Design of a test bench for a sternum prosthesis

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Abstract. The present work shows the three-dimensional design and the simulation of movements in a test bench to reproduce the respiratory cycle in human beings so that the useful life of a sternum prosthesis can be evaluated. A design methodology was used to identify the requirements and subsequently establish the design and selection of the elements. Among the most relevant parameters to consider in the design, the test bench is required to simulate the action of the forces on the prosthesis, which are generated during the respiratory cycle in humans, causing expansion of the rib cage and rib elevation. Additionally, the test bench is capable of applying a compression force to the thorax that produces a seat belt in an automobile to reproduce impact scenarios. The test bench has linear actuators to control the required action force and the applied displacements. Simulations results show that the test bench is capable of reproducing movements on the sternum during the respiratory cycle together with impact conditions, as well as the reliability that the test bench can be used to perform tests that require a high time.

1. Introduction
The sternum is a flat and thick bone, it is located in the anterior part of the thorax, and it measures from 15 to 20 cm length [1]. It consists of three parts: the manubrium is the most comprehensive trapezium-shaped portion located at the top, the body is the most significant part of the sternum, and the xiphoid is the smallest and inferior part of the sternum. Among the main conditions that occur in the human sternum, is the presence of malignant tumours in its bone structure, due to these conditions most of the cases it is necessary to remove the damaged parts [2]. According to the extent of the damage to the sternum, it is necessary to partially or totally remove this bone element. Removing this element from the chest wall leads to both aesthetic and functional problems [3]. Prostheses are used to restore chest function and aesthetics. Although the development of this type of prosthesis is not recent, there is not much information focused on developing tests that evaluate the cycle life that these can meet, therefore, it is not common to find information about the development of test benches to carry out duration tests in this type of prosthesis. Test benches reported in the literature to perform assessments related to the sternum are aimed at analysing the efficiency of the closure systems used to join the sternum after surgery.

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It was consisting of two hydraulic cylinders responsible for providing lateral opening movement in the two segments of the sternum, controlled by a high-precision servo valve and at the same time connected to a mobile structure of the test bench, reported by [4] in 2010. In this work, a 3D design of a test bench to evaluate the useful life of a sternal prosthesis is presented. The normal breathing process in humans was used to represent the movements of the thorax, and elements were used to produce lateral expansion of the thorax and frontal elevation of the ribs. Results show a control diagram of the pneumatic movement actuators.

2. Materials and methods
The methodology used for the design of the test bench begins by defining the specifications; Previous work to this research has been developed to know the behaviour of the thorax on compression load scenarios [5-6], as well as to know different design methodologies that allow custom prostheses to be performed since the requirements are different for each patient [7]. The magnitude of the force is considered according to [8], where he reports in his study that the force exerted by the external intercostal muscles to lift each rib is 30.25N. According to [9] each stage of inspiration and expiration of the normal breathing process in a human being is carried out with a frequency of 1 Hz. In a study developed by [10], reports that the vertical lifting displacement in the ribs is approximately 0.81cm in each one.

The main function that is sought to be obtained through the test bench is to reproduce the normal breathing cycle in a human being since this would represent a real load condition to which the sternum prosthesis would be subjected. In order to reproduce the normal respiration cycle in a human being, the following parameters were considered. The dimensions of the test bench were defined in relation to the real dimensions that the sternum of an adult can reach between 15 to 20 cm length. To transmit the movement to the sternum that is more similar to those generated during the respiratory cycle of the human being, the 3 degrees of freedom that each separate rib has when connecting with the spine was considered as shown in figure 1. The linear actuators of the test bench must have a high fatigue resistance to guarantee the reliability of the obtained results.

![Figure 1. Degrees of freedom in rib-spine joint.](image)

2.1. Design of elements and selection of linear actuators
Pneumatic cylinders are used to apply the lifting force to each rib. As mentioned above, a design specification states that the required force on each linear actuator to lift a rib must be 30.25 N, this force is used to determine the dimensions of the desired pneumatic cylinder. The standard working
The pressure of pneumatic actuators is 6 bar equal to 600000 Pa. The diameter of the piston from the pneumatic cylinder was first determined using equation (1).

\[ P = \frac{F}{A} \]  \hspace{1cm} (1)

Equation to determine the area of the piston, the following value is obtained:

\[ A = 5.04 \times 10^{-5} m^2 = 50.4 mm^2 \]

Equation (2) is used to determine the piston diameter:

\[ D = \left( \frac{4A}{\pi} \right)^{-1} \]  \hspace{1cm} (2)

The pneumatic actuator that is suitable for the application is the model ESNU-8-150-P-A from Festo®. This pneumatic actuator is double-acting; it has a piston diameter of 8 mm. Position sensors can be attached to it in order to control the displacement of the rod from 0 to 150 mm in both directions.

2.2. Three-dimensional modelling of the test bench

The three-dimensional model of the test bench was developed using Solidworks® student version, as shown in figure 2. The design is formed by a rigid structure (1) that provides support to the elements and reduces vibrations since it is formed by a rectangular steel tube 2 inches wide by 3 inches high. Vertebra support (2) is mounted on the structure; there is a spherical joint in this vertebra support where an artificial rib (3) is connected, due to the type of joint, the artificial rib has 3 degrees of freedom. Artificial ribs have a circular cross-section that allows them to be anchored to the sternum prosthesis (4). The vertebra support contains 7 pairs of spherical joints that can vary the separation between them. The number of artificial ribs can be adapted according to the type of prosthesis if it is total or partial. Each artificial rib is connected to the previous one by means of the linear pneumatic actuator (5). Pneumatic actuators have the function of pulling the rib to which they are connected in the same way as the external intercostal muscles work. There is an Ambu-bag (6) between the ribs that produces the lateral expansion of the ribs and the elevation of the sternum prosthesis. The Ambu-bag receives the airflow thanks to the pipe (7) that connects with a flow regulating valve and a directional solenoid valve. Finally, there is a pneumatic linear actuator (8) on top of the test bench structure to apply a frontal load on the sternum prosthesis in relation to the sagittal plane.

Figure 2. The three-dimensional design of the test bench and parts.
2.3. Electropneumatic control system design

The electro-pneumatic control system was developed to govern the signals of the actuators, solenoid valves and limit switches; it was decided to use a programmable logic controller (PLC), since this controller is easy to use, suitable for applications with a large number of inputs and outputs. Signals contain counter functions that are necessary to determine the useful life of the test specimen. According to the three-dimensional modelling, 14 pneumatic actuators are necessary to apply the lifting force to each rib, a central pneumatic actuator to apply displacements on the prosthesis that represent the action of the seat belt during an impact and finally an Ambu-bag to reproduce the expansion of the thorax during breathing. The connection diagrams for these actuators is presented in figure 3.

![Connection diagrams for actuators](image)

**Figure 3.** Electro-pneumatic control system, a) connection diagram for rib actuators, b) Ambu-bag, c) front impact load actuator.

3. Results

By using the software Automation Studio®, student version, it was possible to simulate the movements of the pneumatic actuators, in this software it is also possible to make the ladder control diagram and the connection of all the electro-pneumatic elements. A uniform movement was observed in all the actuators, that is to say, that they reached the limits of their careers at the same time and in the same way they returned simultaneously. By using the software Solidworks®, student version, it was possible to obtain the three-dimensional model of the test bench, with this program, the model of all the pieces was obtained as well as a representation of the movements. The spherical joint, which was used to replicate the union between the rib and the vertebra, generated the appropriate movements to obtain the necessary degrees of freedom in the ribs, as shown in figure 4.

![Three-dimensional model of test bench](image)

**Figure 4.** Degrees of freedom of the rib-vertebra support.
4. Conclusion

Feasibility In this work, the three-dimensional design of a test bench was presented to carry out tests that determine the useful life of the prosthesis for the sternum. Thanks to the simulation of movement in the elements of the test bench, it was possible to corroborate that by integrating pneumatic actuators it was possible to obtain both the expansion of the chest and the elevation of the ribs. The development of the electro-pneumatic control system was carried out to produce a coordinated movement in each rib since the programming was carried out in such a way that all the ribs rise up and fell down simultaneously. In the electro-pneumatic control diagram, it is possible to modify the displacements of the pneumatic actuators to raise the ribs from 0 to 150 mm and from 0 to 300 mm for the front displacement actuator by including limit switches. To control the airflow inside the Ambu-bag, a flow regulating valve was integrated with a pressure regulating valve so that when the Ambu-bag is full, and the pressure starts to increase, it begins to expel the air immediately. On the other hand, incremental counters were integrated into the control system to record the number of cycles that the prosthesis resists at the end of the test. As a future job to this job, we are looking to carry out the manufacturing of this test bench.

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