Data Article

Dataset of angular and compressive responses of biomimetic artificial spinal discs fabricated using multi-material additive manufacturing

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\textbf{A B S T R A C T}

To explore the influence of different biomimetic designs and multi-material additive manufacturing on the performance of a multi-material artificial spinal disc (ASD) in terms of restoring natural mechanics, four biomimetic ASD designs together with a control design are first fabricated using a Stratasys Connex3 Objet500 inkjet-based, multi-material 3D printer and their mechanical responses are measured using in-vitro mechanical testing. The mechanical tests include an angular test and a compression test to measure the ASD’s behavior in the seven most frequent loading scenarios of a spine: flexion, extension, left/right lateral bending, left/right axial rotation, and compression. The angular test is performed using a custom six degrees of freedom, computer-controlled spine testing system together with an optoelectronic motion analysis system, while the compression test is performed using an Instron testing machine. The presented dataset includes 3D models of the five ASD designs, and raw data of the angular and compressive responses at different strain rates of the five ASD designs. This dataset is related to the article “Exploration of the influence of different biomimetic designs of 3D printed multi-material artificial spinal disc on the natural mechanics restoration” where the detailed designs and load

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The dataset helps to gain insights into the influence of different biomimetic design concepts on the mechanics of a multi-material ASD and serves as a reference for the future design of multi-material ASDs.

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### Specifications Table

| Subject | Material Science: Devices and implants |
|---------|----------------------------------------|
| Specific subject area | Artificial spinal disc, Multi-material additive manufacturing, Biomimetic design |
| Type of data | Comma-separated values (CSV) files, Text files, stl files |
| How data were acquired | - 3D modelling: Rhinoceros v6 - ASD fabrication: |
| | • Stratasys Connex3 Objet500 inkjet-based, multi-material 3D printer |
| | - Angular test: |
| | • A custom six degrees of freedom, computer-controlled spine testing system with a six-axis load cell [MC3A, AMTI, U.S.A.] [2] |
| | • An optoelectronic motion analysis system (Optotrac Certus, NorthernDigital, Canada) |
| | - Compression test: |
| | • Instron ElectroPuls E3000 testing machine with a Dynacell loadcell of 3 kN capacity |
| Data format | Raw |
| Parameters for data collection | In the angular test, the specimens are loaded at a rate of 1°/s sequentially in six loading scenarios: extension, flexion, left lateral bending, right lateral bending, right axial rotation, and left axial rotation. A two-second relaxation time is used between subsequent loading scenarios. In the compression test, the specimens are loaded sequentially at a strain rate of 0.001, 0.01, and 0.02 s⁻¹ with a ten-minute relaxation time between subsequent tests. |
| Description of data collection | For angular tests, the moment-angle response of each specimen is recorded. The reaction moment is measured by the six-axis load cell, while the rotation angle is measured by the optoelectronic motion analysis system that records the movement of the top and bottom test head. For compression tests, the force-displacement response of each specimen is recorded, while both the reaction force and the displacement are recorded by the Instron testing machine. |
| Data source location | Angular test: Musculoskeletal Biomechanics, ARTORG Center for Biomedical Engineering Research, University of Bern, Bern, Switzerland |
| | Compression test: Engineering Design and Computing Laboratory, Dept. of Mechanical and Process Engineering, ETH Zürich, Zürich, Switzerland |
| Data accessibility | Yu, Zhiyang; Voumard, Benjamin; Shea, Kristina; Stankovic, Tino (2021), “Dataset of angular and compressive responses of biomimetic artificial spinal discs fabricated using multi-material additive manufacturing”, Mendeley Data, V3, doi: 10.17632/64smxzsbkk.3 https://data.mendeley.com/datasets/64smxzsbkk/3 |
| Related research article | Z. Yu, B. Voumard, K. Shea, T. Stanković, Exploration of the influence of different biomimetic designs of 3D printed multi-material artificial spinal disc on the natural mechanics restoration, Mater. Des. (2021) 110046. https://doi.org/10.1016/j.matdes.2021.110046 |
Value of the Data

- This dataset provides 3D models of five artificial spinal disc (ASD) designs and their rotational and compressive responses measured through in-vitro mechanical testing. This dataset quantifies the influence of multi-material ASD design on the ASD’s performance in terms of natural mechanics restoration. Additionally, this dataset shows the potential provided by multi-material additive manufacturing and biomimicry to tackle the challenge of reproducing the complex behaviors of a natural disc in ASD design.
- Researchers in the field of ASD design and validation will benefit from this dataset through gaining a better understanding of the procedure to perform in-vitro mechanical testing of an ASD, the test data format, and the data analysis procedure.
- This dataset provides researchers with new insights into ASD design by including components that either mimic structures found in a natural disc or base on mechanical metamaterials into an ASD.
- The methodology presented for performing in-vitro mechanical testing of an ASD and data analysis can support researchers in the related field to design and benchmark their own experimental set-ups, as well as to optimize the data collection and analysis procedure.
- The proposed ASD designs will serve as a benchmark or basis for the future design of monolithic, elastomeric, multi-material ASDs.

1. Data Description

The dataset is composed of two parts: the 3D models of the five ASD designs (stored in the folder stl_files), and the raw data of the compressive and angular responses of all the ASD specimens (stored in the folder raw_data). The five ASD designs are denoted as Discs 1-5 and are fabricated using the Stratasys Connex3 Objet500 inkjet-based, multi-material 3D printer. The details of the folder structures and file contents are given as follows.

1.1. Folder: stl_files

This folder provides 3D models of the five ASD designs in stl format that are stored in five subfolders: Disc_1, Disc_2, Disc_3, Disc_4, and Disc_5. In each subfolder, the stl files of the components belonging to the corresponding ASD design are included. For each stl file, the file name describes the index of the ASD design, the component name, and the material used for fabricating the component. For example, Disc_1_endplate_VeroWhite.stl is the stl file of the endplate of Disc 1 for being fabricated using VeroWhite. A total of fourteen stl files are included in this folder.

1.2. Folder: raw_data

This folder contains the raw data of the compressive and angular responses of the five ASD designs that each has five specimens. The raw data contains three datasets. The reaction forces and displacements of the specimens in the compression test recorded by the Instron machine are stored in the folder named Compression. The motions of the specimens in the angular test recorded by the optoelectronic motion analysis system are stored in the folder named Optotrac, while the reaction moments of the specimens in the angular test recorded by the six-axis load cell are stored in the folder named Spine_tester.
1.2.1. Subfolder: Compression

This folder contains the load-displacement responses of the specimens at three different strain rates: 0.001, 0.01, and 0.02 s⁻¹. A total of 75 comma-separated values (CSV) file are included in this folder. This folder contains three subfolders: rate_0.001, rate_0.01, and rate_0.02. Each subfolder further contains five subfolders named d1, d2, d3, d4, and d5 that correspond to Discs 1-5. Each dx (x = 1, 2, 3, 4, or 5) folder contains five CSV files. For each CSV file, the file name indicates the index of the specimen and the ASD design, as well as the strain rate used for loading. For example, Sample_4_d2_Compression_0.02.csv represents the compressive response of the 4th specimen of Disc 2 loaded at a strain rate of 0.02 s⁻¹.

Each CSV file contains three columns, i.e., time (unit: s), extension (unit: mm), and load (unit: N), which represent the test time, the displacement of the top test head, and the reaction force recorded by the load cell of the Instron machine, respectively.

1.2.2. Subfolder: Optotrak

This folder contains the coordinate transformation matrices from the local coordinate systems attached to the bottom test head (O₂X₂Y₂Z₂) and top test head of the spine testing system (O₃X₃Y₃Z₃) to the global coordinate system (O₁X₁Y₁Z₁) recorded during the angular test in six loading scenarios. Based on the definition that \( T_{mn} \) represents the coordinate transformation matrix from coordinate system \( n \) to coordinate system \( m \), the two coordinate transformation matrices are denoted as \( T_{12} \) and \( T_{13} \), respectively. The definitions of the two local coordinate systems \( O₂X₂Y₂Z₂ \) and \( O₃X₃Y₃Z₃ \) are given in Fig. 14 of the manuscript [1], while the definition of the global coordinate system \( O₁X₁Y₁Z₁ \) is given in Fig. 1. The six rotational loading scenarios are: flexion/extension (rotation around the \( X₁ \) axis), left/right lateral bending (rotation around the \( Y₁ \) axis), and left/right axial rotation (rotation around the \( Z₁ \) axis). In the following text, the terms lateral bending and axial rotation are referred to as LB and AR, respectively. The motions of each specimen’s positive and negative rotation around a certain global axis are recorded in the same test run and therefore stored in the same CSV file. A total of 75 CSV files are included in this folder.

This folder contains five subfolders named d1, d2, d3, d4, and d5 that correspond to the five ASD designs. Each dx (x = 1, 2, 3, 4, or 5) folder further contains five subfolders whose names indicate the index of the ASD design and the specimen. For example, folder name Sample_2_d3 represents the 2nd specimen of Disc 3. Each subfolder further contains three subfolders with the names Flex, Lat, Tor corresponding to the recorded motion in flexion/extension, left/right LB, and left/right AR, respectively. For each CSV file, the file name indicates the index of the specimen and the ASD design, and the loading scenario. For example, Sample_2_d3_Tor_Optotrak.csv contains the recorded motion of the 2nd specimen of Disc 3 in left/right AR.

Each CSV file contains 27 columns that describe the frame number (Column 1), together with elements in the coordinate transformation matrix \( T_{12} \) (Columns 2-14) and \( T_{13} \) (Columns 15-27). The column name specifies the corresponding coordinate transformation matrix and the element’s indices in the coordinate transformation matrix based on a zero-based numbering. For example, column name “bot_R10” represents the element in the 2nd row and 1st column of the coordinate transformation matrix \( T_{12} \).

1.2.3. Subfolder: Spine_tester

This folder contains the recorded reaction moments of the specimens in six rotational loading scenarios in the angular test. A total of 75 text files are included in this folder. The reaction moments at positive and negative rotation angles around a certain global axis are recorded in the same test run and thus stored in the same text file. The folder organization is the same as that of the folder Optotrak. For each text file, the file name indicates the index of the specimen and the ASD design, and the loading scenario. For example, Sample_3_d5_Lat.txt refers to the recorded motion of the 3rd specimen of Disc 5 in left/right LB. Each text file contains 11 columns: test time (Column 1), reaction moments about the global \( X₁, Y₁, \) and \( Z₁ \) axis (Columns 2-4), reaction forces on the global \( X₁, Y₁, \) and \( Z₁ \) axis (Columns 5-7), rotation angles around the global \( X₁, Y₁, \) and \( Z₁ \) axis (Columns 8-10), and system time (Column 11).
2. Experimental Design, Materials and Methods

This section gives the detailed procedure for collecting the raw data of the angular and compressive responses of each specimen. First, the five ASD designs together with their material compositions are given in Section 2.1. Next, the procedure for specimen preparation is stated in Section 2.2. The detailed approach to performing angular and compressive test is given in Section 2.3 and Section 2.4, respectively.

2.1. ASD design and materials

As illustrated in Fig. 2, the four biomimetic ASD designs (Discs 1-4) are based on design concepts of either mimicking the functional stiffness gradient (Disc 1) or the structures (Discs 2-4) found in an intervertebral disc (IVD). Disc 5 is a control design for exploring the effects of different types of biomimicry on an ASD’s anisotropic behavior. Three materials provided by the Stratasys Connex3 Objet500 inkjet-based, multi-material 3D printer are used for the ASD design and fabrication: VeroWhitePlus, Agilus, FLX9895. Among those three materials, FLX9895 (Young’s moduli $\approx 5$ MPa) and Agilus (Young’s moduli $\approx 0.5$ MPa) are flexible polymers, while VeroWhitePlus (Young’s moduli $\approx 2$ GPa) is a rigid polymer. All the discs share the same sandwich design that consists of top/bottom endplates and a deformable core in the middle. The endplates of all the discs are fabricated with the rigid material VeroWhitePlus for interfacing.

Fig. 1. Illustration of the global coordinate system.
with adjacent vertebrae. The central cylinder of Disc 1 is fabricated with Agilus and the outer ring is fabricated with FLX9895. Disc 2 and 3 mimic the criss-cross fiber network found in an IVD by including a fiber-like structure. The difference is that the fiber-like structure is realized in Disc 2 as an embedded structure and in Disc 3 as a stand-alone structure. The fiber-like structure fabricated with FLX9895 includes fibers that have a diameter of 1.6 mm and are oriented at an angle of ∼60° to the axis along the disc’s height direction. The matrix of Disc 2 and the central cylinder of Disc 3 are all fabricated with Agilus. Disc 4 comprises a central cylinder fabricated with Agilus and a stand-alone chainmail structure fabricated with FLX9895 that is used to mimic the behavior of an IVD’s collagen fiber network: having negligible bending resistance and being able to reorient and go through big shape-changing when subject to tensile loads. The diameter of the filaments in the chainmail structure is 1.6 mm. The core of Disc 5 is homogeneous and fabricated with Agilus.

2.2. Specimen preparation

With the material composition illustrated in Fig. 3, five specimens of each ASD design are fabricated using the Stratasys Connex3 Objet500 inkjet-based, multi-material 3D printer with the “matte” print option in a layer-by-layer manner along the z-axis of the printing coordinate system shown in Fig. 3. While printing each layer, the print head moves along the x-axis of the printing coordinate system. The support materials of the specimens are removed right after printing using a water jet and the specimens are stored in a dark place for around 24 hours before mechanical testing to minimize the influence of material aging on the specimens’ mechanical properties.

2.3. Angular test

This section presents the detailed approach for performing angular test to measure the angular responses of the specimens, which includes test set-up (Section 2.3.1), specimen mounting
Fig. 3. Illustration of the printing coordinate system and the printing orientation for fabricating the specimen. The height of the specimen is aligned with the z-axis of the printing coordinate system. While printing each layer, the print head moves along the x-axis of the printing coordinate system.

Fig. 4. Angular test set-up for measuring the specimen’s angular responses. (A) The test set-up for angular tests that includes a spine testing system and an optoelectronic motion analysis system. (B) Illustration of the ten markers (Markers 1-10) that are attached to the top and bottom test head of the spine testing system. The two local coordinate systems ($O_2X_2Y_2Z_2$ and $O_3X_3Y_3Z_3$) are defined by the positions of Markers 1-4 and Markers 5-10, respectively.

(Section 2.3.2), and angular test procedure (Section 2.2.3). In addition, the data analysis approach is given in Section 2.2.4.

2.3.1. Test set-up

The test set-up for measuring the angular responses of the specimens is shown in Fig. 4. A, which includes a spine testing system where the specimen is mounted for loading and an optoelectronic motion analysis system (Optotrak Certus, NorthernDigital, Canada) for recording the specimen’s motion. The computer-controlled spine testing system is able to apply six degrees of freedom (DOF) pure moments that are recorded by the six-axis load cell (MC3A, AMTI, U.S.A.). The details of the machine design of the spine testing system are introduced in [2]. The motion of the specimen is recorded by ten markers referred to as Markers 1-10 that are attached to the top and bottom test head of the spine testing system, as illustrated in Fig. 4. B: Markers 1-4 are attached to the bottom test head, while Markers 5-10 are attached
Fig. 5. Illustration of the mounting of the specimen for angular tests and the design of the aluminum plate for specimen mounting. (A) The specimen is mounted to the top/bottom test head using two aluminum plates on the top and bottom to simulate a perfect fixation at the bone-implant interface. (B) The counterweight added to balance the specimen's weight. (C) The aluminum plate for interfacing with the specimen (the side with a pocket, top view in the figure) and the test head (the other side, bottom view in the figure). The pocket has a matching contour to the specimen's shape to allow for an accurate specimen positioning relative to the aluminum plates. The blind hole and the slot are designed to ensure an accurate positioning of the aluminum plate relative to the test head. The cut-through hole is designed for fixing the plate to the test head. (D) The dimensions of the aluminum plate illustrated in the bottom view (unit: mm). The dimensions of the plate match those of the specimen.

2.3.2. Specimen mounting

After setting up the test facilities, the specimen is mounted to the spine testing system for performing angular tests. As illustrated in Fig. 5 A, each specimen is rigidly connected to the top and bottom test head of the spine testing system using two rigid aluminum plates (one at the top and one at the bottom) that are connected to the endplates of the specimen using a superglue (cyanoacrylate adhesive, UHU, Germany). To balance the specimen's weight, a
counterweight is added, as illustrated in Fig. 5B. After the weight compensation, all the reaction forces and moments measured by the spine testing system are set to zero. Such connection simulates a clinical scenario of perfect fixation at the bone-implant interface. As shown in Fig. 5C, the aluminium plate has one central cut-through hole for fixation with the test head, and one blind hole together with a slot alongside the cut-through hole for positioning the aluminium plate relative to the test head. Additionally, the side of the plate that interfaces with the specimen has a pocket with a matching contour to the specimen’s shape to allow for an accurate specimen positioning. The detailed dimensions of the aluminium plate are given in Fig. 5D. The plates are manufactured with aluminium to minimize the effect of the plates’ stiffness on the measured specimen’s rotational response.

2.3.3. Test procedure

After mounting the specimen to the spine testing system, the specimen is sequentially rotated around the \( X_1 \), \( Y_1 \), and \( Y_l \) axis in the global coordinate system \( O_1X_1Y_1Y_l \) defined in Fig. 1. The three consecutive tests performed simulate the following loading scenarios: flexion/extension (rotation around the global \( x \)-axis), left/right LB (rotation around the global \( y \)-axis), and left/right AR (rotation around the global \( z \)-axis). The starting point of each test is determined by rotating the specimen for \( \pm 3 \) degrees around the measured axis relative to the original position to search for the neutral position that has a zero reaction moment. It is to be noted that while measuring the specimen’s reaction moment around a certain axis, the specimen is allowed to move freely in the remaining two axes. For example, when the specimen’s angular response in flexion/extension is being measured, the rotation of the specimen along the global \( y \)- and \( z \)-axis is not constrained.

After determining the starting point, the specimen is loaded using a displacement control mode at a rate of \( 1^\circ/s \) (ramp-loading) and repeated for three cycles. The stopping criteria are set to when the maximum loading angle is reached or the maximum allowable moment of the spine testing system, i.e., 5 Nm is reached. The maximum loading angle is set to 14° for flexion/extension, 12° for left/ right LB, and 24° for left/right AR, which is determined to avoid material failure. The loading is paused for two seconds when the maximum rotation angle in each loading scenario is reached. During the loading, the reaction moment is recorded at a sampling frequency of 100 Hz by the load cell of the spine testing system. In addition, the positions of Markers 1-10 and the measured coordinate transformation matrices from the two local coordinate systems defined at the top and bottom test head (Fig. 4. B) to the global coordinate system (Fig. 1) are recorded with the same sampling frequency, i.e., 100 Hz. The raw data of the recorded reaction moment are stored in the folder Spine_tester, while the raw data of the recorded coordinate transformation matrices are stored in the folder Optottrak.

2.3.4. Data analysis

To get the reaction moment of the specimen, the moment recorded by the spine testing system is smoothed using a 3rd order Butterworth digital filter with a cutoff frequency of 0.02. Since the rotational motion of the bottom test head is not allowed, the rotational angle of the specimen is equal to that of the top test head. Therefore, to extract the rotational angle of the specimen, the Euler angles of the top test head are calculated from the measured coordinate transformation matrix from the local coordinate system attached to the top test head to the global coordinate system (i.e., \( T_{33} \)) based on matrix decomposition [3]. After obtaining the moment–angle response of the specimen in three cycles, the 1.5-2.5 cycle of the specimen’s response is extracted and used for calculating parameters such as neutral zone range and elastic zone stiffness.

2.4. Compression test and data analysis

This section first states the detailed procedure for performing the compression test in Section 2.4.1. Next, the approach to performing data analysis is presented in Section 2.4.2.
2.4.1. Test procedure
The compressive response of each specimen is measured using an Instron ElectroPuls E3000 testing machine with a Dynacell loadcell of 3 kN capacity. As shown in Fig. 6, the specimen is mounted to the bottom plate of the Instron machine using a double-sided tape to avoid relative sliding between the specimen and the bottom plate. After putting the specimen on the bottom plate, the measured force is zeroed to balance the specimen's weight. Next, the starting point of the test is determined by adjusting the position of the top plate to be around 2-3 mm above the specimen's top surface. The specimen is loaded using a displacement control model at a rate of 0.01, 0.1, 0.2 mm/s sequentially to obtain its compressive responses at different strain rates. Given that the specimen’s deformable core has a height of 10 mm, the three loading rates correspond to a strain rate of 0.001, 0.01, and 0.02 s\(^{-1}\), respectively. The reaction force and the displacement of the top plate are recorded by the Instron machine at a sampling rate of 10 Hz and stored in the Compression folder. The stopping criteria of the test is set to when a maximum compressive displacement of 1 mm or the maximum allowable measured force, i.e., 3 kN, is reached. Between two tests at different load rates, the specimen is rested for ten minutes to allow for stress relaxation.

2.4.2. Data analysis
For the data analysis, the starting point of the compression test is first calculated based on a force threshold of 0.01 N. Therefore, data point whose reaction force is below 0.01 N is considered to be collected before the top plate is in contact with the specimen’s top surface. For calculating the linear stiffness at a certain displacement \(x\), a linear regression is performed on eleven consecutive data points whose displacements lie near the displacement \(x\). For example, to calculate the linear stiffness at a displacement of 0.4 mm, the index of the data point whose displacement is close to 0.4 mm at a precision of 0.01 is first calculated. Next, five data points before and five after such data point are obtained. Those eleven data points are used for linear regression to calculate the specimen’s linear stiffness at displacement \(x\).
Ethics Statement

The authors have no competing financial interests or personal relationships that may have influenced the data reported in this work.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT Author Statement

Zhiyang Yu: Conceptualization, Software, Methodology, Validation, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Project administration; Benjamin Voumard: Resources, Software, Methodology, Writing – review & editing; Kristina Shea: Methodology, Resources, Writing – review & editing, Supervision; Tino Stanković: Methodology, Resources, Writing – review & editing, Supervision.

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