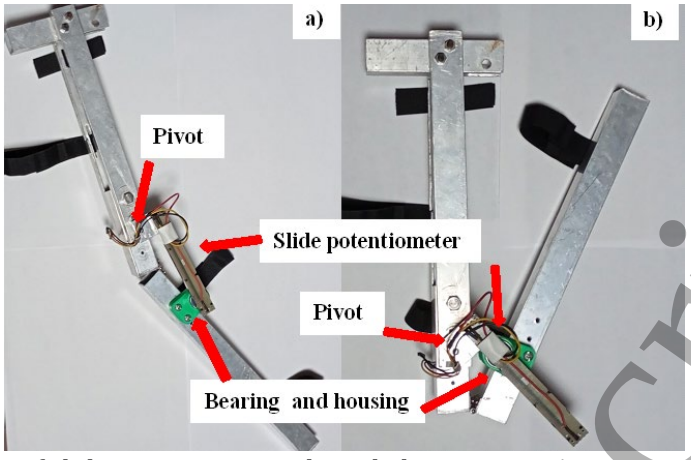


Figure 6. Mechanism of slide potentiometer-based electrogoniometer assembled on the aluminum arm: a) extended, b) flexed.

3. Measurement and Validation Protocol

To validate the four devices, angular measurements were taken at fixed positions from an angle in the elbow joint of 30° to 170°, with 5° increments. Each position was measured five times for each sensor, considering a dwell time of 2 s. A commercial digital electrogoniometer served as the reference standard. The following metrics were evaluated:

- Mean Absolute Error (MAE) relative to the reference.
- Repeatability (Standard deviation across repeated measures).
- Linearity of sensor response (R^2 value).
- Construction cost and integration feasibility.

Data was analyzed using Microsoft Excel and Python (NumPy and SciPy libraries). Graphs and calibration curves were generated to compare actual vs. predicted angles for each prototype.

3.1 Statistical Analysis

To quantitatively compare the performance of the four electrogoniometer designs, a statistical analysis was conducted including one-way analysis of variance (ANOVA) and Bland–Altman agreement analysis.

A one-way ANOVA was performed to determine whether there were statistically significant differences in measurement error (defined as the absolute difference between the electrogoniometer and the reference goniometer) among the four sensing approaches: IR-based, Calibrated IR-based, rotary potentiometer-based, and slide potentiometer-based systems.

The level of significance was set at $\alpha = 0.05$. Prior to ANOVA, normality of the error distributions was assessed using the Shapiro–Wilk test, and homogeneity of variances was evaluated using Levene's test. When significant differences were detected, post hoc pairwise comparisons were conducted using Tukey's honestly significant difference (HSD) test.

In addition to hypothesis testing, agreement between each electrogoniometer and the reference device was evaluated using Bland–Altman analysis. For each measurement pair, the mean of the two methods and their difference were computed. The mean difference (bias) and the limits of agreement (LoA), defined as ±1.96 standard deviations of the differences, were calculated. This analysis provides insight into systematic bias and the dispersion of measurement errors across the full range of motion.

All statistical analyses were performed using Python V. 3.12 (SciPy V. 1.16.1 and StatsModels V. 0.14.0 libraries), and results were considered significant at $p < 0.05$.

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4. Results and discussion

The electrogoniometers were evaluated through five repeated measurements at different elbow angles over a range from 30° to 170°, in 5° increments, and the results were compared with those obtained from a digital goniometer used as the reference. Additionally, the electrogoniometers were mounted on five healthy volunteers to validate their ergonomic design and the measurements obtained. The devices were secured to the shoulder and arm of the volunteer using an orthopedic shoulder support and Velcro fasteners. Figure 7 shows the IR sensor-based electrogoniometer on the volunteer, using the orthopedic support.

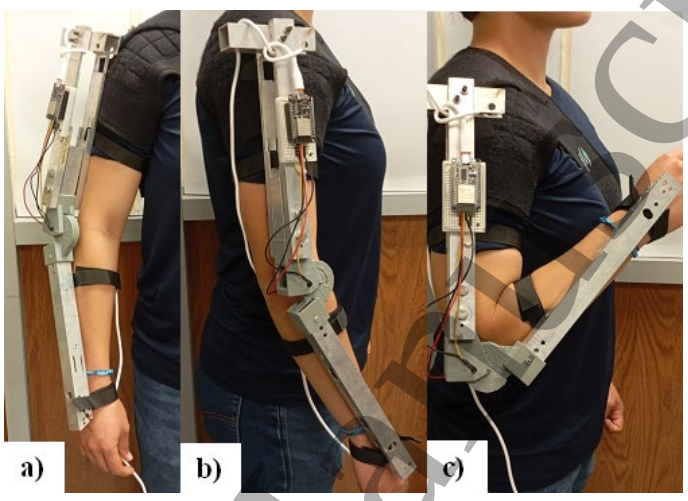


Figure 7. Example of colocation of the IR sensor-based electrogoniometer on a volunteer: a) front view, b) side view extended arm, c) side view flexed arm.

Figure 8 shows the curve for the IR sensor-based electrogoniometer. The sensor exhibited a nonlinear response to the angle. The blue line represents the data of the sensor, and the black line is the function of the linear model.

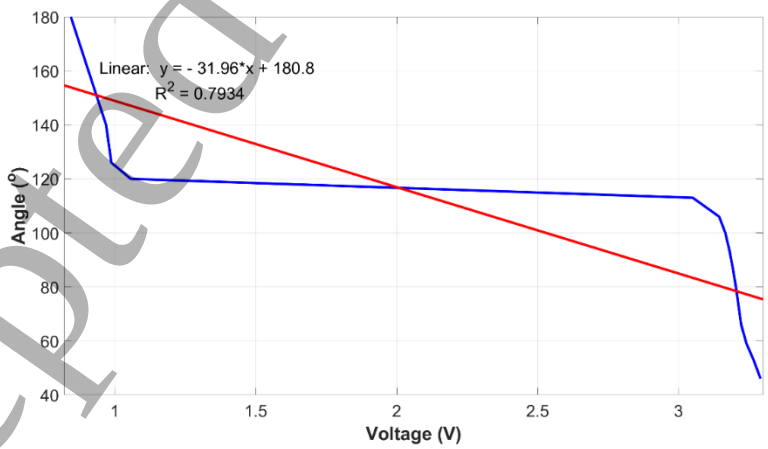


Figure 8. Calibration linear curve for the IR sensor-based electrogoniometer.

Using linear regression, the relationship between voltage and angle is obtained as given by Equation (1):

$$y = -31.96x + 180.8 \qquad (1)$$

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The fit yielded a coefficient of determination (R^2) of 0.7934, indicating the correlation between measured voltage and actual elbow angle. The average Mean Absolute Error (MAE) across all angles was 16.0672°.

Different polynomial regressions were used, for instance, Equation (2) corresponding to the curve in Figure 9 is obtained as follows:

$$y = -62.15x^5 + 588.8x^4 - 2175x^3 + 4010x^2 - 3796x + 1565 \quad (2)$$

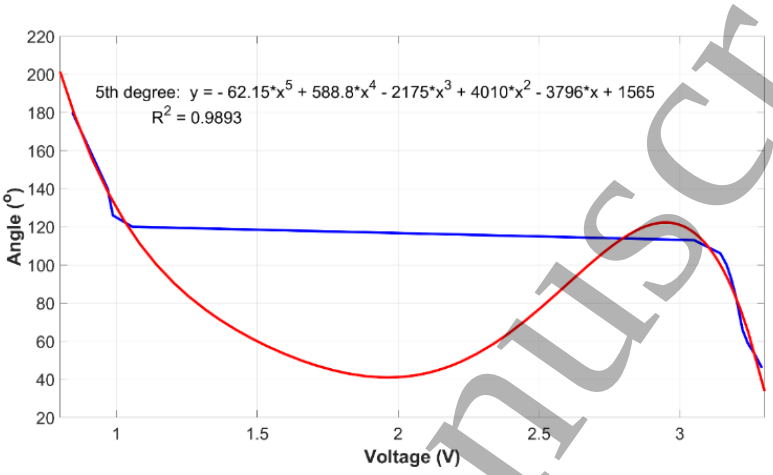


Figure 9. Fitting calibration curve for the IR sensor-based electrogoniometer

The obtained R^2 value is 0.9893; however, the form of the resulting curve does not adequately fit the data obtained from the IR sensor. Therefore, the range is segmented into three sections, each with a different equation depending on the interval. From 100° to 120°, a fitting of (x/80) + 985 is applied to the ADC reading, and from 121° to 170°, a value of 667 is added to the ADC reading, converting this value into voltage using Equation (3):

$$y = \frac{x*3.3}{1024} \quad (3)$$

Fig. 10 shows the fitted response of the calibrated IR electrogoniometer. Using linear regression, the relationship between voltage and angle is obtained as given by Equation (4):

$$y = -380.1x + 1297 \quad (4)$$

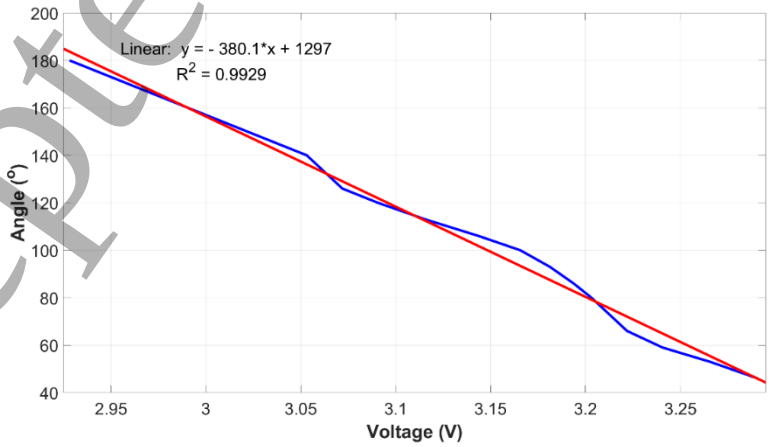


Figure 10. Fitting calibration curve for the IR sensor-based electrogoniometer.

The average Mean Absolute Error (MAE) across all angles was 2.7890°, with the highest deviation at low angles due to sensitivity limits of the IR sensor at close light-source distances. Repeatability was acceptable, with a standard deviation below 5° in most positions.

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It is important to clarify that the piecewise ADC correction and the polynomial angle-calibration model represent two distinct processing stages. Nevertheless, because the same angular measurements were used to fit and evaluate the calibration curve, the original goodness-of-fit metrics do not constitute an independent assessment of predictive accuracy.

Figure 11 shows the placement of the electrogoniometer based on a rotary potentiometer on one of the volunteers. The rotary potentiometer-based system has a strong linear relationship between voltage and angular displacement. The system demonstrated excellent consistency and low noise.

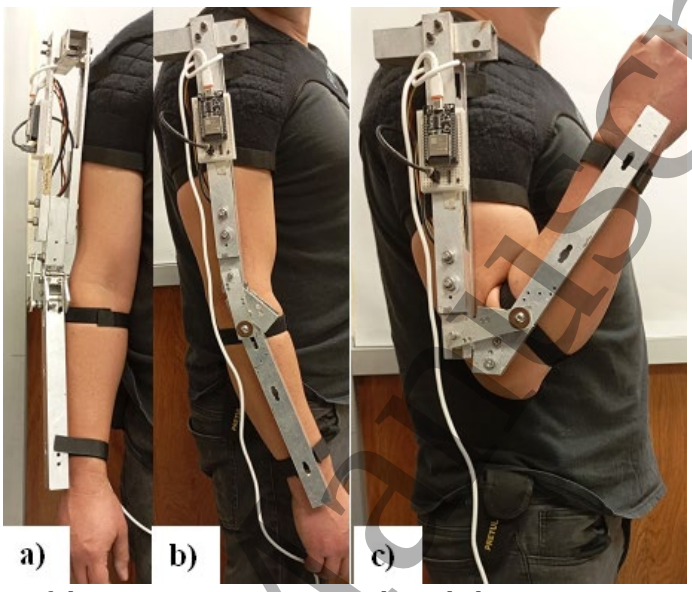


Figure 11. Colocation of the rotary potentiometer-based electrogoniometer on a volunteer: a) front view, b) side view extended arm, c) side view flexed arm.

Figure 12 shows the graphics of the response of the rotary potentiometer and the angle. Using linear regression on the calibration curve, Equation (5) is obtained:

$$y = 69.95x - 4.054 \quad (5)$$

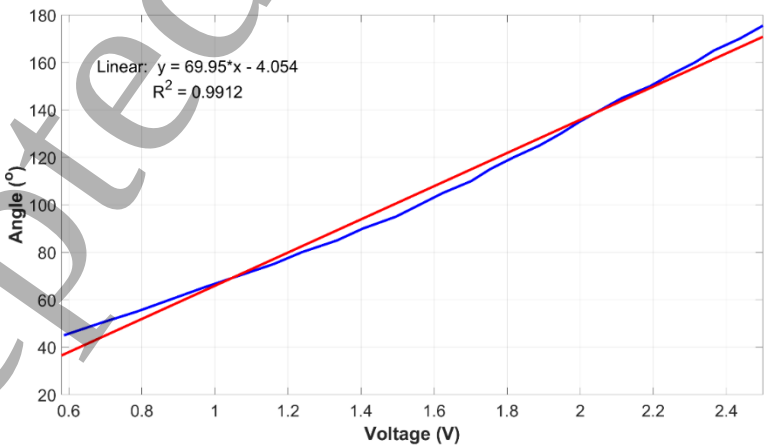


Figure 12. Calibration curve for the rotary potentiometer-based electrogoniometer.

The obtained R^2 value is 0.9912, and the MAE was 3.2856°, and the standard deviation across repeated measures was below 1.5° at all points, demonstrating good repeatability.

Figure 13 shows the placement of the electrogoniometer based on a slide potentiometer on one of the volunteers.

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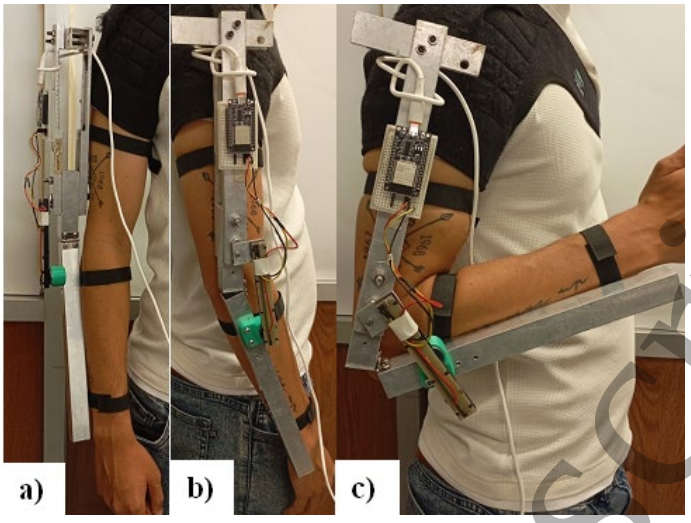


Figure 13. Colocation of the slide potentiometer-based electrogoniometer on a volunteer: a) Front view, b) Side view extended arm, c) Side view flexed arm.

The slide potentiometer-based system displayed a strong linear relationship between voltage and angular displacement, Figure 14.

Using linear regression, the relationship between voltage and angle is obtained as given by Equation (6):

$$y = 70.97x - 69.15\ y = 70.97x - 69.15 \quad (6)$$

A simple linear regression yielded an R^2 of 0.9856. The system demonstrated excellent consistency and low noise. The Mean Absolute Error (MAE) was 4.7194°, and the standard deviation across repeated measures was below 1.8° at all points, demonstrating good repeatability.

The proposed designs of electrogoniometers that can be used and adapted for the measurement of the angular motion of the forearm were evaluated and compared. The results show that the IR-sensor does not have a linear behavior, its measurement is not reliable, and its mechanical adaptation is difficult, because it is necessary to design the parts to mount the IR-sensor, integrating the movement mechanism.

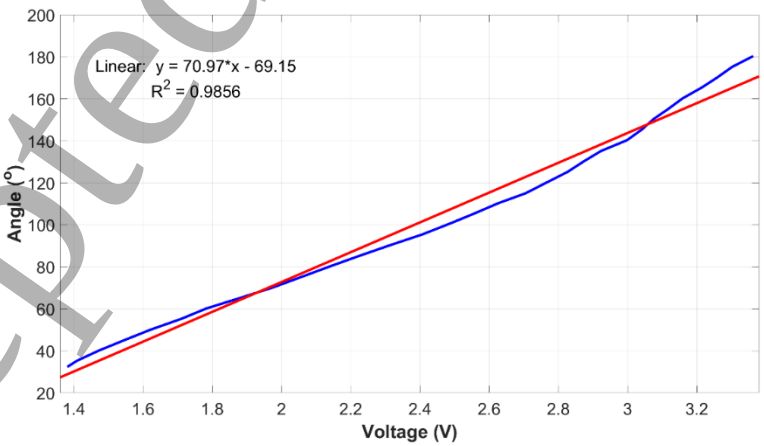


Figure 14: Calibration curve for the slide potentiometer-based electrogoniometer and its linear model.

Potentiometer sensors are capable of delivering reliable angular measurements, offering superior accuracy and simpler signal processing. The IR sensor-based design is a viable alternative when specific integration constraints apply. Similar results were obtained when the angle measurements were performed on the volunteer.

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The parameters to compare electrogoniometers are shown in Table 1, including the cost of the sensors and the elements, as well as the difficulty of their mechanical integration.

Table 1. Comparison of designed electrogoniometers.

Feature	IR-Based Sensor	Adjusted IR-Based Sensor	Rotary Potentiometer-Based Sensor	Slide Potentiometer-Based Sensor
Measurement Range	30° – 170°	30° – 170°	30° – 170°	30° – 170°
Sensor Output	Nonlinear voltage	Nonlinear voltage	Linear voltage	Linear voltage
R^2 (Linearity of Response)	0. 7934	0.9893	0.9912	0.9856
Mean Absolute Error (MAE)	16.0672°	2.7890°	3.2856°	4.7194°
Repeatability (σ)	< 5.0°	< 5.0°	< 1.5°	<1.8°
Sensor Cost	≈ $3.50	≈ $3.50	≈ $10.00	≈ $5.00
Signal Conditioning	Moderate complexity (nonlinear)	Moderate complexity (nonlinear)	Low complexity (linear)	Low complexity (linear)
Mechanical Integration	Requires alignment of a light source	Requires alignment of a light source	Requires modification to integrate the sensor and linkage	Can be adapted externally using screws or strong glue
Environmental Sensitivity	Affected by ambient light	Affected by ambient light	Mechanically stable	Mechanically stable
Ease of Use	High	High	High	High
Ease of mechanical integration	Low: needs its own designed parts to integrate it mechanically	Low: needs its own designed parts to integrate it mechanically	Moderate: The mechanical system needs to be modified to be integrated into the sensor and linkage	High: The pivot and housing bearing can be adapted externally using screws or strong glue
Suitability for Wearables	High (design directly coupled in the mechanism)	High (design directly coupled in the mechanism)	High (compact and robust, could need protection in mobile parts)	High (compact and robust, could need protection in mobile parts)

The proposed evaluation framework distinguishes experimentally measured metrological performance from engineering and usability considerations. Accuracy, repeatability, linearity, and method agreement were quantitatively evaluated in the present study. Cost, mechanical

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integration, signal-conditioning complexity, and environmental sensitivity were considered engineering design criteria.

Parameters such as long-term durability, power consumption, mass, thermal stability, user comfort, and activities of daily living were not quantitatively evaluated and are therefore identified as requirements for subsequent validation.

The reported sensor costs correspond to the specific commercial components used to fabricate the prototypes and should not be interpreted as representative market prices for the corresponding sensing technologies. Component prices vary according to manufacturer, specifications, purchasing volume, and supplier.

The experimental evaluation confirms that the electrogoniometer prototypes fulfill their intended function: measuring elbow flexion-extension with acceptable accuracy and reliability for potential integration into orthotic systems.

However, differences in performance, mechanical integration, and signal behavior lead to distinct advantages and limitations. The results obtained in this study are specific to the sensing elements and mechanical architectures evaluated. Consequently, they should not be interpreted as representative of all IR- or potentiometer-based electrogoniometers. Within the tested configurations and under the same experimental conditions, the slide potentiometer-based architecture provided the most favorable compromise between measurement performance and mechanical integration

The practical implications are discussed below:

• ***IR sensor-based design.*** Optical sensing through an IR sensor offers a cost-effective and innovative approach. It benefits from low power consumption and can be integrated into educational or proof-of-concept environments. However, its sensitivity to ambient light, requirement for precise alignment, and nonlinear behavior make it less suitable for field deployment or long-term wearable applications without additional shielding or compensation.

• ***Rotary potentiometer-based design.*** This system shows high linearity, good repeatability, and mechanical robustness. Its performance is consistent across the full range of motion, and it integrates easily with the elbow axis in the orthosis. The linear voltage output simplifies calibration and signal processing, making it ideal for clinical or home rehabilitation settings where reliability and ease of maintenance are critical.

• ***Slide potentiometer-based design.*** As the rotary potentiometer-based design, this system shows high linearity, good repeatability, and mechanical robustness. It is easier to adapt to the mechanical system, and that is an advantage over the other designs.

The experimental results demonstrate clear differences in performance among the evaluated sensing approaches. The IR-based electrogoniometer exhibited a nonlinear response and higher variability, requiring calibration and segmented fitting to have acceptable repeatability.

In contrast, the potentiometer-based systems showed strong linear behavior and consistent performance. The rotary potentiometer achieved the highest accuracy (MAE ≈ 3.28°, R^2 = 0.9912), with minimal noise and excellent repeatability. The slide potentiometer also demonstrated high linearity (R^2 = 0.9856) and low error (MAE ≈ 4.72°), while offering improved mechanical adaptability.

4.1 Statistical Comparison of Measurement Error

Statistical analysis confirmed that these differences are significant. The one-way ANOVA, presented in Table 2, revealed a statistically significant effect of sensing modality on measurement error ($F(3,112) = 44.45$, $p < 0.001$), indicating that the choice of sensor significantly influences measurement accuracy.

Table 2. ANOVA results of the designed electrogoniometers

Source	df	F	p-value

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Between groups	3	44.45	< 0.001
Residual	112	-	-

Post hoc analysis using Tukey's HSD test, presented in Table 3, showed that the IR-based system exhibited significantly higher error compared to all other configurations, including the calibrated IR, rotary potentiometer, and slide potentiometer systems ($p < 0.001$ in all cases).

Table 3. Tukey HSD results of the designed electrogoniometers.

Comparison	Mean Diff	p-adj	Significant
IR vs IRA	-13.32	<0.001	Yes
IR vs Rotary	-12.58	<0.001	Yes
IR vs Slide	-11.36	<0.001	Yes
IRA vs Rotary	0.74	0.944	No
IRA vs Slide	1.96	0.454	No
Rotary vs Slide	1.22	0.794	No

No statistically significant differences were found among the calibrated IR, rotary, and slide potentiometer systems ($p > 0.05$), suggesting comparable performance in terms of measurement error among these approaches.

These results confirm that while calibration significantly improves the performance of the IR-based system, potentiometer-based designs remain more reliable and consistent overall.

Bland–Altman analysis revealed distinct agreement characteristics among the evaluated systems. The IR-based electrogoniometer, Figure 15 a), exhibited the highest bias (≈ 1.51°), indicating a systematic overestimation relative to the reference. After calibration, the calibrated IR system showed a substantial reduction in bias (≈ 0.22°), Figure 15 b), demonstrating the effectiveness of the calibration approach in reducing systematic error.

The rotary potentiometer-based system showed a minimal negative bias (≈ −0.30°), indicating a slight underestimation, Figure 15 c), while the slide potentiometer-based system presented a small positive bias (≈ 0.29°), Figure 15 d). Both potentiometer-based systems exhibited low bias values, confirming strong agreement with the reference device.

These findings indicate that potentiometer-based electrogoniometers provide highly accurate and consistent measurements, while the IR-based system requires calibration to achieve comparable agreement levels.

From a biomechanical perspective, the error levels observed in the potentiometer-based and calibrated IR-based systems (MAE < 5°) fall within acceptable ranges for clinical and rehabilitation applications. In contrast, the higher error observed in the IR-based system limits its applicability in clinical contexts but may still be acceptable for qualitative motion tracking or educational purposes. These findings highlight the importance of selecting sensing technologies that provide both accuracy and reliability across the full range of motion.

4.2 Discussion

The results highlight that sensor performance is not only determined by the sensing principle but also by the mechanical integration strategy. By decoupling the sensing element

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from direct mechanical loads, the proposed designs improve durability and measurement stability, which are critical for wearable applications.

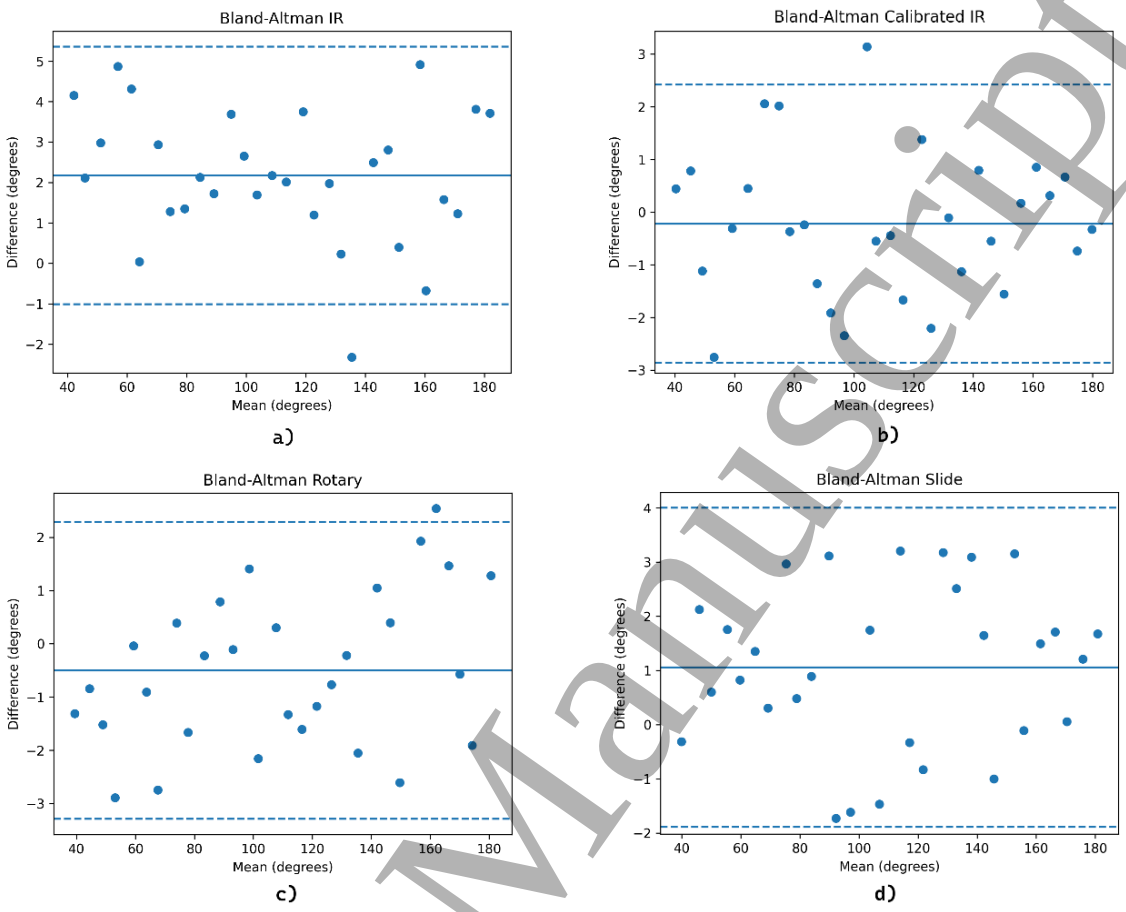


Figure 15. Bland–Altman analysis: a) IR, b) Calibrated IR, c) Rotary potentiometer, d) Slide potentiometer.

The IR-based system showed significantly higher measurement error compared to all other configurations, highlighting its limitations in raw form. However, the calibrated IR system demonstrated a substantial improvement, achieving performance levels statistically comparable to the potentiometer-based systems. This suggests that appropriate calibration strategies can mitigate some of the inherent nonlinearities of optical sensing. The raw ADC readings were corrected using a piecewise adjustment procedure before being converted into adjusted voltage values. These corrected values were subsequently used as inputs to the polynomial calibration model for estimating the elbow angle. Therefore, the reported calibration results should be interpreted as a characterization of the fit to the experimental dataset, rather than as a definitive measure of generalization performance. Independent validation is required to establish the accuracy of the calibrated sensor under previously untested measurement conditions.

The lack of significant differences between the rotary and slide potentiometer systems suggests that practical considerations, such as ease of integration and user comfort, may guide design selection. In this context, the slide potentiometer-based system emerges as a particularly attractive solution due to its balance between performance and adaptability.

Furthermore, the inclusion of statistical and agreement analyses strengthens the validity of the findings. While traditional error metrics provide a general measure of accuracy, Bland–Altman analysis offers deeper insight into measurement consistency, which is essential for biomechanical assessment and clinical decision-making.

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The main contribution of this work lies in demonstrating that low-cost sensing solutions can achieve clinically relevant accuracy when combined with appropriate mechanical design strategies.

Additionally, the study provides a reproducible experimental framework for evaluating electrogoniometer designs, which can be adopted in future research focused on wearable rehabilitation devices.

4.2 Comparison with related approaches

Compared with related low-cost and wearable approaches, the proposed configurations show competitive performance under the controlled conditions of the present study. Shahtalebi and Abouei [9] demonstrated the feasibility of potentiometer-based elbow-angle measurement, while Cerfoglio et al. [15], Fourniol et al. [16], and Pellegrini et al. [17] reported low angular errors using IMU- and capacitive-based wearable systems.

In the present study, the adjusted IR, rotary potentiometer, and slide potentiometer configurations achieved MAEs of 2.7890°, 3.2856°, and 4.7194°, respectively, with R^2 values of 0.9893, 0.9912, and 0.9856, whereas the unadjusted IR configuration showed substantially lower linearity (R^2 = 0.7934) and higher error (MAE = 16.0672°).

Although direct numerical comparison is limited by differences in sensing principles, reference systems, and error metrics among studies, these results demonstrate that the calibrated IR and potentiometric configurations provide measurement performance within the range reported for other low-cost wearable approaches.

Their main advantage lies in combining this performance with commercially available sensors and relatively simple signal-conditioning requirements, while the choice among configurations ultimately depends on the required trade-off between accuracy, calibration, mechanical integration, and implementation complexity.

4.3 Limitations of the study

Although the difference in individual sensor prices is relatively small compared with the potential cost of the complete orthotic system, component cost remains a relevant design consideration when selecting interchangeable sensing elements. Therefore, cost is treated as a secondary engineering criterion rather than as the principal determinant of system superiority.

The present study is designed as a preliminary experimental validation of the proposed low-cost electrogoniometers rather than a clinical validation study. Therefore, the sample size is primarily determined by the availability of volunteers and the experimental time required to properly fit and adjust the devices for each participant.

It is important to emphasize that the sensors integrated into the proposed mechanisms are prototypes representing an initial approach toward a functional solution. Therefore, a more comprehensive evaluation is required before their implementation in orthotic applications.

In particular, the proposed indirect measurement approach enables the use of commercially available sensors by incorporating additional mechanical components that allow the sensing elements to be positioned away from the primary joint-loading interface. This configuration reduces their exposure to excessive mechanical loads and may thereby extend their operational lifespan. Due to the limited duration of the study, it was not possible to conduct durability tests on the proposed sensors and mechanical mechanisms; neither sensor drift nor long-term stability were analyzed. However, this approach involves a trade-off among mechanical complexity, sensor protection, system integration, and cost, which should be carefully evaluated according to the requirements of the intended application.

Differences in the relative position of the aluminum structure reflect prototype attachment and fitting during the preliminary volunteer assessment. These configurations were not used to establish quantitative differences among sensing technologies. Because attachment position,

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soft-tissue movement, and anatomical variability can affect wearable measurements, a systematic assessment of fitting sensitivity was beyond the scope of the present study and is identified as a limitation.

The study was limited to five subjects due to the limited availability of volunteers and their personal schedules, as the participants were recruited from the same educational institution. Recruiting volunteers with sufficient schedule availability proved challenging.

Although the devices are relatively simple to attach, efforts were made to ensure that the experimental conditions were as consistent as possible, particularly with respect to the location of the angular motion measurement point. In addition, the securing straps had to be properly adjusted to prevent device displacement while avoiding discomfort for the user. These procedures required additional time, and in many cases, a sufficiently long continuous period was not available for the experiments.

Therefore, increasing the number of subjects and samples in future studies is necessary to strengthen the statistical robustness and generalizability of the findings.

It is worth noting that the five measurements at each angular position corresponded to repeated measurements under the same mounting condition and were intended primarily to characterize short-term measurement repeatability. They should therefore not be interpreted as five independent mounting/unmounting trials. Attachment repeatability was not independently evaluated.

The ESP32-based acquisition architecture is capable of real-time data acquisition; however, the present validation was performed under quasi-static angular conditions. Dynamic real-time performance remains to be evaluated.

5. Conclusion

The present study demonstrates that low-cost electrogoniometer performance depends on the interaction between sensing technology, calibration strategy, and mechanical integration. This study aims to establish a design and evaluation framework for low-cost electrogoniometers that integrate mechanical innovation with sensor performance analysis.

The indirect sensing architecture is intended to reduce direct mechanical loading on the sensing element, providing a mechanical basis for potentially improving sensor durability, without increasing system complexity or cost. However, durability and fatigue performance were not experimentally evaluated in the present study.

Under controlled quasi-static conditions, the uncalibrated IR configuration exhibited substantially greater measurement error, whereas calibration reduced its error to a level statistically comparable to the potentiometer-based configurations.

The rotary potentiometer provided the second highest measurement accuracy among the tested configurations while the slide potentiometer offered a favorable compromise between measurement performance and mechanical adaptability. These findings support the use of low-cost potentiometric sensing as a promising basis for prototype elbow-motion instrumentation.

Among the evaluated designs, the slide potentiometer-based electrogoniometer offers the most favorable balance between measurement performance and mechanical integration, under the specific experimental framework, making it a suitable candidate for wearable orthotic applications.

By identifying the slide potentiometer-based design as the most balanced solution, this work contributes to the development of accessible and scalable biomechanical monitoring systems.

However, the results should be interpreted as laboratory validation of the evaluated configurations and not as clinical validation. Dynamic performance, long-term stability, durability, and performance across diverse users remain to be established, further bridging the gap between laboratory prototypes and real-world rehabilitation technologies.

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