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CALCULATION OF A DORSIFLEXION ANGLE OF A PROSTHETIC FOOT FOR AMPUTEES BY USING DEVELOPED TACTILE DISPLACEMENT SENSOR

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ABSTRACT:-This research aims to design, construct, and evaluate a tactile sensor for measuring displacements. The sensor is then employed in a developing computerized displacement measurement in order to assess its potential in sensing and evaluating a dorsiflexion angle of a new dynamic prosthetic foot for amputees. The developed system consists of three main parts namely, the sensor, the data acquisition unit that includes an analogue to digital (ADC) module, and a computer to aid in the processing of acquired data.

One type of tactile sensors was used in the investigation. That is Potentiometric-based displacement sensors. That sensor provide analogue output signals, hence, to enable its input to the employed computer these signals are converted to digital type by the developed ADC-based module which is interfaced to the computer via the Enhanced Parallel Port (EPP).

A number of tests were conducted to establish valid calibration of the system. Early experimental results showed that there are matching between the obtained results and the best fit lines when measuring linear displacement and using the traditional calibration method, therefore, the researcher decided to use that developed sensor in measuring the dorsiflexion angle of the new dynamic prosthetic foot and comparing the obtained results with the standard one.

Key words: Prosthetic foot, Dorsiflexion angle, Tactile displacement sensor.

INTRODUCTION

Many components are manufactured today with tolerances in fractions of a micron. Quality control for such parts requires not only an instrument with sufficient accuracy, but also careful operation in a controlled environment. The areas to be considered include:

- Capability of the instrument
- The measurement environment
- The component and its set-up
- Data acquisition and analysis

Performance of a profiling instrument depends on the optimal balance of a number of features; the most important of which are gauge linearity, datum straightness, gauge resolution and noise floor. Poor performance in any one of these areas will produce a poor result. A good assessment of an instrument is to measure an inclined glass flat. Any deviation from a straight line indicates inaccuracies of the form measurement capability of the system. It is vitally important to obtain a good calibration prior to the measurement to set the gain and linearity of the gauge. The quality of the calibration artifact is also important because any errors will be passed through to the measurement results on the actual component.

The instrument should be isolated from physical factors that are likely to affect the measurement, the most obvious being vibration and temperature change. Positioning the instrument in the glare of an outside window facing a busy road is not usually good practice. Air movement can also considerably affect results. In particular instruments should not be sited near air conditioning ducts or doorways. An environmental cabinet should be used for optimum results.

Having ensured that the instrument is ready, attention needs to be given to setting up the component. For example, it is important to correctly level and crest (where appropriate) the component and to take the measurement as symmetrical about the gauge center as possible. In that way the same part of the gauge range (the central and most linear part.) is being used across the component [(1)].

PRINCIPLE OF TACTILE SENSING

Types of Sensors:

Different types of sensors can be used to measure many regular and irregular surfaces or shapes geometry, (roundness and displacement ...etc).

The classification below represents the main types of displacement sensors [(2)] :

• Resistive Displacement Sensors.

• Inductive Displacement Sensors.

• Capacitive Displacement Sensors.

• Piezoelectric Transducers and Sensors.

• Time-of-Flight Ultrasonic Displacement Sensors.

• Laser Interferometer Displacement Sensors.

• Optical Encoder Displacement Sensors.

RESISTIVE DISPLACEMENT SENSORS

This type of sensors can be defined as an electrically conductive wiper that slides against a fixed resistive element. To measure displacement, a potentiometer is typically wired in a "voltage divider" configuration. The circuit output, a function of the wiper position, is an analog voltage available for direct use or digitization. Precision Potentiometers are available in rotary, linear-motion, and string potentiometer forms. See Fig. (1) [3].

In Fig. (2) a potentiometer is used as a variable voltage divider. R_p is the total resistance of the potentiometer, R_L is the load resistance, V_r is the reference or supply voltage, and V_0 is the output voltage. An ideal linear output function. X_P is the maximum position of the wiper. See Fig. (2b).

ELECTRICAL CHARACTERISTICS

Before selecting a potentiometer and integrating it into a measurement system, some electrical characteristics should be considered. See Fig. (3). these include: terminals and taps, taper, electrical Travel, linearity and electrical loading [4].

MECHANICAL CHARACTERISTICS

Mechanical characteristics may also influence measurement quality and system reliability. These include: Mechanical Loading, Mechanical Travel, Operating Temperature, Vibration, Shock, Acceleration, Speed, Contamination and Seals, Misalignment and Lifetime of potentiometer [4].

THE DEVELOPED TACTILE DISPLACEMENT SENSOR AND MEASUREMENT SYSTEM

The sensing process usually indicates that the form of output signal will often be a voltage analogous to the input signal, though sometimes it may be a wave form whose frequency is proportional to the input or pulse train containing the information in some other form.

The aim of this research is to measure the dorsiflexion angle of the SACH foot by using a tactile displacement sensor; therefore, the researcher has decided to choose one type of tactile sensors:

Potentiometric Element Tactile Sensor.

The above type of sensors mainly consist of three parts arranged together to give valid output (voltage difference) according to the input (displacement). These are:

a- The Sensor.

b- The Interface (Analogue to Digital Converter ADC).

c- The Computer.

Fig. (4) Shows a photograph of the equipment and instrumentation used in the development of the sensing system and conducting the experimental work of this research. All components of the developed rig are shown clearly.

POTENTIOMETRIC ELEMENT SENSOR

Fig. (5) Shows the main components of this sensor which consists of a rheostat togethered with a mechanical coupling to record the displacement and convert it to resistance variation.

THE INTERFACE (ANALOGUE TO DIGITAL CONVERTER ADC)

To facilitate the development of a measuring system based on the displacement sensors a data acquisition system based on analogue to digital converter is designed and developed by the researcher. The piezoelectric element sensor and the Potentiometric element sensor are analogue devices and they can provide analogue signals.

To enable computerized data processing it is necessary to convert the analogue signals to digital signals. This necessitates the use of analogue to digital converters. These are usually in the form of integrated circuit chips. In order to convert the analogue output signals of the two sensors into digital form, an analogue to digital converter such as the one shown in Fig. (6) Can be used.

The Specification of the Used ADC

1- ADC number of bits (n) = 12 bits.
2- ADC number of steps =4096 steps.
3- ADC input span =$10V$, $\pm 5V$
4- Resolution (ADC span)/ (ADC number of steps) =2.44mV/step.
5- Variable Sampling rate up to 3000 Sample/sec.
6- Two channels input.
7- Input voltage range (span) of the first channel (A) is $\pm 5V$ and of the second channel is $\pm 100mV$.
8- Variable gain (1, 10, 20).
9- Internal power supply.
10 Connected with the computer via the Enhanced Parallel Port (EPP) to ease connection and it is a low cost method.

Fig.(7) shows a photograph of the developed data acquisition system that is based on analogue to digital converter ADC.

The analogue to digital converter has a characteristic equation which describes its behavior or the relation between the input voltage and the output digit in accordance with the following theoretical assumptions, see Fig. (12).

At (+5) volts a (4095) digit, And at (-5)volts a (0) digit.

Fig. (8) represents the theoretical characteristic equation of the employed analogue to digital converter (ADC), that relates its input analogue voltage and digital output voltage, it is useful to calculate the slope of this line which represent the resolution of the converter.

Slope = (ADC span) / (ADC number of steps)

= 10 / 4096 = 0.00244 V/step.

$$Voltage = 0.00244 Digit - 5 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(1)$$

DISCUSSION AND EXPERIMENTAL EVALUATION OF THE DEVELOPED SENSORS AND MEASUREMENT SYSTEM.

In this research one type of sensing elements was used to develop the tactile displacement sensor:

Potentiometric Tactile Element for The Displacement Sensor

That sensor is manufactured according to a suitable mechanical design and has a moving (linearly) stylus (sensor tip) with finite limit (working range). These sensors provide analogue signals when they start contacting with the work-piece, so to analyze these signals by a personal computer it should have an appropriate facility to interface these two parts (the sensor from one side and the personal computer from the other side). The standard Enhanced Parallel Port is used to facilitate the interfacing with the computer. A suitable software driver is programmed to enable acquiring the measured data and storing them for further analysis. A variable sampling rate is enabled however the maximum sampling rate is 3000 samples per second which is more than sufficient to achieve the objectives.

Many experimental tests using different working circumstances for that sensor were conducted and results are stored in data tables. Tests were repeated with variable parameters such as using another Potentiometric element……..etc. and by analyzing these data (finding the best fitting with a suitable mathematical equation and calculating the mean error, Max. and Min errors, resolution, accuracy, and other engineering parameters).

EXPERIMENTAL RESULTS, ANALYSIS AND SYSTEM CALIBRATION

A wide range of experiments were conducted using the developed measurement system. Results of the experiment are analyzed in order to evaluate the overall performance of the system and to establish best possible calibration of the system.

Potentiometric Sensor

This sensor is simple in structure however it suffers from frictional loading and wears inside its rheostat which decreases its working lifetime.

Early obtained results acquired from the experiments that were conducted by this research showed an excellent working (sensing) characteristic that is clear via its low mean error, high resolution, accepted repeatability and other parameters.

The general characteristics of this sensor could be stated as follows:

- This sensor has a wide working range up to 60mm.
- The measured resolution is about 0.24mm and unable to get less than this value because of the structure of the wounded coil of the used rheostat.
- The sensor exhibits a less value of error, since it is simple in structure.

In order to get accurate results all components of the developed rig should be calibrated by using different ways according to type of the apparatus. Early experiments were done by using already calibrated accurate multimeter and storage oscilloscope to measure the response of the manufactured sensors and to determine the relation between the input (displacement) and the output (voltage or resistance).

Calibration of the Employed ADC

In order to check the accuracy of the employed ADC, a constant 1.5V-DC voltage was supplied to channel "A" in the above ADC, and then the obtained practical result is of a numerical value equal to (2659), meanwhile the associated theoretical value is equal to (2663). It is clear that the difference between the two values is equal to (4 = 0.15%) which represents an acceptable error ratio for such converter [(5)].

Traditional calibration refers to a procedure where an input, either constant or slowly time varying, is applied to an instrument and corresponding output measured, while all other inputs (desired, interfering, modifying) are kept constant at some value. The traditional calibration may be expressed analytically Y=F(x), or graphically, or in a tabulated form where: Y=output quantity, F(x) =input quantity.

DISCUSSION OF ACQUIRED RESULTS

Fig. (9) Shows the relation between the displacement in (mm) and the corresponding resistance in (Ω) for the Potentiometric sensor. This test is conducted several times and at each attempt the slope and mean error are calculated. Mean error is found to fluctuate between (5 - 12.14) Ω, (which represents about 0.4%). It is clear that the relation is linear and the best one is the third which shows the attempt that has a mean error of 5Ω. Sure the existence of error is due to the mechanical structure of the sensor itself where some factors such as friction, wear, contamination, etc. are among these mechanical components. Furthermore the error is caused by measurement process and its physical conditions. All these conducted attempts were done by using a full working range. This process is referred to in this research as traditional calibration.

MEASUREMENT OF DORSIFLEXION ANGLE

Fig (10) shows the designed computerized rig for measuring the dorsiflexion angle of the manufactured dynamic prosthetic foot by using the suggested tactile displacement sensor, where the foot supported on a wooden supporter with an inclination angle of 20° with the horizon, a graduate load was applied on the pylon, starting from 0 N, 196.2 N and so on until reaching to 843.66 N.

To complete the dorsiflexion test a triangular wood piece (20°) must be manufactured, this piece of wood is put under the SACH foot so that the foot touches the triangle and applies force on it; this force simulates the ground reaction force. The researcher begins to add a load starting from 192.2N with increment of 196.2N gradually until reaches to 784.8 after 58.86N was applied and the corresponding dorsiflexion angles measured. By applying the above loads there is a reading on a computer screen appear as a digit or a variance in the attached resistance will be occur and via the employed ADC, these signals will be transformed into digital signals.

Table (1) and Fig. (11) Show. the relation between the gradual applied load (N) and the corresponding digits.

Table (1): The obtained results from the developed rig and for SACH foot**.**

No.	LOAD (N)	DIGIT
1	0	2568
2	196.2	2641
3	392.4	2722
4	588.6	2808
5	784.8	2919
6	843.66	2963

By using Eq. (1) the digit could be transformed into voltage, so Fig. (12) shows the relation between the above digit and the computed voltages.

These voltages are represent an analogue signals so that the employed ADC will convert these analogue signals into digital, also according to Ohm's law there are associated resistance variance corresponding to that change in the obtained voltages after that there is a relation that exchange the resistance into displacements (linear displacements) according to the following figures. See Figs. (13) & (14).

Fig.(13) represents the main relation between the resistance and displacement, and Fig.(14) shows the specific relation between the resistance variance and the corresponding displacements. Table (2) below summarize the above variance between the resistance and the associated displacement.

Table (2): Resistance-Displacement relation.

Displacement (mm)	Resistance (ohm)
0	1266.7
3.142	1446.73
6.549	1644.82
10.225	1852.59
14.971	2124.5
16.825	2230.7

From the above figures it is very clear to find the maximum resistance (2230.7 ohm) and the corresponding displacement (16.825 mm). The standard effective foot length of the used SACH foot is 150 mm [9] and by using trigonometric transformation yields:

$$\tan\theta = \frac{h}{150} \qquad \text{So,} \qquad \theta = \tan^{-1}\left(\frac{h}{150}\right)$$

$$\theta = \tan^{-1}\left(\frac{16.825}{150}\right) = 6.4°$$

So the obtained dorsiflexion angle is about 6.4° which is exactly equal to the standard one.

CONCLUSIONS

1. For the Potentiometric sensing system the repeatability is verified to be valid. The employed Potentiometer showed a stable reading in relation to the input displacement.
2. The developed Data Acquisition System contributes some error that did not exceed 4 numerical values as a maximum case. To achieve such accuracy a network of ground (earth) is established and connected to all components of the employed rig.
3. Measurement of displacement depends on the conditions of the contact between the sensor tip and the work piece (SACH foot), therefore, it should be given a special care to this aspect in order to reduce the error and get precise displacement or profile.
4. The obtained results from the designed tactile sensors prove that there is a good compatibility between the original value of the dorsiflexion angle of the SACH foot and the associated sensed angle (displacement) with an acceptable mean error, so this is considered as verification to the use of these sensors in prosthetic limbs laboratories as measuring tools provided that the accuracy obtained is within the obtained results.
5. It is observed that the interfacing between the sensors and the used personal computer makes the measurement process easy and fast.

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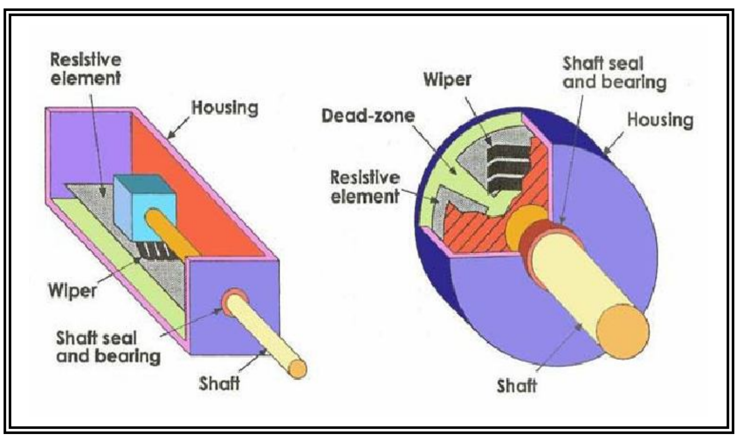
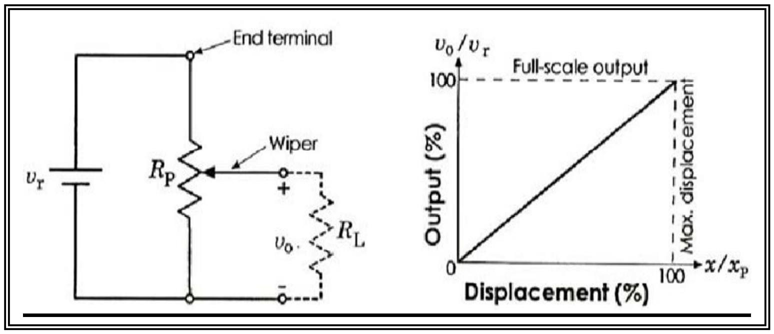


Fig. (1): Commonly termed potentiometers or "pots" [3].



(a) **(b)**

Fig. (2): The Potentiometer diagram [3].

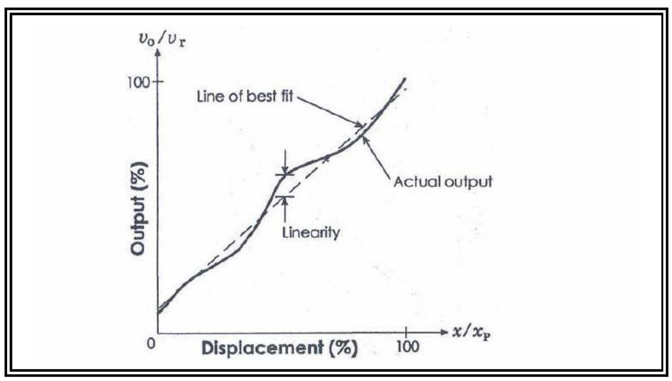


Fig. (3): Expected output from a potentiometer [4].

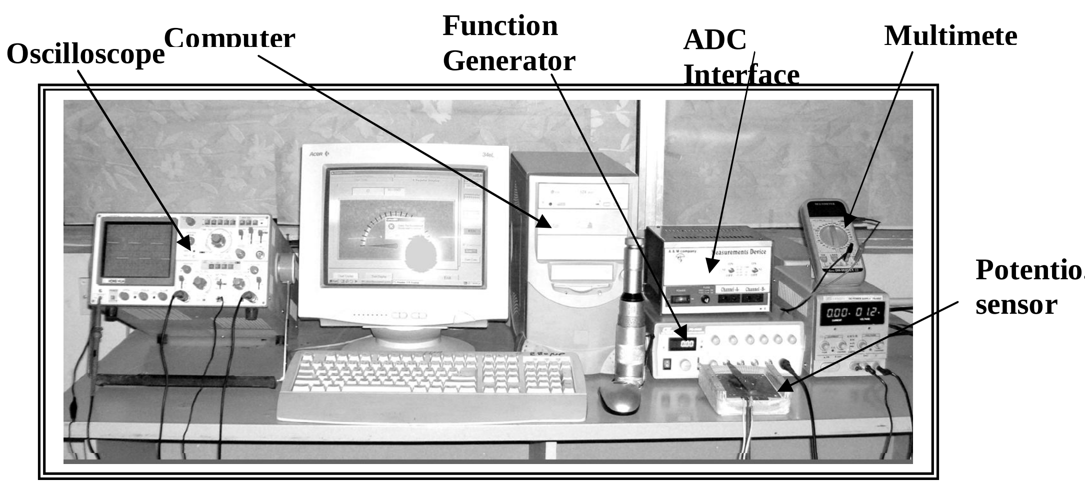


Fig (4): The Tactile Displacement Sensor Rig established in this research.

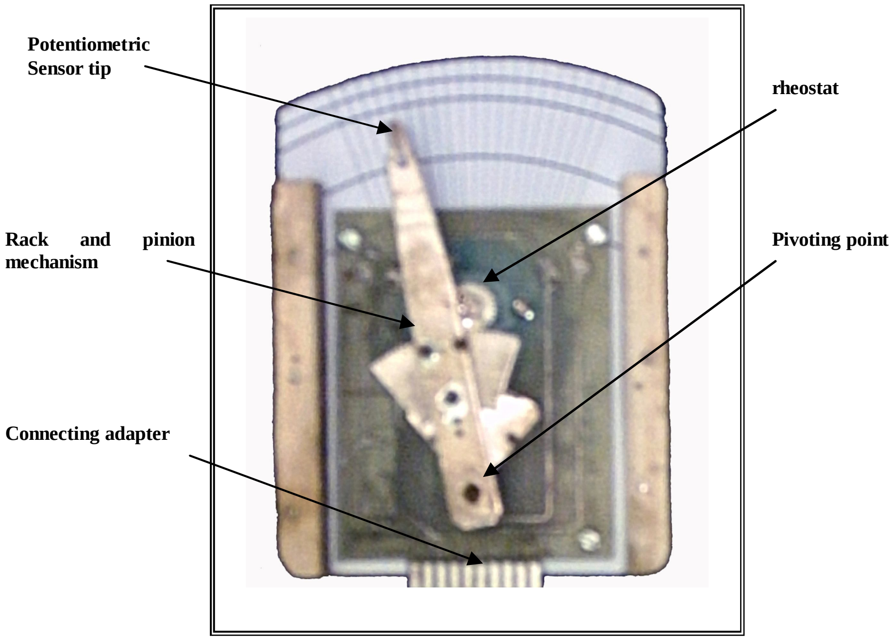


Fig. (5): The main components of the Potentiometric sensor.

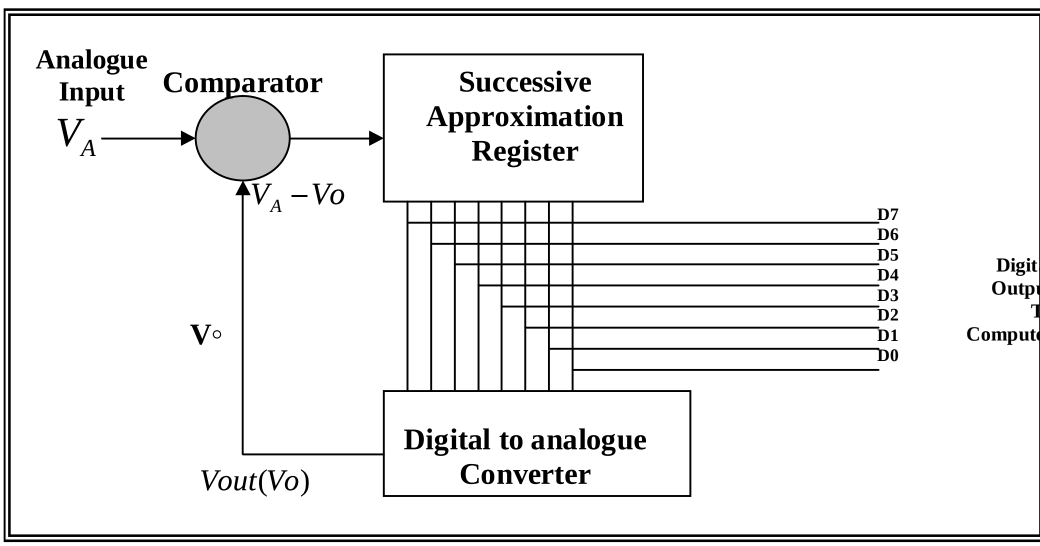


Fig. (6): Simplified block diagram of the ADC [4].

Fig. (7). The developed Data Acquisition System

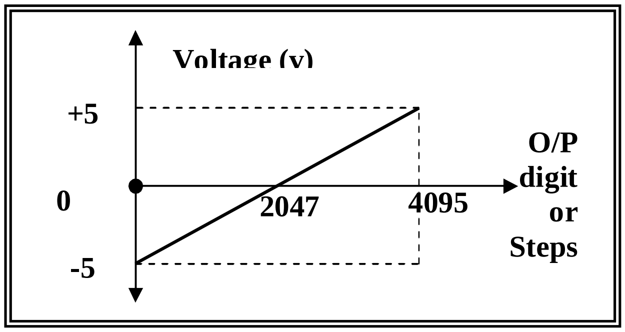
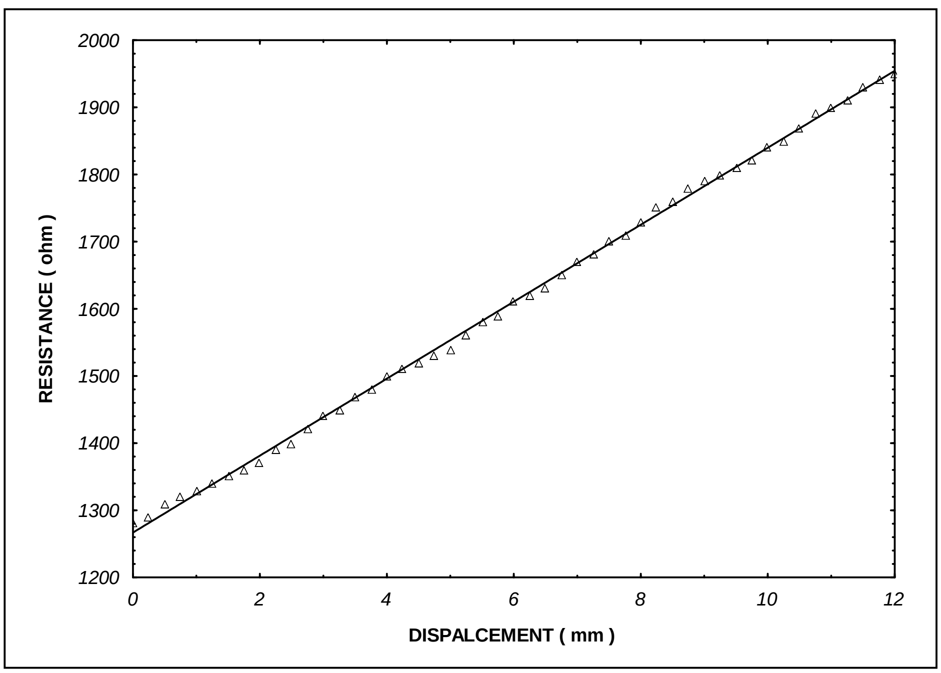


Fig. (8). The characteristic equation of the ADC



R3 (Ω) = 1266.7 + 57.3 X
Mean Error = 5 Ω= 0.4%

Fig. (9): The relation between the experimental applied displacement & the related resistance.

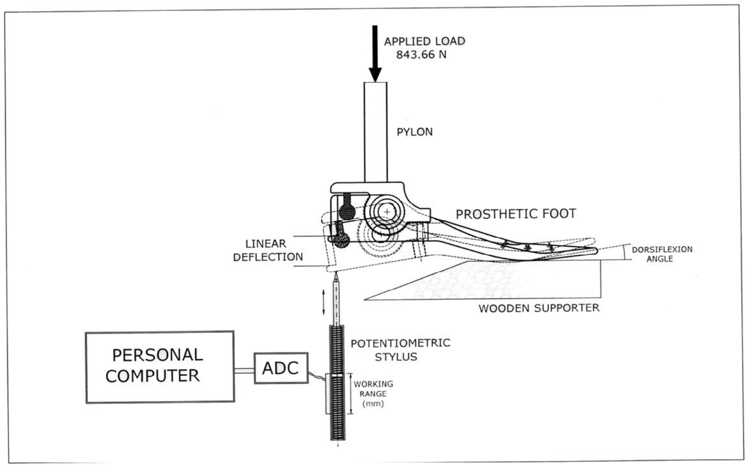


Fig. (10): The computerized rig for measuring the dorsiflexion angle.

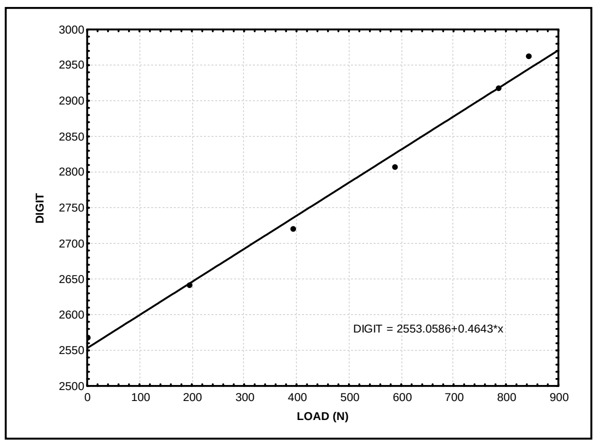


Fig.(11): The applied load-digit relation.

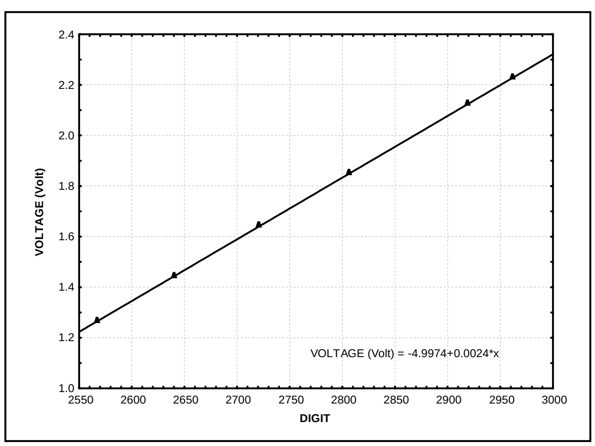


Fig. (12): The relation between the obtained digits and the computed voltages.

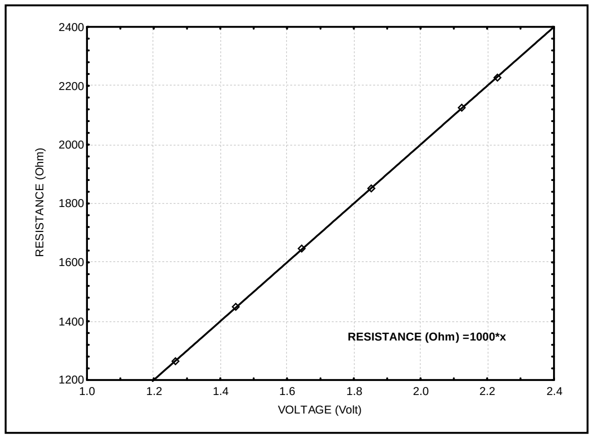


Fig. (13): The relation between Voltage and the associated Resistance.

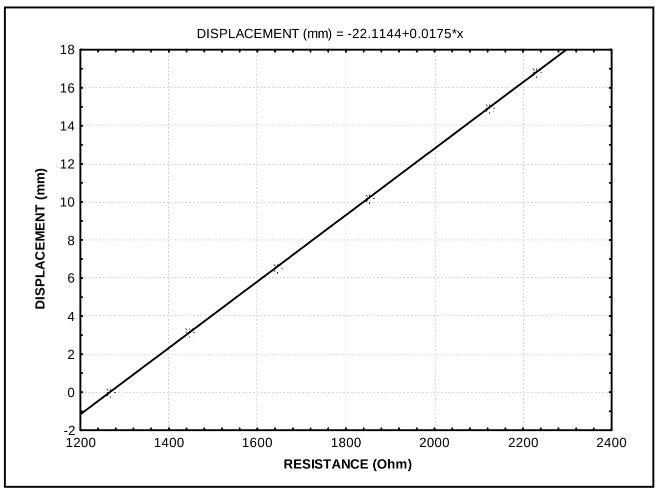


Fig. (14): The relation between Resistance and the associated Displacement.

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الخلاصة

يهدف هذا البحث إلى تصميم وبناء وتقييم متحسس أزاحه تلامسي لقياس الإزاحات كما واستخدم المتحسس لقياس الجانبية في نظام حاسوبي مطور وذلك لتقييم إمكانياته في التحسس والتقييم لزاوية الانحناء الطولي للقدم الصناعية الديناميكية المستخدمة من قبل المعاقين. يتكون النظام المطور من ثلاثة أجزاء رئيسية وهي المتحسس ووحدة استحصال البيانات والتي بدورها تتكون ضمنا من محول اشاره تماثليه إلى رقمية (' Analogue to Digital Converter ADC) والجزء الثالث هو الحاسوب والذي يساعد في معالجة البيانات المستحصله. تم في هذا البحث استخدام نوع واحد من المتحسسات التلامسية وهو متحسس أزاحه تلامسي باستخدام المجهاد(Potentiometric Tactile Displacement Sensor) و يولد هذا المتحسس إشارات خارجه تماثليه ولكي يتمكن الحاسوب من معالجة تلك الإشارات لابد من تحويلها إلى إشارات رقميه وباستخدام محول الإشارات (ADC) والموصل للحاسوب من خلال القناة المتوازية (Enhanced Parallel Port E.P.P.).

أجريت العديد من التجارب العملية لمعايره نظام التحسس المطور. أظهرت النتائج العملية الاوليه وجود تطابق في القيم المستحصله من النظام عن المستقيم الأفضل عند قياس الإزاحات الخطية وباستخدام طريقة المعايرة التقليدية (Traditional Calibration) وعليه قرر الباحث استخدام هذا المتحسس في قياس زاوية الانحناء الطولي للقدم الصناعية الديناميكية الجديدة ومقارنة النتائج المستحصله مع النتائج القياسية.