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Determining the Force Required to Remove a Screw from a Human Vertebra

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The aim of this pilot study was to validate the methodology for mechanical testing of the load-bearing capacity of pedicle screws in real and additively manufactured vertebrae. A special clamping assembly and experimental procedure were designed and constructed to allow reproducible measurement of screw pullout force. Testing was performed on freshly thawed porcine vertebrae and their 3D printed equivalents created from segmentation of CT data. We measured the maximum screw pullout force and the strength of the vertebra material. The results show significant differences between real bone tissue and printed samples, with the printed models showing significantly higher strength. The study verified the functionality of the proposed methodology and provided the basis for the future development of 3D printed vertebrae with mechanical properties corresponding to human bone.

Keywords: Vertebra, Tensile test, Screw, Mechanical properties, 3D printing, Spinal stabilization

1 Introduction

Whiplash injuries include Spinal Cord Injuries are referred to as Spinal Injuries. They are usually part of polytraumas, so-called combined injuries. These injuries are very often associated with head injuries (up to 74 %) and chest injuries (up to 62 %). About 5 % of all injuries are spinal injuries. In spinal injuries, 15 to 40 % of cases are also associated with spinal cord injuries. It is reported that 42 % of injuries are in the cervical spine, 30 % of injuries are in the thoracic region, and 28 % are in the lumbar region. Spinal injuries are characterized by injuries to bones, joints, ligaments, or intervertebral discs.

Cervical spine injuries include:

- Vertebral body fracture;
- Pedicle fractures;
- Vertebral arch fractures;
- Lateral and spinous process fractures;
- Articular process fractures;
- Traumatic disc herniation;
- Spinal ligament injuries with or without vertebral dislocation;
- Spinal cord injuries without evidence of bony injury (SCIWORA) [1].

According to Hrabálek (2011), the most common causes of spinal injuries are:

- Traffic accidents;
- Work-related injuries caused by, for example, falls from a height, landslides, rock falls;
- Sports injuries, which occur especially when jumping into unknown water, water skiing, free climbing, hang gliding, horse riding, mountain biking, downhill skiing, road racing, etc.;
- Falls;
- Violent crimes, including the so-called battered child syndrome [2].

Spinal injuries are further divided into:

- Direct;
- Indirect.

Direct injuries (up to 10 % of cases) involve direct impacts to the spine. These injuries most often occur during:

- Pedestrian-vehicle collisions;

- Impacts on the back;
- Assault, which mainly includes kicks by the attacker in the victim's back, blows to the victim's body with sticks, collapses, gunshot and stab wounds.

Indirect spinal injuries occur most frequently (up to 90 % of cases). Although the injury was caused in another part of the body, the load was transferred to the spine during hyperflexion, hypertension, or when the load was transferred in the vertical axis of the spine. These include injuries caused by:

- Frontal collision in traffic accidents;
- Rear-end collisions with pedestrians, cyclists or people sitting in parked cars;
- Multiple rollovers at high speed;
- Impacts (racing cars, cycling, skiing).

Osteosynthesis is the surgical treatment of complicated, often dislocated fractures, when conservative procedures do not allow for optimal results in terms of the sides of the spinal curve, release of nerve structures, or safe and permanent bone fusion. It is a surgical method of connecting bone structures using a metal material. This material consists of plates, screws or rods, which are combined in various ways to achieve the best possible stability of the bone. The metal material fixes the spine in an optimal position only until the bone muscle is completely formed, which then permanently takes over the function of fixation. For some complicated fractures, this is a year, for less complicated fractures, 3 to 6 months. In some cases, the fixation material can be surgically removed. The current quality of surgical procedures is already at a high level. The issue of experimentally improving quality and finding different options for connecting the vertebrae of the spine has its limitations, as they cannot be tested on living people. The use of cadaveric models is also limited. One option is to use 3D printing of spinal vertebrae and test their connection in laboratory conditions. However, first it will be necessary to find suitable material and 3D printing parameters, as well as a suitable validated procedure for converting CT images of the spine to create validated vertebral models that will be used for 3D printing.

The methodology of this work was based on the results of a number of scientific papers in which the authors dealt with the issue of spinal injuries (Žuravský et al., 2024, Fanta et al., 2022, Ježdík et al., 2021, Lopot et al., 2019, Bittner et al., 2018, Vondrášek et al. 2018).

2 Measurement methodology

Initially, a 3D model was created and printed. The conversion of CT images into 3D models is a process that includes several steps, including data acquisition, processing, and subsequent creation of a 3D model. This process can be summarized into several areas. The first step was to obtain detailed images using computed tomography (CT). The scanner takes a series of X-ray images from different angles and combines them, thereby creating a detailed image of the internal structures of the body, in our case the vertebrae. After obtaining the CT images, it was necessary to perform segmentation, which means separating the area of interest, e.g. bones, organs, tumors, from the surrounding tissues. This step was performed using specialized software that allowed manual or automated labeling of various tissues. In this work, the licensed Radiant software was used (Fig. 1).

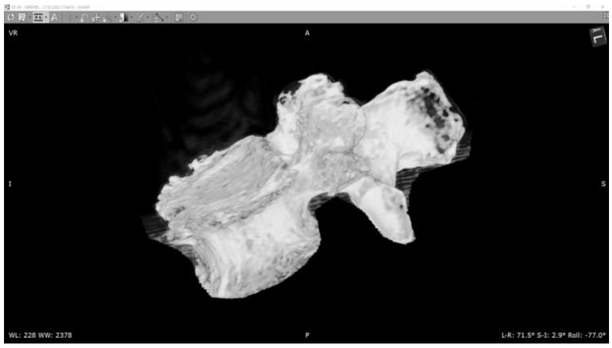


Fig. 1 *Radiant software – creation of the vertebra model*

The segmented images were then processed and converted into a set of layers. These layers were combined into a three-dimensional data structure, usually in DICOM (Digital Imaging and Communications in Medicine) format. A surface model was created from the three-dimensional data structure. This model was generated using surface reconstruction algorithms such as Marching Cubes or similar methods that transformed the segmented layers into a polygonal mesh.

The resulting 3D model often required further modification and optimization. This included surface smoothing, artifact removal, and possibly reducing the number of polygons to simplify the model without losing detail.

The final 3D model was exported to a format that was compatible with 3D printers or other devices for further processing. Common formats include STL, OBJ, or PLY.

In the final stage, the 3D model can be used for 3D printing, where the model is physically manufactured layer by layer, or for digital visualization, which can be useful for medical planning, teaching, or research.

This process made it possible to obtain accurate three-dimensional models of anatomical structures, human vertebrae, which were further used to simulate real bone structures and, after printing, for mechanical testing.

Screws, which are commonly used in PLIF (Posterior Lumbar Interbody Fusion) or TLIF (Transforaminal Lumbar Interbody Fusion) type operations, were drilled into the 3D-printed vertebrae. An example of an X-ray image with screws is shown in Fig. 4. For the purpose of extracting the screw in the vertical axis, a special fixture was constructed to ensure that the vertebrae were held in the desired direction. Real or printed vertebrae were then clamped into the fixture. The fixture allowed for easy insertion of individual vertebrae. Thanks to the interchangeable support pins, it was possible to insert samples of different sizes, and it was always ensured that the tensile test (screw extraction) took place without significant deviation from the vertical axis - checked using a spirit level. Fig. 5 shows a model of a vertebra with a drilled screw in a fixture placed in a tensile testing machine.

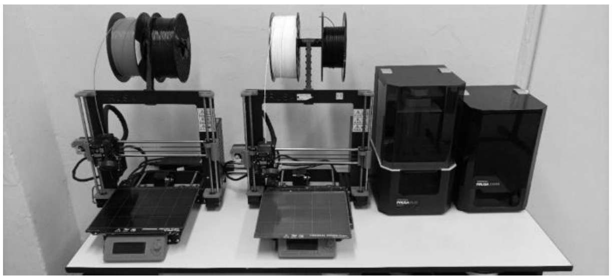
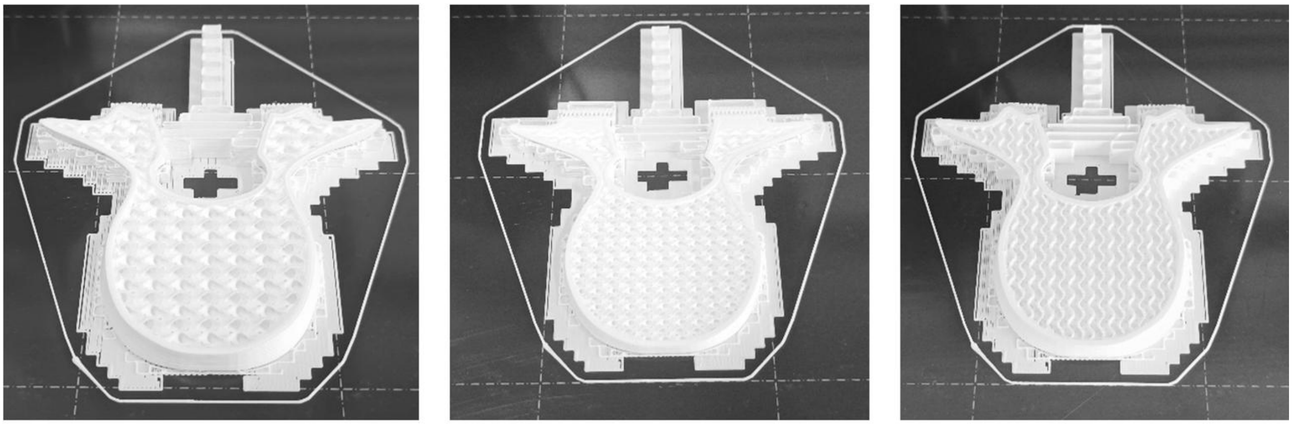


***Fig. 2** Printers used for printing 3D vertebra models (from left 2x Original Prusa i3 MK3S+, Original Prusa SL1S SPEED, Washing and curing station (CW1S))*



a – Density 30 %   b – Density 25 %   c – Density 20 %

***Fig. 3** Examples of vertebrae models with different filling densities [author]*

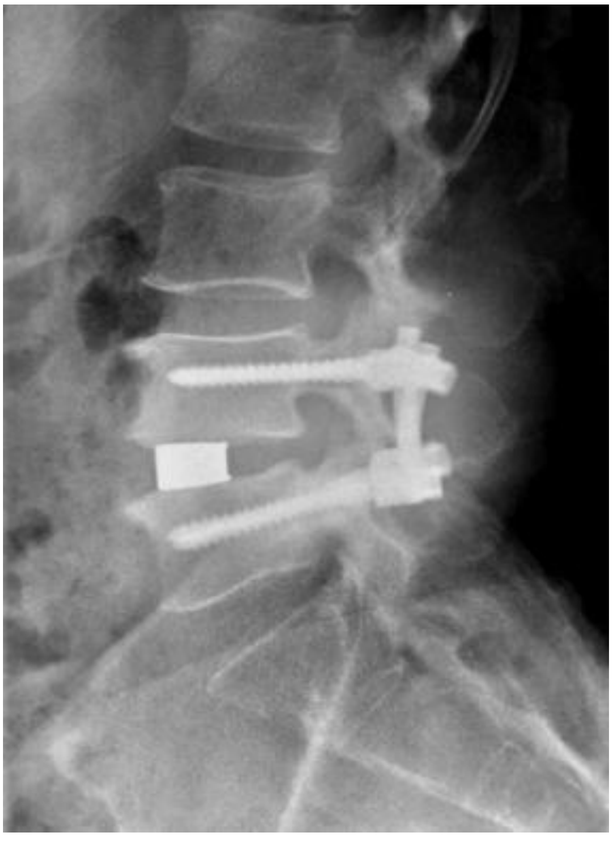


***Fig. 4** Lateral X-ray of the lumbar spine with stabilization of the L4/5 segment using the TLIF technique*

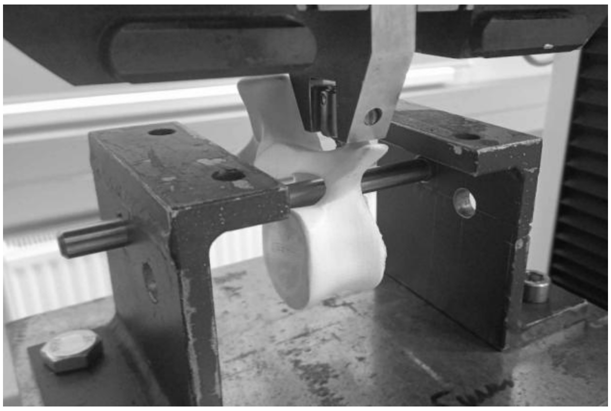


***Fig. 5** 3D printed vertebra model with a screw in the jig of the tensile testing machine*

A titanium pedicle screw was used for testing.

- Diameter 3.5 mm;
- Length 35 mm;
- Full thread.

Mechanical testing of the vertebrae was performed experimentally on a universal testing machine Hegewald & Peschke, Inspekt 100 kN (Fig. 6). The testing machine is capable of developing a maximum tensile and compressive force of 100 kN.

Measurement parameters:

- Loading speed: 5 mm.min^{-1};

- Direction: tension in the axis of the screw;
- Failure criterion: reaching the maximum force (F_{max}) and subsequent loss of load capacity.

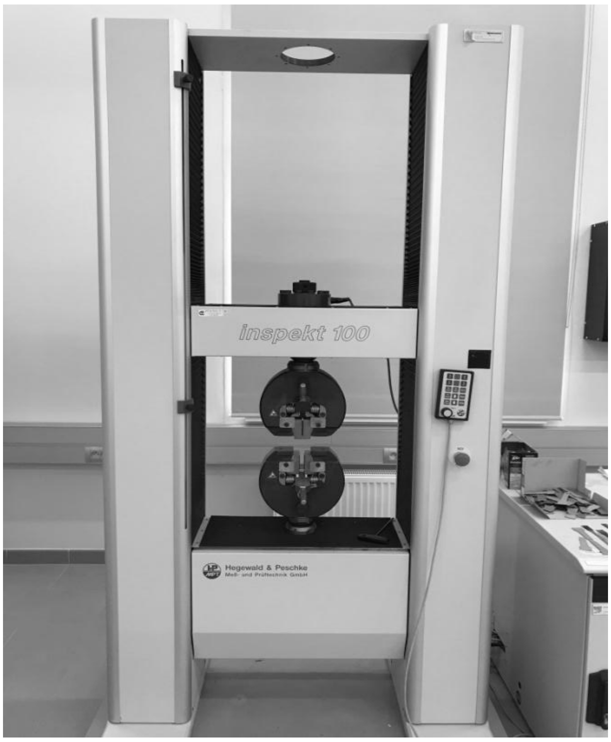


Fig. 6 *Hegewald and Peschke tensile testing machine*

The measured values were:

- Maximum screw load-bearing force – F_{max} [N];
- Vertebral strength limit – Rm [MPa];
- Percentage agreement of screw load-bearing capacity when it is pulled out in identical vertebrae [%].

The samples were labeled in a format indicating whether they were real or printed vertebrae. For printed vertebrae, the parameters of the print were also listed.

- PR – real domestic pig vertebra;
- DR – real wild pig vertebra;
- PT – printed domestic pig vertebra;
- DT – printed wild boar vertebra.

Example of marking is PT1_PR1_SLA_30_8_0.2_1.6. PT1_PR1 means the printed vertebra corresponds in shape to the vertebra from a domestic pig with the designation 1 (e.g. vertebra Th5). SLA is the type of printing material. 30 means 30% print fill. 8 means 8 layers have been done. 0.2 is the gap between the individual layers [mm]. 1.6 is the wall thickness [mm].

Variants of samples used for mechanical testing are clearly shown in Table 1.

Tab. 1 *Variants of measured samples – vertebrae*

Designation of the sample	Description
PR1	the real vertebra of the domestic pig
PR2	the real vertebra of the domestic pig
PR3	the real vertebra of the domestic pig
DR1	real vertebra of a wild boar
DR2	real vertebra of a wild boar
DR3	real vertebra of a wild boar
PT1-PR1_SLA_20_8_0.2_1.6	printed vertebra of a domestic pig – filling 20 %
PT2-PR1_SLA_25_8_0.2_1.6	printed vertebra of a domestic pig – filling 25 %
PT3-PR1_SLA_30_8_0.2_1.6	printed vertebra of a domestic pig – filling 30 %
PT4-PR1_SLA_35_8_0.2_1.6	printed vertebra of a domestic pig – filling 35 %
PT5-PR1_SLA_40_8_0.2_1.6	printed vertebra of a domestic pig – filling 40 %
DT1-PR1_SLA_20_8_0.2_1.6	printed vertebra of a wild boar – filling 20 %
DT2-PR1_SLA_25_8_0.2_1.6	printed vertebra of a wild boar – filling 25 %
DT3-PR1_SLA_30_8_0.2_1.6	printed vertebra of a wild boar – filling 30 %
DT4-PR1_SLA_35_8_0.2_1.6	printed vertebra of a wild boar – filling 35 %
DT5-PR1_SLA_40_8_0.2_1.6	printed vertebra of a wild boar – filling 40 %

3 Measurement results

After the measurement, the values of the screw pullout force F_{max} [N] and the strength limit of the vertebra material *Rm* were determined. Based on the obtained values, the suitability of the proposed clamping device for mounting vertebrae in the testing machine was verified. The approximation of the values of the measured quantities on real vertebrae of domestic and wild pigs, which were not thermally or chemically treated before the screws were drilled, was also determined. The results of the measurements also verified the proposed measurement methodology for the possibility of performing further measurements.

Tab. 2 *Measured results – tensile test*

Sample marking	F_{max} [N]	*Rm* [MPa]
PR1	2 100	42
PR2	2 972	59
PR3	2 669	53
DR1	1 644	33
DR2	1 300	26
PT1-PR1_SLA_20_8_0.2_1.6	1 989	125
PT2-PR1_SLA_25_8_0.2_1.6	1 957	123
PT3-PR1_SLA_30_8_0.2_1.6	2 334	147
PT4-PR1_SLA_35_8_0.2_1.6	2 878	181
PT5-PR1_SLA_40_8_0.2_1.6	3 042	191
DT1-DR1_SLA_20_8_0.2_1.6	1 088	68
DT2-DR1_SLA_25_8_0.2_1.6	1 391	87
DT3-DR1_SLA_30_8_0.2_1.6	1 658	104
DT4-DR1_SLA_35_8_0.2_1.6	1 976	124
DT5-DR1_SLA_40_8_0.2_1.6	1 923	121

Tab. 3 *Matching of measured values – domestic pig – example of processing results*

Sample marking	F_{max} [N]	*Rm* [MPa]	Difference F_{max} [%]
PR1	2100	42	5.3
PT1-PR1	1989	125	
PR2	2972	59	18.7
PT2-PR2	3530	70	
PR3	2669	53	7.8
PT4-PR1	2878	181	

The results were taken from the original measurement and adjusted according to the new terminology.

- Real samples: 1 300 to 2 972 N, strength 26 to 59 MPa.
- Printed samples: 1 088 to 3 042 N, strength 68 to 191 MPa.
- Higher filling density of the printed sample → higher strength → higher F_{max}.

The printed samples showed up to three times the strength compared to real vertebrae.

Fig. 4 to 6 show selected graphical examples of measured results from the tensile test.

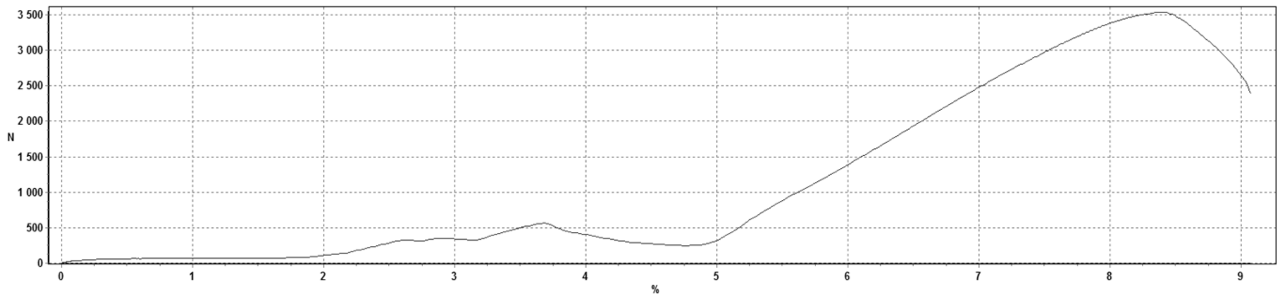


Fig. 4 *Tensile test results graph – sample PT2-PR2*

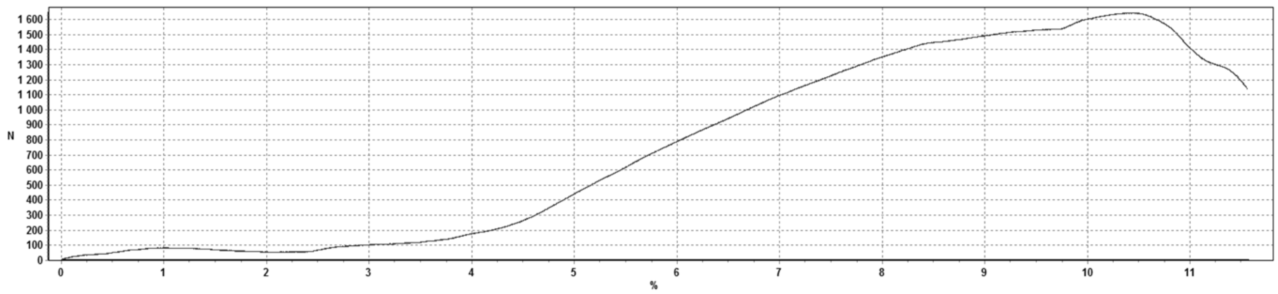


Fig. 5 *Tensile test results graph – sample DR1*

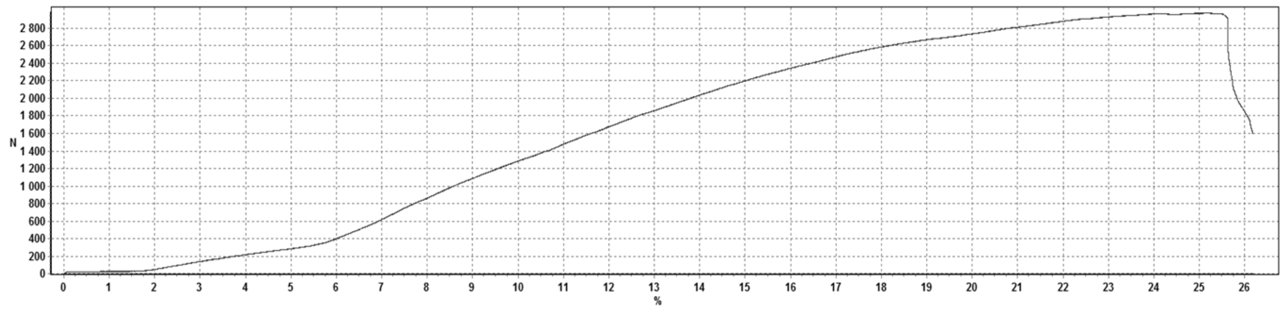


Fig. 6 *Tensile test results graph – sample PR2*

4 Conclusion

This pilot study verified the functionality of the proposed methodology for measuring the tensile load-bearing capacity of pedicle screws in real and 3D printed vertebrae. The newly designed fixture and the used measuring system met the expected requirements for stability, repeatability and measurement accuracy, which allows their further use in the development of mechanically realistic models of vertebrae for laboratory testing.

The results confirmed the expected trend, where SLA printed samples show significantly higher strength and higher screw pullout forces compared to real bone tissue. This difference is mainly due to the isotropic and homogeneous structure of the SLA material without trabecular architecture, higher mechanical parameters of the resin itself and also different properties of the biological material, in which the freezing and thawing process may also play a role. Therefore, in their current form, printed vertebrae represent rather an "overestimated" bone model that does not reflect the natural porosity and heterogeneity of human bone tissue.

The measured tensile forces in porcine vertebrae correspond to the upper limit of the values reported in the literature for cortical or mixed cortical-cancellous bone and are generally higher than those commonly found in humans. This phenomenon is consistent with biomechanical studies that describe porcine spine as a material with higher stiffness, density and bone-volume-fraction (BV/TV) than human bone. Busscher et al. demonstrated that porcine spine exhibits higher stiffness than human segments while maintaining similar movement patterns [9]. Wilke et al. reported in their work clear biomechanical differences between porcine and human spines and confirmed that the porcine model is particularly suitable for validation experiments [10]. Lee et al. also found that undecalcified porcine bone exhibits the highest BV/TV (~23.8%) and is mechanically significantly stronger than osteoporotic human bone [11]. These results are further supported by a systematic review by Hedlund et al., which summarizes that the porcine lumbar spine is commonly used as a robust experimental model with higher stiffness than the human spine [12]. Together, these findings support the interpretation of this study as a validation step, rather than a direct biomechanical analogy to the human spine.

In the next phase of the research, a larger series of measurements will be performed, including a larger number of samples and a wider range of printing materials and parameters, in order to identify the combination that will most closely match the mechanical properties of human bone tissue. The goal is to minimize statistical uncertainty and develop a 3D printed vertebral model that will be a high-quality biomechanical equivalent that allows for reproducible laboratory experiments.

Successful validation of this methodology opens the way to research new approaches in the field of spinal stabilization and to optimize implants and surgical techniques. Ultimately, it may contribute to improving clinical outcomes and returning patients to a higher quality of life after spinal surgery.

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