Use of loading-unloading compression curves in medical device design

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Abstract. The paper presents a method and experimental results regarding mechanical testing of soft materials. In order to characterize the mechanical behaviour of technological materials used in prosthesis, a large number of material constants are required, as well as the comparison to the original. The present paper proposes as methodology the comparison between compression loading-unloading curves corresponding to a soft biological tissue and to a synthetic material. To this purpose, a device was designed based on the principle of the dynamic harness test. A moving load is considered and the force upon the indenter is controlled for loading-unloading phases. The load and specimen deformation are simultaneously recorded. A significant contribution of this paper is the interpolation of experimental data by power law functions, a difficult task because of the instability of the system of equations to be optimized. Finding the interpolation function was simplified, from solving a system of transcendental equations to solving a unique equation. The characteristic parameters of the experimentally curves must be compared to the ones corresponding to actual tissue. The tests were performed for two cases: first, using a spherical punch, and second, for a flat-ended cylindrical punch.

1. Introduction

The tissues from the human body can be modelled from soft materials (muscles, liver, lung) to hard materials (bones, teeth) [1-5]. A strict border between the two classes is difficult to draw, and cartilages can be regarded as materials with intermediary properties. A basic common issue in the design of prosthetic elements is the choice of material to successfully substitute biological tissue, [2]. Modern prosthetic techniques involve the employment of materials behaving as similarly as possible to the original tissue. This is more important for the soft tissues which, unlike hard tissues, present a more pronounced rheological comportment. The manner in which material substitutes original tissue can be characterized qualitatively or quantitatively. The quality aspect occurs mostly when elimination criteria are searched. At the moment when there are available solutions that respond sensitive equal to functional requirements, the quantitative criteria are necessary to evaluate the concordance between the behaviours of the discussed materials. Therefore, for an adequate selection of the material, a
minimum set of parameters necessary to ensure the complete characterization of the prosthetic material’s good functionality must first be identified; then, the methods must be found to quantitatively evaluate the selected parameters with sufficient precision for a good comparison. The mechanical characteristics of a prosthetic material are the most important parameters to be determined for completing the comparison between the prosthesis and original. The soft tissues are characterized by a series of parameters varying over wide ranges. In establishing the mechanical characteristics of soft tissues, a major difficulty consists in the fact that they change rapidly once detached from the living organism. Therefore, finding the mechanical characteristics is desirable in vivo. One of the tests providing information on the mechanical behaviour of materials is the indentation experiment [6-7]. As a principle, the indentation test refers to finding the time dependency of the penetration depth of a punch [8-9] with specified shape when the law of variation for the indentation force is known. It is agreed that the methodology of finding Young’s modulus for elasto-plastic materials form nanoin dentation tests conform to the method proposed by Oliver and Pharr [7] is one of the most suitable and expedite methods. The indentation test allows to find plastic properties by the study of residual deformations [10-11]. The paper continues the work of the authors by finding mechanical properties of materials used in biomechanics, [12-13]. The internal friction of the material can be estimated using the hysteresis loop - curve which can be obtained from the indentation experiment.

2. Proposed device. Description and working principle
The principle of operating of a test-rig proposed for the indentation test is presented next. The idea started from work [14] where, using a Shimadzu nanometer, the variations in time of the normal approach as defined in contact mechanics [15-16] and hysteresis curves for a series of metallic materials were found. The working principle of the device consists in applying a ramp force obtained by the compression and relaxation with constant speed of a helical spring. The variation of the normal approach is presented in figure 1 and figure 2 shows the pressing force variation for one of the tests from [14].

![Figure 1](image1.png)  
**Figure 1.** Normal approach variation with time for indentation test [19].

![Figure 2](image2.png)  
**Figure 2.** Loading force ramp variation for indentation test [19].

The designed device proposes to carry out the same type of loading, but with the possibility of changing the loading time, in order to highlight the effect of loading speed on different parameters. In figure 3 the schematics of the device are presented. The specimen 1 made of test material is set on the table of the device. The punch P is attached firmly to a lever hinged in O. A vertical force of constant value $F$ is moving with steady speed along the rod and the position is indicated by the parameter x. The equation of moments with respect to the joint O shows that the pressing force of the punch upon the specimen is $Q = F \times x / L$ thus proving the linear variation of the force when the speed is constant.

Based on the schematic from figure 3 the test rig from figure 4 was made. The synthetic foam 1, used as specimen to be tested, is loaded using a punch 2. The lever is materialized by a glass plate 3, chosen to allow for specimen visualization. The loading subassembly consists of a moving body 4...
constructed from two bearing balls fastened by a metallic rod that rolls on the glass surface by means of a part 5 to which a nut screw 6 is attached. A screw 7 is set into rotation motion by a direct current motor 8, and thus the nut screw carries out a translational motion. Adjusting the voltage of the motor results in different rotation velocities, and therefore, different velocities for the motion of the load. The pressing load of the punch is evaluated using the electronic balance with strain gauge 9, on the top of which the specimen is placed.

![Figure 3. Principle of experimental device.](image)

The deformation of the specimen is estimated using a dial indicator 10. The simultaneous values of the loading force and penetration depth are required for the study. To this end, using a mirror 11, the image of the indicator’s dial is brought in the same plane as the indication of the electronic balance. Both images are video captured using a camera 12, and the recording is divided into frames using specialized software.

![Figure 4. Actual test-rig from laboratory.](image)

The joint O is accomplished using two identical bearing balls having the centres at the same height. An image obtained with the camera is presented in figure 5 and the scale of the balance and the dial of the indicator can be simultaneously observed.
3. Experimental results and discussions
A first test of the device was made using as specimen a polyurethane ball pressed between two planes, the inferior one set on the top of the balance, and the upper one materialised by the glass plate, figure 6. The advantage of using the glass plate is that it allows monitoring the variation of contact surface in real time.

The graph from figure 8 presents the hysteresis loop for the test in figure 6. The experimental data were interpolated by power curves having the form:

$$F = C \delta^\alpha$$

The parameters $C$ and $\alpha$ were found using the experimental data in Cartesian form. This made the application of the least squares method more difficult since the minimization condition of objective function:

$$F(C, \alpha) = \sum_k [C \delta_k^\alpha - F_k]^2$$

conduces to a system of equations with two variables, $C$ and $\alpha$. Solving the system assumes finding the unknown $\alpha$ exponent as root of the transcendental equation:

$$h(\alpha) = \sum_k \left[ \sum_k \delta_k^\alpha F_k / \sum_k \delta_k^{2\alpha} - F_k \right] \delta_k^\alpha \ln \delta_k .$$

Next the $C$ constant is found with the relation:
\[ C = \sum_{k} \delta_{k}^{\alpha} F_{k} / \sum_{k} \delta_{k}^{2\alpha}. \] 

The experimental points and interpolation curves that trace the hysteresis loop are presented in figure 8. The data from figure 8 were plotted in double logarithmic coordinates, figure 9, where it can be noticed that the experimental points are gathering in the vicinity of the point that separates the loading phase from the unloading phase. 

![Figure 8](image1.png)  
**Figure 8.** Experimental data and interpolation curves.  

![Figure 9](image2.png)  
**Figure 9.** Experimental data and interpolation lines in double logarithmic coordinates. 

For the curves from figure 8, the values of the exponents found are: for the compression phase \( \alpha = 1.138 \), and for the relaxation phase \( \alpha = 1.495 \); the last value, very close to \( \alpha = 3/2 \) attests an elastic behaviour for the unloading phase. The difficulty of applying the method as presented above consists in the fact that it is practically impossible to find or obtain spherical tissue specimens. For practical cases, it is preferable to consider the material to be tested as a half-infinite matrix, indented by a punch of different shapes. Two methods are presented in figures 10 and 11: using a spherical punch and a flat-ended cylindrical punch with limited area. The solution from figure 12 is known as compression testing when the material to be tested is pressed between two flat plates, large enough to produce the deformation of the entire specimen. 

The test rig was adjusted to obtain the same maximum force and identical time periods, testing the same specimen, a prism of synthetic sponge. The experimental deformations for the two tests are presented in figure 13 and the load vs. time are shown in figure 14. As expected, the normal approaches for the spherical punch are larger than the deformations obtained using the flat-ended cylindrical punch. From figure 15 it is noticed that the test rig ensures a ramp load for both cases. Additionally, the perfect similitude between the plots from figures 1 and 13 and figures 2 and 14 respectively, is remarked. The only difference occurs at deformation curves that in figure 1 do not return to zero due to plastic deformations. The dependencies deformation and force vs. time, respectively can be regarded as parametric equations of the hysteresis loop plotted in figure 15. It can be observed that the area of hysteresis loop is much greater for the spherical punch compared to the flat one.
Figure 10. Spherical punch.

Figure 11. Finite plane punch (flat-ended cylinder).

Figure 12. Compression testing.

Figure 13. Normal approach variation for the two punches (red - sphere and blue – flat-ended cylinder).

Figure 14. Load vs. time for the two punches (red - sphere and blue – flat-ended cylinder).
The work corresponding to the two tests was found using the following relation:

$$L = \sum_{k>0} (\delta_k - \delta_{k-1}) \frac{F_k + F_{k-1}}{2}$$

(5)

and it was observed that the work of internal friction forces is, for the spherical punch, approximately ten times greater than the one for the flat punch.

**Figure 15.** Hysteresis loops for spherical and flat punches.

The conclusion which arises is that the behaviour of the tested material is better described by the spherical punch indentation experiment. Compared to the flat-ended punch experiment, the spherical one has two more advantages: the first consists in the fact that for the spherical indenter case, the dimensions of the contact area are reduced and thus the local behaviour of the material of the specimen is obtained, differing from the flat indenter which gives an average information on the same parameter; the second advantage refers to the specimen-punch contact initiation, which for the flat-ended punch must be specially positioned to ensure contact on the entire flat surface quite from the start. Without taking these matters into account, the specimen-punch contact would be a non-conform contact and the data would be erroneous at the beginning of the test. As noted, the data from the start of the test present an essential effect on the interpolation and modelling of experimental data (the $\alpha$ exponent).

**4. Conclusions**

The paper proposes a method for finding the indentation curves and hysteresis loops with the aim of comparing the features of a prosthetic material with those of a soft organic tissue. Starting from the constructive principle of a nano-hardness tester used in the characterization of metallic materials, a device accomplishing a ramp loading of the specimen is proposed. The difference between the actual device and the instrument mentioned consists in the loading manner. For the instrument, the variable load is obtained by the compression - relaxation of an elastic element, while for the proposed device the variation of the load is obtained by a constant load moving along a lever that has a punch attached at the end and acts upon the specimen. In a first phase, a trial was made for the device using a soft spherical specimen made of artificial foam, and good results were obtained. The spherical shape of the specimen is a major inconvenient in applying the method for actual materials. Therefore the method was modified for spherical punch or flat-face punch of finite dimension indenting specimens that can be assimilated to half-infinite matrices. The force variation and approach variation curves were similar to the curves given by the initial hardness tester. The only difference consists in the indentation curves which for the artificial foam do not present plastic deformation. The analysis of hysteresis loops corresponding to the two punch shapes prove that the spherical punch is more advantageous compared
to the flat-ended cylindrical punch, being more sensitive and permitting the strictly local characterisation of the material, while the flat indenter accomplishes an average value of the aimed parameter. The work is the starting point for a series of researches on characteristics of organic tissues, with the intention to compare these with synthetic materials when subjected to different maximum forces and load variation laws.

5. References
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