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Strain and deformation measurement for prosthetic parts using the Arduino microcontroller and strain gauges instruments

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Abstract
This study presents a methodology for measuring strain in any part of the prosthetic assembly using computerized strain gauges. The data acquisition is fabricatedby adopting an Arduino Uno microcontroller board. This research focuses on developing simple strain system methodologies for immediately measuring surface deformation of prosthetic parts.A prosthetic fibre carbon pylon was constructed based on additive manufacturing processing using the 3D printer for experimental testing and simulating. A strain gauge sensor merged with a microcontroller system to record the strain value of the constructed pylon. The test experiment was implemented under a load of patient weight during walk or movement.The results show that both experimental and numerical methods havea small error ratefor strain values over the testedpylon surface.Thus, the results obtained are in agreement between the values of strain evaluated by the finite element method and the values of strain recorded by laboratory experiment. Therefore, the result proves the proposed system has satisfactory accuracy.
Key words ; strain, prosthetic pylon, Arduino, 3D printer, strain gauge.

1- Introduction:

Amputations of limbs are becoming more common worldwide as a result of the increasing number of traffic accidents and vascular-related diseases [1,2]. Upper and lower amputees often use a prosthesis (artificiallimb) as a rehabilitation tool to restore their appearance and daily activities [3]. As illustrated in Figure (1), the prosthesis is composed of several essential components, which included a socket, shank, ankle, and foot.

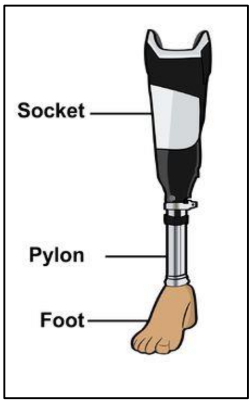

Fig (1):The essential components of prosthetic

Many studies deal with measuring and developing the strain calculation in the prosthetic parts because of its importance in knowing the mechanical and biomechanical behaviour of the prosthesis parts, especially in the research field.Chang-Yong Koet. al.,their study was to develop and validate a sensor to measure interfacial shear forces on the residual limb in the socket oflower-extremity amputees [4].YanggangFeng et al used the strain gauge for adjusting ankle angle measurement for transtibialprosthesis [5].YanggangFenget. al.,adopted one strain gauge bridge to detect gait events for the prosthesis, which can reflect the entire deformation of the footplate on a prosthesis [6].Carlos Eduardo Datteet. al.utilized the strain gauge methodologies to measure the microstrain around the implants and their connections to access excellent prosthetic contacts. As a result, they have emerged for betteraesthetic and biomechanical performance to prevent peri-implant boneloss [7].

Fromthe previous searches note that the strain systems areessential to evaluatethe strain value in parts of prosthetic applications; for this reason, This research focuses on the development of simple strain system methodologies for measuring surface deformation of prosthetic parts without the need for laboratory preparations, as well as providing the system at a low cost so that it can be used by researchers and in experimental settings during the manufacturing of prosthetics and orthoses.

2- Materials and Methods

2.1 Electronic instruments

The strain measurement system consists of a strain sensor, amicrocontroller type Uno is selected due to its low cost and simple manipulation, a power bank, and an LCD. The strain gauge sensor is a device used to measure the strainsof an object. The principle working of resistance strain gauge is based on the strain effect produced when a conductor or semiconductor material is mechanical deformation under the action of external forces.When force is applied to a strain gauge, its resistance varies, resulting in a changing electrical output .Strain gauges use this approach to quantify force, weight, deformation, and tension .When properly connected to an object or device, strain gauges can measure the contraction or expansion of an object even if it is just a small amount because they are small and highly sensitive. The strain sensor used in the strain system is shown in figure (3).

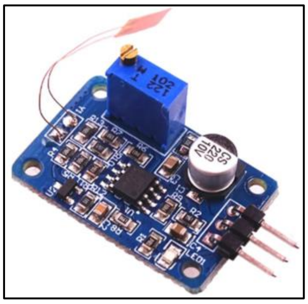

Fig (3): Strain gauge sensor

The Arduino is connected to the strain sensor in the strain measurement system. The Vcc is connected to one strain gauge terminal, while the grounded is connected to the other. The strain sensor's analogue output voltage, represented by Vo, will be used as Vcc at the analogue input point. The LCD with I2C has four pins: SDA, SCL, GND, and 5 volts (VCC), which were all attached to the Arduino at the same time.The "set cursor(x,y)" function selects the position on LCD. Data will be displayed on the LCD according to "LCD.print(data)", as illustrated in Figure (4).

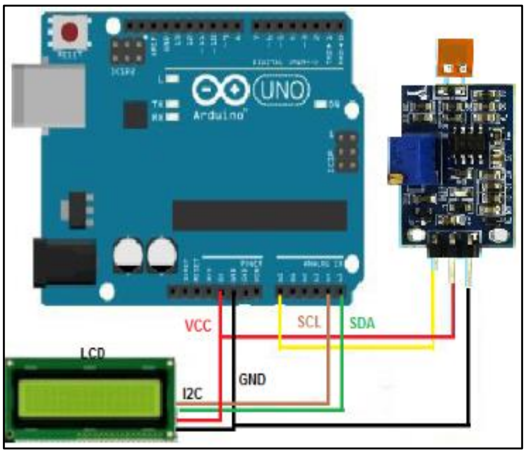

Fig (4): Connect the components of the strain measuring system

2.2 Pylon construction

In this study, a pylon for lower limb prosthesis usages is manufactured from carbon fibre filaments using a 3D printer device. The pylon dimension is 30 mm outer diameter with a length equal to 250 mm.The pylon is one of the important components of the prosthesis. When the patient uses the lower prosthesis, the pylon will be subjected to stress and strain due to the patient weight.Therefore, it is necessary to measure the value of strain to know the mechanical behaviour of the prosthetic part. Generally, in the prosthetic field, calculating the strain value theoretically required using numerical analysis and achieving the mechanical tests to know the mechanical properties of the materials that used in the manufacture of the prosthetic part, in addition to drawing an engineering model of the partsthese aforementioned steps require time to evaluate the value of strain numerically.

3- Experimental Work

In this study, a strain gauge system was adopted to measure the strain directly and instantaneously for any part of a prosthetic system without the need to (build an engineering model or mechanical test of the materials used in manufacturing).

Measuring the strain chain included connecting the strain gauge that senses the mechanical deformation under the action of external forces to the Arduino. The data collected was not only savedon a laptop but also displayed in LSD as shown in figure (5).

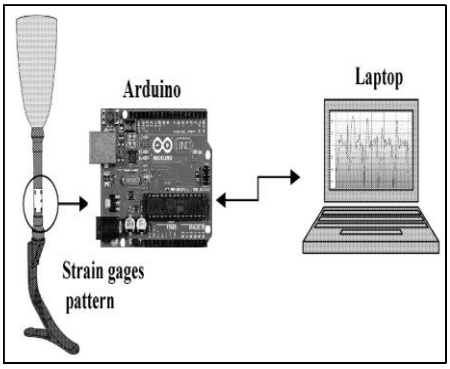

Fig (5): Strain system connection chain

The strain of a 3D printed carbon fibre pylon was measured when the pylon is assembled to the lower limb prosthesis. For the practical method, strain sensors adhered at different areas of the pylon surface by epoxy, as shown in figure (6).

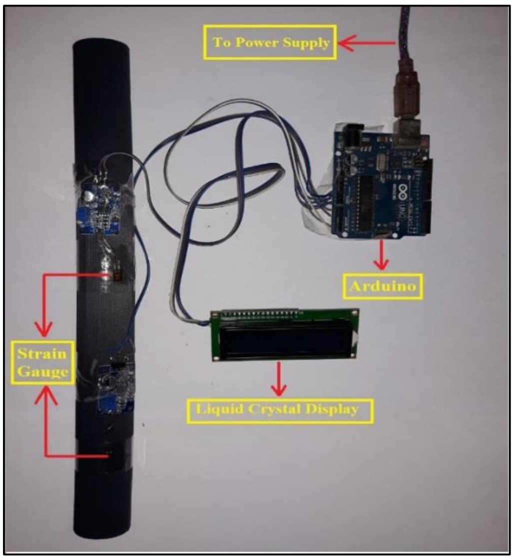

Fig (6):Connectionthe strain system withthe pylon

The strain system records the readings of the strain value that occurred in the pylon when the patient's weight was applied during his movement and walking, as shown in figure (7). After recording the strain values practically, these values are compared with the strain values obtained from the numerical analysis using the ANSES 14.5 software to evaluate and validatethe readings obtained.

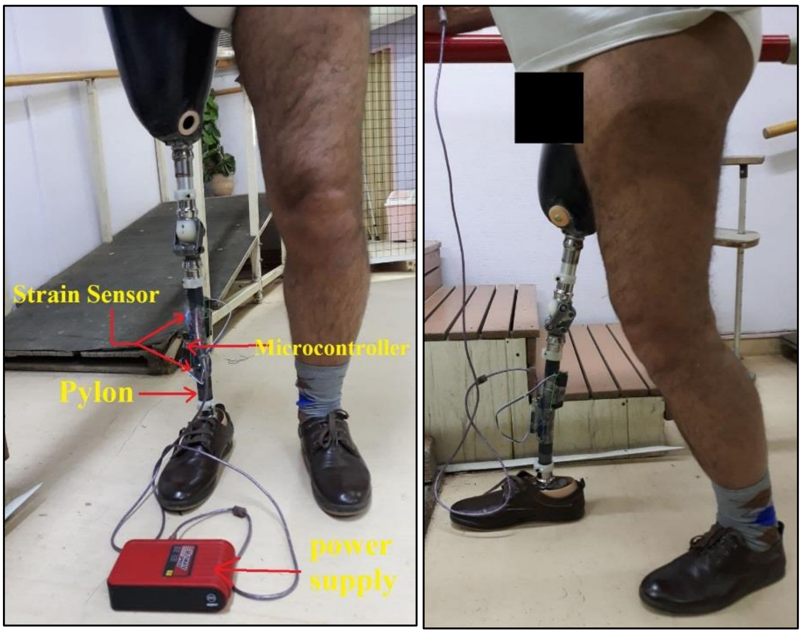

Fig (7):Recording strain readings in the pylon while the patient is standing and walking.

3.1 Tensile Test

To measure the strain theoretically using the numerical analysis method requires a tensile test to know the mechanical properties of the material used to manufacture the pylon. The purpose of the tensile test results is to be used as input data to the finite element method simulation program (ANSYS14.5).The carbon fibre tensile test specimenswere 3D printedaccording to ASTM-D638-V dimensions [8], as shown in figure (8).

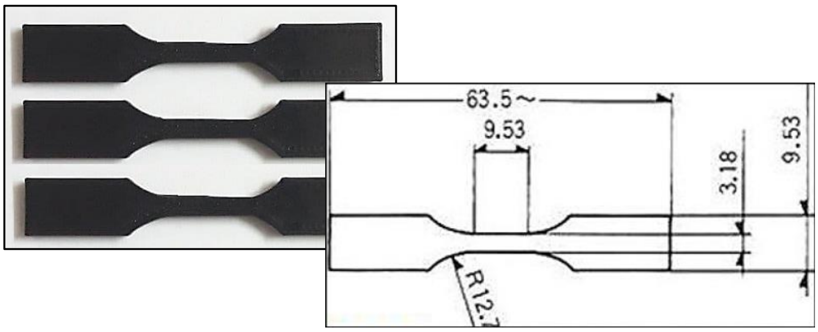

Fig (8):Dimensions of 3-D printed specimens

The tensile test result showed that the σ_{Ultim}= 58 MPa, σ_{Yeild}= 41MPa, and E = 1.62 GPa, as illustrated in figure (9). These values will be used as input data for the boundary conditions to calculate strain theoretically using the finite element analysis (ANSES 14.5 software)

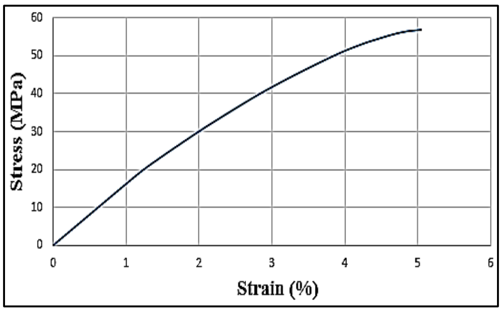

Fig (9): The stress-strain curve of the carbon fibre filament specimen

3.2 The Calibration of the Strain Gauge Sensor

To obtain reliable strain values, a calibration was carried out for the strain sensor. The sensors were fixed on the surface of the pylon with epoxy. After the sensor was installed, the voltage readings read on the LCD screen were rest, then several weights were applied on the pylon, and the voltage reading resulting from applying each weight was recorded. A relationship is drawn between the weight applied and the value of the voltage to represent the calibration diagram of the sensor. To convert the calibration chart from the relationship between weight and voltage to the relationship between force and voltage, the value of the applied weights is multiplied by the ground gravity,as shown in figure (10).

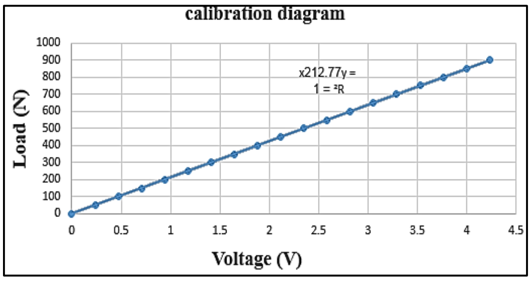

Fig (10): The calibration diagram showed the relationship between force and voltage.

The relationship between the strain and the voltage can be obtained by the following producer. The stress $\sigma = P/A$, where the (P) equals the applied load on the pylon, and (A) is the cross-section area of the pylon, which is equal to 0.0025 m^2.
$\sigma = E\times\varepsilon$, Where the (E) is the modules of elasticity of pylon material equal to 1.62 GPa, finally, $\varepsilon = P/A\times E$. The relationship between the strain and voltage can be shown in figure(11). Calibration is used within the Arduino programming settings so that the system is ready to measure the strain.

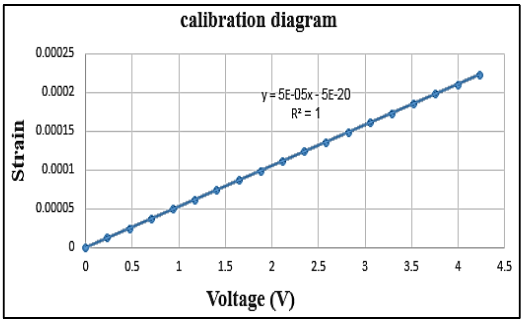

Fig (11): The calibration diagram showed between the strain and voltage.

Three study cases were used for patients suffering from the amputation of the lower extremities. The first case was for a patient who weighed 58 kg, the second for a patient who weighed 69 kg, and the third was for a patient who weighed 82 kg. The pylon was combined with the prosthetics of the three study cases, and the strain readings were taken while the patients were walking.

3.3 Boundary condition and Strain Analysis

A mathematical model was built for numerical analysis, and then applied the boundary condition to review the results. The boundary condition of the pylon involves inserting the result of the mechanical test of pylon material as input data with applying the patient's weight on the upper end of the pylon while the lower end is fixed, as shown in figure (12). Figure (12 -A) shows the boundary condition for a case study with a weight of 58 kg or a load 589 N, and figure (12-B) represented the boundary condition for the second case study with a weight of 68 kg or a load of 676 N, while figure (12-C) illustrated the boundary condition for a third case study with a weight 82 kg or a load 804 N.

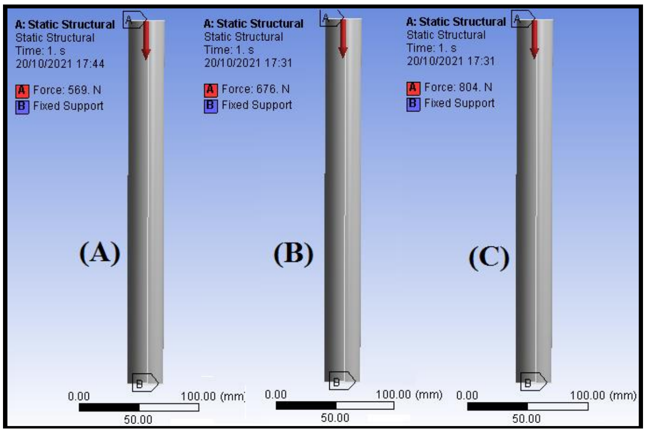

Fig (12):The boundary condition of the pylon for three cases study.

4- Result and Discussion

The strain generated in the prosthetic pylon was calculated in two ways, the first one is theoretical in which the numerical was used analysis, and the second one is the practical in which the strainmeasurement system was used.The theoretical results of measuring strain values showed that the value of strain generated in the pylonis equal to (0.0021, 0.0017,and 0.00145)when a patient weight of (82,69,and 58) kg as respectively is applied as a boundarycondition to it as shown in the figure (13)case (A, B, C).

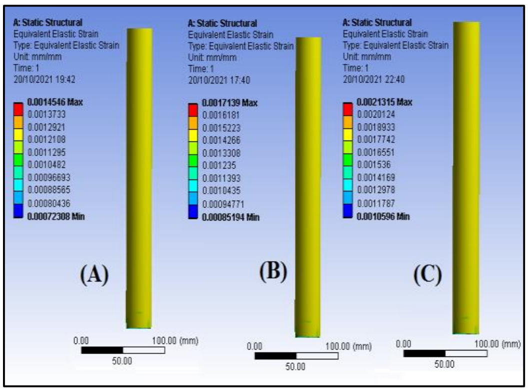

Fig (13): The strain analysis of the pylon for three cases study.

While the practical results resulting from reading the values of the strain sensor fixed on the wall of the pylon showed that the value of strain generated in the pylon equals (0.001989, 0.001667, and 0.0014) when a patient weight of (82,69, and 58) kg respectively is applied during a patient walk at the practical test as listed in the table (1).

Patient Weight (Kg)	Reading Volt (v)	Strain Measured by Arduino	Strain Measured by ANSYS
82	3.76	0.001989	0.0021
69	3.172	0.001667	0.0017
58	2.669	0.0014	0.00145

When comparing the practical results with the theory, it was found that the difference between the readings is very small. The amount of difference in the value of strain is equal to (0.00011, 0.000033, and 0.00005) in the case of a patient with a weight of (82,69 and 58) kg, which is equivalent to (5.2,1.9, and 3.2) % as respectively.The summarized results showed the strain measurement system is accurate and reliable in calculating the values of strain and useful in many mechanical applications because it is easy to operate as well as does not require laboratory preparations. In addition, the readings obtained are instant.

5- Conclusion

The following conclusions can be drawn from the present study:

1. The percentage difference between practical and theoretical methods readings does not exceed (5.2,1.9, and 3.2) % for the tested cases, which is a very significant percentage.
2. The use of the strain measurement system does not require examining the tested material to know the mechanical properties, nor to build an engineering model to analyze the part to be examined theoretically, but the readings are obtained using the strain system in a faster, direct, and instantaneous manner.
3. By comparing the results, it is concluded that the readings of the strain measurement system have high accuracy and reliability, and the system can be used to know the certain values of the parts subjected to loads.

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