Characterization Method for Bending Sensor Applied for Smart Glove

Michela Borghetti
Department of Information Engineering
University of Brescia
Brescia, Italy
michela.borghetti@unibs.it

Nicola Francesco Lopomo
Department of Design
Politecnico di Milano
Milano, Italy
nicola.lopomo@polimi.it

Mauro Serpelloni
Department of Information Engineering
University of Brescia
Brescia, Italy
mauro.serpelloni@unibs

Commentato [MS1]: Chiedo a te di togliere qualche riferimento, ho visto che l'hai fatto con Mendley e non voglio scombussolare. Togli quelli doppi o tripli, dovrebbero essere circa 8 articoli da togliere.

***Abstract*— Nowadays accurate measurements of hand movements of workers in sectors such as manufacturing, aerospace, and healthcare are requested for different purposes, such as health analysis or human-robot interactions. In Industry 4.0, analyzing how workers interact with tools, machinery, and processes by hand it is important to achieve optimal performance, quality control, safety, and ergonomics. Several techniques - motion capture and wearable sensors - are available with different levels of accuracy and applicability. In particular smart gloves, and in specific bend sensors, represent a viable solution to measure comfort level, but commercial solutions lack accuracy and affordability. For this reason, new sensors applied to wearable devices and therefore suitable characterization methods are needed. In this paper, a novel platform that emulates the finger movements is proposed to test sensors used to measure the rotation of two or more finger joints. For example, one bend sensor is used to measure more than one finger joint. The platform integrates a dummy little and index finger of average dimensions. With respect to previous works, the proposed method was used to test commercial bend sensors bent in two points, corresponding to two finger joints. The experimental results confirmed the sensor characteristics, especially regarding the linearity (the maximum error is less than 2.5%) and the repeatability (the maximum error is less than 3.8%). Finally, a relationship between the resistance and the curvature was found when the sensor was bent in two points, obtaining the same characteristics in terms of linearity and repeatability.**

Keywords—smart glove; bend sensor; resistive sensor; calibration setup.

I. Introduction

The need for accurate measurement of hand movements of workers has grown significantly across different sectors - from manufacturing and assembly [1] to aerospace [2] and healthcare [3]. An accurate analysis of how workers interact with tools, machinery, and processes by hand is essential for achieving optimal performance and quality control [4]. Not only precise movements but also safety and ergonomics are important aspects in the controlled setting of an assembly line or the crucial tasks associated with manufacturing processes [5]. The acquired data serves as a foundation for refining processes, mitigating risks of errors, and ensuring the well-being of the workforce. Moreover, as automation and robotics continue to integrate into various industrial domains, the importance of measuring hand movements and the comfort level of workers becomes evident. Operators need to have seamless control over machinery, and accurate force measurement becomes a key element in preventing damage, optimizing performance, and guaranteeing a safe working environment [6]. Also, telerobotics has become essential in a smart factory, considering its applications in industrial harsh environments or internet-based teleoperation [7]. Beyond manufacturing processes, the advent of virtual reality (VR) and augmented reality (AR) technologies introduces a new dimension to the need for measuring hand movements, as these innovations are increasingly integrated into industrial training and simulations [8].

According to the final applications, several techniques can be adopted to measure finger movements. Motion capture (MoCap) systems use cameras and markers to track the movement of reflective markers placed on the worker's hands. These systems provide three-dimensional (3D) coordinates of hand movements. This technique is the gold standard, especially in clinical environments, for its high accuracy, but the marker placement is a time-consuming procedure and markers may introduce constraints on hand movements [9]. A markerless MoCap system is a non-intrusive method for the extraction of valuable data without the need for physical sensors or markers on the hands during motion tracking. This approach could be a trade-off between usability, costs, and accuracy, but it has some limitations as the impossibility of capturing hand and finger out-of-sight movements [10] and exerted force by the fingers.

Instrumented gloves are an alternative and valid solution for real-time application in industrial settings. Indeed, an instrumented glove is a wearable sensor-based method. The glove is equipped with one or more types of sensors, such as inertial measurement units (IMUs) [11], magnetic sensors [12], flex sensors [13], optical fibers [14], and pressure sensors [15]. These sensors can placed on a fabric glove or a flexible PCB, or fixed with rings and bracelets [10], [17]. These sensors can capture data on hand and finger movements or exerted force. The gloves are non-intrusive and allow for natural hand movement, making them suitable for various industrial tasks.

Among the different sensors for measuring finger movements, flex resistive sensors - in particular bend sensors - could be a good trade-off between costs, accuracy, and ease of use for ergonomic evaluation [13]. Bend sensors are resistive sensors that change their resistance according to their bending. They are usually placed over the joint fingers to measure the flexion and extension of one or more finger joints. They are easy to use, and they are suitable for real-time measurements. Indeed, if IMUs are suitable for hand gesture recognition, they should be correctly placed on the finger joints, and complex algorithms are required to obtain joint angle measurements. Electromagnetic tracking - based on measuring the magnetic field strength at a certain location - encounters two primary sources of issues in industrial settings. Instruments or objects made of conductive or ferromagnetic material disrupt the magnetic field and consequently affect measurements. Furthermore, the presence of a nearby magnetic field poses challenges to the usability of electromagnetic tracking. Finally, also fiber optic sensors have some disadvantages, such as cost, complexity, and mechanical factors.

Despite over the last two decades, hundreds of smart wearable gloves and sensors were proposed especially for clinical applications, many research efforts still need to be made to reduce the costs, increase the wearability, and guarantee good accuracy [18]. A large number of sensors contributes to the enhancement of measurement precision, but it increases the discomfort for the worker, the costs, and the data fusion algorithm. The choice and the placement of the sensors are crucial aspects to consider at the design stage. On the other hand, the design of a wearable smart glove implies the adaptability of the glove on different hand sizes. Finally, despite commercial flex sensors can be used to measure gestures and comfort level, they do not represent yet the best solutions in terms of sensor response (especially repeatability and drift) and accuracy [19], and thus new sensors are demanded, especially adopting printed electronics [20]. The typical setup to test bend sensors off the glove is a rigid hinge, far away from the finger shape and dimensions [21], and this aspect can lead to a mismatch between the characterization curve and actual response when the sensor is mounted on the glove. For the sensor characterization and testing, the design of a suitable finger model is demanded, especially when one bend sensor is used to measure more than one finger joint to lower the costs when the application does not require high degree of accuracy, such as the evaluation of the comfort level.

According to these needs, this work is focused on the design of a characterization setup for bending and strain sensors, especially when a single sensor is positioned over two or more joints to measured them. Starting from the anatomy of the hand and the range of motion of the finger, a platform with two dummy fingers, one representing the index and the other the little, was proposed. The results of preliminary simulation of movements of the three joints of the two fingers were also reported. The method for measuring the joint angles and the resistance of the bend sensor was also proposed. Finally, the platform was used to test a commercial bend sensor.

II. Design of the Characterization Sensor Setup

A. *Design of a dummy finger for sensor characterization*

For this work, a dummy index and a dummy little were developed to characterize the bend sensor. This setup allowed to flexibly recreate the real application, allowing to carry out repeated tests and evaluate the actual variability of the measurement system applied to a simulator that best represents the target application.

For an accurate model, an investigation of the constituent parameters of a hand was done. The research in the literature concentrated on the maximum flexion angles (depicted in Fig. 1), lengths, and diameters of the various phalanges of the fingers. As confirmed in the literature, the range of motion (ROM) of the finger flexion depends on the finger (index or little), joint type (metacarpophalangeal, proximal interphalangeal, or distal interphalangeal joint), measuring equipment (goniometer, magnetic resonance imaging, MoCap system, *etc.*), and type of test (active, passive, or functional). For this reason, we calculated the average of the values reported in the review [22] and shown in Table I. The maximum flexion of the joint is similar for both. The finger dimensions differ according to ethnicity, age, the gender even between the right and the left hands [23]. Despite this great variability, for this work, we considered the dimensions reported in [23], [24] and in Table II. In Fig. 2 a picture of the fabricated test bench and the nominal dimensions.

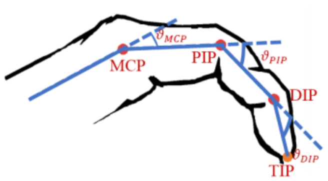

Fig. 1 - Position of the phalangeal joints. The proximal phalanx length is the distance between MCP and PIP, the medial phalanx is the distance between PIP and DIP, and the distal phalanx is the distance between TIP and DIP. (MCP = Metacarpophalangeal joint, PIP = proximal interphalangeal joint, DIP = distal interphalangeal joint).

TABLE I. Range of Motion of Finger Flexion

	Index	*Little*
MCP	75	80
PIP	102	101
DIP	71	75

The range of motion is presented in degrees.

TABLE II. Hand Anthropometry

Phalanx	*Index*	*Little*
Proximal (L_1)	39.78	32.74
Medial (L_2)	22.38	18.11
Distal (L_3)	15.80	15.90
Diameter finger	20.16	16.80

The dimensions are presented in mm

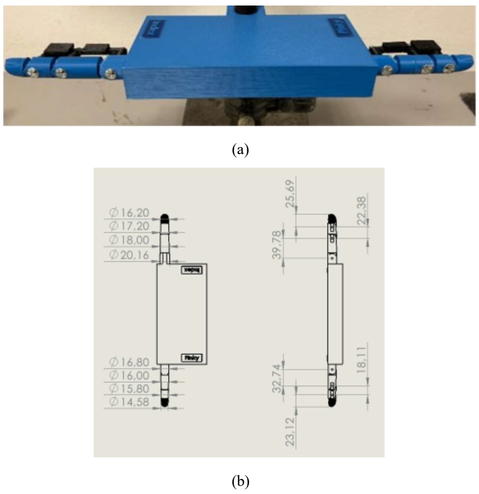

Fig. 2 – (a) Dummy index and little finger designed for bend sensor characterization. (b) 3D model design and its nominal dimensions in millimeters (mm).

According to the literature results, the prototype of the index and little finger was produced by fused deposition modeling 3D printing. The prototype is made of polyethylene terephthalate glycol, due to chemical resistance, durability, and excellent formability for manufacturing. The model was designed using 3D Computer Aided Design software.

B. Bend sensor characterization setup

The final characterization setup is shown in Fig. 3.

- The finger (in the case of the figure is the dummy index finger) wears a Lycra glove, which is the typical material used for smart gloves.
- Spectrasymbol sensor FS-L-0095-103-ST (overall dimensions: (112.24 x 6.35 x 0.43) mm^3 size, sensitive area: (95.25 x 3.5) mm^2) is selected to test the characterization setup. This sensor is a bend sensor made of a conductive layer (carbon ink) - which increases its resistance when bent - printed on a polymeric substrate. To achieve the linear response, several silver pads are printed over the sensitive area with the effect of lowering the resistance (around 8500 Ω when the sensor is flat). The bend sensor is glued to one end on the dummy proximal phalanx (1 mm from the PIP joint), while the other is kept in contact with the dummy proximal phalanx and the base with plastic rings. In this way, the sensor is free to slide along the finger without being affected by strains during the joint rotation. Its resistance is calculated by measuring the voltage across the sensor, which is combined with a static resistor (nominal value of 10 kΩ at 1% of tolerance) to form a voltage divider.
- Two Arduino Nano 33 BLE Sense devices are fixed laterally to measure the rotation of MCP and PIP joints. The Arduino device embeds a 9-axis inertial sensor system composed by a 6-axis inertial measurement unit BMI270 with an accuracy of about 1% and a geomagnetic sensor BMM150 with a maximum heading accuracy of about ±2.5°. The joint rotation (roll) is calculated by Arduino from the input of the accelerometer and the gyroscope using the Kalman filter [25]. The printed structure and the Arduino were fixed to minimize the pitch angle since the finger joints are designed to have only one degree of freedom. This solution for inertial measurement on the identified phalanges has the advantage of being very small, light and flexible compared to other commercial solutions. One Arduino is used to feed with V_{cc} (=3.27 V) the voltage divider, composed of the bend sensor and the static resistor (R_0); furthermore, it measures (ADC resolution set to 12 bits) the voltage V_0 across R_0 for determine the sensor resistance R_{Sens}, according to the formula (1).

$$R_{Sens} = R_0\left(\frac{V_{cc}}{V_0} - 1\right) \quad (1)$$

Arduino devices are battery-powered and the measurements were sent via Bluetooth Low Energy to a notebook for visualization, elaboration, and storage.

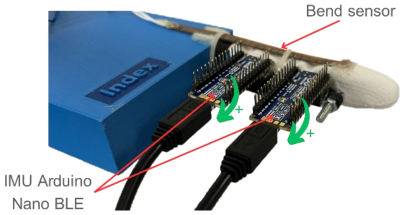

Fig. 3 – Characterization setup for the index finger. The arrows indicate the roll (joint rotation around X axis).

C. Range of Motion of the dummy grasping a rod

One important task to monitor for the comfort evaluation is the grasp of objects and tools. Objects with cylinder shapes, such as the handle of the handlebars, were considered a way to test smart gloves because they make the test more repeatable and the results comparable with other types of tests. For this reason, the joint rotations of MCP, PIP, and DIP were calculated when the finger grasped a cylinder object with a radius r ranging from 30 mm to 200 mm, with a step of 10 mm.

In order to find the joint rotation and thus the correlation between MCP and PIP angle, a simulation of the finger movement was performed, considering only the flexion movement. The finger is considered as a continuous line that is composed of three connected straight-line segments. The three joints of each finger were considered points belonged to the circumference of radius *r* and the distance between one joint and the consecutive is the same listed in Table II (MCP-PIP is L_1, PIP-DIP is L_2 DIP-tip is L_3). According to the trigonometric rules, the rotation of the three joints is found (Eq. (2)).

$$\begin{cases} \vartheta_{MCP} = \operatorname{asin}\dfrac{L_1}{2r} \\ \vartheta_{PIP} = \operatorname{asin}\dfrac{L_2}{2r} + \vartheta_{MCP} \\ \vartheta_{DIP} = \operatorname{asin}\dfrac{L_3}{2r} + \vartheta_{PIP} \end{cases} \quad (2)$$

Positions and angles of the index joints (MCP, PIP and DIP) according to the radius of the grasped rod are shown in Fig. 4.

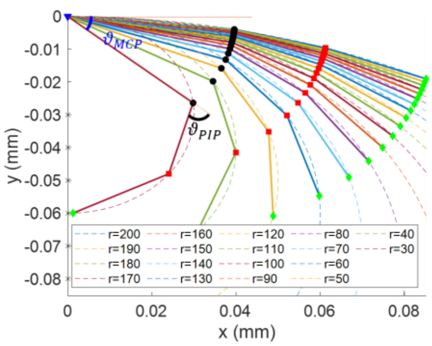

Fig. 4 – Simulated trajectory of the index grasping cylinder with radius r.

Similar results were obtained also for the little. When the radius decreases, the index MCP and PIP joints increases from 5.7° to 64.7° and from 8.9° to 95.3°, respectively; the little MCP and PIP joints increases from 4.7° to 48.1° and from 7.3° to 72.4°, respectively.

D. Bend sensor characterization tests

To test the system and the sensors, three tests were configured considering both the index and the little dummy. The analyzes were carried out by repeating the tests and the movement several times, on different days and repositioning the system at the end of each session.

- TEST1: Rotation of the MCP joint from 0° to the maximum reported in Table I (depending to the tested finger), while the PIP and DIP joint were fixed at 0°.
- TEST2: Rotation of PIP joint from 0° to the maximum reported in Table I (depending to the tested finger), while MCP and DIP joint were fixed at 0°.
- TEST3: Coordinated rotation of MCP and PIP according to the results found simulating the grasp of a rod of 30 mm radius, while the DIP joint was fixed at 0°.

The joint rotation was varied with a step of 5°.

The accuracy of the voltage reading by Arduino was evaluated with a multimeter HP34401 in TEST1.

III. Results and Discussion

Before performing all the tests, the accuracy of the Arduino readings with respect to a reference instrument was evaluated. The maximum absolute difference between the voltage measured by Arduino ADC and the multimeter was less than 2 mV and it did not depend on joint angle and dummy finger. This deviation causes a resistance error of 32 Ω (0.32% of reading) with respect to the one obtained by the multimeter measurement.

In Fig. 5, the relationship between the angle measured by the IMU located at the dummy proximal phalanx and the resistance by Arduino is shown. The response of the sensor is linear as expected and also confirmed in [19]. The “fitting” line is calculated by using the least squares estimation method. Similar results were obtained when the sensor was fixed to the little finger, as shown in Fig. 6. The error bars represent the maximum deviation calculated by the propagation of error formula reported in [26] and supposing a voltage error of 2 mV, the maximum deviation obtained between the multimeter and Arduino measurements. The error due to the voltage measurement is negligible considering an angle step of 5°. The repeatability error of the sensor obtained by repeating the TEST1 three times is 3.6% on average (maximum 5%) for both tests. The linearity error is less than 2.5%, and it is maximum when the joint angle is 0°. The linearity is also confirmed by the R-squared value, which was better than 0.996 in all the tests. For the index, regardless of the joint type, the calibration curve of the sensor (angle, ϑ, versus resistance, R) was found combining the result of TEST 1 and TEST 2. The fitting line is $\vartheta = 0.01492 \cdot R - 126$ with R^2-value=0.996.

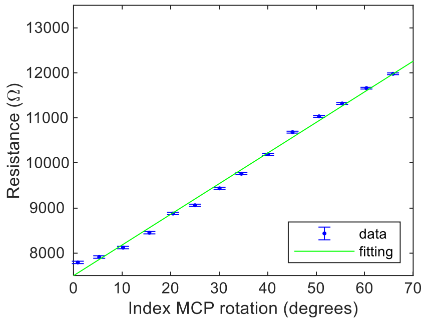

Fig. 5 – Experimental relationship between dummy index MCP angle and resistance (TEST 1 – index finger).

Similar results were obtained also in TEST2 both for index and little, as shown in Fig. 7 and Fig. 8. The linearity error is less than 2.7%, and it is maximum when the joint angle is 0°. The linearity is also confirmed by the R-squared value, which was better than 0.9955 in all the tests. For the index, regardless of the joint type, the calibration curve of the sensor (angle, ϑ, versus resistance, R) was found combining the result of TEST1 and TEST2. The fitting line is $\vartheta = 0.01516 \cdot R - 128$ with R^2-value=0.996.

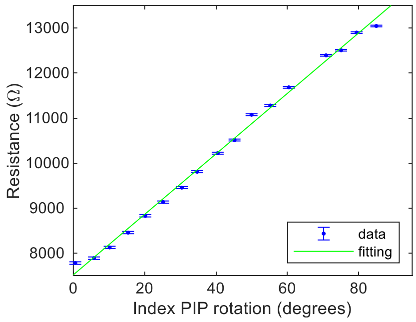

Fig. 6 – Experimental relationship between dummy little MCP angle and resistance (TEST 1 – little finger).

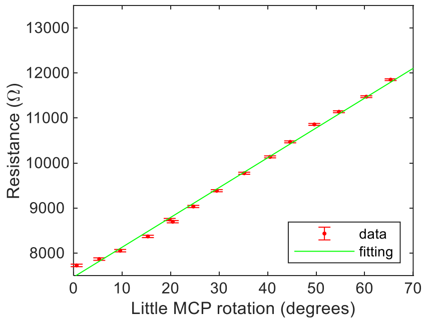

Fig. 7 – Experimental relationship between dummy index PIP angle and resistance (TEST 2 – index finger).

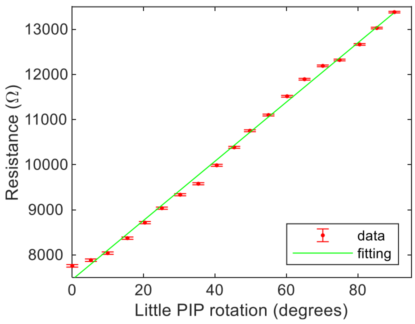

Fig. 8 – Experimental relationship between dummy little PIP angle and resistance (TEST 2 – little finger).

By comparing the sensor response in TEST1 and TEST2, the angular coefficient and y-intercept of the best lines shown in Fig. 4, Fig. 5, Fig. 6 and Fig. 7 slightly increase with joint angle, less than 3.6% and 0.5%, respectively and this could depends on the different size of the finger and the resistance drift over time.

In Fig. 9, the results of TEST3 for both the dummy fingers are shown. The sum of the measured MCP and PIP was reported on the x-axis, while the measured resistance calculated from the voltage measurements was reported on the y-axis. The fitting line changes and the R^2-value slightly gets worse (0.9825 for little finger test) with respect to the results found in TEST1 and TEST2, but this could depend on the type of bending. Indeed, in TEST3, the bend sensor is bent in two different points (the two joints are rotated), and this changes the bending angle.

Conversely, Fig. 10 represents the relationship between the curvature (the reciprocal of the radius ranging from 30 mm to 200 mm) and the measured resistance. The calibration curve differs according to the size of the finger, as expected, but it is linear; R^2-value for index case is 0.990, while it is 0.980 for the little finger case. As general consideration, the experimental results show that when the angle is small, the possible linearity of the sensor response is lost. This is negligible for the target application of the proposed smart glove.

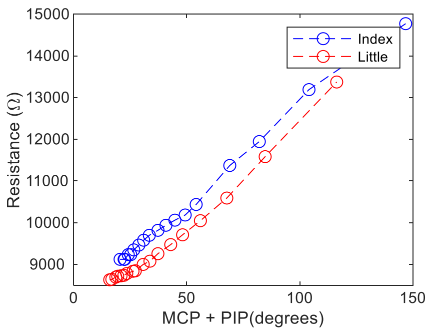

Fig. 9 – Experimental results obtained in TEST 3 for index and little (coordinated rotation of MCP and PIP, according to simulation results). The sum of the MCP and PIP joint angle is reported on the x-axis.

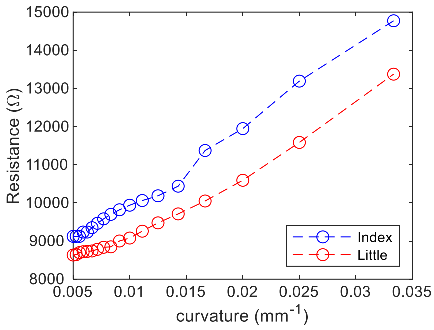

Fig. 10 – Angle and resistance relationship in TEST 3 for index and little. The angle is obtained from the linear relationship between the resistance and one joint angles by using the least squares estimation method.

IV. Conclusion

In this work, we proposed a method to test sensors to be integrated into a smart glove for the comfort level evaluation of workers. The method consists in the designing of a platform that emulate the finger and three tests to find the relationship between the joint flexion and the resistance. For the finger design, an analysis of the literature was performed and indications of the standard dimensions of the fingers and their range of motion were proposed. This method is mainly useful for bend sensors and especially when they are used to measure more finger joints with a single sensor. A single sensor for each finger can be enough for the detection of gesture or comfort level to lower the complexity, the weight, and the costs of the smart glove. The method was used to test a bend sensor, which was found a valid solution for evaluating the functional finger movements. The linear response, good repeatability, stability, and reproducibility confirm the possibility of using this kind of sensor in this application. In future work, we focused on the design and development of a smart glove for measuring finger movements and also the forces exerted by fingertips against objects.

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