**Double-spiral: A bio-inspired pre-programmable compliant joint with multiple degrees of freedom**

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**Abstract**

Geometry and material are two key factors that determine the functionality of mechanical elements under a specific boundary condition. Optimum combinations of these factors fulfill desired mechanical behavior. By exploring biological systems, we find widespread spiral-shaped mechanical elements with various combinations of geometries and material properties functioning under different boundary conditions and load cases. Although these spirals work towards a wide range of goals, some of them are used as nature’s solution to compactify highly extensible prolonged structures. Characterizing the principles underlying the functionality of these structures, here we profited from the coiling-uncoiling behavior and easy adjustability of logarithmic spirals to design a pre-programmable compliant joint. Using the finite element method, we developed a simple model of the joint and investigated the influence of design variables on its geometry and mechanical behavior. Our results show that the design variables give us a great possibility to tune the response of the joint and reach a high level of passive control on its behavior. Using 3D printing and mechanical testing, we replicated the numerical simulations and illustrated the application of the joint in practice. The simplicity, pre-programmability, and predictable response of our double-spiral design suggest that it provides an efficient solution for a wide range of engineering applications, such as articulated robotic systems and modular metamaterials.

**Keywords:** Structural intelligence, passive control, high extensibility, biomimetics, finite element method, 3D printing.

1. **Introduction**

Theodore Andrea Cook referred to spirals as *“the curves of life”.*1 This is perhaps the best description for these ubiquitous patterns that appear as an enormous nebula in space or as the lophophore of tiny phoronids on earth. Spirals can also be found in dynamic phenomena, such as the motion of fish swarms and wave turbulence, as well as in static forms, such as seashells and animals’ horns. This specific curve has inspired mankind since the beginning, and this has made spirals even more omnipresent in our everyday life.1,2

Questions about the reasons behind the presence of spirals and their functions are as diverse as the forms of the existing spirals. Researchers from different fields have been trying to answer these questions and shed light on both the complexity of spiral patterns and their potential applications. Although Archimedes studied and formulated spiral curves for the first time in the third century BC,3 mathematicians are still trying to formulate a variety of spiral patterns in the 21st century AD.4 Biologists have been discovering spiral patterns in the natural world at different scales.5–7 Artists and architects have been using spirals as an inspiration source for thousands of years specially because of their aesthetic features.1,2,8 Nevertheless, as functional patterns, they give us advantages beyond their beauty. A trace used in data storage,9 optimization algorithm,10 wearable thermoelectric generator,11 supramolecular chemical springs,12 stretchable electronics,13 soft actuators,14,15 antennas,16 metamaterials,17 and planar springs18 are only a few examples of numerous engineering applications inspired by spirals.

The spiral mechanical joints and hinges that are currently used in engineering applications are designed for limited deformations.19–24 In contrary, many functional spirals in animal and plant structures experience high deformations through coiling and uncoiling. The intromittent organs of beetles,25 proboscis of Lepidoptera,26 rostra of weevils,27 tentacles of octopuses,28 chameleon tail,29 fern fronds,30,31 and millipede body32 are only a few examples of highly extensible biological spirals. Our aim here is to use spiral-inspired strategies to design and manufacture mechanical elements with high extensibility. Such bioinspired elements can be used as compliant joints for controlling the relative motion of mechanical components in a passive-automatic way. For this purpose, we develop geometrically distinct spiral-inspired models, referred to as ‘double-spirals’, and characterize their mechanical behavior under various practical loading scenarios. We show how the design variables can be used to control the coiling-uncoiling behavior of the models in a wide range, making them ideal templates for developing pre-programmable structural components. We use 3D printing and mechanical testing to validate our numerical simulations and illustrate the performance of our double-spiral joints in practice.

**2. Methods**

**2-1. Modeling and** **finite element analysis**

***Development of models***

A logarithmic spiral can be defined using the following equation in a polar coordinate system

, (1)

where  is the radius of the spiral at , and  is the polar slope. If , the spiral turns clockwise, and if , the spiral grows counterclockwise. In the case that , the spiral becomes a circle of radius .2

Using equation (1) and the programming software MATLAB (R2012a, MathWorks, Natick, MA), we plotted two spiral curves with the same polar slope but different initial radii (**Fig. 1a**). These two curves formed a spiral surface. By rotating the spiral surface about the origin of the coordinate system by 180 degrees, we regenerated the same surface (**Fig. 1b**). We then used a few straight lines to connect the ends and bases of the spirals and form a closed surface (**Fig. 1c**). We referred to this design as ‘double-spiral’.

The double-spiral was used as a template to develop the reference joint. For this purpose, we imported the plot to the finite element (FE) software package ABAQUS/Standard v. 6.14 (Simulia, Providence, RI). In Abaqus, we developed a two-dimensional (2D) joint model and simulated its behavior subjected to in-plane loading scenarios. We used four-node bilinear plane-stress quadrilateral elements with reduced integration (CPS4R) to mesh the models. These elements are general purpose and can result in accurate solutions, in reasonable computation time. Following a mesh sensitivity analysis, the size of the elements was set to be 0.1 mm.

We used a similar procedure to develop six new double-spiral joint models by decreasing and increasing one of the following design variables in our reference model in each step: the polar slope (), initial thickness (), and the angle of rotation () of the spirals. The design variables for the developed models are listed in **Table 1**. We selected the design variables to obtain models that were not too small, so that they could be 3D printed with a reasonable accuracy, and not too large, so that they could be manufactured within a reasonable time.

***Material properties, loadings, and boundary conditions***

We assigned material properties of thermoplastic polyurethane filament (Flexfill TPU 98A, Fillamentum addi(c)tive polymers, Czech Republic) to our double-spiral models. For this purpose, we defined a non-linear stress-strain relationship as that given in **Table 2** for each element of the models, and used a Poisson’s ratio and a material density of 0.3 and 1230 kg m-3, respectively.33

Using the Abaqus implicit solver, we simulated the quasi-static behavior of the developed models under different loading scenarios, which involved tension, sliding, compression, and rotation. In all loading scenarios, one side of the models was completely fixed, and a constant displacement was applied to the opposite side. We limited the displacements to avoid large strains in the elements of the FE models and focus on their elastic behavior. The following loading scenarios were simulated (**Fig. 2**):

* *Tension*. In this loading scenario, we pulled the free end of each model and extended it up to its total length.
* *Sliding*. Here we displaced the free end of each model in two opposite directions by subjecting it to an equal force. The force was set to extend the structure up to its total length.
* *Compression*. Here we placed the models between two rigid plates. We then displaced one plate towards the other one that was set to be fixed. The displacement was set to be 17 mm for all models which is about half of the initial distance between two plates.
* *Rotation*. We rotated the free end of the joints by π radian, bringing the two ends of the models together.

Considering that most deformations involved physical contacts, we used a self-contact formulation between the coils of the models. We also used a surface-to-surface contact formulations between rigid plates used in compression and the models to prevent their penetration into each other.34

**2-2. Prototyping and mechanical testing**

We used 3D printing to manufacture the reference joint and used that to validate our numerical simulations. The model was printed using a fused deposition modeling (FDM) 3D printer (Prusa i3 MK3S, Prusa Research, Praha, Czech Republic) and a semi-flexible polyurethane filament (Flexfill TPU 98A, Fillamentum addi(c)tive polymers, Czech Republic). This filament is characterized by its high tear resistance, tensile strength, and elasticity, compared to other widely used thermoplastics such as PLA.33 Fixtures were printed using a commercially available polylactic acid (PLA) filament (Prusa Research, Praha, Czech Republic). 3D printing settings are given in **Table 3**. We used a ZwickiLine uniaxial tensile testing machine (Zwick Roell, Ulm, Germany) equipped with a 500 N load cell (Xforce P load cell, Zwick Roell) to quantify the behavior of the 3D printed reference joint under tension. Four specimens were manufactured, and each tested for three times. The loading and boundary conditions were set to be as those used in the numerical simulation of tension. In addition to this, we also tested the 3D printed joint manually by subjecting it to the loading scenarios described earlier (i.e., tension, sliding, compression, and rotation).

For further validation, we developed and fabricated a sample double-spiral joint to test its performance in practice. The initial thickness, polar slope, and angle of rotation of this double-spiral were set to be 3 mm (), 0.1, and 3π radians, respectively. First, we employed the joint in an experiment to characterize its behavior in tension, compression, and sliding, and then, used the same joint in a separate experiment to quantify its rotational behavior.

**3. Results**

**3-1. Finite elements analysis**

***Mechanical behavior of the reference double-spiral joint***

We simulated the behavior of the reference double-spiral joint under five different loading scenarios (**Fig. 2**). Five force-displacement curves were obtained (**Fig. 3**). Some of them could be approximated by multiple lines, whereas the others looked more complicated. Despite the differences, the behavior of the double-spiral under all loading scenarios could be mainly categorized in three phases:

1. The first phase is the **initial clearance.** This resulted from the specific geometry of the joint, specifically the free space between the coils. This clearance resulted in a low-stiffness regime without a noticeable increase in the magnitude of the load. In this phase, there was no contact between the coils.
2. The second phase is **unrolling.** This is the largest deformation regime of the double-spiral joint, in which the relationship between the force and displacement is almost linear.
3. The third and last phase is **unfolding.** This phase comes after unrolling and can be affected or followed by material’s large tensile strain. Although it is a short phase, it increases the stiffness dramatically and makes the overall force-displacement curve nonlinear.

The deformation of the double-spiral joint subjected to tension and sliding resulted in J-shaped curves that included the three phases mentioned earlier (**Fig. 3a-c**), although the initial clearance (1-2 in **Fig. 3a-c**) was almost negligible compared to the other two phases. In contrast, the initial clearance phase comprised a larger portion of the force-displacement curve in compression and rotation (**Fig. 3d, e**). This is because the maximum displacement applied to the joint in these two loading scenarios was much smaller than the displacement applied in tension and sliding. Even though the response of the model to compression was nonlinear, its structural stiffness increased gently unlike tension and sliding (**Fig. 3d**). Multiple linear segments with successively increasing slopes formed the force-displacement curve. By increasing the contact between the coils in the reference joint at each step, the slope of the force-displacement curve increased slightly. In rotation on the other side, after the initial clearance phase, structural stiffness did not change, and we observed a linear behavior resulted from the unrolling of the base of the structure (**Fig. 3e**).

In sliding, displacements to the left and right directions resulted in different behaviors. First, there was an early peak in the force-displacement curve when sliding the model to the left direction (**Fig. 3b**). This peak appeared because of the unrolling of the bases of the joint, which are the thickest parts of the structure, in the beginning of the deformation in this direction. Second, the maximum displacement was about 20 percent higher in the left direction than that in the right direction. In other words, there was an inversion of anisotropy in the sliding of the double-spiral in two directions.

The deformation of the reference double-spiral under each loading scenario is presented in **Video S1**.

***Influence of the design variables on the mechanical behavior of the joint***

By changing the design variables of the reference double-spiral, we developed six other double-spiral models (**Table 1**). We used them to understand the influence of the design variables on the mechanical behavior of the double-spiral (**Fig. 4**). Surface area is the first parameter presented here for comparing the joints and their differences, as it represents the amount of material needed to manufacture these structures. Design variables with an almost equal influence on the surface area, had different influences on the behavior of the double-spiral. The polar slope mostly influenced the displacements of the model, whereas changing the initial thickness dramatically affected the force values. Changing the angle of rotation affected both force and displacement values almost equally. The results suggest that the response of the double-spiral to loadings can be broadly tuned by adjusting the three design variables that control the geometry of the spiral.

**3-2. Prototyping, mechanical testing, and application**

To verify the validity of our modeling method and simulation procedure, we manufactured and tested the reference double-spiral joint (**Fig. 5a, Video S2**). To measure the quality of the fit, we averaged the data from the experiments (n=12) and compared the force values corresponding to the defined deformation phases (i.e., initial clearance, unrolling, and unfolding) achieved from the experimental tests and finite element simulation. Although our numerical model slightly underestimated the force, the simulation resulted in a good agreement with the experimental data. Hence, the comparisons confirm the validity of the numerical study. For further validation, we also used the printed joint for replicating the simulated deformation patterns, the results of which are given in **Fig. 5b**, and **Video S3**.

To test the performance of the fabricated sample double-spiral joint in application, we conducted two experiments. In the first experiment, while one side of the joint was fixed, we applied an equal force to the other side of the joint subjecting that to tension, compression and sliding in two opposite directions (**Fig. 5c, Video S4**). The experiment demonstrated the anisotropic deformation of the double-spiral under equal forces. In the second test, we employed the fabricated double-spiral as a joint in a system to passively control the motion of its components and distinguish objects with different masses (**Fig. 5d**, **Video S5**). Two round objects with the same size rolled on a rigid part. The 3-gr object did not move the components and rolled directly, whereas the 30-gr object rotated the double-spiral joint and rolled through a different path. This is a simple, proof-of-concept example that illustrated the potential of the double-spiral for making an adaptive system.

**4. Discussion**

Spiral patterns are omnipresent in nature.1,2 Although they fulfill various functions, one of their key functions is the coiling of hyper-elongated deformable structures in the resting position. This property has been used, for example, in butterflies’ proboscis,26 octopuses’ tentacle,28 and millipedes’ body.32 Inspired by these examples, we developed a double-spiral structure that can be used as a highly extensible joint. We combined computer simulations, 3D printing and mechanical testing to characterize the behavior of our design.

Our joint can be categorized as a highly extensible dual-stiffness structure. It can be extended up to five times its original length under tension or sliding. The extension of the joint (especially in tension) includes two almost linear distinct deformation regimes: a long low-stiffness and a short high-stiffness regimes. In other words, the structure transforms from a flexible to a stiff state during its extension. This reversible non-linear behavior of the double-spiral comes from its geometry and can be tuned by changing its design variables. The variable stiffness structures, such as our double-spiral, are of particular interest in shape morphing applications, where low stiffness is necessary during shape change and high stiffness is needed for load bearing purposes when the shape change is completed.35–38

The double-spiral joint is an anisotropic system. This is true for the behavior of the system in tension, compression, and sliding. Unlike tension, deformations are small in compression and the joint exhibits high load bearing capacity. The sliding of the joint to the left and right occurs with an inversion of anisotropy. Although the structure highly extends subjected to sliding forces in both directions, it is stiffer in the beginning when is pulled to the left. This adjustable anisotropy could be a desired characteristic in specific engineering systems.39-41

The simple equation of the logarithmic spiral makes the design tunable by simply adjusting only a few design parameters. Numerical simulations conducted using a simple model of the double-spiral successfully predicted its mechanical behavior under different loading scenarios with good accuracy. Our results showed that we can reach a high level of passive control on the behavior of the double-spiral and broadly tune its deformation phases (i.e., initial clearance, unrolling, and unfolding) through the design variables (**Fig. 4**). The free space between the coils of the structure increases its initial clearance displacement. The higher number of coils leads to a higher unrolling displacement. Increasing the thickness of the spirals results in the higher force required to deform the structure but has no remarkable effect on the maximum displacements. The thickness of the spiral reduces from its base to end. While we can control the initial thickness of our double-spiral (thickness at the base) directly, two other design variables (polar slope and angle of rotation) affect the thickness at the end of the spiral. The unfolding force is mostly influenced by this thickness.

Besides the design variables which were extracted from the equation of the logarithmic spiral in a polar coordinate system (i.e., polar slope, initial thickness, and the angle of rotation), there could be other variables with considerable influence on the geometry of double-spiral joint and its mechanical behavior. As an example, here we investigated the influence of the connection between the two spirals within our double-spiral structure on its tensile behavior. Specifically, we developed a new model with four folds instead of two (**Fig. 6**). The result showed that although the initial clearance and unrolling phases remained almost constant, the unfolding force and displacement increased (by about 55% and 10%, respectively). A future study should test the effect of this and other potential geometric parameters on the behavior of the double-spiral. Future studies should also investigate the behavior of the double-spirals under other loading scenarios, such as torsion and lateral bending, as here we only focused on their in-plane behavior. This can further increase the range of applications in which the double-spirals can be utilized.

Manufacturing is a vital process that can remarkably affect the functionality of designed structures. 3D printing is one of the most common and effective manufacturing methods that enables us to fabricate high-resolution structures with extremely complex geometry and material composition, directly from 3D computer-aided-design models.42 From the wide range of available printers with different technologies, an easily accessible single-nozzle FDM 3D printer is a suitable tool for the fast and low-cost fabrication of our developed double-spiral joint using a single material. The fixed cross-sectional profile of the designed double-spiral joint simplifies and speeds up the manufacturing process, facilitates its integration in potential applications, reduces the costs of assembly, and eliminates the need for multiple materials. Hence, we anticipate wide-spread future applications of our compliant joint. Double-spiral joints could be used in articulated robots or modular metamaterials to passively control the relative motion of blocks and result in unconventional mechanical behavior of these systems. However, future studies are required to analyze the static and dynamic behavior of the double-spiral and optimize its geometry for each application.

**4. Conclusion**

In this article, we presented a pre-programmable compliant joint, called double-spiral, inspired by the coiling-uncoiling behavior of highly extensible natural spirals. We used numerical simulations, 3D printing, and mechanical experiments to investigate its mechanical behavior under different loading scenarios. The remarkable characteristics of this structure, such as the easily tunable design, multiple degrees of freedom, adjustable anisotropy, and high extensibility, suggest that the bioinspired structure has potential engineering applications. The passive-automatic control, which has achieved through the design strategies alone, make the double-spiral an ideal structure for robotic applications, for example to develop soft extensible robots or adjustable hinges. Our double-spiral design represents a striking example of mechanical intelligence (MI), recently introduced by the authors,43 which aims to develop bioinspired solutions to design a new generation of engineering components that can automatically respond to applied loads without requiring complicated actuations.

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**Author Contributions**

Conceptualization: M.J., S.G., H.R.; methodology: M.J., S.G., H.R.; data curation: M.J.; formal analysis: M.J.; funding acquisition: M.J., S.G., H.R.; project administration: S.G., H.R.; resources: S.G.; supervision: S.G., H.R.; validation: M.J.; visualization: M.J.; writing—original draft preparation: M.J.; writing—review and editing: M.J., S.G., H.R.

**Conflicts of interest statement**

The authors declare there are no conflicts of interest to disclose.

**Data availability**

All supporting data are made available either in the article or the electronic supplementary material. The FE models can be made available on request: please contact MJ at m.jafarpour1992@gmail.com; mjafarpour@zoologie.uni-kiel.de.

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**Tables**

**Table 1.** Double-spiral models and their corresponding design variables.

|  |  |
| --- | --- |
| Reference | Evolved |
|  | Polar slope | Initial thickness | Angle of rotation |
|  |  |  |  |  |  |  |
| Design variable: ***polar slope*** |
| **0.10** | ***0.05*** | ***0.20*** | **0.10** | **0.10** | **0.10** | **0.10** |
| Design variable: ***initial thickness* (r0,2 - r0,1) [mm]** |
| **1.50** (15-13.5) | **1.50** (15-13.5) | **1.50** (15-13.5) | ***0.75*** (15-14.25) | ***2.25*** (15-12.75) | **1.50** (15-13.5) | **1.50** (15-13.5) |
| Design variable: ***angle of rotation* [rad]** |
| **2.5π** | **2.5π** | **2.5π** | **2.5π** | **2.5π** | ***2π*** | ***3π*** |

**Table 2.** Stress-strain relationship for thermoplastic polyurethane filament (Flexfill TPU 98A, Fillamentum addi(c)tive polymers, Czech Republic).33

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Stress (MPa) | 0 | 12.1 | 22.1 | 28.4 | 37.8 |
| Strain | 0 | 0.1 | 0.5 | 1 | 3 |

**Table 3.** Settings used for 3D printing of the models.

|  |
| --- |
| 3D printing settings |
| Filament type | Thermoplastic polyurethane | Polylactic acid |
| Filament name | Flexfill TPU 98A | PLA |
| Produced by | Fillamentum addi(c)tive polymers, Czech Republic | Prusa Research, Praha, Czech Republic |
| Filament diameter (mm) | 1.75 | 1.75 |
| Nozzle diameter (mm) | 0.4 | 0.4 |
| Extrusion temperature (°c) | 240 | 215 |
| Bed temperature (°c) | 50 | 60 |
| Layer height (mm) | 0.2 | 0.2 |
| Fill pattern | Gyroid | Gyroid |
| Fill density (%) | 20 | 60 |

**Figure captions**

**Fig 1.** Double-spiral design. a) Two logarithmic spirals with the same polar slope and different initial radii forming a spiral surface. b) rotation of the first spiral surface about the origin of the coordinate system by 180 degrees for generating a second spiral surface. c) addition of lines for connecting the free ends and bases of the spirals to form a closed surface.

**Fig 2.** Simulated loading scenarios. Shaded areas show the fixed boundary conditions, and arrows show the direction of the applied loads.

**Fig 3.** Force–displacement curves from the simulation of the mechanical behavior of the reference double-spiral model. Results are given for the following loading scenarios: in-plane a) tension, b) sliding to the left, c) sliding to the right, d) compression, and e) rotation. Using red dots, each curve is divided into segments corresponding to specific phases of the behavior of the structure under different loading scenarios. The deformation of the reference double-spiral at each red dot is given next to the curves.

**Fig 4.** Influence of the design variables on the mechanical behavior of the developed double-spiral joint. The forces and displacements of the similar deformation phases in each loading scenario are averaged and normalized (by dividing them to the corresponding values of the reference model).

**Fig 5.** 3D printing, testing, and application of the double-spiral joints. a) Comparison of the force-displacement curves and force values obtained from the numerical and experimental tensile tests on the reference double-spiral. b) The reference double-spiral joint under (i) tension, (ii) sliding to the left, (iii) sliding to the right, (iv) compression, and (v) rotation. c) Fixing one side of the sample double-spiral and applying equal forces to its opposite side in four different directions to illustrate its anisotropic behavior. Shaded areas show the fixed boundary conditions, and arrows show the direction of the applied loads. d) Using the sample double-spiral joint for separating objects with different masses. While (i) the 3-gr round object rolls directly, (ii) the 30-gr object turns the double-spiral joint and continues moving in a different path.

**Fig 6.** Influence of the connection between the spirals of the double-spiral structure on its mechanical behavior. Comparison of the force-displacement curves from the simulation of the tensile behavior of the models with two- and four-fold connections between their spirals.