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Design and Fabrication of an Electromechanical Tester to Perform Two-dimensional Tensile Testing for Flexible Materials

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Abstract

There are many diseases that affect the arteries, especially those related to their elasticity and stiffness, and they can be guessed by estimating and calculating the modulus of elasticity. Hence, the accurate calculation of the elastic modulus leads to an accurate assessment of these diseases, especially in their early stages, which can contribute to the treatment of these diseases early. Most of the calculations used the one-dimensional (1D) modulus of elasticity. From a mechanical point of view, the stresses to which the artery is subjected are not one-dimensional, but three-dimensional. Therefore, estimating at least a two-dimensional (2D) modulus of elasticity will necessarily be more accurate. To the knowledge of researchers, there is a lack of published research on this subject, as well as a paucity of research that designed and implemented a 2D tensile testing device (2DTTD). However, there is no inspection of arterial flexibility and elasticity using the 2DTTD adequately studied before. Therefore, the aim of this work is to design and implement the 2DTTD to scrutinize if there is a difference between the 1D and 2D tensile examination. Different sized rectangular silicone specimens were manually fabricated; they were tested individually using the fabricated 2DTTD, which mainly comprises four actuators synchronously working with the same velocity and axial load force, two at each axis. As expected using the 2DTTD, the dimensions of the specimen remarkably influence the tensile testing results; the strain and stress rates and the modulus of elasticity were influenced. To validate the acquired 2D tensile testing results, the 1D tensile testing was performed using the same fabricated 2DTTD and compared to results gained using another tensile testing apparatus. During the verification process, the input data for models calibration were sufficiently and accurately provided. The results showed reasonable precision and reliability in calculations of the 2D stress and strain rates during the whole deformation process. Each mechanical device that has been used has the possibility to stretch and squeeze the sample and log the change in the specimen elongation.

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The authors thought that the present experimental methodology was applied to the linear mechanical device successfully, where the encoder that is attached to tested samples was in the principal direction. The present method is used to measure the deformation in a manner that differs from the traditional digital image correlation method, which required a toolset that is more expensive, where it incorporates high-accuracy optical equipment.

Keywords: Encoder; Load cell; Synchronous stepper linear actuator; Two-dimensional tensile testing.

1.1 Introduction

Cardiovascular diseases are the first reason of death globally. These diseases have been the world's biggest killers since 2000. It is also forecasted that the number of victims of cardiovascular diseases will increase to 23.3 million by 2030, while these diseases will remain the main cause of death [1]. The study for 2D compatible cardiovascular materials has gone on for more a century, the quest has become more included as the need for flexible polymeric materials became apparent, the silicon rubber was used after responses were assessed to different materials [2,3]. Silicone rubber is a polymeric biomaterials that utilized in many medicine applications such as artificial arterial aneurysms and stenosis [4,5], changing a part or a function of the human body and arteries in reliable, safe, economical and physiologically acceptable manner [6,7,8]. Rectangular sections are employed with different sizes that can be adopted to effectively obtain a 2D stress state. While silicon rubber material uniaxial static characteristics have been studied extensively, their 2D static and characteristics are not well established one reason for this is the difficulty of conducting 2D tests [9]. 2D tensile testing is a versatile method to inspection the mechanical characterization and a complete description of planar materials, which can be obtained through a fewer amount of samples comparing with to 1D tensile testing. Typical variety of engineering materials are tested in 2D configuration include silicone elastomers and biological soft tissues. Putra and his colleagues [10] studied the 2D tensile testing of four silicone elastomer manufactured by additive manufacturing for wearable biomedical devices. Their 2D test device consists of four stepper linear actuators synchronously moved in opposing directions to drag four arms of the sample, they used a digital camera for strain measurement and examine the region of interest of the sample zone, and the digital image correlation system was used to acquire the displacement and deformation. The powder paint was sprayed to the surface of the sample to prepare the sample for digital image correlation. Their study explained that the effects of thickness are unimportant in the stress strain curve of an silicone elastomer with solid cross-section. Few previous works focused on using linear mechanical devices that are attached to the sample in the principal directions, and all those contributions focused on utilizing a unidirectional type of tensile testing, but with different design and gripping techniques. Johlitz and Diebels [10] implemented 1D and 2D tensile testing on silicone rubber material that was prepared by mixing two elastosis materials. Their 2D testing device has four-step engines of the company Intelligent Motions Systems Inc., which are laid out in a cruciform manner. During their experiments to map the deformation of their measuring field, they used two force sensors to measure the force and a camera (Marlin F-131B, Allied Vision Technologies Ltd). Their results showed that the 1D tensile testing described the material behavior only in a small range, while their 2D tensile testing showed that an extrapolation of uniaxial results to multiaxial loading situations does not lead to an accurate description of the complicated loading situation.

We designed and implemented a two-dimensional tensile testing device in a new methodology that differs from that currently used, using linear mechanical devices mainly comprises of four actuators synchronously working with the same velocity and axial load force, two at each axis, to estimate the stress and strain in two principal directions to account an effect of the 2D tensile testing on the specimens deformation pattern, using different sized fabricated rectangular silicone specimens, which tested individually using the fabricated 2DTTD.

1.2 Methods

We will quantify the magnitude of the tensile stress and strain in two principal directions for the elastic specimens fabricated using silicone rubber material [RTV-2, China] in different sizes described later. Due to its importance to validate our experimental testing methodology, the 1D tensile testing will be performed using the fabricated 2DTTD.

1.2.1 Experimental Set-up

The manufactured 2D tensile testing device was equipped with four linear actuators (DC servomotors), two load cells, a gripping system, and strain measurement techniques. Through, the movement of a linear actuator and a certain displacement is applied to the tested specimens using four independent motors. Two load cells are set along the two orthogonal load directions to measure the normal reaction forces explicated by the samples. While the gripping system transfers the load from the linear actuator to the specimen. All 2D tensile tests were performed in the rectangular plane on silicone specimens of different sizes. The main elements of the experimental apparatus are illustrated in Figure (1) and described below:

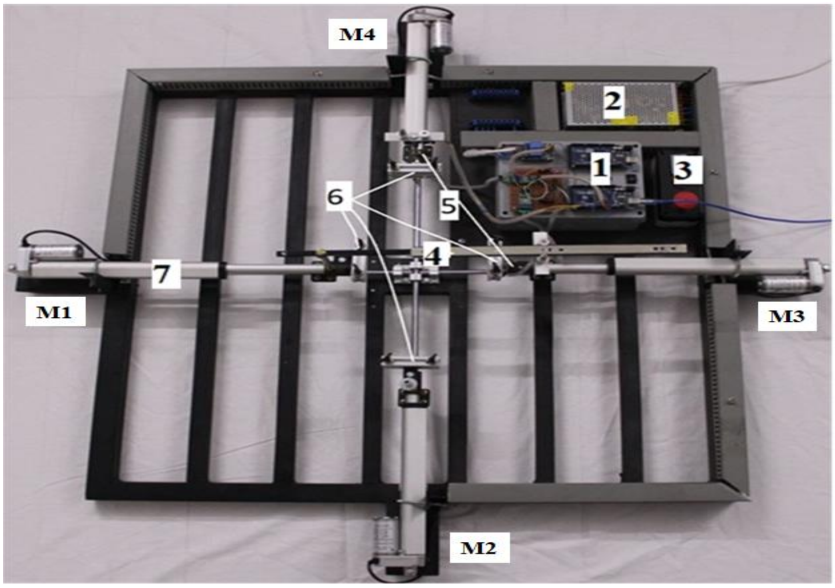

Figure 1: The main elements of the experimental set-up. Four independent linear DC motors [hydj12-250]. *1* represents the control circuit. *2* represents the control power supply. *3* represents the emergency switch. *4* represents the encoder guid. *5* represents two-load cells. *6* represents Four-grippers. *7* represents the DC linear actuator.

Actuators: They are moved synchronously and driven by four independent linear DC motors [hydj24-250, China]. Each motor is supported by using linear guide, which is supplied by DC 24 Volts, marked as M1, M2, M3, and M4 with M1 and M3 on the lateral axis and M2 and M4 on the longitudinal axis, as shown in Figure (1). Hence, at each axis of measuring during all the experiments, two actuators were linearly and oppositely moved in 8 mms-1of velocity. 700 N of fixed load force was applied in both axes of testing.

Elastic specimens: twelve rectangular rubber silicone [RTV-2, China] models of uniform isotropic specimens were made; eight to use in the 2D tensile testing and four to use in 1D measurements, which were used to verify gained results. These specimens were manufactured using a 50:1 silicone/catalyst ratio. The thickness of them was 0.5, 1.0, 1.25, and 1.5mm. All specimens used in the 2D testing have a length of 90 mm but in different widths, 40mm and 50mm. While all samples that were used to verify the results had dimensions of 90mm × 50mm. Each specimens gripped to manufactured gripper with footprint length of 10 mm in each side. The mold of specimens were 3-D printed. The catalyst used to solidify the liquid silicone material were mixed and injected into the molds to form the silicone rubber specimens. The mixture needed about four hours in order to cure at ambient temperature. The manner and technique that used to made the elastic specimens are based on Wisam and Khir [4], which have been also used in Igor and his colleagues [5].

Grippers: Four grippers were manufactured and used to hold the samples, distributed one at each edge of the specimen, connected directly to the actuators of the load cell. The gripper is made-up of two parts of aluminum profile 20mm×20mm, that put overlapping each other and are fixed together by the screw as shown in Figure (2).

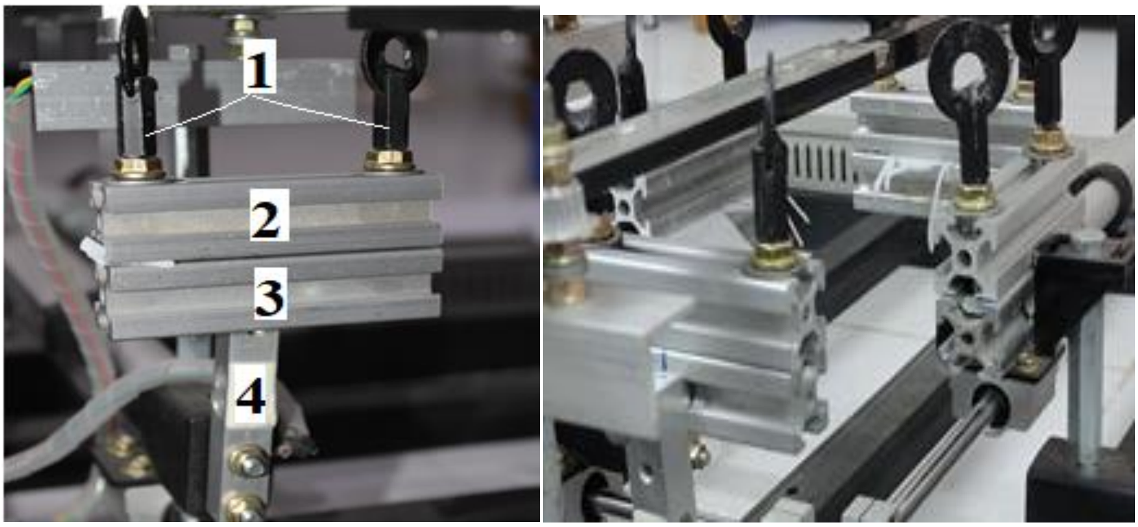

Figure 2: Manufactured grippers which consists of a screw (1), upper part (2), lower part (3), and the load cell (4).

Measurements: Two encoders have been used as transducers to convert the linear motion of actuators into a corresponding electrical signal. The encoders were coupled with an aluminum pulley in a close direction and with a metallic bar and a belt in another direction as shown in Figure (3). The metallic bar and belt transfer the linear movement to the encoder by rotating the pulley that couples with the encoder. Then, the aluminum pulley converts the linear motion of the bar to the rotation movement. The encoder measures the displacement by converting the rotational movement to electric pulses. Each tick of the encoder means 1mm of displacement. Two encoders have been fixed to the grippers to measure the strain. The tensile stress was measured using the load cell fixed perpendicularly between the motor and gripper. The real-time force measurement is realized by a two-load cell (20kgf) that is fixed on the gripper on one side and to the movement part of the actuator on another side. The Arduino software with Microsoft excel was used to sample and analyze the data, offline. Arduino mega was used to control all processes as shown in Figure (4) and display the results of the tensile stress, strain, and modulus of elasticity of samples in Microsoft excel.

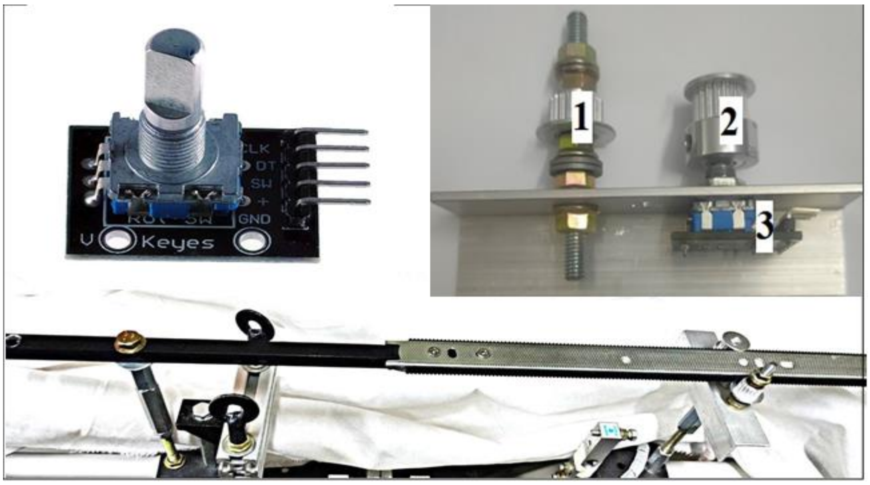

Figure 3: (*Upper right*) the aluminum pulley that used to couple the encoders in a close direction, where (1) refers to the pulley roller and (2) refers to the aluminum pulley while (3) represents the encoder. (*Upper left*) the encoder type that used to convert the linear motion of actuators into a corresponding electrical signal. (*Lower*) the metallic bar and the belt that used to restrict direction of the movement.

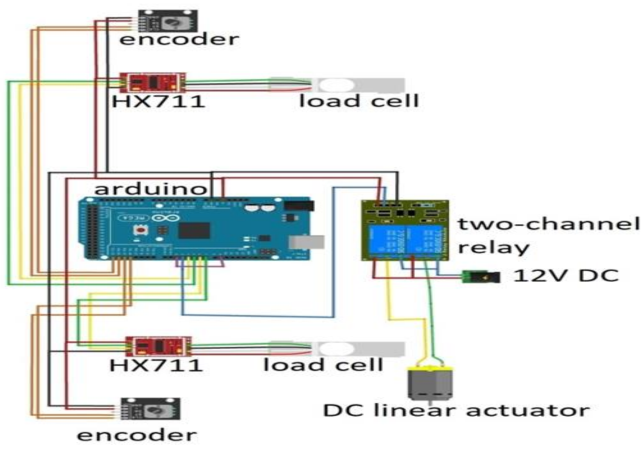

Figure 4: The electric circuit of the shield of HX711 that was used in the fabricated 2DTTD enables the Arduino mega controller to sense load cell signals.

Load cell: Consists of four strain gauges arranged in special methodology, using the principle of the electrical circuit called Wheatstone bridge, to gauge alteration in the force exerted, which transferred from the actuator to the specimen via the gripper. Every single gauge, during the deformation process by stressing, individually alters its resistance that allows sensing by the change in strain gauge, which occurs in the bridge arms. The input excitation (power supply) of the bridge was 5 volts while the output signal was 50 millivolts.

Amplifier: The output signal of the used load cell is very small, so to sense it by the microcontroller (Arduino Mega) the amplifier HX711 24-bit converter was used to amplify its output analog signal to digital signal, which was readable by the controller, as mentioned in Figure (4).

1.3 Results

1.3.1 One-dimensional tensile testing results

In our experimental methodology, 1D tensile testing was performed to validate the outcomes of our tester. Where silicone rubber specimens in 0.5, 0.75, 1, and 1.25mm of thickness, were tested using the load cell and encoder that are located in the lateral direction of 2DTTD, where the length of all specimens was 90mm. Tables 1 and 2 show the stress data acquired according to the 1D testing performed.

Table 1: The 1D tensile testing results using the fabricated 2DTTD. Results shown represent the average of four sequential tensile tests. All tested samples had dimensions of 90mm × 50mm.

Thickness [mm]	Specimen's area [mm^2]	Stress [kPa]
0.5	45	608.9176
0.75	67.5	728.08512
1	90	835.02502
1.25	112.5	881.568456

Table 2: The 1D tensile testing results using the fabricated 2DTTD. Results shown represent the average of four sequential tensile tests. All tested samples had dimensions of 90mm × 40mm.

Thickness [mm]	Specimen's area [mm^2]	Stress [kPa]
0.5	45	896.66452
0.75	67.5	860.0129067
1	90	926.12831
1.25	112.5	954.95772

1.3.2 Two-dimensional tensile testing results

The stress results for 2D tensile testing for different thickness, 0.5, 0.75, 1, and 1.25mm, are presented in Table (3).The values of stress and strain at the moment of a specimen's failure are remarked.

Table 3: The 2D tensile testing results using the fabricated 2DTTD. Results shown represent the average of four sequential tensile tests. All tested samples had dimensions of 90mm × 50mm.

Thickness [mm]	Specimen's area [mm^2]	Stress [kPa]
0.5	45	549.097092
0.75	67.5	717.401376
1	90	781.554852
1.25	112.5	806.7335904

1.4 Validation of the gained results

Practically, and to give greater reliability of the results obtained, the manufactured samples, which were tested using our load cell, were examined using the load cell located in one of the laboratories of University of Technology, Iraq (JIANQIAO 20kN, China), as shown in Table 4.

Table 4: The error of the 1D tensile testing that performed on specimens had dimensions of 90mm × 50mm. (1) refers to the fabricated 2DTTD while (2) refers to JIANQIAO 20kN load cell, China. Results shown represent the average of four sequential tensile tests.

Thickness [mm]	Results gained using load cell 1		Results gained using load cell 2		Force error %	Displacement error %
	Force [N]	Displacement [mm]	Force [N]	Displacement [mm]		
0.5	41.239	42.5	40.099	46.391	2.84296	8.387403
0.75	59.731	39.5	62.981	42.221	5.160286	6.44466
1	84.92	40.25	80.210	41.912	5.87209	3.965451
1.25	108.635	61.25	106.830	62.877	1.6896	2.587592

The percentage error between the acquired results, using the fabricated 2DTTD and the results gained using the JIANQIAO 20kN load cell (JLC), was calculated according to equation (1).

$$\text{Error \%} = \frac{\text{2DTTD data} - \text{JLC data}}{\text{2DTTD data}} \times 100\% \qquad (1)$$

1.5 Discussion

The aim of this experimental work is to enrich the field of knowledge that deal with the subject of modulus of elasticity to inspect accurately the arterial flexibility, consequently more precisely calculating for the pulse wave velocity, which is the most significant variable in the wave intensity analysis for the wave propagating through the arterial system. The performed 2D tensile tests were based on a linear mechanical methodology, using a new technique that has not been applied before to calculate the 2D tensile stress.

The 2D tensile testing device is fabricated and equipped with four DC linear actuators, two load cells, fabricated gripping tools, and stress and strain measurement techniques. As a reaction to linear actuators' movement, certainly generated forces are orthogonally applied to stretch the silicone rubber specimens during the tensile testing process. In this testing, we have experimentally investigated the 2D tensile stress using elastic specimens in 4 different thicknesses and 2 different widths. Also, we have compared the 1D values based on the tensile testing of the fabricated 2DTTD with those measured experimentally, using another load cell.

The main result is the 2D tensile testing that is differed from the outcomes of 1D tensile testing. Further, in all testing, either in 2D or 1D tensile testing, the size of the manufactured elastic specimen affects the behavior and profile of testing; the modulus of elasticity is highly affected by the size of the tested specimen. When the sample is tensioned, the thickness decreases and the surface area increases. In order to validate outcomes, 1D tensile testing gained using the fabricated 2DTTD was compared to 1D tensile testing that was measured using JIANQIAO 20kN load cell. The results show that the 1D tensile stress that is measured experimentally is in good agreement with that estimated using another device in all of our elastic specimens, especially at the specimen in 1.25mm of thickness. This reinforces the experimental results of the present work and shows the inaccuracy of using the 1D tensile stress calculations. That inaccuracy clearly affects the estimated mechanical properties of the cardiovascular system. All specimens are made of the same material but in different thicknesses. The relation between the 1D stress and the 1D strain is evidently almost linear within the range of elastic testing. But the gained simultaneous measurements from our 2D tensile tests, using the fabricated 2DTTD, may somewhat affect that linear range. Furthermore, the thickness of the specimen influences that linear behavior. As stated in previously published 1D tensile tests, the tested specimens' ultimate tensile stress was increased when the thickness increase; 608.9176, 728.08512. 835.02502, and 881.568456 kPa for specimens with 90mm×50mm. The corporation between the 1D testing with the 2D testing is shown in Table (6). The results show the influence of the 2D tensile on the tensile stress magnitude of the elastic material, consequently the modulus of elasticity and the mechanical properties of arterial system. The results show that the stress of the 2D tensile testing was greater than the stress and the 1D tensile testing. Because the samples in the 2D testing are tensioned from two sides, while the samples in the 1D testing are tensioned from one sides only, so the stress applied to the tested samples is low and the elongation of the sample to reach the failed point is low, thus the modulus of elasticity of the 2D tensile testing may be lower than the modulus of elasticity of the 1D tensile testing. The results shown in Table (6) represent the average of four sequential tensile tests.

Table 6: The performed attempts of the 1D tensile testing. The length of all tested specimens was 90 mm and the width is 50mm. Forceavg and Disavg are the force and displacement, respectively, which were used in the analysis of outcomes of this work.

Thickness	Force 1	Force 2	Force 3	Force 4	Forceavg	Dis 1	Dis 2	Dis 3	Dis 4	Disavg
0.5	31.512	30.02	26.225	21.847	27.401	49.25	49.75	48	49	49
0.75	45.331	45.992	50.641	54.624	49.147	47.75	49	48	49.25	48.5
1	76.2	71.554	73.099	79.754	75.152	58.5	58.25	60.25	59	59
1.25	99.851	98.411	101.921	110.661	102.711	61	61.25	64.25	63.5	62.5

Below is the process of stopping (attachinterrupt) actuators of the manufactured load cell using Arduino code. Our novel methodology for interrupting senses the dropping in load cell readings and transfers it to the part of code that is responsible for switching off the relay of the actuator. Actuators begin to tensile the specimen, when the starting bottom switches on, causing changes in load cells readings as represented by (a, b) in the code below. Load cell's ability was increased according to the tension force; after 300 g (2.941 N), the code will be able to sense any failure in the tested specimen by determining a drop in load cells force value, which leads to stop code’s flow and turn off actuator’s relay.

```
int x = a ;

int y = b ;

if(analogRead(A0) > 1000  ){

digitalWrite(3,LOW); }

if ( x >300 || y > 300 ){

digitalWrite(9,HIGH);

}else {

digitalWrite(9,LOW);

}

attachInterrupt(digitalPinToInterrupt(2),issue,FALLING);

}

}
```

```
}

void issue(){

digitalWrite(3,HIGH);

}
```

1.6 Limitations

There is no potentiometer that can measure displacement above 25cm, consequently, the encoder was used to measure the deformation in this work. Additionally, the backlash in the linear actuators, which led to unsynchronized movement with other actuators, needed to enhance by adding metal rings to the gear of the actuators. Most characteristics of the cardiovascular system are determined based on the pulse wave speed that propagated inside its vessels. The pulse wave speed is a function of the modulus of elasticity, so estimating at least the two-dimensional modulus of elasticity will necessarily gain a more accurate determination for the wave speed. The flexible materials used in this work are different from those available in most humans. In addition, the silicone rubber specimens tested in the present tensile testing are stiffer than in vivo arteries. The goal of this experimental work is to examine the 2D tensile effect on the flexibility results of those offered by previous in vivo studies, and how it may affect the results of their investigations. We do expect the 2D tensile stress will affect the outcomes or conclusions of published works. Consequently, the related previous publications need to substitute the 2D tensile stress with the 1D tensile stress in their methodology of calculation of modulus of elasticity.

1.7 Conclusions

This work has tried to achieve and complete several objectives hat is associated with the 2D tensile testing, which was performed on the silicone rubber material to investigate its 2D tensile stress. A number of concluding remarks were observed and can be summarized as follows: the fabricated tensile testing device has reasonable precision and reliability in the whole deformation process and provided accurate and sufficient data compared with the traditional one-dimensional tensile testing device; this experimental work succeeded in using the encoder as a linear mechanical device to sense the change in displacement; the present outcomes offer remarkable insights for the 2D tensile stress magnitude and its effect on the flexibility value of the mechanical properties of cardiovascular system, warrant additional experimental works to establish the accurate physiological magnitude; and the results of our work urge us and the rest of the researchers to reconsider estimating and using the value of modulus of elasticity, especially in the equations used to calculate the velocity of the wave traveling in the arteries.

1.8 Conflict of interests

The authors declare that they have no conflict of interests.

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