TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 69, Issue II, June, 2026

MECHATRONIC SYSTEM FOR SIMULATING THE BIOMECHANICAL BEHAVIOUR OF THE LUMBAR VERTEBRAE

Daniel BESNEA, Edgar MORARU, Victor CONSTANTIN, Iolanda-Constanta PANAIT, Vlad-Andrei STĂNESCU, Valentin NĂSTASE, Cosmina CHIUJDEA

Abstract: *The subject of the paper focuses on the use of rapid prototyping technologies in the construction and validation of a mechatronic system for simulating loading and unloading with different load conditions between the lumbar vertebrae, with the main purpose of evaluating their biomechanical behaviour. The three-dimensional model of the lumbar vertebrae and intervertebral discs was obtained by using specific programs that allow the generation of digital anatomical structures with appropriate accuracy based on medical imaging techniques. The physical models of the L1, L2, L3 and L4 vertebrae were obtained out of Polylactic Acid (PLA) using Fused Deposition Modelling (FDM) technology, and the three intervertebral discs, made out of a silicone material, were manufactured using molding methods. A mechatronic system for simulating the biomechanical behaviour of the lumbar vertebrae was designed and assembled. A series of experiments was carried out in which the loading and unloading of the vertebrae was simulated in relation to the three stationary positions of the motor, and the loads applied were measured in the case of each intervertebral disc. In a second experiment, the number of motor stops would increase and results were obtained for the three intervertebral discs at loading and unloading in 11 points. The outcomes of the simulations run on the experimental stand can give a general idea of how the lumbar spine behaves biomechanically.*

Key words: *Additive manufacturing; Fused Deposition Modelling; Biomedical; Silicone molding; Mechatronic system; Biomechanical behaviour; Lumbar vertebrae; Intervertebral discs.*

1. INTRODUCTION

Additive manufacturing processes offer the possibility of producing complex parts that would be difficult or impossible to achieve using subtractive manufacturing methods. By using additive technologies, the need for additional processing steps can be eliminated, as printing these parts can be done in a single operation. At the same time, additive manufacturing allows for rapid design adaptation without requiring preparation time or additional costs, finding its place in multiple important applications in the field [1-4].

A special place where additive processes have a significant impact is the medical field [5-7]. In the medical sector, rapid prototyping technologies are used both in diagnostics and in education or research, to create physical models of the objects being studied (anatomical replicas) or to shorten the time required to produce prostheses. The ability to make a physical replica of a specific anatomical structure provides an important advantage in planning and simulating difficult surgical interventions, such as those in craniomaxillofacial surgery, where complex and variable geometries are involved.

Even though virtual models are useful for planning complex surgical interventions and three-dimensional simulation, using a physical model is preferable. A real model allows for the preliminary examination of many risks or difficulties that may arise during the operation, visualization of possible movements during the intervention, and precise assessment of the intervention area [8,9]. The manufacturing of medical models is achieved by going through three stages, namely, data acquisition, image processing, and physical creation of the

Received: 28.04.26; **Similaritie**s: 07.05.26: **Reviewed**:28.04. /28.04.26: **Accepted** 08.06.26.

prototype. In the scientific world, there is a constant interest in studying the biomechanical behavior of anatomical parts (including lumbar vertebrae), and the use of additive technologies for this purpose can facilitate research in this regard [10-13].

A biomechanically validated finite element model (FEM) was created by Pitzen et al. [11] to predict the biomechanical behavior of the human lumbar spine during compression. They first conducted a in vitro analysis on six cadaveric human lumbar spine segments L2–L5, and contrasted the results to those obtained by FEM. They came to the conclusion that FEM results should be viewed as a trend even though the results were comparable.

Wandra led an effort to develop two spinal cage models using 3D printing. The prototypes were fabricated using titanium ELI grade via Direct Metal Laser Sintering (DMLS) and were used to experimentally validate the FEM results. His two models were designed with different infill geometries, showing that a gyroid infilled cage experienced higher stress concentrations compared to a solid infilled one, but it effectively reduced stress shielding and is more likely to support bone in-growth [14].

Chin et al. [15] performed the first reported successful 3D printed L1-L3 lumbar vertebrae implant on a 51 year old man suffering from recurrent Giant cell tumors (GCT) in the lumbar region.

They used the MIMICS 15.0 software to accurately create and size the model of the vertebral prosthesis on the basis of preoperative 2D imaging studies and manufactured it out of a porous titanium alloy. Creating the prosthetic by using 3D printing technologies allowed them to ensure osseointegration and enable fixation to surrounding anatomical structures, which could not be achieved with traditional cage/titanium mesh implants.

Although there is a considerable variety of additive manufacturing technologies, such as selective laser melting [16] or vat photopolymerization [17], in this paper the focus will be on Fused Deposition Modelling (FDM) technology, because the FDM process was specifically used to create the mechanical structures in the experiments and case studies presented in this paper, due to the low cost of consumable materials (Polylactic Acid - PLA was used as the material for all components), as well as the 3D printers used.

The paper describes the custom solution adopted for the creation of an experimental stand intended to simulate the loading and unloading between the lumbar vertebrae under various conditions. The experimental stand was developed to allow the study of the mechanical behavior of vertebrae and intervertebral discs in a controlled manner.

The study also focuses on the use of rapid prototyping technologies in building the biomechanical model of the lumbar vertebrae, starting from its acquisition through specific medical imaging techniques. After the digital medical models were generated, they were used to print the vertebrae using FDM additive technology.

To accurately simulate the biomechanical behavior of the spine, it was also necessary to create models of intervertebral discs. These were made by molding silicone material. For this purpose, a special mold was designed and materialized, thus replicating the elastic properties of real intervertebral discs.

2. MATERIALS AND METHODS

The lumbar vertebrae are essential for the mechanical support and mobility of the spine, and can be affected over time by various medical conditions. Research into this anatomical region is vital for improving clinical diagnosis and treatments [18]. For these reasons, lumbar vertebrae L1-L4 were selected for use in this study.

The first step in creating the experimental stand was the use of the special program - 3D Slicer for visualizing and analyzing medical data, but also for generating precise three-dimensional models of the vertebrae and intervertebral discs.

The 3D Slicer program offers a series of advanced tools that allow the segmentation and reconstruction of anatomical structures from data originating from medical imaging techniques, such as Magnetic Resonance Imaging (MRI) or Computed Tomography (CT).

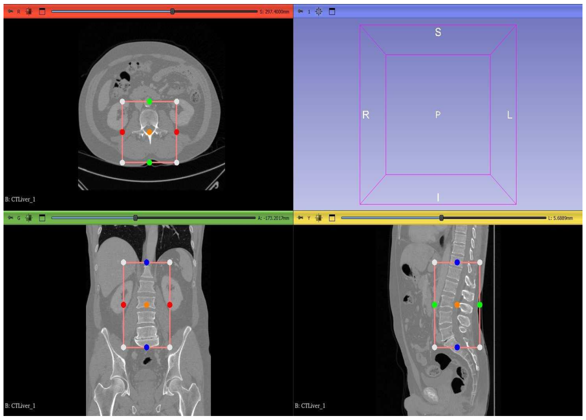


Fig. 1. The area of nterest where the vertebrae L1, L2, L3 and L4 are located.

Next, the tomographic scan was cropped, in order to focus on the area of interest, more precisely the area where the L1, L2, L3 and L4 vertebrae are found (Fig.1). The tomographic scan is cut for each plane separately, axial, coronal and sagittal. After this step, each vertebra was segmented by identifying and delimiting specific structures or regions of interest in the medical image. Four segmentations were obtained for each vertebra. To include only bone structures in the segmentation process of each vertebra, the range of voxel intensity thresholds was specified. It is essential that the adjustment of values is correctly performed to obtain an accurate and anatomically relevant segmentation. Removing soft tissue from segmentation reduces data complexity and improves image quality of the structures of interest. Once each vertebra has been selected, the "Grow from seeds" function is used to expand the selected area to include all neighboring pixels/voxels. Following all the specific operations and adjustments performed using the 3D Slicer program, the 3D model of the vertebrae was obtained (Fig.2). Based on these results, physical modelsof the lumbar vertebrae (Fig. 3.) were fabricated via Fused Deposition Modeling, using an Ender-3 V3 3D printer, together with Cura software to slice the STL files for printing The specimens were printed with a black Polymaker PolyTerra PLA fillament of 1.75 mm diameter. The choice is justified not only by its sustainability and cheap price, but also because it is a biobased and biodegradable 3D printing material.

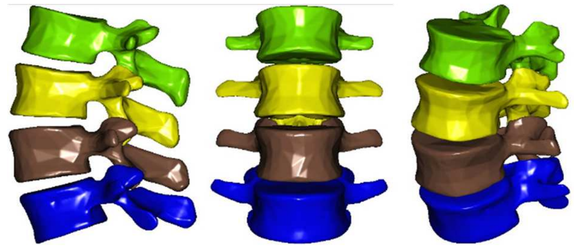


Fig. 2. The final 3D model obtained for the L1, L2, L3 and L4 vertebrae.

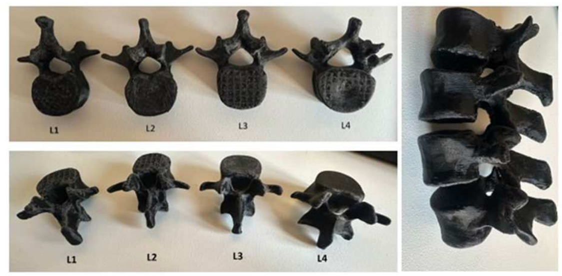


Fig. 3. 3D printed models of lumbar vertebrae.

Using a similar process to that used to obtain the 3D model of the vertebrae, the 3D model of the intervertebral discs was generated (Fig.4). The intervertebral discs were made of a silicone material. An ideal approach for molding intervertebral discs would be to create a set of three molds, but because their profile is relatively similar, and for economic reasons, a single mold was designed.

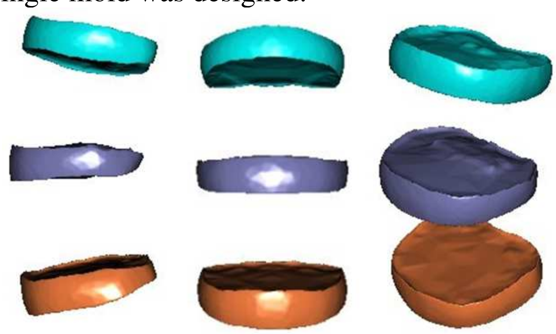
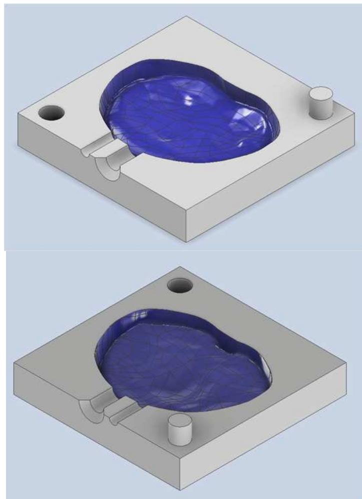
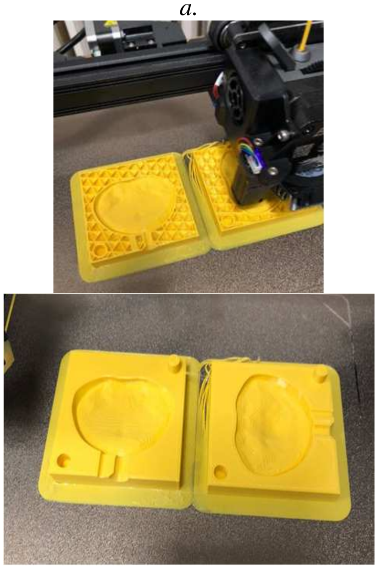


Fig. 4. 3D model of intervertebral discs.

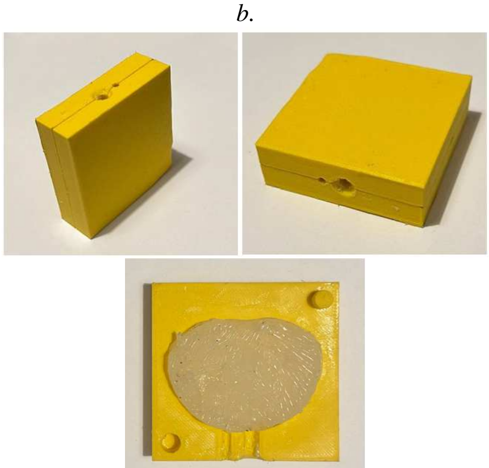
In order to join and fix the mold during processing, it is necessary to make fixing elements, and in order to fill the cavity and evacuate the air present inside, two channels were made. The process of making the intervertebral disc is shown in Fig.5 (a total of 3 molding processes were carried out to make 3 intervertebral discs).



a.



b.



c.

Fig. 5. The process of making the intervertebral disc:
a – designed molds; b – 3D printing of molds; c – molding system and the obtained intervertebral disc.

It is known that the anatomical position of the vertebrae is not uniform, so for this reason, fixation elements must be designed and adapted to fit each vertebra separately. After analyzing the 3D model (Fig.6), it is found that the attachment position of the L1 vertebra is equal to the attachment position of the L4 vertebra, respectively L2 equal to L3. The difference between the two axes passing through the center of the attachment points L1 and L4, respectively L2 and L3, is 5 mm.

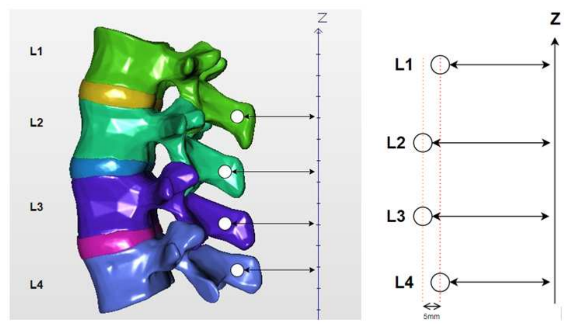
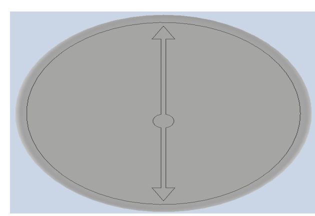
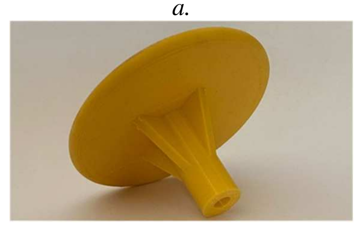


Fig. 6. Relative positions of the vertebrae.

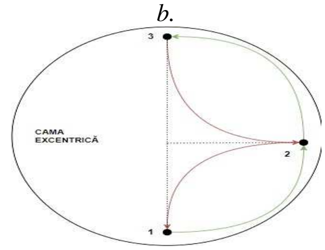
To load and unload the vertebrae and intervertebral discs, an eccentric cam was designed (Fig. 7).



a.



b.



c.

Fig. 7. Making the eccentric cam: a - position identification elements; b – 3D printed cam; c - motor stop positions.

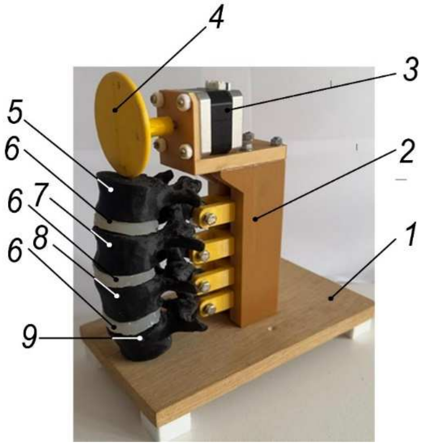


Fig. 8. Final assembled mechatronic system for simulating the biomechanical behaviour of the lumbar vertebrae: 1-support; 2 - column; 3 - stepper motor; 4 - eccentric cam; 5- vertebrae L1; 6 - intervertebral disk; 7 - vertebrae L2; 8 - vertebrae L3; 9 - vertebrae L4.

For easier identification of the cam position during operation, two arrows were made indicating the minimum or maximum value between the point of contact with the first vertebra and the center of the shaft mounting hole (Fig.7a). FDM additive technology was also used to create the cam (Fig.7b). It is also desired that the motor stops in three positions (Fig.7c). To perform this simulation of loading and unloading between the lumbar vertebrae, in addition to the designed and assembled experimental stand (Fig.8), an electronic system is also implemented, and the main components are as follows: a stepper motor and a driver for it, resistive force sensors, an electronic display and a button. All these components are connected to a microcontroller.

As it can be seen in Fig.7c, two cycles are presented, namely the vertebrae loading cycle (drawn in green, 1-2-3) and their unloading cycle (drawn in red, 3-2-1). The meaning of these positions is: Position 1 is the initial position, here the pressing load is 0. Every time a new simulation is performed the motor will be in this position; Position 2 will be obtained by rotating the stepper motor 90° from position 1. The intervertebral discs will be compressed by 2.4 mm, due to the pressing load generated by the rotation of the eccentric cam; Position 3 is the position where the compression of the vertebrae is maximum, more precisely 5 mm. This is obtained by rotating the stepper motor 90° from position 2.

3. EXPERIMENTAL RESULTS

To create the electronic system (Fig. 9), the main electronic components are: a stepper motor and a driver for it, resistive force sensors, an electronic display connected to a microcontroller. To evaluate the performance of the stand and measure the behavior of the lumbar vertebrae, a series of experiments were conducted in which the loading of the vertebrae was simulated in relation to the three stationary positions of the motor. Resistive force sensors were calibrated and mounted to measure the loads applied to the vertebrae and intervertebral discs. Data was collected and displayed in real time on the Liquid Crystal Display (LCD) interface. In the first experiment, the loads occurring at each intervertebral disc were individually measured and determined in percentage, for the 3 positions of the motor. The results obtained from the measurements represent the value of the electrical resistance of the resistive sensor after charging or discharging it. When the sensor is not charged, its electrical resistance is maximum, 1023kΩ, and the display shows 0%. When the sensor is charged, the electrical resistance decreases, and the display shows a value expressed as a percentage.

In the case of the first intervertebral disc, in position P1, upon loading, the vertebrae and intervertebral discs are not compressed, and the measured load value is 0%. In position P2, upon loading, the vertebrae and intervertebral discs are compressed by 2.4 mm, and the measured load value is 65% (Fig.10). In the last position, P3, upon loading, the vertebrae and intervertebral discs are compressed by 5 mm, and the measured load value is 91%. In the first position, P3, upon unloading, the lumbar spine is compressed by 5 mm, and the measured load value is 91%. In the second position, P2, upon unloading, the lumbar spine is decompressed by 2.4 mm, and the measured load value is 60%. In the last position, P1, upon unloading, the lumbar spine is completely decompressed, and the measured load value is 0%.

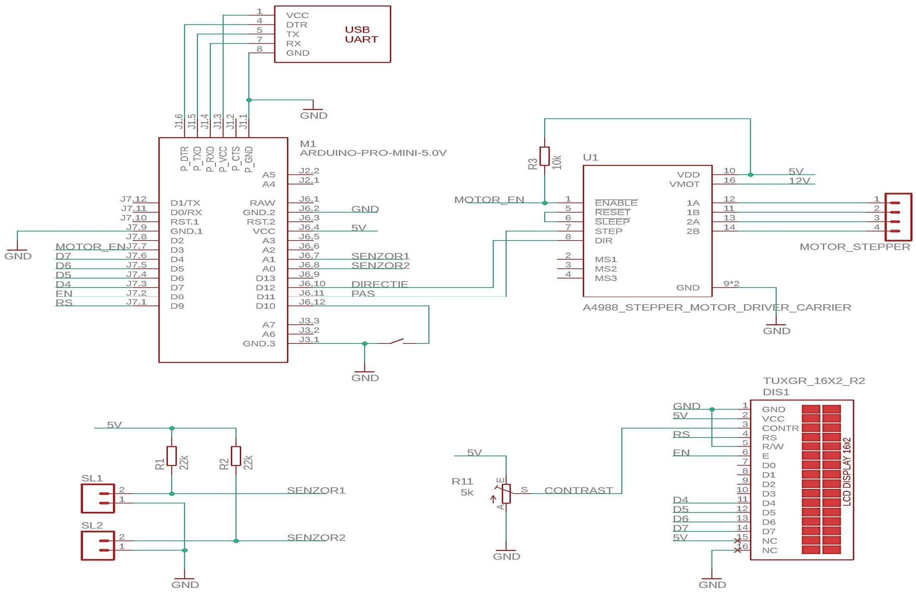


Fig. 9. Electronic diagram of the experimental stand.

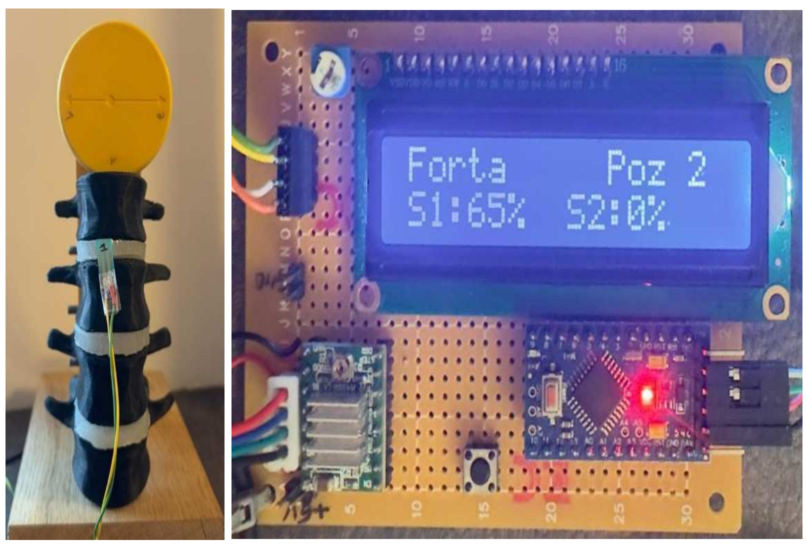


Fig. 10. Simulation of the first intervertebral disc in position P2.

In the case of the second intervertebral disc, in position P2, upon loading, the vertebrae and intervertebral discs are compressed by 2.4 mm, and the measured load value is 56%. In the last position, P3, upon loading, the vertebrae and intervertebral discs are compressed by 5 mm, and the measured load value is 82%. In the first position, P3, upon unloading, the lumbar spine is compressed by 5 mm, and the measured load value is 82%. In the second position, P2, upon unloading, the lumbar spine is decompressed by 2.4 mm, and the measured load value is 52%. In the last position, P1, upon unloading, the lumbar spine is completely decompressed, and the measured load value is 0%.

In the case of the third intervertebral disc, in position P2, upon loading, the vertebrae and intervertebral discs are compressed by 2.4 mm, and the measured load value is 33%. In the last position, P3, upon loading, the vertebrae and intervertebral discs are compressed by 5 mm, and the measured load value is 75%. In the first position, P3, upon unloading, the lumbar spine is compressed by 5 mm, and the measured load value is 75%. In the second position, P2, upon unloading, the lumbar spine is decompressed by 2.4 mm, and the measured load value is 30%. In the last position, P1, upon unloading, the lumbar spine is completely decompressed, and the measured load value is 0%.

The experimental data obtained during loading and unloading for the three intervertebral discs are presented in Fig. 11.

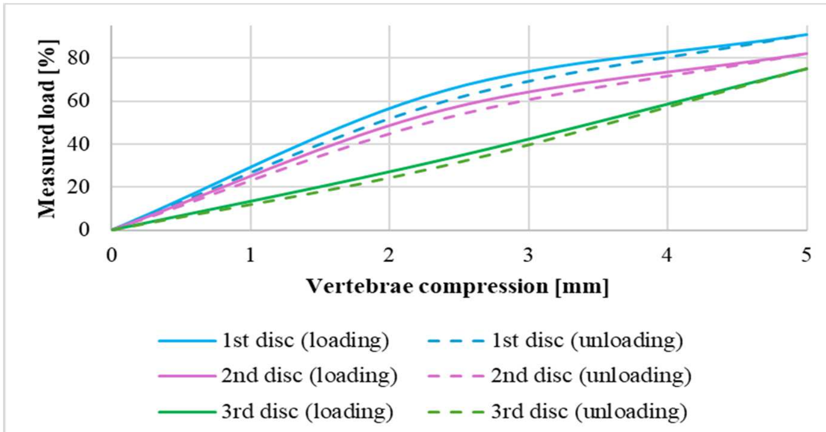


Fig. 11. Experimental results obtained for three intervertebral discs.

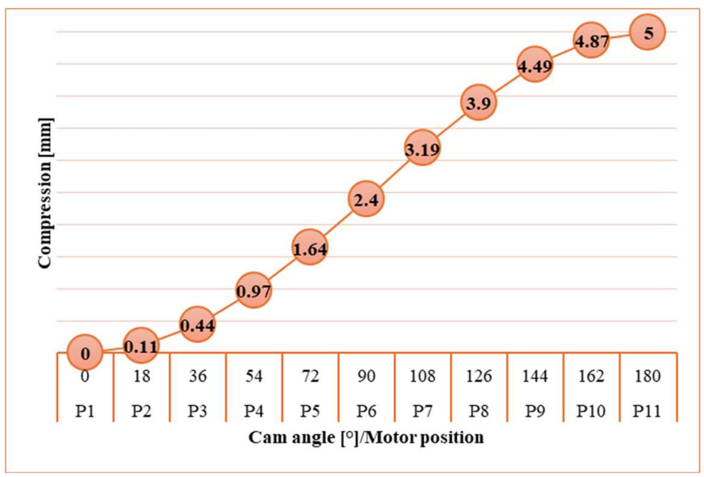


Fig. 12. Lumbar spine model compression in function of motor position.

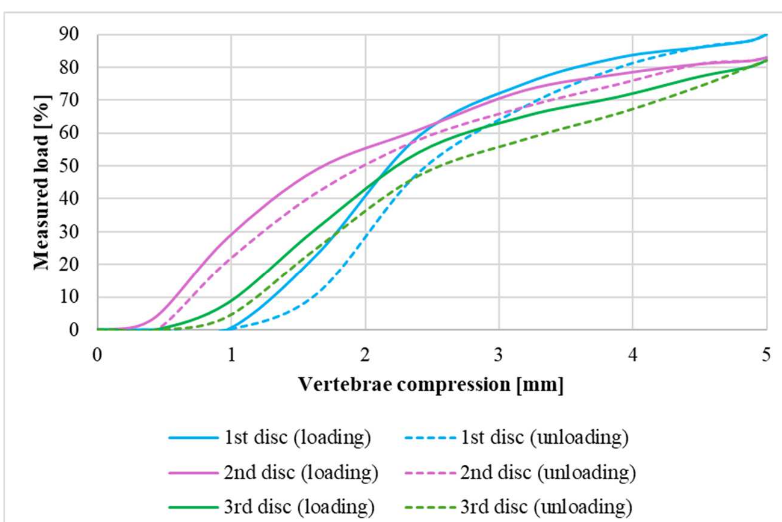


Fig. 13. Experimental results obtained for three intervertebral discs at loading and unloading in 11 points.

In the second experiment, the Arduino microcontroller code was modified so that the stepper motor would stop in 11 steps. Thus, the eccentric cam would rotate 18 degrees in 18 steps up to 180 degrees. The compression of the vertebrae at each cam rotation is determined by design, and Fig. 12 graphically shows the variation of the compression of the vertebrae as a function of the cam angle.

Fig.13 presents the experimental results obtained from the second experiment where 11 evaluation points were used.

4. CONCLUSIONS

The use of rapid prototyping technologies and 3D modeling software are essential aspects in terms of biomechanical experimentation of anatomical replicas, especially in the case of FDM technology which is efficient both in terms of costs and production time. Regarding the creation of the 3D digital model of the vertebrae based on data obtained using medical imaging techniques, this process would have been much more difficult if the 3D Slicer program had not been used.

When it comes to the study of lumbar vertebrae, the literature provides several FEM investigations, as well as multiple additive manufacturing technologies used in the manufacturing of prototypes and even functional prosthesis. However, experimental benches for researching the biomechanical behaviour of lumbar vertebrae, have yet to be widely developed.

The use of the eccentric cam in the experimental stand mechanism allowed for the controlled and variable simulation of the loads that occur on the vertebrae and intervertebral discs.

Following the simulations performed on the experimental stand, where the loads occurring at each intervertebral disc were individually measured and determined in percentage, for the 3 positions of the motor, the results obtained can provide an overview of the biomechanical behavior of the lumbar spine.

Upon loading, the first intervertebral disc, the measured load value was 0%, 65% and 91% in positions P1,P2 respectively P3, where the discs were compressed by 0mm, 2.4 mm and 5 mm. The second disc, compressed by 2.4 mm in P2 and by 5 mm in P3, measured a load value of 56% respectively 82%. Similarly, the third disc measured a load value of 33% in P2 and 75% in P3, with equivalent levels of compression under load.

When unloading, in the first position, P3, the lumbar spine is compressed by 5 mm, in P2 by 2.4 mm, and is completely decompressed in P1. The recorded values of the load were: 91%, 60% and 0%; for the first disc; 82%, 52% and 0%; for the second disc and 75%, 30% and 0%; for the third disc.

By increasing the motor stops to 11 steps, consequently, the rotation of the eccentric cam to 18 steps of 18 degrees up until 180 degrees, we can observe the variation of the compression of the vertebrae as a function of the cam angle, unique to the design at hand.

One of the key observations is the presence of a difference between the loading and unloading curves for all three intervertebral discs. This difference can be explained by the behavior of the silicone material from which the intervertebral discs are made. After compression, upon unloading, the discs do not instantly return to their original shape.

It was also observed that the load is not distributed evenly along the simulated spine model. The load decreases from one vertebra to the next, indicating an uneven transmission of the simulated load.

This variation suggests that the structure of the discs and vertebrae, as well as the mechanical structure of the experimental stand, influence the distribution of load along the spine. This aspect may also exist in the physiological reality where vertebral discs and vertebrae respond differently to applied loads due to variations in the mechanical properties of the tissues.

The results obtained do not fully correspond to the load applied to the vertebra. This discrepancy is due to the pressure sensors used, which do not cover the entire surface of the intervertebral discs.

Thus, the measurements may only partially reflect the actual load distribution, influencing the accuracy of the collected data. To optimize the results obtained, it is recommended to use larger and more precise pressure sensors. Future studies aim to use other technologies and materials to create the anatomical prototype, as well as to improve the electronic subsystem in order to obtain results even closer to the real biomechanical model.

5. REFERENCES

[1] Pereira, T, Kennedy, J.V., Potgieter, J., *A comparison of traditional manufacturing vs additive manufacturing, the best method for the job*, Procedia Manufacturing, pp. 11-18, 30, 2019.

[2] Amaya-Rivas, J.L., Perero, B.S., Helguero, C.G., Hurel, J.L., Peralta, J.M., Flores, F.A., Alvarado, J.D., *Future trends of additive manufacturing in medical applications: An overview*. Heliyon, 2024.

[3] Wong, K.V., Hernandez, A., *A review of additive manufacturing*, International scholarly research notices, 1, 2012, 208760.

[4] Gibson, I., Rosen, D.W., Stucker, B., *Additive Manufacturing Technologies Rapid Prototyping to Direct Digital Manufacturing*, Springer, 2010.

[5] Peron, M., Saporiti, N., Shoeibi, M., Holmström, J., Salmi, M., *Additive manufacturing in the medical sector: from an empirical investigation of challenges and opportunities toward the design of an ecosystem model*, International Journal of Operations & Production Management, pp. 387-415, 45, 2, 2025.

[6] Ahmad, M., Javaid, M., Haleem A., *A study on fused deposition modeling (FDM) and laser-based additive manufacturing (LBAM) in the medical field*, Intelligent Pharmacy, pp. 381-391, 2, 3, 2024.

[7] Putra, N.E., Zhou, J., Zadpoor, A.A., *Sustainable Sources of Raw Materials for Additive Manufacturing of Bone-Substituting Biomaterials*, Advanced Healthcare Materials, 13, 1, 2024, 2301837.

[8] Berce, P., Bâlc, N., Caizar, C., Pacurar, R., Radu, A.S., Bratean, S., Fodorean, I., *Manufacturing technologies by adding material and their applications*, Romanian Academy Publisher, Bucharest, 2014.

[9] Berce, P., Bâlc, N., Ancău, M., Cosma, S., Jidav, H., Caizar, C., Chezan, H., *Fabricare*a *Rapida a Prototipurilor*, Editura Tehnică, Bucuresti, 2000.

[10] Braileanu, P.I., Simion, I., Bou-Said, B., Prisecaru, D.A., Crisan N., *Custom hip stem additive prototyping using smart materials*. Mater. Plast, pp. 152-158, 57, 2, 2020.

[11] Pitzen, T., Geisler, F., Matthis, D., Müller-Storz, H., Barbier, D., Steudel, W.I., *A. Feldges, A finite element model for predicting the biomechanical behaviour of the human lumbar spine,* Control Engineering Practice, pp. 83-90, 1, 1, 2002.

[12] Bozyiğit, B., Oymak, M.A., Bahçe, E., Uzunyol, Ö. F., *Finite element analysis of lattice designed lumbar interbody cage based on the additive manufacturing*, Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine, pp. 991-1000, 23, 8, 2023.

[13] Whatley, B.R., Kuo, J., Shuai, C., Damon, B.J., Wen, X, *Fabrication of a biomimetic elastic intervertebral disk scaffold using additive manufacturing*, Biofabrication, 3, 1, 2011, 015004.

[14] Wandra, R. *3D Printing of Lumbar Spine Cages Manufactured through: Finite Element Analysis and Experimental Validation*. Materials Today: Proceedings, pp. 585–592, 50, 2022.

[15] Chin, B.Z., Ji, T., Tang, X., Yang, R., Guo, W., *Three-Level Lumbar En Bloc Spondylectomy with Three-Dimensional−Printed Vertebrae Reconstruction for Recurrent Giant Cell Tumor*. World Neurosurgery, pp. 531-537, 129, 2019, e1.

[16] Gao, B., Zhao, H., Peng, L., Sun, Z., *A review of research progress in selective laser melting (SLM)*, Micromachines, pp. 57, 14, 1, 2022.

[17] Awad, A., Xu, X., Ong, J.J., Goyanes, A., Basit, A.W., *Vat Photopolymerisation additive manufacturing for pharmaceutical applications. In Nano-and Microfabrication Techniques in Drug Delivery: Recent Developments and Future Prospects*, pp. 99-124, 2023, Cham: Springer International Publishing.

[18] Prakash, Prabhu, L.V., Saralaya, V.V., Pai, M.M., Ranade, A.V., Singh, G., Madhyastha,

S., *Vertebral body integrity: a review of various anatomical factors involved in the lumbar region*, Osteoporosis international, pp. 891-903, 18, 2007.

Sistem mecatronic pentru simularea comportamentului biomecanic al vertebrelor lombare

Rezumat. Articolul prezintă un mod de utilizare a tehnologiilor de prototipare rapidă în construcția și validarea unui sistem mecatronic pentru simularea încărcării și descărcării în diferite condiții între vertebrele lombare, cu scopul principal de a evalua comportamentul lor biomecanic. Modelul tridimensional al vertebrelor lombare și discurilor intervertebrale a fost obținut prin utilizarea unor programe specifice care permit generarea precisă a structurilor anatomice digitale, bazate pe tehnici de imagistică medicală. Modelele fizice ale vertebrelor L1, L2, L3, si L4 au fost construite din acid polilactic (PLA), utilizând tehnologia de imprimare 3D – FDM, iar cele trei discuri intervertebrale, fabricate din material siliconic, au fost obținute prin metode formative. A fost proiectat și realizat un sistem mecatronic pentru simularea comportamentului biomecanic al vertebrelor. Au fost realizate o serie de experimente privind încărcarea și descărcarea vertebrelor în raport cu cele trei poziții stationare ale motorului şi au fost obținute rezultate pentru cele trei discuri intervertebrale la încărcare și descărcare în 11 puncte. Rezultatele obținute pe standul experimental pot oferi o idee generală despre cum se comport din punct de vedere biomecanic coloana lombară.

Cuvinte cheie: *fabricaţie aditivă, extrudare termoplastică, biomedical, matrițe din silicon, sistem mecatronic, comportament biomecanic, vertebre lombare, discuri intervetebrale.*

Daniel BESNEA, PhD, Associate Professor, National University of Science and Technology POLITEHNICA Bucharest, Department of Mechatronics and Precision Mechanics, d_bes@yahoo.com, Splaiul Independentei 313, Bucharest, Romania.

Edgar MORARU, PhD**,** Lecturer, National University of Science and Technology POLITEHNICA Bucharest, Department of Mechatronics and Precision Mechanics, edgar.moraru@upb.ro, Splaiul Independentei 313, Bucharest, Romania.

Victor CONSTANTIN, PhD**,** Associate Professor, National University of Science and Technology POLITEHNICA Bucharest, Department of Mechatronics and Precision Mechanics, victor.constantin@upb.ro, Splaiul Independentei 313, Bucharest, Romania.

Iolanda-Constanta PANAIT, Eng., National University of Science and Technology POLITEHNICA Bucharest, Industrial Process Equipment Department, iolanda_pan@yahoo.com, Splaiul Independentei 313, Bucharest, Romania.

Vlad-Andrei STĂNESCU, PhD student, Assistant, National University of Science and Technology POLITEHNICA Bucharest, Department of Mechatronics and Precision Mechanics, vlad.stanescu1507@upb.ro, Splaiul Independentei 313, Bucharest, Romania.

Valentin NĂSTASE, Eng., National University of Science and Technology POLITEHNICA Bucharest, Department of Mechatronics and Precision Mechanics, nastase.eduard24@gmail.com, Splaiul Independentei 313, Bucharest, Romania.

Cosmina CHIUJDEA, PhD student, Assistant, National University of Science and Technology POLITEHNICA Bucharest, Department of Machine Parts and Tribology, cosmina.chiujdea@upb.ro, Splaiul Independentei 313, Bucharest, Romania.