

# **Compliant Double-Spirals as Mechanical Elements: From Design to Application**

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## Abstract

Mechanical elements are fundamental components that form the building blocks of mechanical systems. These elements play essential roles in transmitting forces, facilitating motion, and enabling the overall functionality of a system. The design of mechanical elements involves the application of scientific principles and engineering techniques required to find the optimum combinations of design parameters, such as material composition and geometry. Choosing a proper combination ensures the efficiency, functionality, and reliability of the system under specific loading and boundary conditions. This process is usually used to develop an element inspired by concepts already existing in engineering or nature. In this study, inspired by natural spirals experiencing high deformations through coiling and uncoiling in animals and plants, compliant double-spirals were developed. Using the finite-element method, the mechanical behavior of geometrically different double-spirals in response to various loading scenarios was simulated, aiming to investigate the relationship between their geometries and structural properties. 3D printing and mechanical testing were then used to study the performance of the developed double-spirals in practice. Easily adjustable design, multiple degrees of freedom, reversible non-linear extensibility, and tunable deformability are advantageous characteristics of double-spirals, which were observed in the conducted simulations and experiments. By taking advantage of these characteristics, double-spirals were used in the development of modular metastructures, adaptive grippers, a mechanical interlocking system, and an adaptive impact absorber to prove the potential of double-spirals as mechanical elements with widespread technical applications. Moreover, a software package was developed as a user-friendly tool to facilitate the design and modeling of double-spirals for future studies. This research provides a better understanding of double-spirals and their mechanical properties, which might be desirable in various engineering fields, such as robotics, aerospace, and medical engineering. The insights achieved from this study can contribute to further advancements in the exploration of double-spirals and their utilization in innovative mechanical systems.

## Kurzzusammenfassung

Mechanische Elemente sind grundlegende Komponenten, die die Bausteine mechanischer Systeme bilden. Diese Elemente spielen eine wesentliche Rolle bei der Übertragung von Kräften, der Ermöglichung von Bewegung und der Gewährleistung der Gesamtfunktionalität eines Systems. Das Design mechanischer Elemente beinhaltet die Anwendung wissenschaftlicher Prinzipien und technischer Verfahren, die erforderlich sind, um die optimalen Kombinationen von Designparametern wie Materialzusammensetzung und Geometrie zu finden. Die Wahl einer geeigneten Kombination gewährleistet die Effizienz, Funktionalität und Zuverlässigkeit des Systems unter spezifischen Belastungs- und Randbedingungen. Dieser Prozess wird üblicherweise verwendet, um ein Element zu entwickeln, das von bereits in der Technik oder Natur existierenden Konzepten inspiriert ist. In dieser Studie wurden, inspiriert von natürlichen Spiralen, die in Tieren und Pflanzen hohe Deformationen durch Auf- und Abwickeln erfahren, nachgiebige Doppelspiralen entwickelt. Unter Verwendung der Finite-Elemente-Methode wurde das mechanische Verhalten geometrisch unterschiedlicher Doppelspiralen in Reaktion auf verschiedene Belastungsszenarien simuliert, um die Beziehung zwischen ihrer Geometrie und strukturellen Eigenschaften zu untersuchen. 3D-Druck und mechanische Tests wurden dann verwendet, um die Leistung der entwickelten Doppelspiralen in der Praxis zu studieren. Leicht anpassbares Design, mehrere Freiheitsgrade, reversible nichtlineare Dehnbarkeit und einstellbare Verformbarkeit sind vorteilhafte Eigenschaften von Doppelspiralen, die in den durchgeführten Simulationen und Experimenten beobachtet wurden. Durch die Nutzung dieser Eigenschaften wurden Doppelspiralen in der Entwicklung von modularen Metastrukturen, adaptiven Greifern, einem mechanischen Verriegelungssystem und einem adaptiven Stoßdämpfer verwendet, um das Potenzial von Doppelspiralen als mechanische Elemente mit weitreichenden technischen Anwendungen zu beweisen. Darüber hinaus wurde ein Softwarepaket als benutzerfreundliches Werkzeug zur Erleichterung des Designs und der Modellierung von Doppelspiralen für zukünftige Studien entwickelt. Diese Forschung bietet ein besseres Verständnis von Doppelspiralen und ihren mechanischen Eigenschaften, die in verschiedenen Ingenieursfeldern wie Robotik, Luft- und Raumfahrt und medizinisches Ingenieurwesen wünschenswert sein könnten. Die Erkenntnisse aus dieser Studie können zu weiteren Fortschritten bei der Erforschung von Doppelspiralen und ihrer Nutzung in innovativen mechanischen Systemen beitragen.

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## Chapter 1:

### Introduction

Mechanical systems consist of linked elements working together to accomplish defined tasks. These elements operate within the context of a larger system, responding to specific input loads and delivering the desired output. The characteristics and behavior of elements besides the interactions between them play a critical role in determining the performance of the whole system [1,2]. The behavior of each element is influenced by parameters which need to be determined during the design process.

Designing a mechanical element is a structured process that involves several key steps. It typically starts with a comprehensive understanding of functions that the element is being designed for. Once the requirements are clear, the next step is the conceptual design, which often involves sketching and creating basic prototypes [3-5]. Material selection is another critical aspect. Engineers must choose materials that align with the performance requirements. Factors such as strength, stiffness, weight, and costs must be carefully considered in this decision [6]. Detailed design follows, where the chosen concept is refined, and precise specifications, such as exact dimensions, tolerances, and the specific manufacturing process, are determined. Once the detailed design is complete, the element is typically built for testing. Testing may involve applying loads, measuring structural integrity, and evaluating how well the element meets design specifications. Results obtained from tests often lead to design revisions and improvements, reflecting an iterative aspect of the process [7,8].

Design is an ongoing and iterative process in engineering, perpetually influenced by the dynamic nature of technology and society, aiming to respond to emerging requirements, whether prompted by environmental considerations, the quest for higher efficiency, or the necessity for cost-effective solutions. By leveraging innovative materials, manufacturing techniques, and computational tools, engineers continually try to create elements that are more effective, efficient, and sustainable [8-10]. Due to the scientific and technological advances over the course of decades, the design process now offers various options to consider, aiming to enhance the efficiency of developed systems. A few of these options will be reviewed in the following.

- **Computer-based tools.** These tools have revolutionized the design process, empowering engineers to create, visualize, and analyze complex structures and systems with high accuracy and detail. Computer-aided design (CAD) software allows for precise drafting and modeling of designs. It supports quick modification of the models, enabling engineers to fine-tune them to meet exact specifications [11,12].

Numerical simulations play a key role in the design process by allowing engineers to create a virtual prototype of a system and simulate its real-world performance. This enables engineers to explore a wide range of design variations and scenarios, assess the influence of different load cases on the integrity of their developed system, identify potential issues, and make improvements early in the design phase, thereby saving time and resources [13,14].

Furthermore, through programming, engineers can develop custom software solutions tailored to their specific design needs, including the automation of tasks. Iterative optimization algorithms can be implemented in the design process to reach optimum values of design variables with the aim of achieving multiple objectives and solving complex challenges [15,16].

- **Rapid prototyping.** Nowadays, rapid prototyping is an indispensable tool in the design process, offering engineers the ability to quickly transform concepts into tangible prototypes with high speed and precision. These prototypes offer valuable insights into the functionality of a design, helping to identify potential issues and areas for improvement. Moreover, rapid prototyping reduces the cost and time associated with traditional manufacturing methods, making it a cost-effective solution for small-batch production and custom design projects [17,18].

One of the most prominent rapid prototyping methods is 3D printing, also known as additive manufacturing (AM), which can be used to fabricate parts directly from CAD models. This method encompasses various technologies, including fused deposition modeling (FDM), stereolithography (SLA), selective laser sintering (SLS), and more, each with its unique approach to manufacturing objects with complex shapes and intricate details [17-20].

Among the various techniques of 3D printing that are currently in use, FDM stands out as one of the most widely adopted and accessible technologies. This simple, quick, and low-cost method operates by extruding a thermoplastic filament layer by layer to create a 3D part. The versatility of FDM 3D printers extends to the wide variety of filaments that can be utilized. These filaments come in various materials, each offering unique mechanical properties suited for specific engineering applications, including different levels of strength, flexibility, durability, impact resistance, wear resistance, and heat resistance [21]. Engineers benefit from this diversity, enabling them to fine-tune their designs and select the ideal material to meet their specific mechanical requirements.



- **Biomimetics.** It refers to the approach of using strategies evolved in nature to solve design challenges. By drawing inspiration from nature, engineers adopt innovative design solutions and develop systems with higher efficiency [22-25]. In contrast to conventional engineering structures, which were typically developed to have constant mechanical properties and perform single tasks, bio-inspired structures are engineered to be multi-functional and have adaptive properties. These novel structures can combine properties traditionally seen as mutually exclusive, such as light weight, high load-bearing capacity, and high toughness. Furthermore, they can dynamically adjust their behavior, shape, or properties and adapt to changing conditions. Bio-inspired designs with enhanced functionality are in growing demand, and in some cases, they are becoming mandatory for integration into modern systems [26-29]. Consequently, more efforts must be made to promote low-cost and easily accessible nature-inspired solutions for the development of highly efficient engineering designs.

Employing the tools and strategies outlined above, different steps of the design process have been implemented in this thesis for the development of a compliant mechanical element, called double-spiral. Inspired by natural spirals and spiral-based structures available in engineering, compliant double-spirals were designed with specific characteristics and functions.

Spirals are among the most abundant and well-known patterns in nature, found in significantly different sizes and having a wide range of functions [30-32]. Nevertheless, regardless of their size, where they are found and what their function is, most natural spirals take the form of logarithmic curves, fractal shapes characterized by their infinite self-similarity. This geometric feature is why natural spirals are referred to as logarithmic or growth spirals [31,32].

Claws, horns, teeth, fangs, stings, beaks, thorns, and shells are examples of stiff and hard spiral structures available in nature [33-36]. These structures possess morphologies, microstructures, and material distributions that enable them to efficiently withstand various mechanical loads. Functions such as digging, pulling, scratching, fighting, biting, and puncturing subject these structures to multi-axial complex loading conditions and put them at high risk of mechanical damage [34-39]. Nature leverages the structural strategy of growing in the form of spirals to achieve optimized geometries that support the biomechanical functionalities of these structures and help them endure repetitive loads and harsh environmental conditions without mechanical failure.

The curved shape of these structures enables them to properly apply loads from different directions and facilitates functions such as pulling and holding. Moreover, it optimizes their performance in response to multiple types of loads, e.g., compression and bending [36,37]. The tapered shape of these structures reduces their weight, makes a sharp tip suitable for penetrating, and

provides a larger base to enhance their load-bearing capacity. Furthermore, the tapered shape improves impact absorption in these structures and contributes to a more uniform stress distribution [35-39]. Although all the mentioned spiral structures share a curved and tapered shape, their specific geometry is tailored to the tasks and functions they perform in nature. Different spiral curves result in shapes with distinct geometrical parameters, such as curvature, length, aspect ratio, sharpness, and surface area.

In addition to the rigid spiral structures, nature presents another group of spiral structures with characteristics entirely in contrast with those of the first group. Hyper-elongated structures, such as lepidoptera's proboscis, beetles' flagellum, octopuses' arms, and chameleons' tail, have evolved to experience repetitive large deformations [40-45]. All these structures are able to easily shift between two states: a compact, coiled state and a long, uncoiled state.

- The proboscis is coiled in its resting position, allowing butterflies and moths to fly and freely approach flowers. Uncoiling it after landing enables them to extract nectar from the long spurs of flowers [40].
- The extraordinarily long intromittent organ of male beetles is usually coiled in many loops and stored in their abdomen. However, when needed, the flagellum uncoils to penetrate into the long and coiled spermathecal duct of the female beetle [41,42].
- Octopuses can move their remarkably flexible arms independently. Deforming these arms freely in different directions enables octopuses to swim, walk on the seabed, bury themselves, capture their prey, and grasp various objects with great conformability [43,44].
- The long prehensile tail of chameleons with arboreal lifestyle is used to coil around perches, help them climb from branches, and hold onto objects [45].

These examples show how very long and highly deformable structures in nature take advantage of their spirally curved morphology as a self-compacting mechanism. Besides the effects that the tapered shape of these structures has on their weight, movements, and functionality, it is advantageous for achieving higher compactness [40,41,44,45]. Tapering serves as a strategy to maximize the length of the structure that can be coiled into a specific space.

Natural spirals, with their vast diversity in forms, features, and behavior, have become a rich source of inspiration for engineers [30-32]. However, since bio-inspiration is not necessarily a process of exact copying from nature, human-designed spirals are sometimes different from natural spirals in their geometry and function. Modifications, simplifications, and even improvements in line with human needs are usually involved in this process [22-25].

Thanks to mathematicians, the ability to develop spirals with significantly different shapes using simple mathematical equations has facilitated their application in technical designs. Various types of two- and three-dimensional (2D and 3D) spirals, such as Archimedean, hyperbolic, parabolic, Galilean, lituus, logarithmic, Fibonacci, Cornu, helix, helicoid, and non-smooth spirals, are categorized and formulated for use [31]. Another well-known geometrical modification implemented in spiral-based designs, which is the focus of this thesis, involves the assembly of multiple spirals connected to each other, aiming to use them as joints or to make a network of connected unit cells [46-59]. Among the structures made by assembling multiple interconnected spirals, the developed designs consisting of two spirals are called double-spirals [46,47].

Like spirals in natural systems, double-spirals have been used in technical applications for a wide range of deformations. Torsional and ortho-planar springs working as joints or hinges are examples of double-spirals that have been developed for limited deformations [46-51]. On the other hand, highly deformable double-spirals have been used as bridges in the island-bridge electronics [52-54]. These double-spiral interconnects are designed to enable electrical connections between parts of a device while allowing it to undergo mechanical deformations. Planar or 2D lattices consisting of multiple interconnected spirals are another example of spiral-based designs in engineering. When these lattices are made of soft materials, their high extensibility is valuable for the development of stretchable electronics and soft robots [55,56]. Using stiff materials with low toughness for fabrication makes them suitable candidates for achieving complex 3D shapes by plastically deforming the rigid plates [57-59].

Previous studies have mainly focused on utilizing spirals to ensure a more uniform stress distribution and consequently a larger deformability without failure. However, double-spirals made from highly elastic and flexible materials could offer advantages beyond their inherent compactness and extensibility. This study aims to leverage the ability to simply manipulate the geometry of double-spirals and investigate their mechanical behavior using both numerical and experimental methods, while harnessing them as functional mechanical elements for transmitting motion and force in a passive-automatic way.

The thesis is structured into six chapters, with this brief introduction as the starting point. In Chapter 2, the double-spiral is introduced as a compliant joint, with a focus on the influence of design variables on its geometry and mechanical behavior under different loading scenarios. Chapter 3 explores the potential of compliant double-spirals when used as the modules of mechanical metastructures, demonstrating how the combination of double-spirals in specific configurations can be used to obtain desired mechanical properties. Chapter 4 is devoted first to the presentation

of a user-friendly software package suitable for designing double-spirals, and then to the development of different spiral-based structures that showcase the potential of double-spirals in various technical applications. A general discussion of all results presented in this thesis and some outlooks for future studies are provided in Chapter 5. A concise conclusion is outlined in Chapter 6.

## References

- [1] Pahl, G., 1994. Fundamentals of engineering design. In Beitz, W. and Küttner, K.H. (eds.) *Dubbel handbook of mechanical engineering*. London, UK: Springer-Verlag.  
DOI: 10.1007/978-1-4471-3566-1\_5
- [2] Petrescu, R.V., Aversa, R., Akash, B., Abu-Lebdeh, T., Apicella, A. and Petrescu, F.I., 2018. Some aspects of the structure of planar mechanisms. *American Journal of Engineering and Applied Sciences*, 11(1), pp. 245-259.  
DOI: 10.3844/ajeassp.2018.245.259
- [3] Sydenham, P.H., 1981. Mechanical design of instruments: 3: Fundamental concepts of systems nature (Part A). *Measurement and Control*, 14(1), pp. 5-10.  
DOI: 10.1177/002029408101400101
- [4] Sturges Jr, R.H., O'Shaughnessy, K. and Reed, R.G., 1993. A systematic approach to conceptual design. *Concurrent Engineering*, 1(2), pp. 93-105.  
DOI: 10.1177/1063293X9300100202
- [5] Carey, K. and Blatnik, S., 2003. Introducing design principles. In *Design concepts with code: An approach for developers*. Berkeley, CA, USA: Apress, pp. 37-71.  
DOI: 10.1007/978-1-4302-0790-0\_2
- [6] Mansor, M.R. and Sapuan, S.M., 2017. *Concurrent conceptual design and materials selection of natural fiber composite products*. Singapore: Springer.  
DOI: 10.1007/978-981-10-6591-0
- [7] Askeland, D.R., 1991. Mechanical testing and properties. In *The science and engineering of materials*, 2nd ed., Dordrecht, Netherlands: Springer, pp. 63-80.  
DOI: 10.1007/978-94-009-1842-9\_6
- [8] Simon, H.A., 1975. *A student's introduction to engineering design: Pergamon unified engineering series*. Oxford, UK: Pergamon Press.  
DOI: 10.1016/C2013-0-05679-4
- [9] Khaheshi, A. and Rajabi, H., 2022. Mechanical intelligence (MI): A bioinspired concept for transforming engineering design. *Advanced Science*, 9(32), 2203783.

- DOI: 10.1002/advs.202203783
- [10] Peralta, M.E. and Soltero, V., 2021. Sustainable manufacturing: Needs for future quality development. In Gupta, K. and Salonitis, K. (eds.) *Sustainable manufacturing*. Amsterdam, Netherlands: Elsevier, pp. 1-28.  
DOI: 10.1016/C2018-0-00912-3
- [11] Kutz, M. (ed.) 2015. *Mechanical engineers' handbook, volume 2: Design, instrumentation, and controls*, 4th ed., Hoboken, New Jersey, USA: John Wiley & Sons.  
DOI: 10.1002/9781118985960
- [12] Kamrani, A.K. and Nasr, E.A., 2010. Computer-based design and manufacturing. In *Engineering design and rapid prototyping*. New York, NY, USA: Springer, pp. 187-198.  
DOI: 10.1007/978-0-387-95863-7
- [13] Kutz, M. (ed.) 2015. *Mechanical engineers' handbook, volume 1: Materials and engineering mechanics*, 4th ed., Hoboken, New Jersey, USA: John Wiley & Sons.  
DOI: 10.1002/9781118985960
- [14] Novak, M. and Dolšak, B., 2008. Intelligent FEA-based design improvement. *Engineering Applications of Artificial Intelligence*, 21(8), pp. 1239-1254.  
DOI: 10.1016/j.engappai.2008.03.013
- [15] Saridakis, K.M. and Dentsoras, A.J., 2008. Soft computing in engineering design—A review. *Advanced Engineering Informatics*, 22(2), pp. 202-221.  
DOI: 10.1016/j.aei.2007.10.001
- [16] Roy, R., Hinduja, S. and Teti, R., 2008. Recent advances in engineering design optimisation: Challenges and future trends. *CIRP Annals*, 57(2), pp. 697-715.  
DOI: 10.1016/j.cirp.2008.09.007
- [17] Kamrani, A.K. and Nasr, E.A., 2010. Rapid prototyping. In *Engineering design and rapid prototyping*. New York, NY, USA: Springer, pp. 339-354.  
DOI: 10.1007/978-0-387-95863-7
- [18] Hashimi, H. and Basith, A., 2017. Design, planning, machining, and manufacturing using rapid prototyping technologies in modern engineering. *International Journal of Scientific Research and Management*, 5(1), pp. 5064-5074.  
DOI: 10.18535/ijserm/v5i1.07
- [19] Bikas, H., Stavropoulos, P. and Chrysosolouris, G., 2016. Additive manufacturing methods and modelling approaches: A critical review. *International Journal of Advanced Manufacturing Technology*, 83, pp. 389-405.  
DOI: 10.1007/s00170-015-7576-2

- [20] Ngo, T.D., Kashani, A., Imbalzano, G., Nguyen, K.T. and Hui, D., 2018. Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. *Composites Part B: Engineering*, 143, pp. 172-196.  
DOI: 10.1016/j.compositesb.2018.02.012
- [21] Dave, H.K. and Davim, J.P. (eds.) 2021. *Fused deposition modeling based 3D printing*. Cham, Switzerland: Springer International Publishing.  
DOI: 10.1007/978-3-030-68024-4
- [22] Farzaneh, H.H. and Lindemann, U., 2018. *A practical guide to bio-inspired design*. Berlin, Heidelberg, Germany: Springer Vieweg Verlag.  
DOI: 10.1007/978-3-662-57684-7
- [23] Vincent, J.F., Bogatyreva, O.A., Bogatyrev, N.R., Bowyer, A. and Pahl, A.K., 2006. Biomimetics: Its practice and theory. *Journal of the Royal Society Interface*, 3(9), pp. 471-482.  
DOI: 10.1098/rsif.2006.0127
- [24] Lenau, T.A., 2009. Biomimetics as a design methodology-Possibilities and challenges. In *Proceedings of the International Conference on Engineering Design (ICED)*, Palo Alto, CA, USA, 24-27 August, pp. 121-132.
- [25] Bar-Cohen, Y., 2006. Biomimetics—Using nature to inspire human innovation. *Bioinspiration & Biomimetics*, 1(1), pp. P1-P12.  
DOI: 10.1088/1748-3182/1/1/P01
- [26] Wagg, D., Bond, I., Weaver, P. and Friswell, M. (eds.) 2008. *Adaptive structures: Engineering applications*. Chichester, West Sussex, UK: John Wiley & Sons.
- [27] Liu, Z., Meyers, M.A., Zhang, Z. and Ritchie, R.O., 2017. Functional gradients and heterogeneities in biological materials: Design principles, functions, and bioinspired applications. *Progress in Materials Science*, 88, pp. 467-498.  
DOI: 10.1016/j.pmatsci.2017.04.013
- [28] Yin, S., Guo, W., Wang, H., Huang, Y., Yang, R., Hu, Z., Chen, D., Xu, J. and Ritchie, R.O., 2021. Strong and tough bioinspired additive-manufactured dual-phase mechanical metamaterial composites. *Journal of the Mechanics and Physics of Solids*, 149, 104341.  
DOI: 10.1016/j.jmps.2021.104341
- [29] Benedetti, M., Du Plessis, A., Ritchie, R.O., Dallago, M., Razavi, S.M.J. and Berto, F., 2021. Architected cellular materials: A review on their mechanical properties towards fatigue-tolerant design and fabrication. *Materials Science and Engineering: R: Reports*, 144, 100606.  
DOI: 10.1016/j.mser.2021.100606

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- [30] Cook, T.A., 1979. *The curves of life: Being an account of spiral formations and their application to growth in nature, to science, and to art: With special reference to the manuscripts of Leonardo da Vinci*. New York, NY, USA: Dover Publications.
- [31] Tsuji, K. and Müller, S.C. (eds.) 2019. *Spirals and vortices: In culture, nature, and science*. Cham, Switzerland: Springer.  
DOI: 10.1007/978-3-030-05798-5
- [32] Ball, P., 2016. *Patterns in nature: Why the natural world looks the way it does*. Chicago, Illinois, USA: The University of Chicago Press.
- [33] Evans, A.R., Pollock, T.I., Cleuren, S.G., Parker, W.M., Richards, H.L., Garland, K.L., Fitzgerald, E.M., Wilson, T.E., Hocking, D.P. and Adams, J.W., 2021. A universal power law for modelling the growth and form of teeth, claws, horns, thorns, beaks, and shells. *BMC Biology*, 19, 58.  
DOI: 10.1186/s12915-021-00990-w
- [34] Shojaei, M.F., Mohammadi, V., Rajabi, H. and Darvizeh, A., 2012. Experimental analysis and numerical modeling of mollusk shells as a three dimensional integrated volume. *Journal of the Mechanical Behavior of Biomedical Materials*, 16, pp. 38-54.  
DOI: 10.1016/j.jmbbm.2012.08.006
- [35] Mattheck, C. and Reuss, S., 1991. The claw of the tiger: An assessment of its mechanical shape optimization. *Journal of Theoretical Biology*, 150(3), pp. 323-328.  
DOI: 10.1016/S0022-5193(05)80431-X
- [36] Lautenschlager, S., 2014. Morphological and functional diversity in therizinosaur claws and the implications for theropod claw evolution. *Proceedings of the Royal Society B: Biological Sciences*, 281(1785), 20140497.  
DOI: 10.1098/rspb.2014.0497
- [37] Bar-On, B., Barth, F.G., Fratzl, P. and Politi, Y., 2014. Multiscale structural gradients enhance the biomechanical functionality of the spider fang. *Nature Communications*, 5, 3894.  
DOI: 10.1038/ncomms4894
- [38] Drake, A., Donahue, T.L.H., Stansloski, M., Fox, K., Wheatley, B.B. and Donahue, S.W., 2016. Horn and horn core trabecular bone of bighorn sheep rams absorbs impact energy and reduces brain cavity accelerations during high impact ramming of the skull. *Acta Biomaterialia*, 44, pp. 41-50.  
DOI: 10.1016/j.actbio.2016.08.019
- [39] Johnson, K.L., Trim, M.W., Horstemeyer, M.F., Lee, N., Williams, L.N., Liao, J., Rhee, H. and Prabhu, R., 2014. Geometric effects on stress wave propagation. *Journal of Biomechanical Engineering*, 136(2), 021023.

- DOI: 10.1115/1.4026320
- [40] Krenn, H.W., 2010. Feeding mechanisms of adult Lepidoptera: Structure, function, and evolution of the mouthparts. *Annual Review of Entomology*, 55, pp. 307-327.  
DOI: 10.1146/annurev-ento-112408-085338
- [41] Matsumura, Y., Kovalev, A.E. and Gorb, S.N., 2017. Penetration mechanics of a beetle intromittent organ with bending stiffness gradient and a soft tip. *Science Advances*, 3(12), eaao-5469.  
DOI: 10.1126/sciadv.aao5469
- [42] Matsumura, Y., Yoshizawa, K., Machida, R., Mashimo, Y., Dallai, R., Gottardo, M., Kleinteich, T., Michels, J., Gorb, S.N. and Beutel, R.G., 2014. Two intromittent organs in *Zorotypus caudelli* (Insecta, Zoraptera): The paradoxical coexistence of an extremely long tube and a large spermatophore. *Biological Journal of the Linnean Society*, 112(1), pp. 40-54.  
DOI: 10.1111/bij.12260
- [43] Kier, W.M., 2016. The musculature of coleoid cephalopod arms and tentacles. *Frontiers in Cell and Developmental Biology*, 4, 10.  
DOI: 10.3389/fcell.2016.00010
- [44] Huffard, C.L., 2006. Locomotion by *Abdopus aculeatus* (Cephalopoda: Octopodidae): Walking the line between primary and secondary defenses. *Journal of Experimental Biology*, 209(19), pp. 3697-3707.  
DOI: 10.1242/jeb.02435
- [45] Luger, A.M., Ollevier, A., De Kegel, B., Herrel, A. and Adriaens, D., 2020. Is variation in tail vertebral morphology linked to habitat use in chameleons?. *Journal of Morphology*, 281(2), pp. 229-239.  
DOI: 10.1002/jmor.21093
- [46] Ahmad, B., Barbot, A., Ulliac, G. and Bolopion, A., 2022. Remotely actuated optothermal robotic microjoints based on spiral bimaterial design. *IEEE/ASME Transactions on Mechatronics*, 27(5), pp. 4090-4100.  
DOI: 10.1109/TMECH.2022.3145646
- [47] Racu, C.M. and Doroftei, I., 2018. Compliant mechanism for ankle rehabilitation device. Part II: Optimization and simulation results. *IOP Conference Series: Materials Science and Engineering*, 444(5), 052015.  
DOI: 10.1088/1757-899X/444/5/052015
- [48] Hendrich, N., Wasserfall, F. and Zhang, J., 2020. 3D printed low-cost force-torque sensors. *IEEE Access*, 8, pp. 140569-140585.  
DOI: 10.1109/ACCESS.2020.3007565
- [49] Tian, Y., Zhou, C., Wang, F., Lu, K. and Zhang, D., 2020. A novel compliant mechanism based system to calibrate spring constant of AFM cantilevers. *Sensors and Actuators A: Physical*, 309, 112027.



- DOI: 10.1016/j.sna.2020.112027
- [50] Zolfagharian, A., Gharaie, S., Gregory, J., Bodaghi, M., Kaynak, A. and Nahavandi, S., 2022. A bioinspired compliant 3D-printed soft gripper. *Soft Robotics*, 9(4), pp. 680-689.  
DOI: 10.1089/soro.2020.0194
- [51] Xiang, C., Li, Z., Wang, F., Guan, Y. and Zhou, W., 2023. A 3D printed flexible electroadhesion gripper. *Sensors and Actuators A: Physical*, 363, 114675.  
DOI: 10.1016/j.sna.2023.114675
- [52] Lv, C., Yu, H. and Jiang, H., 2014. Archimedean spiral design for extremely stretchable interconnects. *Extreme Mechanics Letters*, 1, pp. 29-34.  
DOI: 10.1016/j.eml.2014.12.008
- [53] Alcheikh, N., Shaikh, S.F. and Hussain, M.M., 2019. In-plane deformation mechanics of highly stretchable Archimedean interconnects. *AIP Advances*, 9(1), 015224.  
DOI: 10.1063/1.5053967
- [54] Yuan, X. and Wang, Y., 2023. Nonlinear stretching mechanics of planar Archimedean-spiral interconnects for flexible electronics. *Thin-Walled Structures*, 185, 110568.  
DOI: 10.1016/j.tws.2023.110568
- [55] Dong, L., Wang, D., Wang, J., Jiang, C., Wang, H., Zhang, B., Wu, M.S. and Gu, G., 2022. Modeling and design of periodic polygonal lattices constructed from microstructures with varying curvatures. *Physical Review Applied*, 17(4), 044032.  
DOI: 10.1103/PhysRevApplied.17.044032
- [56] Liu, J., Guo, H., Liu, H. and Lu, T., 2023. Designing hierarchical soft network materials with developable lattice nodes for high stretchability. *Advanced Science*, 10(8), 2206099.  
DOI: 10.1002/advs.202206099
- [57] Zarrinmehr, S., Ettihad, M., Kalantar, N., Borhani, A., Sueda, S. and Akleman, E., 2017. Interlocked archimedean spirals for conversion of planar rigid panels into locally flexible panels with stiffness control. *Computers & Graphics*, 66, pp. 93-102.  
DOI: 10.1016/j.cag.2017.05.010
- [58] Chen, R., Turman, C., Jiang, M., Kalantar, N., Moreno, M. and Muliana, A., 2020. Mechanics of kerf patterns for creating freeform structures. *Acta Mechanica*, 231, pp. 3499-3524.  
DOI: 10.1007/s00707-020-02713-8
- [59] Darnal, A., Mantri, K., Shahid, Z., Kalantar, N. and Muliana, A., 2023. The influence of inelastic materials on freeform kerf structures. *Thin-Walled Structures*, 193, 111292.  
DOI: 10.1016/j.tws.2023.111292

## Chapter 2:

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

### 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.

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## 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, especially 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 springs [18] 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 contrast, 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 body [32] 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 bio-inspired 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, 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

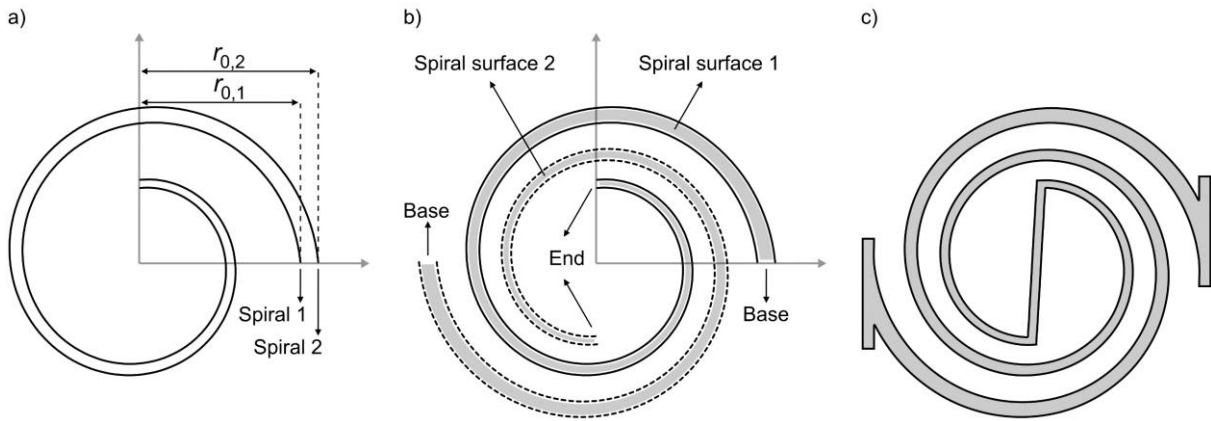
#### 2.1.1. Development of models

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

$$r = r_0 e^{-k\theta}, \quad (1)$$

where  $r_0$  is the radius of the spiral at  $\theta = 0$ , and  $k$  is the polar slope. If  $k < 0$ , the spiral turns clockwise, and if  $k > 0$ , the spiral grows counterclockwise. In the case that  $k = 0$ , the spiral becomes a circle of radius  $r_0$  [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  $\pi$  radians, 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 refer to this design as “double-spiral.”










**Fig 1.** Double-spiral design. a) Two logarithmic spirals with the same polar slope and different initial radii forming a spiral surface. b) Rotating the first spiral surface about the origin of the coordinate system by  $\pi$  radians to generate the second spiral surface. c) Adding lines for connecting the free ends and bases of the spirals to form a closed surface.

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 within a 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 ( $k$ ), initial thickness ( $r_{0,2} - r_{0,1}$ ), and the angle of rotation ( $\theta_{\max}$ ) 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.

**Table 1.** Double-spiral models and their corresponding design variables. Bold numbers in each row show the variables.

Reference	Evolved					
	Polar slope		Initial thickness		Angle of rotation	
						
Design variable: Polar slope						
0.10	<b>0.05</b>	<b>0.20</b>	0.10	0.10	0.10	0.10
Design variable: Initial thickness ( $r_{0,2} - r_{0,1}$ ) [mm]						
1.50 (15-13.5)	1.50 (15-13.5)	1.50 (15-13.5)	<b>0.75</b> (15-14.25)	<b>2.25</b> (15-12.75)	1.50 (15-13.5)	1.50 (15-13.5)
Design variable: Angle of rotation [rad]						
$2.5\pi$	$2.5\pi$	$2.5\pi$	$2.5\pi$	$2.5\pi$	<b><math>2\pi</math></b>	<b><math>3\pi</math></b>

### 2.1.1. 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  $1230 \text{ kg m}^{-3}$ , respectively [33].

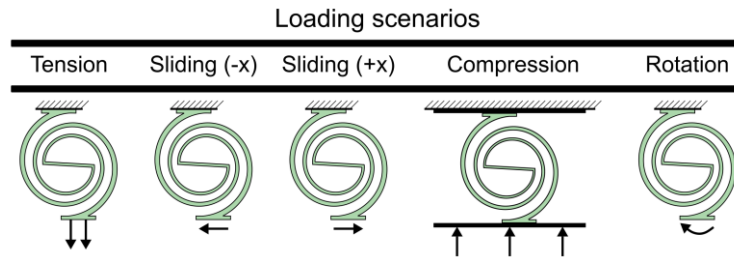
Using the Abaqus implicit solver, we simulated the quasi-static behavior of the developed models under different loading scenarios, which involved tension, sliding, compression, and rotation. In all loading scenarios, one side of the models was completely fixed, and a constant displacement was applied to the opposite side. We limited the displacements to avoid large strain in the elements

of our FE models and focused on their elastic behavior. The following loading scenarios were simulated (Fig. 2):

- **Tension.** Here, we pulled the free end of each model and extended it up to its total length.
- **Sliding.** 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.** In this loading scenario, 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 the two plates.
- **Rotation.** We rotated the free end of each model by  $\pi$  radian, bringing its two ends together.

**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



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

Considering that deformations involved physical contacts, we used a self-contact formulation between the coils of double-spirals, and a surface-to-surface contact formulation between the rigid plates used in compression and the double-spirals 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, each tested 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).

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

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

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 ( $r_{0,2} - r_{0,1} = 15 - 12 = 3$ ), 0.1, and  $3\pi$  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-element analysis

#### 3.1.1. 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 into three phases:

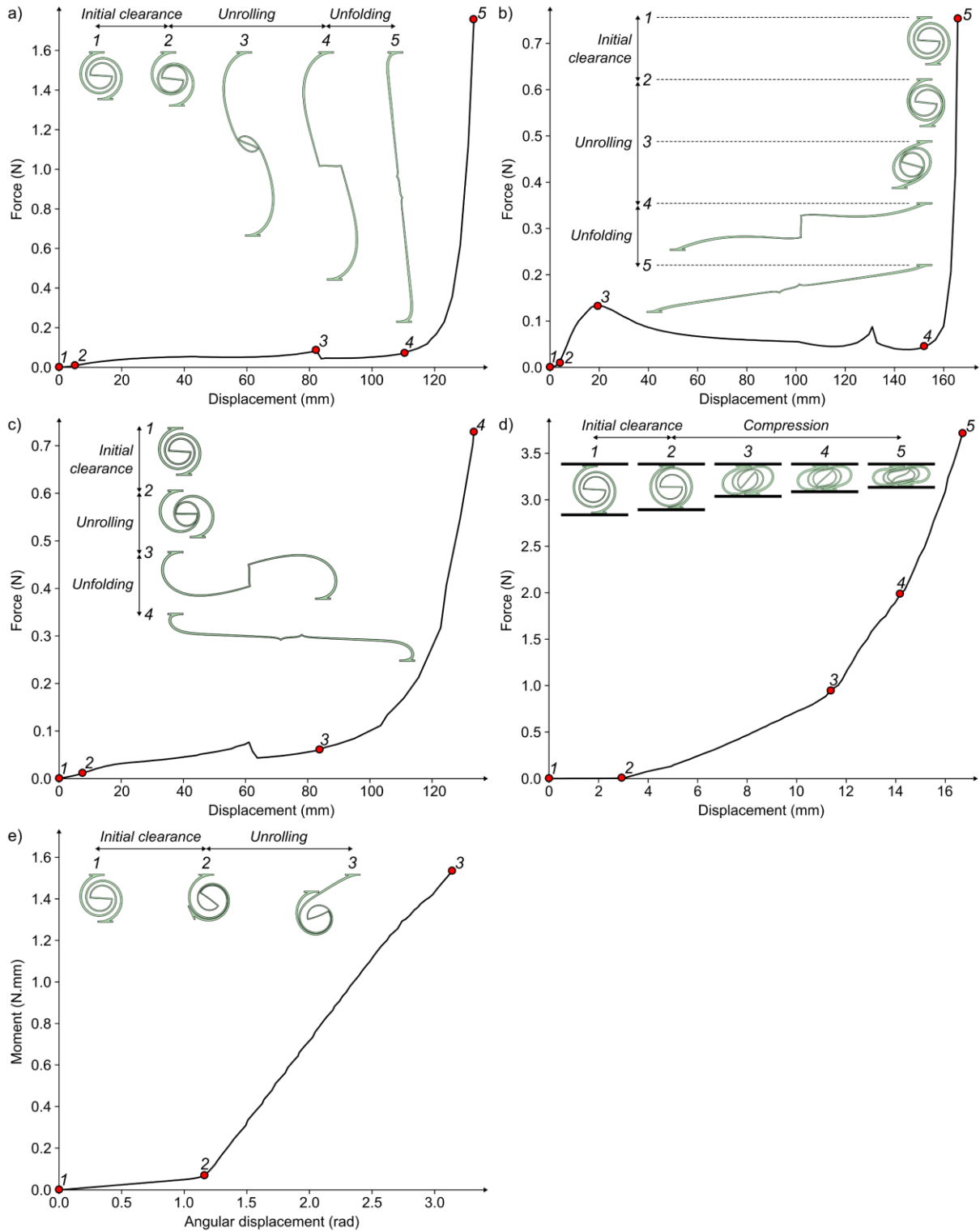
- The first phase is the *initial clearance*. This resulted from the specific geometry of the joint, specifically the free space between the coils. This clearance resulted in a low-stiffness regime without a noticeable increase in the magnitude of the load. In this phase, there was no contact between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

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 non-linear, 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 resulting 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 electronic supplementary material, Video S1.





**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.

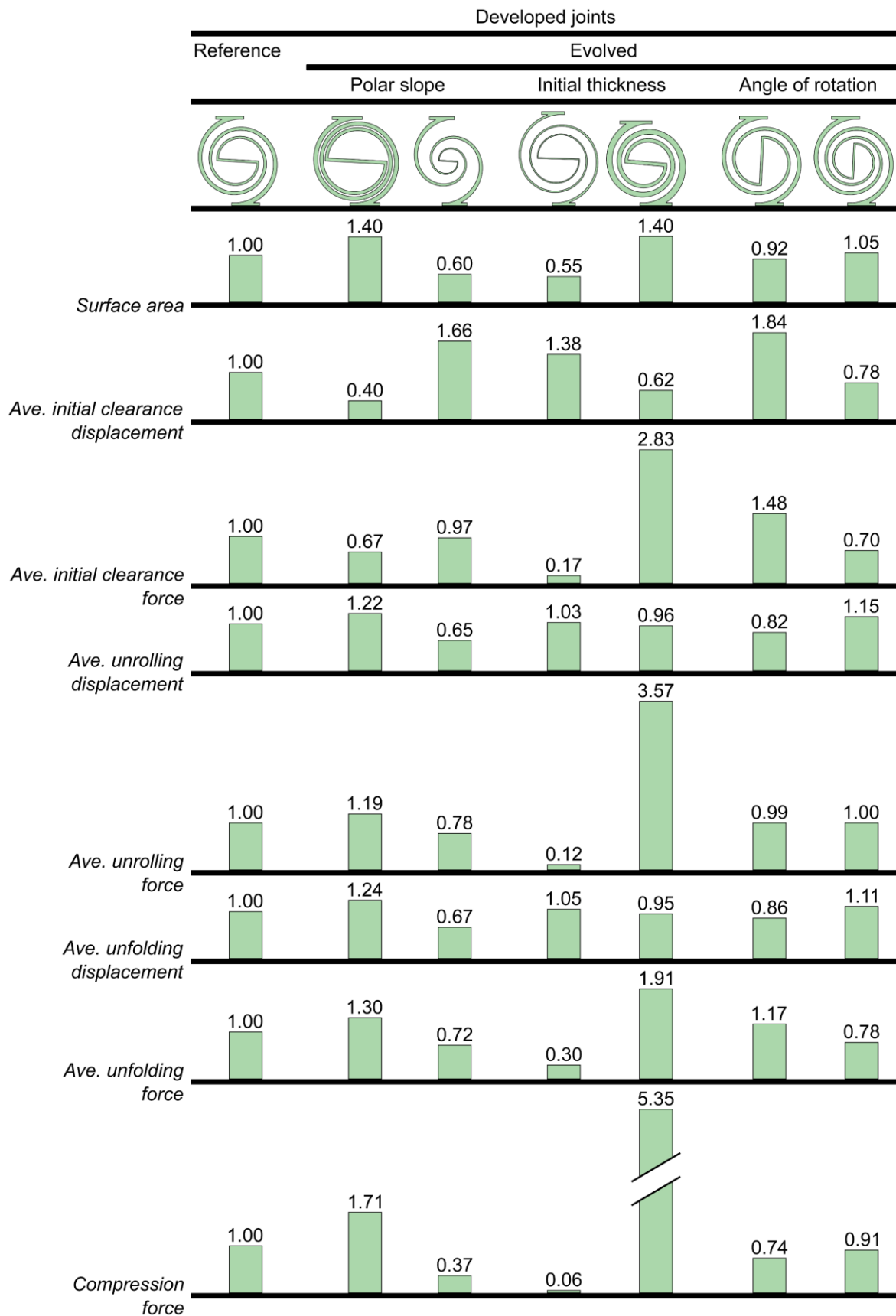
### 3.1.2. Influence of the design variables on the mechanical behavior of the joint

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.

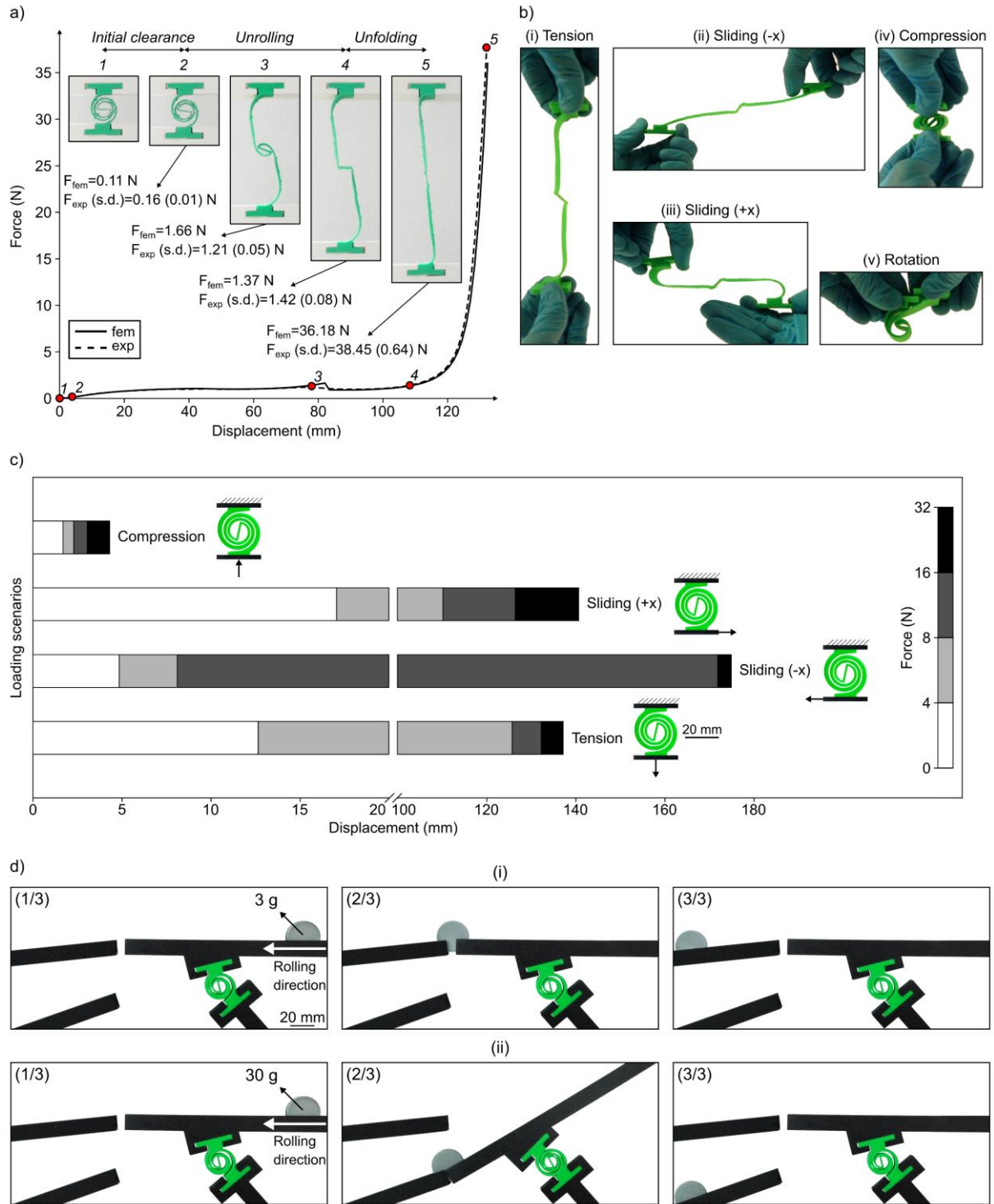
## 3.2. Prototyping, mechanical testing, and application

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 of the same size rolled on a rigid part. The 3 g object did not move the components and rolled directly, whereas the 30 g 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 double-spirals for making an adaptive system.



**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 (divided by 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 g round object rolls directly, (ii) the 30 g object turns the double-spiral joint and continues moving in a different path.

## 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.

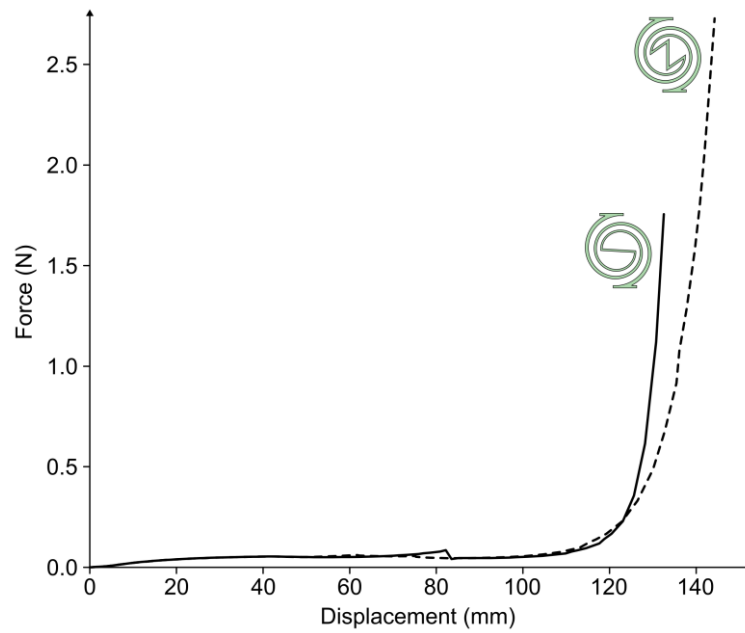
Our joint can be categorized as a highly extensible dual-stiffness structure. It can be extended up to five times its original length under tension or sliding. The extension of the joint (especially in tension) includes two almost linear distinct deformation regimes: a long low-stiffness and a short 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 the 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.



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

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 into 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-spirals can 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.

## 5. 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 bio-inspired structure has potential engineering applications. The passive-automatic control of the structure, which is achieved through the design variables alone, makes 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 bio-inspired solutions to design a new generation of engineering components that can automatically respond to applied loads without requiring complicated actuations.

## Supplementary materials

The data that support the findings of this study are available online at [44]:

<https://doi.org/10.6084/m9.figshare.c.6360049.v1>

- **Video S1.** Numerical simulation of the mechanical behavior of the reference double-spiral under tension, sliding, compression, and rotation.
- **Video S2.** Tensile deformation of the reference double-spiral joint in experimental test and numerical simulation.
- **Video S3.** Deformation of the reference double-spiral joint under tension, sliding, compression, and rotation.

- **Video S4.** Anisotropic behavior of the double-spiral joint in four different directions.
- **Video S5.** Using the double-spiral joint in an application for separating objects of different masses.
- **File S1.** 2D and 3D models of the double-spirals developed in this study for numerical simulations and 3D printing.

## References

- [1] Cook, T.A., 1979. *The curves of life: Being an account of spiral formations and their application to growth in nature, to science, and to art: With special reference to the manuscripts of Leonardo da Vinci*. New York, NY, USA: Dover Publications.
- [2] Tsuji, K. and Müller, S.C. (eds.) 2019. *Spirals and vortices: In culture, nature, and science*. Cham, Switzerland: Springer.  
DOI: 10.1007/978-3-030-05798-5
- [3] Heath, T.L. (ed.) 2022. *The works of Archimedes*. New York, NY, USA: Dover Publications.
- [4] Anatriello, G. and Vincenzi, G., 2016. Logarithmic spirals and continue triangles. *Journal of Computational and Applied Mathematics*, 296, pp. 127-137.  
DOI: 10.1016/j.cam.2015.09.004
- [5] Nikolov, S., Petrov, M., Lymperakis, L., Friák, M., Sachs, C., Fabritius, H.O., Raabe, D. and Neugebauer, J., 2010. Revealing the design principles of high-performance biological composites using ab initio and multiscale simulations: The example of lobster cuticle. *Advanced Materials*, 22(4), pp. 519-526.  
DOI: 10.1002/adma.200902019
- [6] Sun, H., Kong, X., Park, H., Liu, F., Lee, Z. and Ding, F., 2022. Spiral growth of adlayer graphene. *Advanced Materials*, 34(12), 2107587.  
DOI: 10.1002/adma.202107587
- [7] Zhou, C., Zhang, X., Ai, J., Ji, T., Nagai, M., Duan, Y., Che, S. and Han, L., 2022. Chiral hierarchical structure of bone minerals. *Nano Research*, 15(2), pp. 1295-1302.  
DOI: 10.1007/s12274-021-3653-z
- [8] Golasz-Szolomicka, H. and Szolomicki, J., 2019. Architectural and structural analysis of selected twisted tall buildings. *IOP Conference Series: Materials Science and Engineering*, 471(5), 052050.  
DOI: 10.1088/1757-899X/471/5/052050
- [9] Taylor, J., 2002. *DVD demystified*. Maidenhead, UK: McGraw-Hill.



- 
- [10] Omar, M.B., Bingi, K., Prusty, B.R. and Ibrahim, R., 2022. Recent advances and applications of spiral dynamics optimization algorithm: A review. *Fractal and Fractional*, 6(1), 27.  
DOI: 10.3390/fractalfract6010027
- [11] Liang, L., Wang, M., Wang, X., Peng, P., Liu, Z., Chen, G. and Sun, G., 2022. Initiating a stretchable, compressible, and wearable thermoelectric generator by a spiral architecture with ternary nanocomposites for efficient heat harvesting. *Advanced Functional Materials*, 32(15), 2111435.  
DOI: 10.1002/adfm.202111435
- [12] Zhang, X., Zou, J., Tamhane, K., Kobzeff, F.F. and Fang, J., 2010. Self-assembly of pH-switchable spiral tubes: Supramolecular chemical springs. *Small*, 6(2), pp. 217-220.  
DOI: 10.1002/smll.200901067
- [13] Qaiser, N., Damdam, A.N., Khan, S.M. and Hussain, M.M., 2020. Symmetrical orientation of spiral-interconnects for high mechanical stability of stretchable electronics. In *IEEE International Conference on Flexible and Printable Sensors and Systems (FLEPS)*, Manchester, UK, 16–19 August, pp. 1–4. IEEE.  
DOI: 10.1109/FLEPS49123.2020.9239530
- [14] Li, Q., Wang, X., Dong, L., Liu, C. and Fan, S., 2019. Spirally deformable soft actuators and their designable helical actuations based on a highly oriented carbon nanotube film. *Soft Matter*, 15(47), pp. 9788-9796.  
DOI: 10.1039/C9SM01966A
- [15] Wang, D., Li, L., Serjouei, A., Dong, L., Weeger, O., Gu, G. and Ge, Q., 2018. Controllable helical deformations on printed anisotropic composite soft actuators. *Applied Physics Letters*, 112(18), 181905.  
DOI: 10.1063/1.5025370
- [16] Neebha, T.M., Andrushia, A.D. and Durga, S., 2020. A state-of-art review on antenna designs for ingestible application. *Electromagnetic Biology and Medicine*, 39(4), pp. 387-402.  
DOI: 10.1080/15368378.2020.1821707
- [17] Li, S. and Yang, J., 2021. Topological transition in spiral elastic valley metamaterials. *Physical Review Applied*, 15(1), 014058.  
DOI: 10.1103/PhysRevApplied.15.014058
- [18] Georgiev, N. and Burdick, J., 2017. Design and analysis of planar rotary springs. In *IEEE/RJSJ International Conference on Intelligent Robots and Systems (IROS)*, Vancouver, Canada, 24–28 September, pp. 4777-4784. IEEE.  
DOI: 10.1109/IROS.2017.8206352

- [19] Yao, G., Liu, P., Lu, S. and Yan, P., 2022. Design and analysis of additive manufactured flexure hinge with large stroke and high accuracy. *International Journal of Precision Engineering and Manufacturing*, 23(7), pp. 753-761.  
DOI: 10.1007/s12541-022-00657-8
- [20] Ahmad, B., Barbot, A., Ulliac, G. and Bolopion, A., 2022. Remotely actuated optothermal robotic microjoints based on spiral bimaterial design. *IEEE/ASME Transactions on Mechatronics*, 27(5), pp. 4090-4100.  
DOI: 10.1109/TMECH.2022.3145646
- [21] Scarcia, U., Berselli, G., Palli, G. and Melchiorri, C., 2017. Modeling, design, and experimental evaluation of rotational elastic joints for underactuated robotic fingers. In *IEEE-RAS International Conference on Humanoid Robots (Humanoids)*, Birmingham, UK, 15–17 November, pp. 353-358. IEEE.  
DOI: 10.1109/HUMANOIDS.2017.8246897
- [22] Zolfagharian, A., Lakhi, M., Ranjbar, S., Tadesse, Y. and Bodaghi, M., 2022. 3D printing non-assembly compliant joints for soft robotics. *Results in Engineering*, 15, 100558.  
DOI: 10.1016/j.rineng.2022.100558
- [23] Scarcia, U., Berselli, G., Melchiorri, C., Ghinelli, M. and Palli, G., 2016. Optimal design of 3D printed spiral torsion springs. In *ASME Conference on Smart Materials, Adaptive Structures and Intelligent Systems (SMASIS)*, Stowe, Vermont, USA, 28–30 September, V002T03A020. ASME.  
DOI: 10.1115/SMASIS2016-9218
- [24] Lagoda, C., Schouten, A.C., Stienen, A.H., Hekman, E.E. and van der Kooij, H., 2010. Design of an electric series elastic actuated joint for robotic gait rehabilitation training. In *IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob)*, Tokyo, Japan, 26–29 September, pp. 21-26. IEEE.  
DOI: 10.1109/BIOROB.2010.5626010
- [25] Matsumura, Y., Yoshizawa, K., Machida, R., Mashimo, Y., Dallai, R., Gottardo, M., Kleinteich, T., Michels, J., Gorb, S.N. and Beutel, R.G., 2014. Two intermittent organs in *Zorotypus caudelli* (Insecta, Zoraptera): The paradoxical coexistence of an extremely long tube and a large spermatophore. *Biological Journal of the Linnean Society*, 112(1), pp. 40-54.  
DOI: 10.1111/bij.12260
- [26] Krenn, H.W., 2010. Feeding mechanisms of adult Lepidoptera: Structure, function, and evolution of the mouthparts. *Annual Review of Entomology*, 55, pp. 307-327.  
DOI: 10.1146/annurev-ento-112408-085338

- [27] Matsumura, Y., Jafarpour, M., Reut, M., Shams Moattar, B., Darvizeh, A., Gorb, S.N. and Rajabi, H., 2021. Excavation mechanics of the elongated female rostrum of the acorn weevil *Curculio glandium* (Coleoptera; Curculionidae). *Applied Physics A*, 127, pp. 1-11.  
DOI: 10.1007/s00339-021-04353-8
- [28] Huffard, C.L., 2006. Locomotion by *Abdopus aculeatus* (Cephalopoda: Octopodidae): Walking the line between primary and secondary defenses. *Journal of Experimental Biology*, 209(19), pp. 3697-3707.  
DOI: 10.1242/jeb.02435
- [29] Luger, A.M., Ollevier, A., De Kegel, B., Herrel, A. and Adriaens, D., 2020. Is variation in tail vertebral morphology linked to habitat use in chameleons?. *Journal of Morphology*, 281(2), pp. 229-239.  
DOI: 10.1002/jmor.21093
- [30] Voeller, B.R., 1960. Regulation of “fiddlehead” uncoiling in ferns. *Naturwissenschaften*, 47(3), pp. 70-71.  
DOI: 10.1007/BF00708854
- [31] Vasco, A., Moran, R.C. and Ambrose, B.A., 2013. The evolution, morphology, and development of fern leaves. *Frontiers in Plant Science*, 4, 345.  
DOI: 10.3389/fpls.2013.00345
- [32] Shear, W.A., 2015. The chemical defenses of millipedes (Diplopoda): Biochemistry, physiology and ecology. *Biochemical Systematics and Ecology*, 61, pp. 78-117.  
DOI: 10.1016/j.bse.2015. 04.033
- [33] Fillamentum, and addi(c)tive polymers. 2019. Flexfill TPU 98A technical data sheet.
- [34] Smith, M., 2009. *Abaqus/standard user's manual, version 6.9*. Dassault Systèmes Simulia Corp, Providence, RI.
- [35] Khaheshi, A., Tramsen, H.T., Gorb, S.N. and Rajabi, H., 2021. Against the wind: A load-bearing, yet durable, kite inspired by insect wings. *Materials & Design*, 198, 109354.  
DOI: 10. 1016/j.matdes.2020.109354
- [36] Khaheshi, A., Gorb, S.N. and Rajabi, H., 2021. Spiky-joint: A bioinspired solution to combine mobility and support. *Applied Physics A*, 127, pp. 1-7.  
DOI: 10.1007/s00339-021-04310-5
- [37] Mintchev, S., Shintake, J. and Floreano, D., 2018. Bioinspired dual-stiffness origami. *Science Robotics*, 3(20), eaau0275.  
DOI: 10.1126/scirobotics.aau0275
- [38] Ibrahimi, M., Paternò, L., Ricotti, L. and Menciassi, A., 2021. A layer jamming actuator for tunable stiffness and shape-changing devices. *Soft Robotics*, 8(1), pp. 85-96.  
DOI: 10.1089/soro.2019.0182

- 
- [39] Sano, K., Ishida, Y. and Aida, T., 2018. Synthesis of anisotropic hydrogels and their applications. *Angewandte Chemie International Edition*, 57(10), pp. 2532-2543.  
DOI: 10.1002/anie.201708196
- [40] Gong, Q., Wu, J., Gong, X., Fan, Y. and Xia, H., 2013. Smart polyurethane foam with magnetic field controlled modulus and anisotropic compression property. *RSC Advances*, 3(10), pp. 3241-3248.  
DOI: 10.1039/C2RA22824F
- [41] Xiao, Y., Mao, J., Shan, Y., Yang, T., Chen, Z., Zhou, F., He, J., Shen, Y., Zhao, J., Li, T. and Luo, Y., 2020. Anisotropic electroactive elastomer for highly maneuverable soft robotics. *Nanoscale*, 12(14), pp. 7514-7521.  
DOI: 10.1039/D0NR00924E
- [42] Askari, M., Hutchins, D.A., Thomas, P.J., Astolfi, L., Watson, R.L., Abdi, M., Ricci, M., Laureti, S., Nie, L., Freear, S. and Wildman, R., 2020. Additive manufacturing of metamaterials: A review. *Additive Manufacturing*, 36, 101562.  
DOI: 10.1016/j.addma.2020.101562
- [43] Khaheshi, A. and Rajabi, H., 2022. Mechanical intelligence (MI): A bioinspired concept for transforming engineering design. *Advanced Science*, 9(32), 2203783.  
DOI: 10.1002/advs.202203783
- [44] Jafarpour, M., Gorb, S. and Rajabi, H., 2023. Double-spiral: A bioinspired pre-programmable compliant joint with multiple degrees of freedom. Figshare.  
DOI: 10.6084/m9.figshare.c.6360049

## Chapter 3:

# Double-spirals offer the development of pre-programmable modular metastructures\*

### Abstract

Metamaterials with adjustable, sometimes unusual properties offer advantages over conventional materials with predefined mechanical properties in many technological applications. A group of metamaterials, called modular metamaterials or metastructures, are developed through the arrangement of multiple, mostly similar building blocks. These modular structures can be assembled using prefabricated modules and reconfigured to promote efficiency and functionality. Herein, we developed a novel modular metastructure by taking advantage of the high compliance of pre-programmable double-spirals. First, we simulated the mechanical behavior of a four-module metastructure under tension, compression, rotation, and sliding using the finite-element method. Then, we used 3D printing and mechanical testing to illustrate the tunable anisotropic and asymmetric behavior of spiral-based metastructures in practice. Our results show the simple reconfiguration of the presented metastructure toward the desired functions. The mechanical behavior of single double-spirals and the characteristics that can be achieved through their combinations make our modular metastructure suitable for various applications in robotics, aerospace, and medical engineering.

**Keywords:** Mechanical intelligence, structured materials, functional design, finite-element method, 3D printing.

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## 1. Introduction

Structured materials with unprecedented tunable properties have been increasingly developed in recent years and found applications in robotics [1,2], electronics [3], energy harvesting systems [4,5], biomedical engineering [6], aerospace engineering [7,8], structural engineering [9], etc. [10-12]. These materials, which are referred to as metamaterials, are engineered to exhibit properties that are derived from their architecture, rather than constituent materials [13,14]. Negative swelling ratio [10], negative thermal-expansion coefficient [15], negative Poisson's ratio [16], negative moduli [17], anisotropic behavior [18,19], reversible non-linear deformability [20,21], programmability [22,23], and shape memorability [24] are some of the obtained mechanical properties.

Modular metamaterials consist of rationally designed modules or unit cells linked to each other. In these materials, desired mechanical properties can be achieved by engineered deformation of the consisting modules [25-27]. Hence, knowing the characteristics of each module is crucial when developing a metamaterial. The geometry, material composition, and spatial arrangement of modules are key factors that determine the behavior of modular metamaterials under different boundary conditions and loadings. Structures used as modules for the development of modular metamaterials vary from rotating rigid shapes [28-31], the wide range of honeycomb designs [32-34], and re-entrant structures [35-37] to horseshoe-shaped structures [10], foldable obelisk-like units [25], bio-inspired double-layer hinges [38], helical structures [39], and many other different designs [2,19,22,40,41].

The aim of this study is to investigate the potential of pre-programmable compliant double-spiral structures, which have been recently introduced by our team, when used as the modules of a metastructure. Adjustable design, multiple degrees of freedom, high extensibility, and reversible non-linear deformability are properties of the double-spirals that make them particularly interesting for the development of deformable structures [42]. We expect that pre-programmable double-spiral modules will enable us to control the mechanical properties of a metastructure in different directions in a passive-automatic way.

Using the finite-element method (FEM), we simulate the mechanical behavior of a four-module metastructure under different loading scenarios. We also manufacture two modular metastructures using 3D printing and illustrate their performance in practice. Our results show that the combination of different double-spirals can lead to tunable anisotropy, asymmetric behavior, pre-programmable shape change, spatial heterogeneity, and simple reconfiguration of the developed metastructure.

## 2. Methods

### 2.1. Modeling and finite element analysis

Following the method adopted by Jafarpour et al. [42], we used the equation of logarithmic spirals in the polar coordinate system (equation 1) to plot spiral curves using the programming software MATLAB (MathWorks).

$$r = r_0 e^{-k\theta}, \quad (1)$$

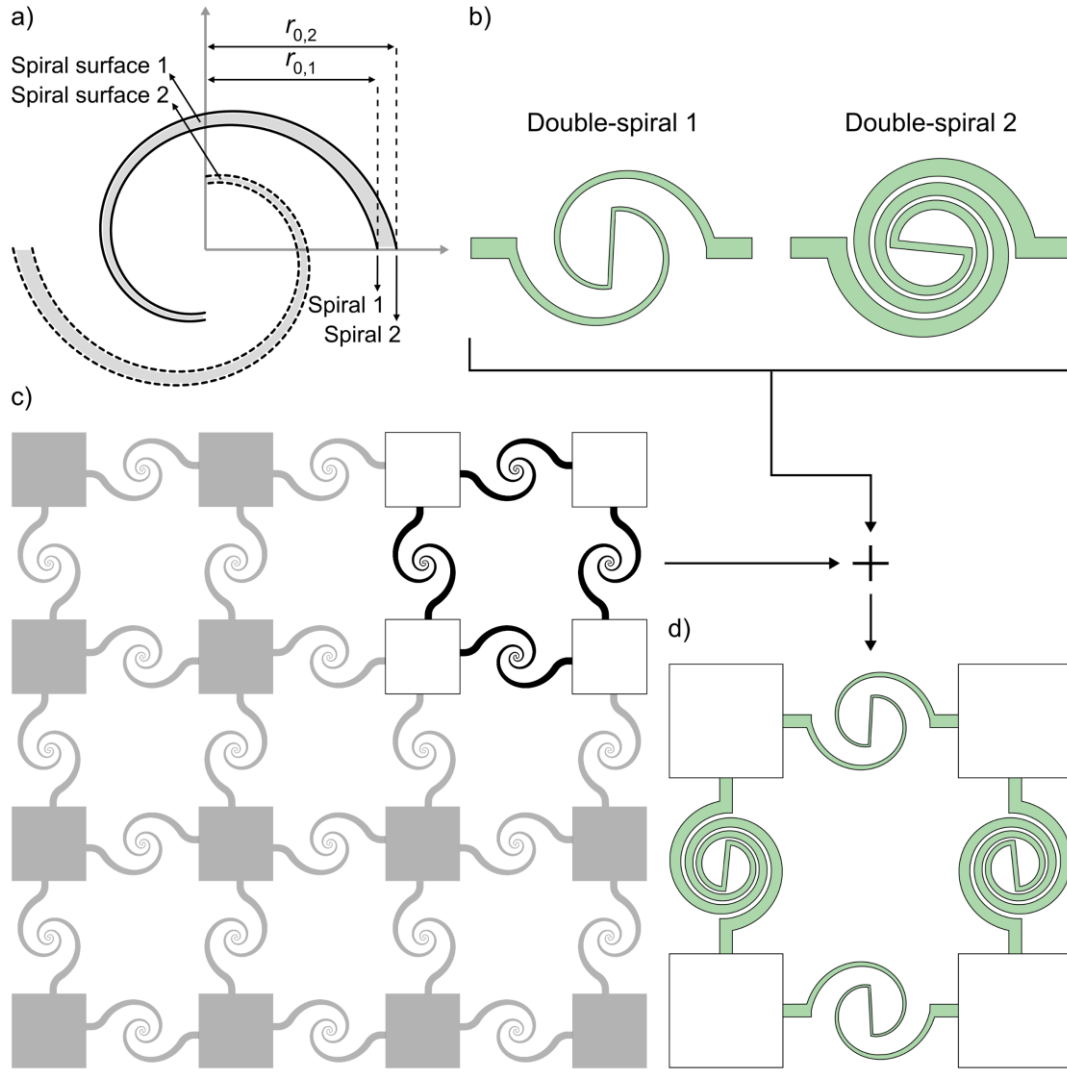
In the above equation,  $r_0$  is the radius of the spiral at  $\theta = 0$ , and  $k$  is the polar slope [43].

We plotted two logarithmic spirals with different initial radii ( $r_{0,1} = 13.5$  mm,  $r_{0,2} = 15.0$  mm) but an equal polar slope ( $k = 0.2$ ) from 0 to  $1.5\pi$  radians. We then rotated them around the origin of the coordinate system by  $\pi$  radian to generate two other spirals. These four spiral curves formed two spiral surfaces (Fig. 1a). After connecting the bases and the ends of spirals with straight lines, the plot was imported to the finite-element software package ABAQUS/Standard v. 6.14 (SIMULIA) to develop the two-dimensional (2D) numerical model of the first double-spiral, named double-spiral 1 (Fig. 1b).

The same procedure was used to develop a geometrically different double-spiral to investigate the behavior of a combination of double-spirals employed as the modules of a modular metastructure. We set the initial thickness, polar slope, and angle of rotation of double-spiral 2 to be 3 mm ( $r_{0,2} - r_{0,1} = 15 - 12 = 3$ ), 0.1, and  $3\pi$  radians, respectively (Fig. 1b). The values of the design variables were selected to obtain models with significantly different geometries. Double-spiral 1 is much shorter, thinner, and more curved than double-spiral 2.

A modular metastructure, in which double-spiral modules were connected to blocks forming a square, was designed here (Fig. 1c). We employed two models of each double-spiral 1 and 2 to develop a four-module metastructure (Fig. 1d). We used this planar model to simulate its mechanical behavior subjected to in-plane loading scenarios in Abaqus. The model was meshed using four-node bilinear plane-stress quadrilateral elements with reduced integration (CPS4R). A mesh sensitivity analysis was conducted to set the size of the elements. The 0.1 mm elements resulted in accurate solutions in reasonable computational time. We used the self-contact formulation in Abaqus to define the physical contacts between interacting surfaces [44].

The material properties of the thermoplastic polyurethane (Flexfill TPU 98A, Fillamentum additive polymers, Czech Republic) presented in Table 1 were assigned to the model [45].



**Fig 1.** Development of 2D models of double-spirals and four-module metastructure. a) Plotting four spiral curves to generate two spiral surfaces for the development of double-spiral 1. b) Double-spiral 1 and 2 models. c) A modular metastructure consisting of double-spiral modules connected to blocks. d) Employing double-spirals 1 and 2 to develop a four-module metastructure.

**Table 1.** Mechanical properties of the thermoplastic polyurethane filament (Flexfill TPU 98A, Fillamentum addi©tive polymers, Czech Republic) [45].

Density ( $\text{kg m}^{-3}$ )	1230	Stress (MPa)	0.0	12.1	22.1	28.4	37.8
Poisson's ratio	0.3	Strain	0.0	0.1	0.5	1.0	3.0

We used the Abaqus implicit solver to simulate the quasi-static behavior of the model under different loading scenarios. In all loading scenarios, the boundary conditions and loads were applied to the rigid blocks that were connected to the double-spirals. We avoided the large strain behavior of the elements and focused on reversible elastic deformations by limiting the load values. The following loading scenarios were simulated to characterize the performance of the spiral-based modular metastructure (Fig. 2):



- **Tension.** Here, we extended the model once in the vertical and once in the horizontal directions (with respect to the horizon). In both cases, we clamped the model on one side and pulled it on the opposite side until the double-spirals reached their maximum lengths (Fig. 2a).
- **Compression.** In this loading scenario, we compressed the model twice in two perpendicular directions, while the blocks on the opposite side were fixed (Fig. 2b). The compression was accomplished by applying a 2 N force.
- **Rotation.** Under rotation, the model was clamped at the two opposite blocks b1 and b3, and then only one of the two other blocks, i.e., b2, was subjected to a counterclockwise (CCW) moment (equal to 50 N.mm). Under the same loading and boundary condition, we then rotated the same block clockwise (CW) (Fig. 2c).
- **Sliding.** In this loading scenario, first we fixed the blocks on one side, here b1 and b4, and pulled one of the two other blocks, i.e., b3, downward by 50 mm, whereas b2 could move only vertically. We then clamped the model at a different side, i.e., b3 and b4, and pulled b2 horizontally to reach the same displacement, while b1 was restricted in the vertical direction (Fig. 2d).




## 2.2. Prototyping and mechanical testing

We manufactured two double-spirals used in the numerical simulations with a fused deposition modeling (FDM) 3D printer (Prusa i3 MK3S, Prusa Research, Praha, Czech Republic) to test their behavior and validate our numerical results. Double-spirals and fixtures were printed using a semi-flexible polyurethane filament (Flexfill TPU 98A, Fillamentum addi(c)tive polymers, Czech Republic) and a polylactic acid (PLA) filament (Prusa Research, Praha, Czech Republic), respectively. A ZwickiLine uniaxial testing machine (Zwick Roell, Ulm, Germany) equipped with a 500 N load cell (Xforce P load cell, Zwick Roell) was used to quantify the tensile behavior of the manufactured double-spirals. Three specimens of each double-spiral were tested (three times each) under the same loading and boundary conditions used in the numerical simulation of tensile loading (Fig. 3).

In the next step, we fabricated three double-spirals with distinct geometries using TPU filament and connected them to each other using connecting blocks made of PLA to develop modular metastructures with adjustable properties. We then tested their mechanical performance in practice. The values selected for design variables to obtain the 3D models of double-spirals, and the 3D printing settings are given in Table 2. We assembled the printed parts to make a beam-like and a cubic metastructure and characterized their behavior in two different experiments. First, we fixed one end of the beam structure and applied a 250 N.mm moment to its other end to investigate its

behavior in bending (Fig. 4). Then we used our uniaxial testing machine to quantify the compressive behavior of the cubic structure in three different directions (Fig. 5).

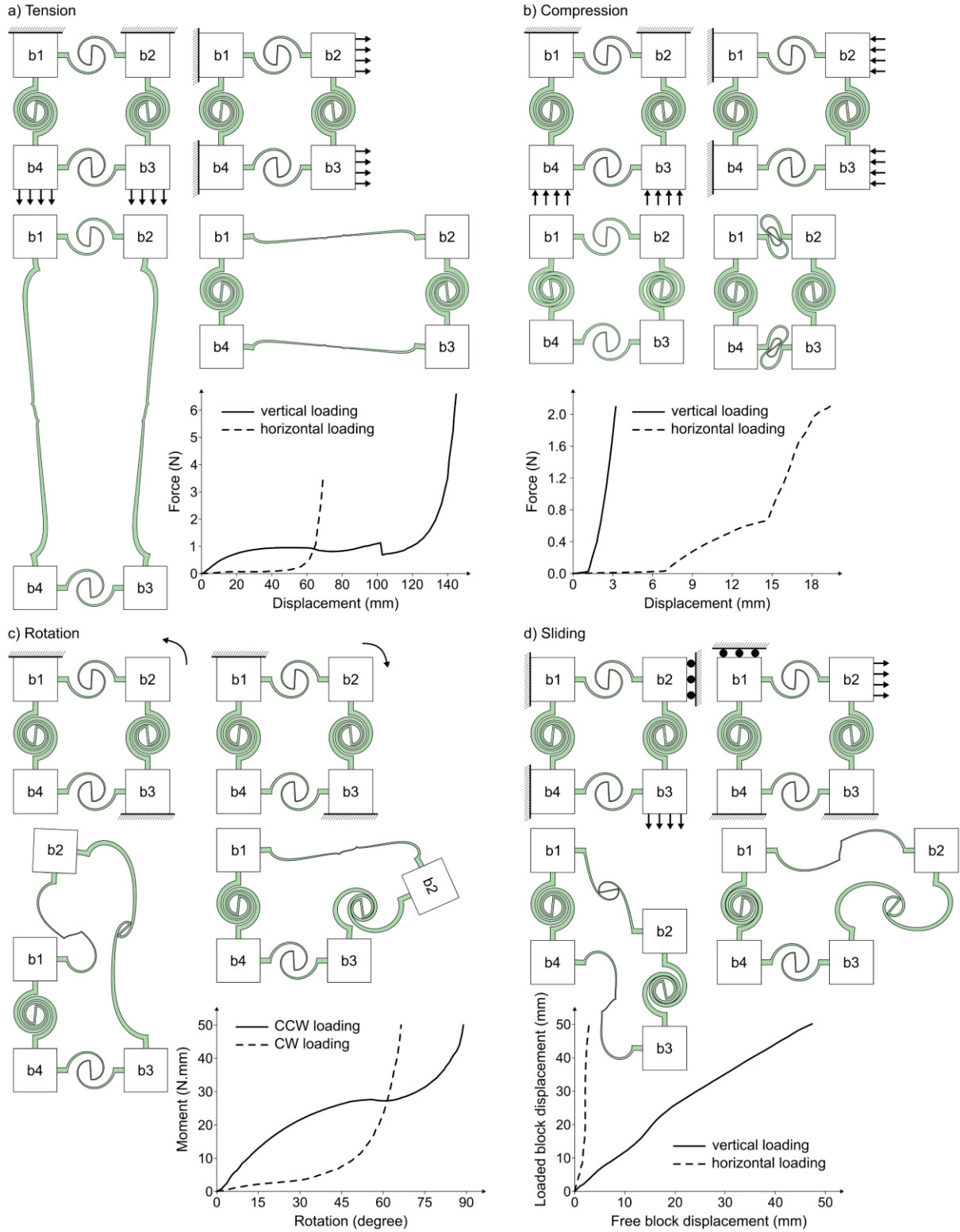
**Table 2.** Double-spiral models developed for 3D printing, besides their corresponding values of design variables, and settings used for 3D printing.

3D modeling				
Developed double-spirals		Double-spiral 1	Double-spiral 2	Double-spiral 3
				
Design variables	Polar slope	0.10	0.20	0.05
	Initial thickness (mm)	3.0	2.5	1.0
	Angle of rotation (rad)	$3\pi$	$1.5\pi$	$4\pi$
	Extrusion height (mm)	20	20	20
3D printing settings				
Filament	Thermoplastic polyurethane (Flexfill TPU 98A)		Polylactic acid (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		20	

### 3. Results

#### 3.1. Finite-element analysis

The double-spirals, their arrangement in the presented metastructures, and used loading scenarios are only a few examples of the many potential combinations of design, loading, and boundary conditions. We presented these specific combinations to illustrate the potentials of our modular metastructure for a range of practical applications.



**Fig 2.** Simulation of the mechanical behavior of the four-module metastructure model. Results are given for the following loading scenarios: in-plane a) tension, b) compression, c) rotation, and d) sliding. Shaded areas show the fixed boundary conditions, and arrows show the direction of the applied loads.

The force-displacement diagram resulted from the simulation of tension showed that both tensile force and displacement in the vertical direction were about twice those in the horizontal

direction (Fig. 2a). The compressive force-displacement diagram showed that the metastructure was about six times stiffer under compression in the vertical direction than in the horizontal direction (Fig. 2b). These two loadings show the anisotropy of the developed metastructure.

Rotating a block of the model (b2 in Fig. 2c) in two opposite directions (CW and CCW) demonstrated its asymmetric behavior. Although the rotational deflections of b2 subjected to the same moment in two directions were not much different, the work required for the CCW deformation was about four times that for the CW deformation. The moment-rotation diagram shows the different stiffnesses of the metastructure in the two directions and their variations as the deformation increases.

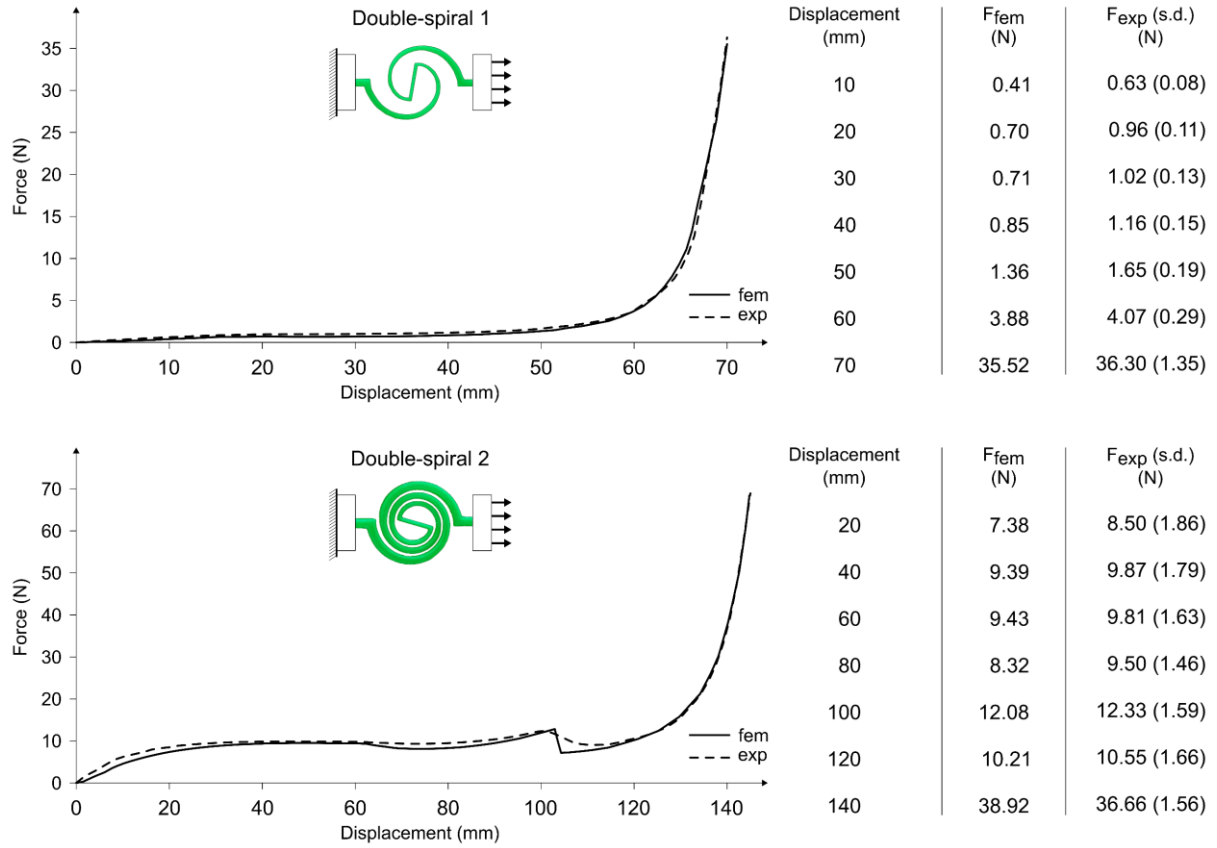
The force-displacement curves illustrate non-linear behavior of the metastructure, related to the specific phases of the deformation of double-spirals under different loading scenarios (i.e., initial clearance, unrolling, and unfolding) [42]. The tension and rotation of the metastructure in two different directions occur with an inversion of anisotropy. In tension, 0.5 N force is enough to unroll double-spiral 1 horizontally and reach the high-stiffness unfolding phase (around 60 mm displacement). However, the vertical 0.5 N force extends double-spiral 2 by only 10 mm. Nevertheless, the metastructure has higher extensibility in the vertical direction when it is subjected to larger tensile forces. The same scenario lies behind the inversion of anisotropy in the CW and CCW rotations of the metastructure.

We used the sliding scenario to indicate the behavior of the free block which was not loaded (b2 in the vertical sliding and b1 in the horizontal sliding, Fig. 2d). In the vertical loading, the displacement of the loaded block (b3) led to almost the same displacement of the free block (b2). However, in the horizontal loading, when we moved the block (b2) horizontally, the free block (b1) did not move and therefore the whole structure showed a different deformation pattern compared to the vertical loading (Fig. 2d).

### 3.2. Prototyping and mechanical testing

Here, we 3D printed the double-spirals used in the numerical simulations and characterized their tensile behavior experimentally to verify the validity of our simulations. To this goal, we averaged the force-displacement curves from the experiments ( $n=9$ ) and compared that to the numerical force-displacement curve (Fig. 3). The quality of the fit was measured by comparing the average force values resulted from the two methods at the same displacements. The comparisons show

that for both double-spirals, a good agreement exists between the numerical and experimental J-shaped curves.

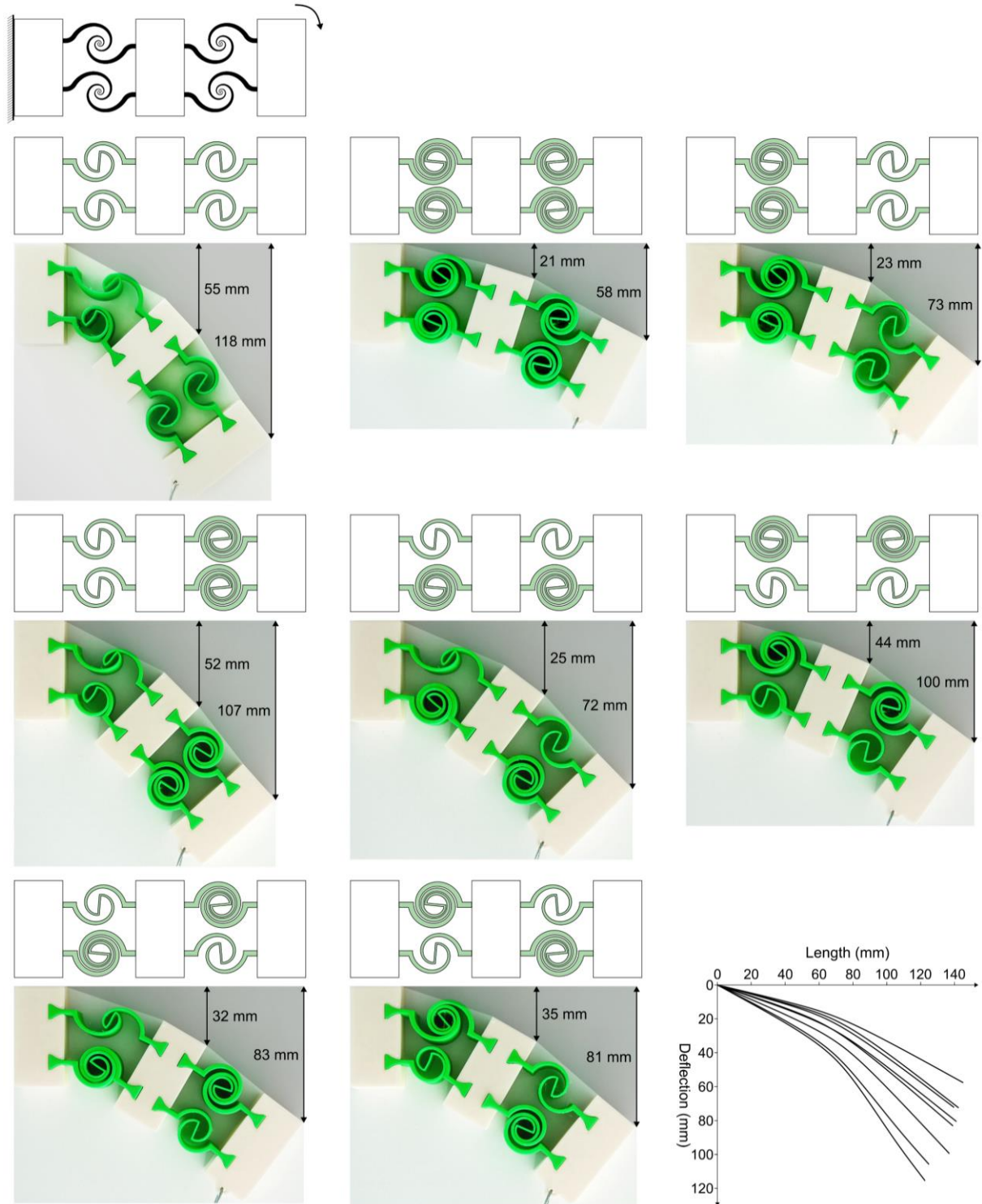


**Fig 3.** 3D printing and testing of two double-spirals used in the numerical simulations. Comparison of the force–displacement curves and force values obtained from the numerical and experimental tensile tests on double-spirals 1 and 2.

Two spiral-based metastructures were manufactured and tested in the next step. First, a beam-like modular metastructure was developed using double-spirals 1 and 2, that were horizontally connected to three blocks (Fig. 4). Four double-spirals were arranged in eight different combinations. Fixing one end of these structures and applying an equal moment to their free end resulted in different deformation patterns. The deflection of the middle point of beams varied from 21 mm to 55 mm, and the deflection of their tip varied from 53 mm to 118 mm. This demonstrates the asymmetric behavior and tunable structural stiffness of the developed structures that results from the different combinations of two double-spirals with different thicknesses, lengths, and polar slopes.

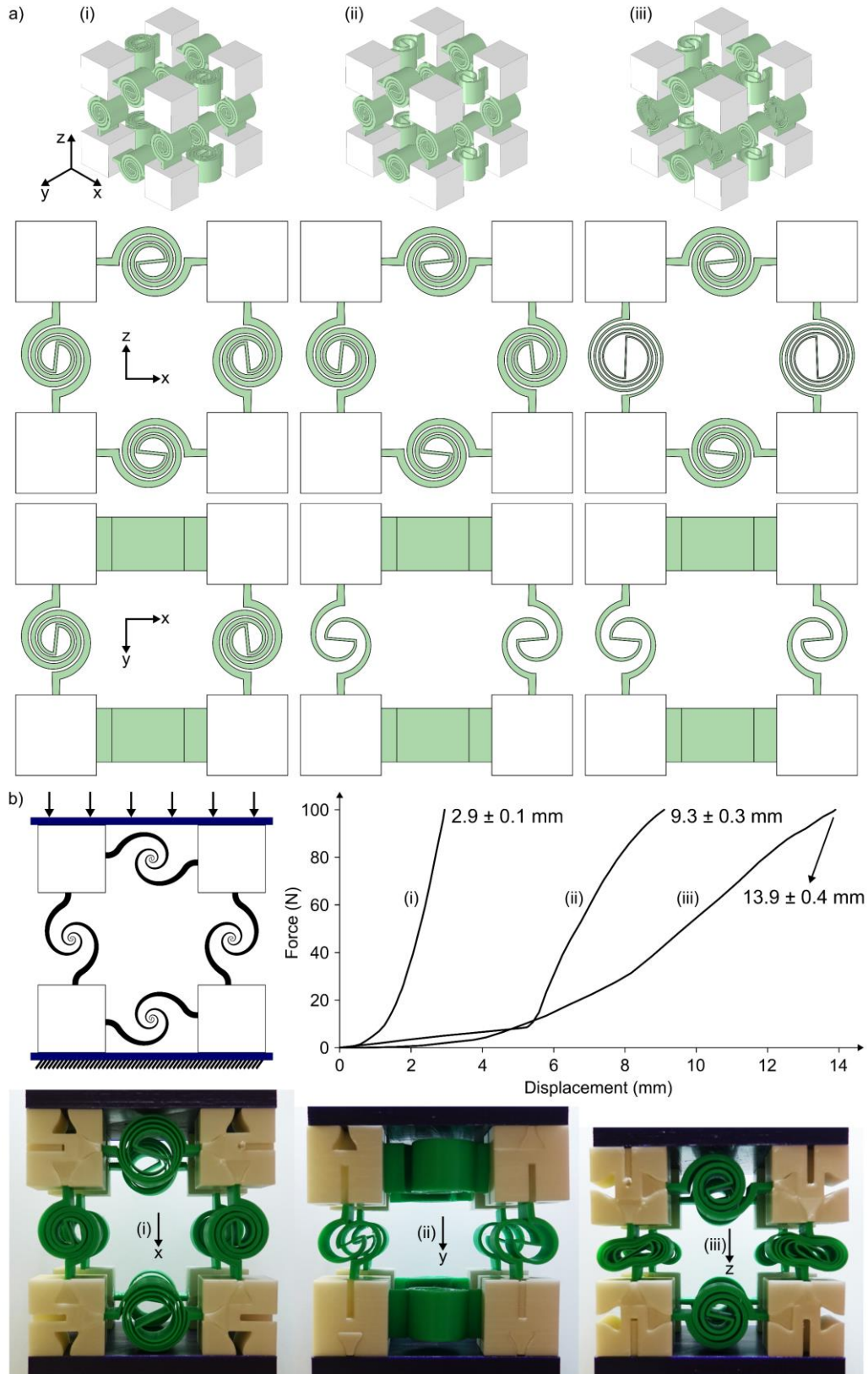
We then used double-spirals 1, 2, and 3 to connect eight blocks in the form of a cube and developed three cubic modular metastructures (Fig. 5a). The first cube was made up of double-spiral 1 only and was expected to have the same compressive stiffness in all three directions of the

Cartesian coordinate system (Fig. 5a-i). The second cube, consisting of double-spirals 1 and 2, could behave the same in x and z directions, but different in y direction (Fig. 5a-ii).



**Fig 4.** 3D printing and testing of a beam-like modular metastructure. Eight structures were developed using double-spirals 1 and 2 arranged in eight different ways. The structures were fixed at one end and a 250 N.mm moment was applied to their free end. The shaded area shows the fixed boundary condition, and the arrow shows the direction of the applied moment. The deflections of the loaded structures can be compared using the displacement values written next to the blocks and the plot illustrating their deflections all together.





**Fig 5.** 3D printing and testing of a cubic modular metastructure. a) Three cubes were developed using double-spirals 1, 2, and 3. b) The third cube was placed between two plates, and a 100 N force was used to displace one plate towards the other one that was fixed. The force-displacement diagram shows the anisotropic behavior of the cubic metastructure in x, y, and z directions. The average values of the maximum displacement ( $n=5$ ) and their standard deviations are written next to the corresponding curves.

To have a cubic metastructure with a specific mechanical characteristic in each direction, we used four of each double-spirals 1, 2, and 3 and developed the third cube (Fig. 5a-iii). The compressive behavior of this cube was quantified in three directions (Fig. 5b). We placed it between two plates and used a 100-N force to displace one plate towards the other one that was fixed. Repeating this test five times in each direction resulted in  $2.9 (\pm 0.1)$  mm,  $9.3 (\pm 0.3)$  mm, and  $13.9 (\pm 0.4)$  mm displacement of the plate in the x, y, and z direction, respectively. The compression of the double-spirals starts with a low-stiffness deformation phase, which arises from the free space between their coils, and continues with a gradual increase in the stiffness, which results from the contact between the coils [42]. The different compressive behaviors of the metastructure in x, y, and z directions are mainly caused by the different free space available between the coils of the double-spirals and their thicknesses, which can be simply adjusted by changing the values of the design variables.

## 4. Discussion

Modular metastructures consisting of exchangeable modules can be used in different applications in which simple adjustability is a requirement. In this study, we used only two/three geometrically different double-spirals as modules of spiral-based modular metastructures to obtain distinct mechanical behaviors under the same load. Our results showed that the geometrical design variables of the double-spirals can be used to pre-program the behaviors observed. The spatial arrangement of the double-spirals, type of loading, and boundary condition determine the behavior of the spiral-based modular metastructure.

Using our double-spirals in the developed metastructure enabled us to tune the stiffness of the metastructure in different directions and how it changes during the application of the external loads. Our results illustrated the high reversible extensibility, variable stiffness, anisotropy, and asymmetric behavior of the developed metastructures. We could tune all these features by changing the design variables of the double-spirals and controlling the structural stiffness in each direction. These characteristics can be a great advantage to many engineering structures, such as mechanical hinges [46,47] biomedical implants [19], asymmetric casts and splints [48], flexible body armors [49], and load-bearing yet collision-resistant kites [50].

Programmed shape change in response to mechanical loads is another interesting property of the developed metastructures. Shape changes can enable engineering structures to transform into predictable shapes when loaded, to change their performance and/or improve their efficiency [22,23]. In this study, the sliding loading scenario conducted horizontally and vertically resulted in



two different deformation patterns (Fig. 2d). The difference is due to the internal boundary condition that double-spirals passively apply on each block. Numerical and experimental results suggest that this shape change can be pre-programmed by using different double-spirals with suitable geometrical design variables (Fig. 2d, 4). Varying the orientation of the modules from the horizontal and vertical directions to angled directions is another strategy that can also change the local boundary condition on the blocks and influence the behavior of the metastructure.

Since the modular metastructure developed here comprises individual modules, the dimensions of the metastructure can be easily changed by adding or removing double-spirals. Employing double-spirals with various mechanical behaviors in a larger structure could result in spatial heterogeneity or gradient of properties. However, there is a constraint against increasing this heterogeneity. Complex aperiodic architectures could hinder the desired functionality of a structure and prevent its coherent and predictable response [22,51]. Therefore, any design should provide a trade-off between the high level of controllability and complexity.

In this study, we presented the concept of using compliant double-spirals as the modules of a modular metastructure. The results showed the potential of double-spirals for this purpose. Considering that our simulations were conducted on small assemblies of double-spirals, future studies should focus on characterizing the behavior of spiral-based metastructures in large scales. A combinatorial design theory [22], an inverse-design method [51], and a structural stiffness matrix-based computational method [52] are a few examples that can be used to predict the mechanical behavior of large spiral-based modular metastructures. Further investigations should examine the performance of the double-spirals with different geometries and material compositions under long-term loadings. Artificial intelligence (AI) has progressed researches on metamaterials significantly [12] and can be used in future studies to obtain double-spirals with geometries optimized for specific applications. The arrangement of the modules in the developed metastructure is another factor that remains to be tested to improve its mechanical behavior.

## 5. Conclusion

In this article, we presented a modular metastructure that consists of compliant double-spirals and investigated its mechanical behavior under different loading scenarios. Our results showed that by combining double-spirals in specific configurations, we can exploit desired properties, including tunable anisotropy, asymmetric behavior, pre-programmable shape change, and spatial heterogeneity, besides the advantageous features of single double-spirals, such as simply adjustable design, multiple degrees of freedom, high extensibility, and reversible non-linear deformability. Further-

more, if any unexpected modification is necessary, the use of independently exchangeable modules in the modular metastructure makes its reconfiguration feasible. Individual double-spirals could be printed fast at low costs using a single material and be readily assembled. The metastructure presented in this study can offer an alternative design for engineered materials that are currently in use in various engineering fields. Compact, yet highly extensible double-spirals make the metastructure adequate for aerospace engineering products which need to be portable and stowable. Highly tunable non-linear deformations of the spiral-based metastructure in different directions suggest it could provide an efficient solution to the development of biomedical engineering devices for rehabilitation. The metastructure comprised pre-programmable double-spirals, which control the motion of components in a passive-automatic way, could be of particular interest in articulated robots.

## References

- [1] Wang, L., Yang, Y., Chen, Y., Majidi, C., Iida, F., Askounis, E. and Pei, Q., 2018. Controllable and reversible tuning of material rigidity for robot applications. *Materials Today*, 21(5), pp. 563-576. DOI: 10.1016/j.mattod.2017.10.010
- [2] Khajehtourian, R. and Kochmann, D.M., 2021. Soft adaptive mechanical metamaterials. *Frontiers in Robotics and AI*, 8, 121. DOI: 10.3389/frobt.2021.673478
- [3] Ma, Y., Feng, X., Rogers, J.A., Huang, Y. and Zhang, Y., 2017. Design and application of 'J-shaped' stress-strain behavior in stretchable electronics: A review. *Lab on a Chip*, 17(10), pp. 1689-1704. DOI: 10.1039/C7LC00289K
- [4] Jiao, P., Yang, Y., Egbe, K.I., He, Z. and Lin, Y., 2021. Mechanical metamaterials gyro-structure piezoelectric nanogenerators for energy harvesting under quasi-static excitations in ocean engineering. *ACS Omega*, 6(23), pp. 15348-15360. DOI: 10.1021/acsomega.1c01687
- [5] Jiao, P., Zhang, H. and Li, W., 2023. Origami tribo-metamaterials with mechanoelectrical multistability. *ACS Applied Materials & Interfaces*. 15(2), pp. 2873-2880. DOI: 10.1021/acsami.2c16681
- [6] Jang, K.I., Chung, H.U., Xu, S., Lee, C.H., Luan, H., Jeong, J., Cheng, H., Kim, G.T., Han, S.Y., Lee, J.W. and Kim, J., 2015. Soft network composite materials with deterministic and bio-inspired designs. *Nature Communications*, 6(1), 6566. DOI: 10.1038/ncomms7566

- 
- [7] Jefferson, G., Parthasarathy, T.A. and Kerans, R.J., 2009. Tailorable thermal expansion hybrid structures. *International Journal of Solids and Structures*, 46(11-12), pp. 2372-2387.  
DOI: 10.1016/j.ijsolstr.2009.01.023
- [8] Morgan, J., Magleby, S.P. and Howell, L.L., 2016. An approach to designing origami-adapted aerospace mechanisms. *Journal of Mechanical Design*, 138(5), 052301.  
DOI: 10.1115/1.4032973
- [9] Cveticanin L., 2020. Mechanical metastructure in structural engineering: A short review. *Current Trends in Civil & Structural Engineering*, 6(1), pp. 459-466.  
DOI: 10.33552/CTCSE.2020.06.000633
- [10] Zhang, H., Guo, X., Wu, J., Fang, D. and Zhang, Y., 2018. Soft mechanical metamaterials with unusual swelling behavior and tunable stress-strain curves. *Science Advances*, 4(6), eaa8535.  
DOI: 10.1126/sciadv.aar8535
- [11] Surjadi, J.U., Gao, L., Du, H., Li, X., Xiong, X., Fang, N.X. and Lu, Y., 2019. Mechanical metamaterials and their engineering applications. *Advanced Engineering Materials*, 21(3), 1800864.  
DOI: 10.1002/adem.201800864
- [12] Jiao, P. and Alavi, A.H., 2021. Artificial intelligence-enabled smart mechanical metamaterials: Advent and future trends. *International Materials Reviews*, 66(6), pp. 365-393.  
DOI: 10.1002/adem.201800864
- [13] Yu, X., Zhou, J., Liang, H., Jiang, Z. and Wu, L., 2018. Mechanical metamaterials associated with stiffness, rigidity and compressibility: A brief review. *Progress in Materials Science*, 94, pp. 114-173.  
DOI: 10.1016/j.pmatsci.2017.12.003
- [14] Bertoldi, K., Vitelli, V., Christensen, J. and Van Hecke, M., 2017. Flexible mechanical metamaterials. *Nature Reviews Materials*, 2(11), 17066.  
DOI: 10.1038/natrevmats.2017.66
- [15] Qu, J., Kadic, M., Naber, A. and Wegener, M., 2017. Micro-structured two-component 3D metamaterials with negative thermal-expansion coefficient from positive constituents. *Scientific Reports*, 7(1), 40643.  
DOI: 10.1038/srep40643
- [16] Kolken, H.M. and Zadpoor, A.A., 2017. Auxetic mechanical metamaterials. *RSC Advances*, 7(9), pp. 5111-5129.  
DOI: 10.1039/C6RA27333E
- [17] Zadpoor, A.A., 2016. Mechanical meta-materials. *Materials Horizons*, 3(5), pp. 371-381.  
DOI: 10.1039/C6MH00065G

- 
- [18] Layman, C.N., Naify, C.J., Martin, T.P., Calvo, D.C. and Orris, G.J., 2013. Highly anisotropic elements for acoustic pentamode applications. *Physical Review Letters*, 111(2), 024302.  
DOI: 10.1103/PhysRevLett.111.024302
- [19] Xu, S., Shen, J., Zhou, S., Huang, X. and Xie, Y.M., 2016. Design of lattice structures with controlled anisotropy. *Materials & Design*, 93, pp. 443-447.  
DOI: 10.1016/j.matdes.2016.01.007
- [20] Mousanezhad, D., Ebrahimi, H., Haghpanah, B., Ghosh, R., Ajdari, A., Hamouda, A.M.S. and Vaziri, A., 2015. Spiderweb honeycombs. *International Journal of Solids and Structures*, 66, pp. 218-227.  
DOI: 10.1016/j.ijsolstr.2015.03.036
- [21] Bonatti, C. and Mohr, D., 2017. Large deformation response of additively-manufactured FCC metamaterials: From octet truss lattices towards continuous shell mesostructures. *International Journal of Plasticity*, 92, pp. 122-147.  
DOI: 10.1016/j.ijplas.2017.02.003
- [22] Coulais, C., Teomy, E., De Reus, K., Shokef, Y. and Van Hecke, M., 2016. Combinatorial design of textured mechanical metamaterials. *Nature*, 535(7613), pp. 529-532.  
DOI: 10.1038/nature18960
- [23] Konaković-Luković, M., Panetta, J., Crane, K. and Pauly, M., 2018. Rapid deployment of curved surfaces via programmable auxetics. *ACM Transactions on Graphics (TOG)*, 37(4), pp. 857-869.  
DOI: 10.1145/3197517.3201373
- [24] Wang, J., Hong, L. and Jiao, P., 2023. Graphene-reinforced shape memorable chiral metamaterials: Theoretical analysis with experimental and numerical validations. *Materials & Design*, 226, 111648.  
DOI: 10.1016/j.matdes.2023.111648
- [25] Yang, N., Zhang, M., Zhu, R. and Niu, X.D., 2019. Modular metamaterials composed of foldable obelisk-like units with reprogrammable mechanical behaviors based on multistability. *Scientific Reports*, 9(1), 18812.  
DOI: 10.1038/s41598-019-55222-7
- [26] Liu, W., Jiang, H. and Chen, Y., 2022. 3D programmable metamaterials based on reconfigurable mechanism modules. *Advanced Functional Materials*, 32(9), 2109865.  
DOI: 10.1002/adfm.202109865
- [27] Mao, J.J., Wang, S., Tan, W. and Liu, M., 2022. Modular multistable metamaterials with reprogrammable mechanical properties. *Engineering Structures*, 272, 114976.  
DOI: 10.1016/j.engstruct.2022.114976

- [28] Grima, J.N., Alderson, A. and Evans, K.E., 2005. Auxetic behaviour from rotating rigid units. *Physica Status Solidi (b)*, 242(3), pp. 561-575.  
DOI: 10.1002/pssb.200460376
- [29] Attard, D. and Grima, J.N., 2008. Auxetic behaviour from rotating rhombi. *Physica Status Solidi (b)*, 245(11), pp. 2395-2404.  
DOI: 10.1002/pssb.200880269
- [30] Gatt, R., Mizzi, L., Azzopardi, J.I., Azzopardi, K.M., Attard, D., Casha, A., Briffa, J. and Grima, J.N., 2015. Hierarchical auxetic mechanical metamaterials. *Scientific Reports*, 5(1), 8395.  
DOI: 10.1038/srep08395
- [31] Jamalimehr, A., Mirzajanzadeh, M., Akbarzadeh, A. and Pasini, D., 2022. Rigidly flat-foldable class of lockable origami-inspired metamaterials with topological stiff states. *Nature Communications*, 13(1), 1816.  
DOI: 10.1038/s41467-022-29484-1
- [32] Mousanezhad, D., Haghpanah, B., Ghosh, R., Hamouda, A.M., Nayeb-Hashemi, H. and Vaziri, A., 2016. Elastic properties of chiral, anti-chiral, and hierarchical honeycombs: A simple energy-based approach. *Theoretical and Applied Mechanics Letters*, 6(2), pp. 81-96.  
DOI: 10.1016/j.taml.2016.02.004
- [33] Bodaghi, M., Damanpack, A.R., Hu, G.F. and Liao, W.H., 2017. Large deformations of soft metamaterials fabricated by 3D printing. *Materials & Design*, 131, pp. 81-91.  
DOI: 10.1016/j.matdes.2017.06.002
- [34] Zhang, Y., Ren, X., Jiang, W., Han, D., Zhang, X.Y., Pan, Y. and Xie, Y.M., 2022. In-plane compressive properties of assembled auxetic chiral honeycomb composed of slotted wave plate. *Materials & Design*, 221, 110956.  
DOI: 10.1016/j.matdes.2022.110956
- [35] Grima, J.N., Gatt, R., Alderson, A. and Evans, K.E., 2005. On the potential of connected stars as auxetic systems. *Molecular Simulation*, 31(13), pp. 925-935.  
DOI: 10.1080/08927020500401139
- [36] Xu, N. and Liu, H.T., 2020. A novel 3-D structure with tunable Poisson's ratio and adjustable thermal expansion. *Composites Communications*, 22, 100431.  
DOI: 10.1016/j.coco.2020.100431
- [37] Gong, X., Ren, C., Sun, J., Zhang, P., Du, L. and Xie, F., 2022. 3D zero Poisson's ratio honeycomb structure for morphing wing applications. *Biomimetics*, 7(4), 198.  
DOI: 10.3390/biomimetics7040198

- 
- [38] Rajabi, H., Eraghi, S.H., Khaheshi, A., Toofani, A., Hunt, C. and Wootton, R.J., 2022. An insect-inspired asymmetric hinge in a double-layer membrane. *Proceedings of the National Academy of Sciences*, 119(45), e2211861119.  
DOI: 10.1073/pnas.2211861119
- [39] Cimolai, G., Dayyani, I. and Qin, Q., 2022. Multi-objective shape optimization of large strain 3D helical structures for mechanical metamaterials. *Materials & Design*, 215, 110444.  
DOI: 10.1016/j.matdes.2022.110444
- [40] Ma, Z., Lin, J., Xu, X., Ma, Z., Tang, L., Sun, C., Li, D., Liu, C., Zhong, Y. and Wang, L., 2019. Design and 3D printing of adjustable modulus porous structures for customized diabetic foot insoles. *International Journal of Lightweight Materials and Manufacture*, 2(1), pp. 57-63.  
DOI: 10.1016/j.ijlmm.2018.10.003
- [41] Dong, L., Wang, D., Wang, J., Jiang, C., Wang, H., Zhang, B., Wu, M.S. and Gu, G., 2022. Modeling and design of periodic polygonal lattices constructed from microstructures with varying curvatures. *Physical Review Applied*, 17(4), 044032.  
DOI: 10.1103/PhysRevApplied.17.044032
- [42] Jafarpour, M., Gorb, S. and Rajabi, H., 2023. Double-spiral: A bioinspired pre-programmable compliant joint with multiple degrees of freedom. *Journal of the Royal Society Interface*, 20(198), 20220757.  
DOI: 10.1098/rsif.2022.0757
- [43] Tsuji, K. and Müller, S.C. (eds.) 2019. *Spirals and vortices: In culture, nature, and science*. Cham, Switzerland: Springer.  
DOI: 10.1007/978-3-030-05798-5
- [44] Smith, M., 2009. *Abaqus/standard user's manual, version 6.9*. Dassault Systèmes Simulia Corp, Providence, RI.
- [45] Fillamentum, and addi(c)tive polymers. 2019. Flexfill TPU 98A technical data sheet.
- [46] Pinski, J., Shirinzadeh, B., Ghafarian, M., Das, T.K., Al-Jodah, A. and Nowell, R., 2020. Topology optimization of stiffness constrained flexure-hinges for precision and range maximization. *Mechanism and Machine Theory*, 150, 103874.  
DOI: 10.1016/j.mechmachtheory.2020.103874
- [47] Eraghi, S.H., Toofani, A., Khaheshi, A., Khorsandi, M., Darvizeh, A., Gorb, S. and Rajabi, H., 2021. Wing coupling in bees and wasps: From the underlying science to bioinspired engineering. *Advanced Science*, 8(16), 2004383.  
DOI: 10.1002/advs.202004383

- 
- [48] Khaheshi, A., Gorb, S.N. and Rajabi, H., 2021. Spiky-joint: A bioinspired solution to combine mobility and support. *Applied Physics A*, 127(3), 181.  
DOI: 10.1007/s00339-021-04310-5
- [49] Rawat, P., Zhu, D., Rahman, M.Z. and Barthelat, F., 2021. Structural and mechanical properties of fish scales for the bio-inspired design of flexible body armors: A review. *Acta Biomaterialia*, 121, pp. 41-67.  
DOI: 10.1016/j.actbio.2020.12.003
- [50] Khaheshi, A., Tramsen, H.T., Gorb, S.N. and Rajabi, H., 2021. Against the wind: A load-bearing, yet durable, kite inspired by insect wings. *Materials & Design*, 198, 109354.  
DOI: 10.1016/j.matdes.2020.109354
- [51] Yang, N. and Silverberg, J.L., 2017. Decoupling local mechanics from large-scale structure in modular metamaterials. *Proceedings of the National Academy of Sciences*, 114(14), pp. 3590-3595.  
DOI: 10.1073/pnas.1620714114
- [52] Yin, X., Wang, B.C., Liu, L., Zhang, L.Y. and Xu, G.K., 2022. A structural stiffness matrix-based computational mechanics method of epithelial monolayers. *Journal of the Mechanics and Physics of Solids*, 169, 105077.  
DOI: 10.1016/j.jmps.2022.105077

## Chapter 4:

# Double-spiral: A bio-inspired functional design with potential technical applications\*

### Abstract

Spiral, one of the most well-known functional patterns in nature, has long served as a source of inspiration for humans in the creation of numerous spiral-based designs. Double-spiral is a design derived from spirals, which has been previously presented and utilized as a compliant joint. Advantageous properties of double-spirals, such as easily adjustable design, multiple degrees of freedom, reversible extensibility, and tunable deformability make them promising candidates for the development of structures that exhibit unique behavior and achieve desired functions. In this article, we first develop the Double-Spiral Design software to facilitate the design and modeling of double-spirals. We then design and manufacture five different spiral-based structures, including (i) a freeform passive gripper, (ii) a highly extensible enveloping gripper, (iii) a mechanical interlocking structure, (iv) an adaptive impact absorber, and (v) a compliant planar joint. Through practical experimentation, we test the functionality of the developed structures and showcase the potential of double-spirals for being used in various technical applications. This study represents a significant step towards a better understanding of double-spirals and demonstrates their broad but unexplored potential in engineering design.

**Keywords:** Biomimetics, bio-inspired design, adaptive design, 3D printing, soft robotics.

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\*This chapter is currently in the peer-review process.



## 1. Introduction

Bio-inspired design encompasses an interdisciplinary approach that utilizes nature's strategies to develop advanced technological solutions. By adopting or deriving insights from biological structures, we can design and manufacture products that are more efficient and durable [1-5]. Although fundamental differences between natural and technological systems cause numerous difficulties in the implementation of biologically inspired solutions into real technological applications, this approach has been increasingly applied in various technical fields.

Biomimetics usually requires an abstraction step rather than a simple and direct copying approach. Engineers often try to modify or simplify complex natural designs to suit human needs and overcome manufacturing limitations. Sometimes they can mimic only one aspect of a biological system and develop a solution for a specific engineering problem, but sometimes they use a concept inspired from the nature for a broad range of totally different purposes [1-4].

Spiral, as an omnipresent geometrical pattern in nature, serves as a profound source of inspirations for humans [6,7]. Engineers across various disciplines have leveraged the spiral pattern, each offering their unique perspective, modifying its structure, and adapting it to meet requirements of specific applications. Spiral has inspired the development of numerous engineering structures and systems, including flexible electronics [8,9], springs [10-12], joints [13,14], metamaterials [15-18], wearable thermoelectric generators [19], soft actuators [20-24], antennas [25], soft grippers [26,27], and heat exchangers [28,29].

Compliant double-spirals have been presented recently as novel spiral-based structures [14]. They are inspired by the coiling-uncoiling behavior observed in deformable natural spirals, such as the tentacles of octopuses [30], tail of chameleons [31], tendrils of plants [32], among others [33-36]. Double-spirals hold significant potential in practical applications due to their distinctive behavior when subjected to loading [14]. These structures offer the ability to undergo substantial and predictable deformations, making them particularly valuable in stretchable electronics, soft robots, or biomedical engineering devices where large deformations are necessary [37-39]. Having a high level of control on geometry-function relationship in double-spirals allows us to develop structures with desired stability and load-bearing capacity, while still benefiting from their high extensibility, adaptability, and durability. The purpose of this study is to demonstrate the potential of double-spirals by harnessing their unique properties and incorporating them into a broad range of novel meticulously designed structures with potential for technical applications.

Herein, we first develop a software package with a graphical user interface (GUI) to provide a user-friendly tool for designing double-spirals with different geometries. We then use the data exported from this software to make three-dimensional (3D) models of spiral-based designs. Using a 3D printer, we manufacture them and investigate their mechanical behavior under different loadings. Our results show that structures developed using compliant double-spirals are great examples of engineered designs that harness the mechanical compliance of their consisting elements (double-spirals here) to create motion when force is applied and achieve desired functionalities. By demonstrating the performance of double-spirals in different structures, this study proves their potential in further technical applications.

## 2. Double-Spiral Design software

A software package, called Double-Spiral Design, was developed using python scripting to facilitate the design and modeling of double-spirals (see Supplementary data). In this software, either logarithmic or Archimedean spiral curves can be used to develop double-spirals with desired geometries (Fig. 1). The ability to choose between the logarithmic and Archimedean spirals facilitates the design of double-spirals with diverse geometries. While a double-spiral consisting of logarithmic spiral curves has a variable thickness, Archimedean spiral curves form a double-spiral with almost constant thickness (Fig. 1b). Equations (1) and (2) were used to define the logarithmic and Archimedean spirals in the polar coordinate system, respectively:

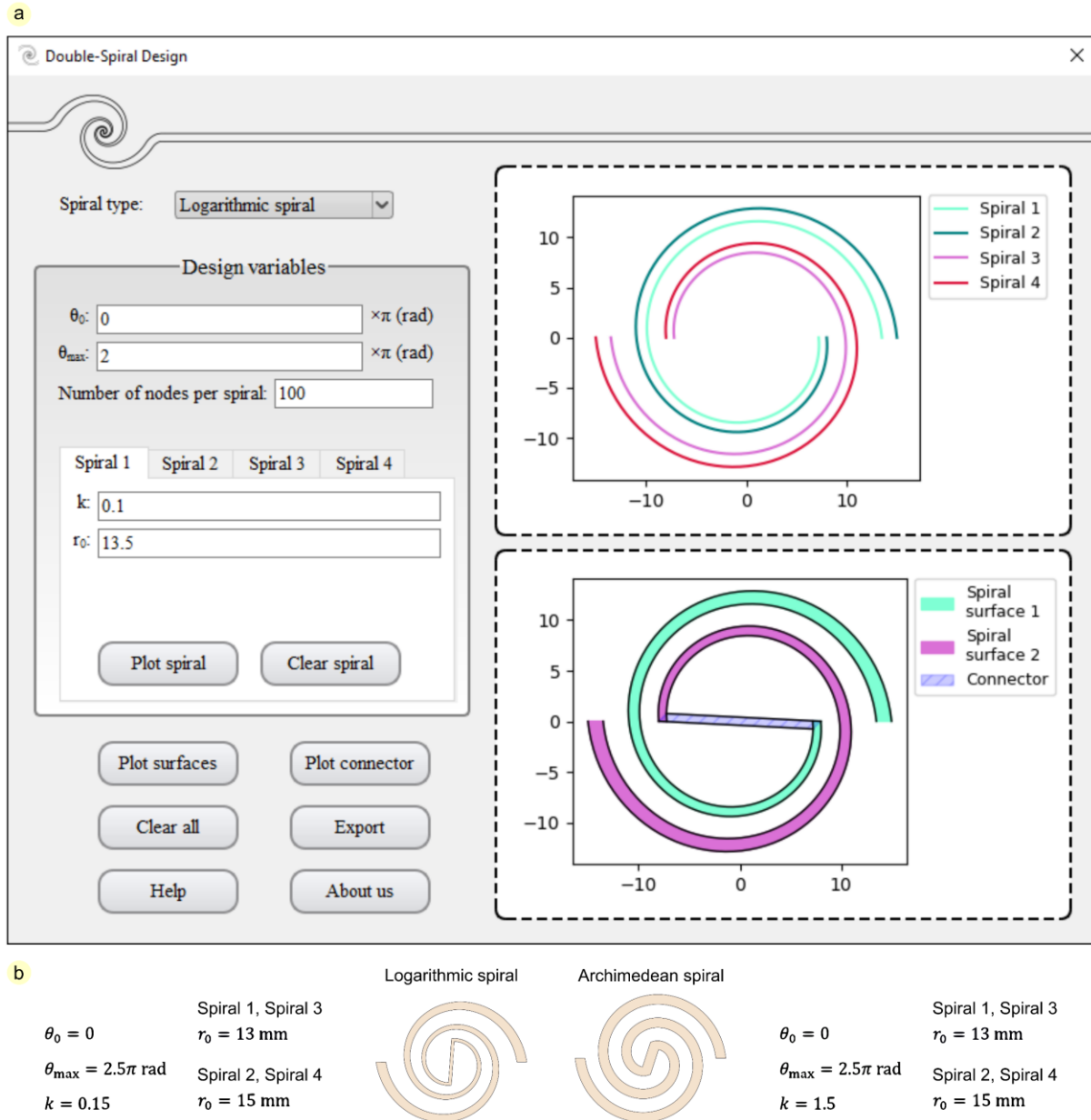
$$r = r_0 e^{-k\theta}, \quad (1)$$

In this equation,  $r_0$  is the radius of the spiral at  $\theta = 0$ , and  $k$  is the polar slope.

$$r = r_0 - k\theta \quad (2)$$

Here,  $r_0$  is the radius of the spiral at  $\theta = 0$ , and  $k$  is the variation of the radius of the spiral with a rotation equal to one radian [7].

The software uses the values of the design variables as inputs to plot four spiral curves (Fig. 1a). Plotting spiral curves 1 and 2 forms spiral surface 1, whereas plotting spiral curves 3 and 4, which are rotated about the origin of the coordinate system by 180 degrees, forms spiral surface 2. The user can then ask the software to connect the inner ends of the plotted spiral surfaces to each other by two straight lines as a connector and accomplish the cross-sectional profile of a double-spiral model. Finally, the Double-Spiral Design software enables the user to save all plotted curves and surfaces in different formats (.csv, .dxf, .xlsx, .html, .txt, .step, and .stl).



**Fig 1.** Double-Spiral Design software. a) User interface of the software. After choosing between the logarithmic and Archimedean spirals, the user can define design variables for the spiral curves 1-4 to plot spiral surfaces 1 and 2. The desired double-spiral can be developed by plotting the connector. The data of all spiral curves and surfaces can be exported from the software in different formats. b) An example of each logarithmic and Archimedean double-spirals and their corresponding design variables.

### 3. Spiral-based structures

We imported the data from the Double-Spiral Design software to the Abaqus software v. 6.14 (SIMULIA), developed five spiral-based structures (.stl files available as Supplementary data), and tested their performance in practice (Table 1). We used a fused deposition modeling (FDM) 3D printer (Prusa i3 MK3S, Prusa Research, Praha, Czech Republic) and a semi-flexible polyurethane

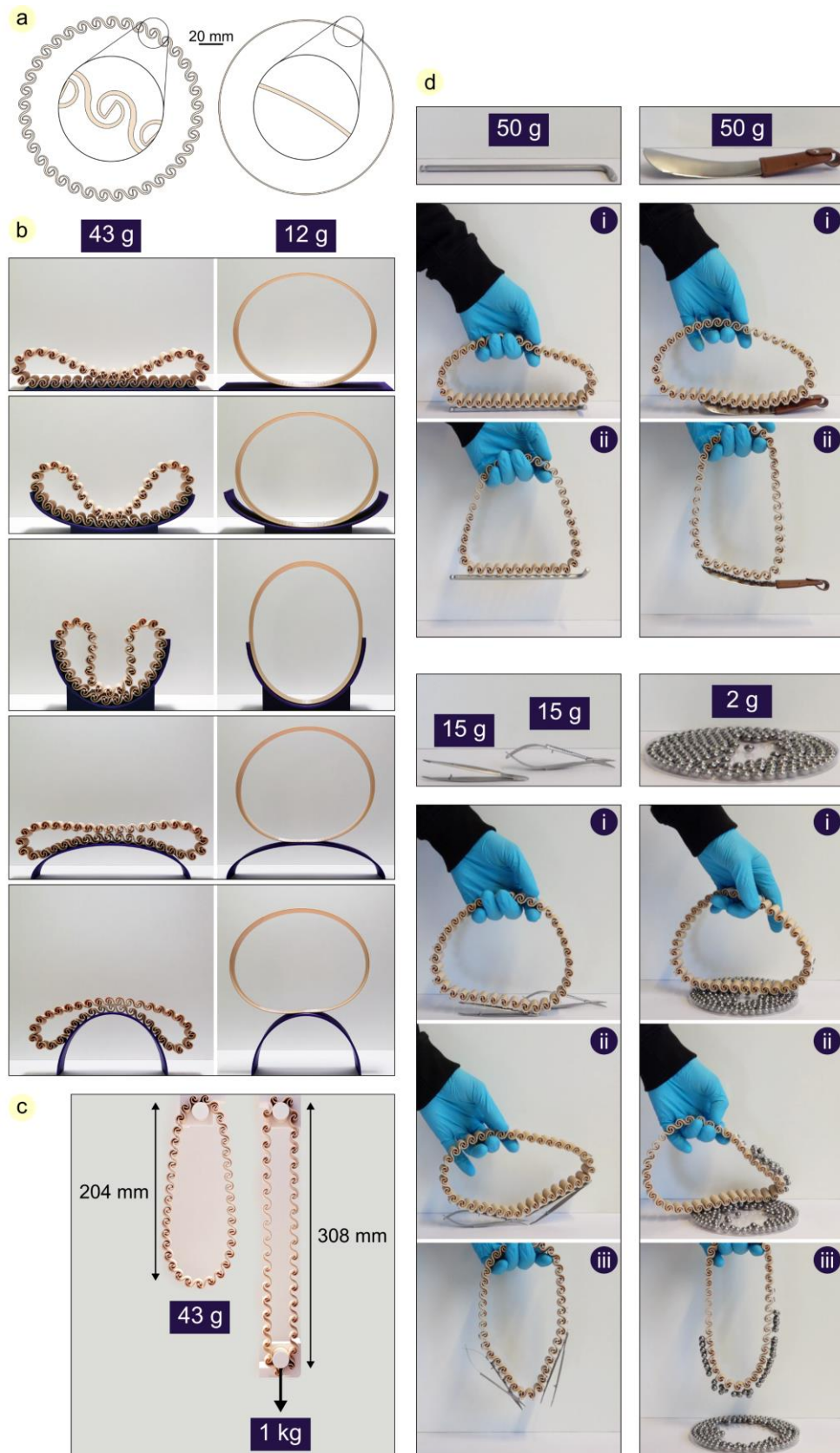
filament (Flexfill TPU 98A, Fillamentum addi(c)tive polymers, Czech Republic) to manufacture the models. Fixtures and all other parts required for the experiments were printed with a polylactic acid (PLA) filament (Prusa Research, Praha, Czech Republic). The settings used for 3D printing and the values of design variables defined for the development of double-spirals are given in Table S1 and Table S2, respectively. The mechanical behavior of the developed structures was characterized using a ZwickiLine uniaxial testing machine (Zwick Roell, Ulm, Germany) equipped with a 500 N load cell (Xforce P load cell, Zwick Roell, Ulm, Germany).

**Table 1.** Spiral-based structures developed in this study, their specifications, and the desired characteristics.

Spiral-based structure	Design specification	Desired characteristic
Freeform passive gripper	A chain of double-spirals in the form of a loop	- Local deformation - Large, accumulated deformation
Highly extensible enveloping gripper	Six double-spirals forming a triangular structure	- High extension - Reversible deformation - Inherent compliance
Mechanical interlocking structure	Double-spirals consisting of two geometrically different spiral coils	- Asymmetric rotation
Adaptive impact absorber	A series of double-spirals with different thicknesses	- Adaptive stiffness - High extension
Compliant planar joint	Double-spirals with low extrusion height	- In- and out-of-plane deformation

### 3.1. Freeform passive gripper

Taking advantage of high rotational deformability of a chain of double-spirals, we designed a structure with enhanced adaptability. We connected a set of double-spirals with similar geometries to form a loop (Fig. 2a). The double-spiral loop deforms easily because each double-spiral can deform locally. In other words, it perfectly conforms to objects of various shapes due to the inherent deformability of each double-spiral. To clarify this feature, we designed another loop with the same diameter and 1 mm thickness (the average thickness of double-spirals), but having no double-spiral, and compared their deformability. We brought them in contact with five substrates with distinct curvatures: a flat surface, two concave, and two convex surfaces with a small and a large curvature. The structures were released to conform to the substrates due to their own weight (Fig. 2b). In all cases, the double-spiral loop exhibited a higher compliance and conformity to the substrates than the simple loop having no double-spiral.



**Fig 2.** Freeform passive gripper. a) 2D view of the double-spiral and circular loops. b) Deformation of the loops under their own weight in contact with a flat, two concave, and two convex surfaces. c) Deformation of the hung double-spiral loop under its own weight and a 1 kg mass. d) Using the double-spiral loop equipped with tiny disc magnets to pick up a 50 g Allen wrench, a 50 g shoehorn, two 15 g tweezers, and multiple 2 g steel beads.

In contrast to its high compliancy in bending and compression, the double-spiral loop exhibits increased stiffness when subjected to tensile forces, allowing it to withstand considerable tensile loads (Fig. 2c). These characteristics are particularly advantageous when the structure is employed as a gripper, enabling it on the one hand to efficiently adapt to objects of various geometries and on the other hand to endure their weights. Two principles of (i) the multichain structure and (ii) being compliant in compression while strong in tension, are well-known from insects' tarsi [40-43] and biological attachment devices [44-46], respectively.

To demonstrate the functionality of this design, we added small magnets (Neodymium Rare Earth Magnets, 3×1.5 mm) to the outer surface of the double-spiral loop and made a magnetic gripper for grasping objects of various shapes and masses. We tested the performance of the developed gripper by picking up five randomly selected objects: a 50 g Allen wrench, a 50 g shoehorn, two 15 g tweezers, and multiple 2 g steel beads (Fig. 2d, Video S1).

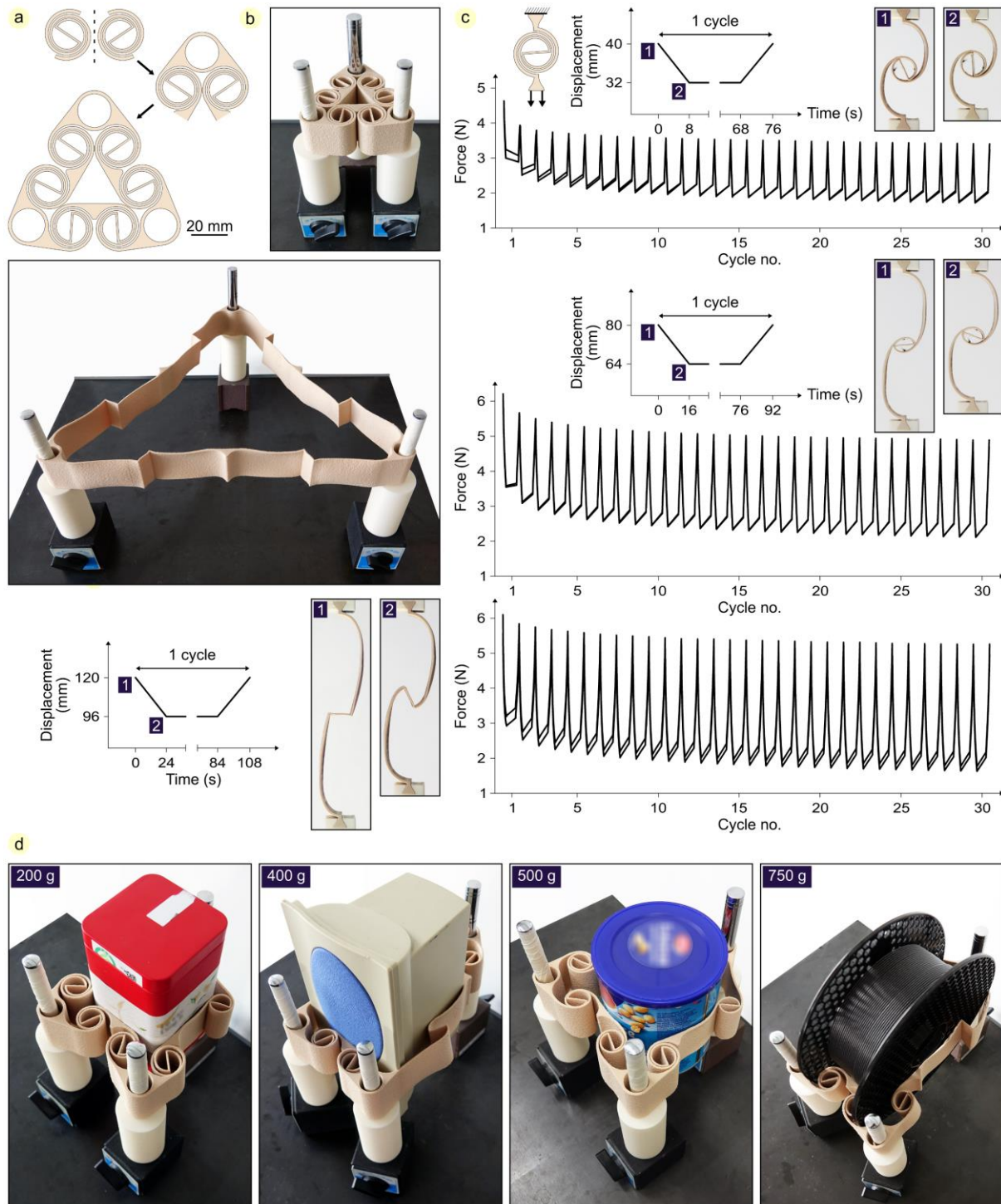
### 3.2. Highly extensible enveloping gripper

Here, we take advantage of high extensibility and reversible deformability of double-spirals. We designed and manufactured a triangular structure by assembling three couples of symmetric double-spirals (Fig. 3a). This structure was developed to be used as a three-jaw enveloping gripper. Owing to the high reversible extensibility of the double-spirals, the area inside the gripper (i.e., the area surrounded by the double-spirals) can be remarkably increased. Specifically, by extending double-spirals up to their total length, the area surrounded by the gripper extends up to 100 times its initial state, and when released, the double-spiral gripper returns to its original coiled state (Fig. 3b, Video S2a). While the inherent compliance of the double-spirals enables the gripper to adapt to objects of various shapes, their reversible behavior enables the gripper to generate the required normal force for the static friction with diverse-shaped objects, developing a stable grip.

To further investigate the performance of the designed gripper, we 3D printed two double-spirals and quantified their loading-unloading behavior through tensile tests (Fig. 3c). We fixed one side of each double-spiral, pulled its other side to extend it up to a specific length (i.e., 40, 80, and 120 mm), unloaded it down to 80 % of its initial extension (i.e., 32, 64, and 96 mm), and held it for 60 s. This process was repeated 30 times for each extension length. In this experiment, the uncoiling process corresponds to the gripper being extended up to a specific area relative to the size of the object. Once extended, it is then released to grip the object. The gripper must maintain the position to securely hold the object; thereafter, it can extend once again to release the object. The resulting force-displacement graphs show that: (i) The force required to keep the double-spirals extended in



various positions increases during the 60 s holding time of each cycle. (ii) The values of holding forces in all three extension lengths are rather the same and become more stable by increasing the number of cycles.

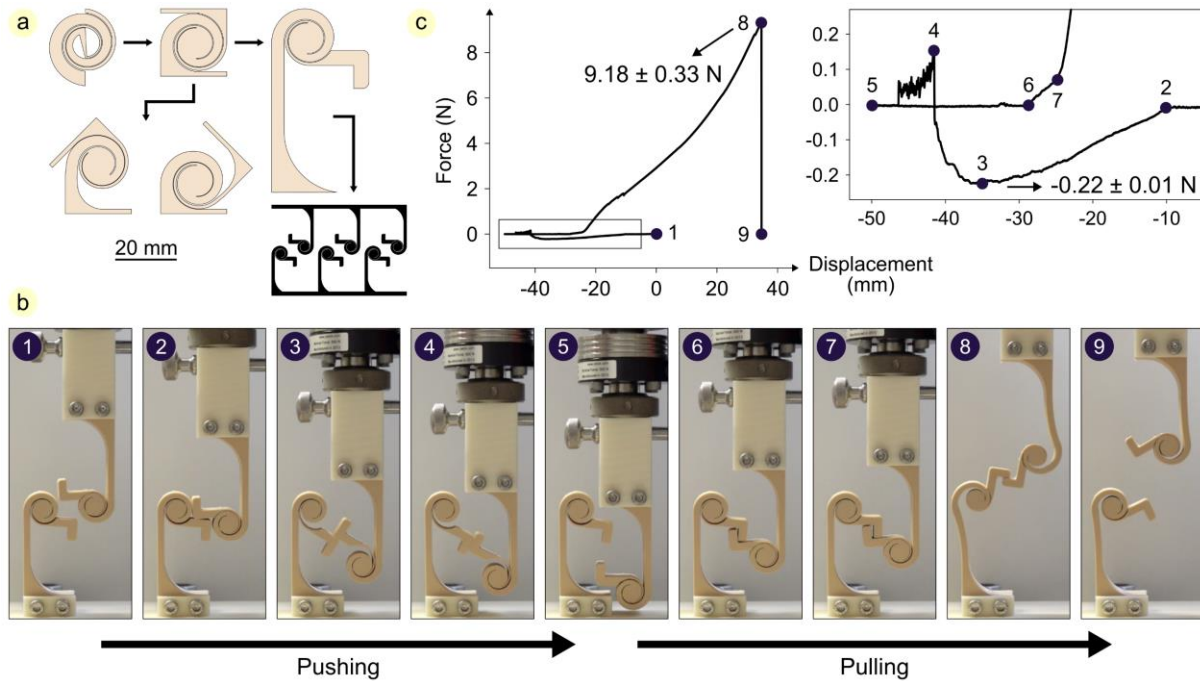


**Fig 3.** Adaptive frictional gripper. a) Modelling the three-jaw gripper using three couples of symmetric double-spirals. b) The 3D printed gripper placed on three legs in its initial and extended states. c) Quantifying the mechanical behavior of two 3D printed double-spirals under a cyclic loading regarding their function in the gripper. d) Gripping a 200 g cubic can, a 400 g loudspeaker, a 500 g cylinder can, and a 750 g filament spool using the developed spiral-based gripper.

In the last step, we tested the functionality of the three-jaw gripper and used it to grip four objects of different shapes and masses, ranging from 200 g to 750 g (Fig. 3d, Video S2b). It is shown here how the three-jaw gripper can envelop the objects and adapt to their shapes. Furthermore, the experiment demonstrates that the gripper can overcome the weight of objects and hold them by taking advantage of the frictional forces.

### 3.3. Mechanical interlocking structure

Herein, a double-spiral with asymmetric behavior in rotation is designed. This double-spiral consists of two spiral coils with different design variables and geometries: a thin and a thick spiral with low and high stiffness, respectively (Fig. 4a). We used this feature of the designed double-spiral to develop a mechanical interlocking structure.



**Fig 4.** Mechanical interlocking structure. a) Developing a double-spiral consisting of a thin and a thick spiral coil with low and high stiffness, respectively. The asymmetric rotation of this double-spiral is used to design a mechanical interlocking structure. b) 3D printing and testing the performance of the developed interlocking structure. c) The force-displacement graph resulting from experiments illustrates the anisotropic behavior of the structure in two different directions.

To characterize the performance of the structure, we manufactured it in two parts. We fixed one part and subjected the other part to a compressive and then a tensile force to measure the force required for their attachment and detachment, respectively (Fig. 4b, Video S3). We performed the experiment three times and calculated the results as mean  $\pm$  SD (Fig. 4c). The results show that



the pulling force is more than 40 times the pushing force. By adjusting the design variables of two spiral coils forming the compliant double-spiral, anisotropic behavior of the structure can be tuned. This characteristic facilitates the development of tunable and reversible attachment.

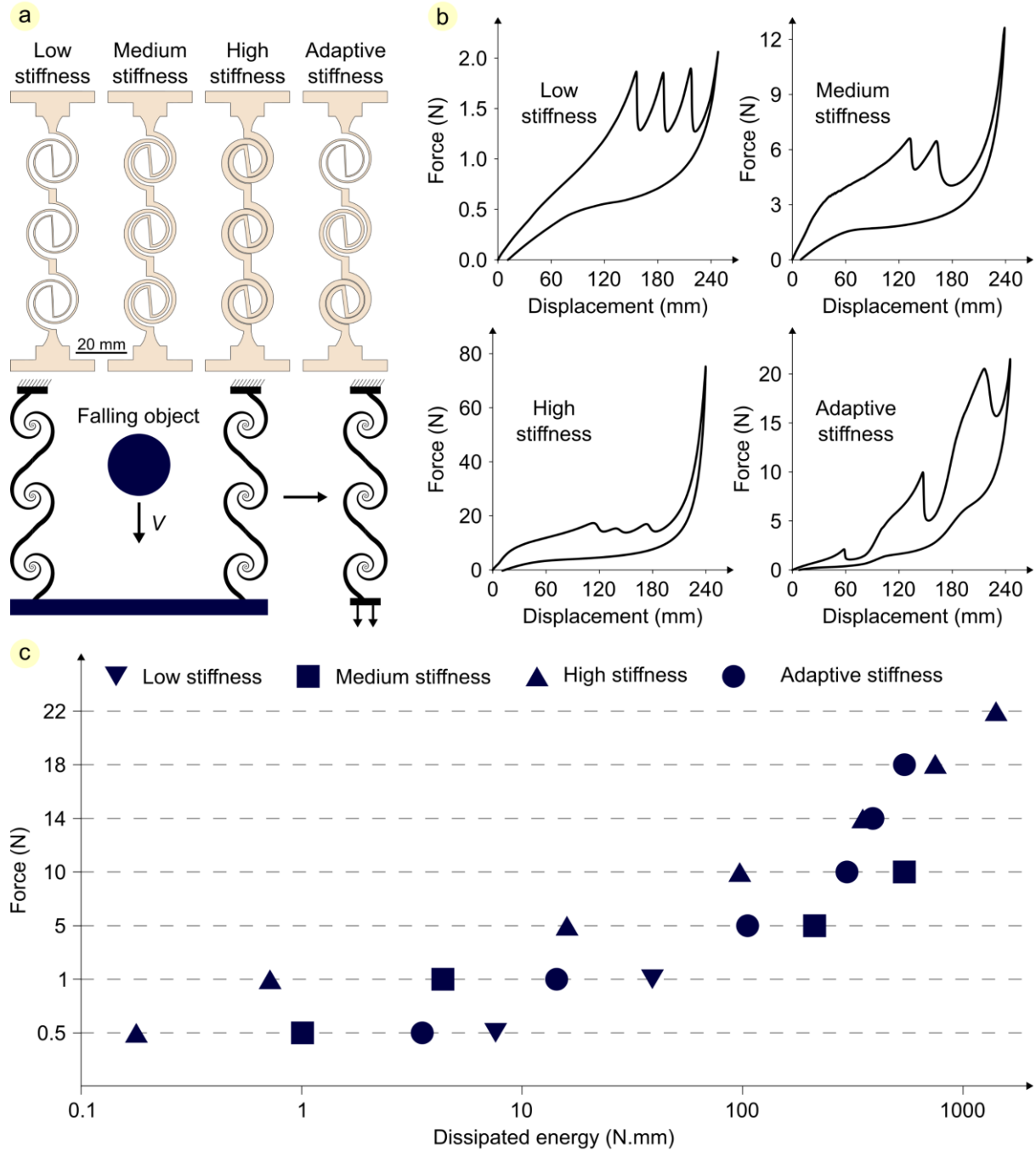
### 3.4. Adaptive impact absorber

Simple adjustability of the geometry of double-spirals and their predictable non-linear mechanical behavior was used here to design an adaptive impact absorber. The aim was to reduce the impact force exerted on falling objects of different masses by using the high extensibility of double-spirals. To achieve this goal, we developed three double-spirals with different initial thicknesses (i.e., 1, 2, and 3 mm) and interconnected them in four distinct ways (Fig. 5a). Three double-spirals with the smallest thickness (i.e., 1 mm) were connected to form a low stiffness structure (Fig. 5a). By connecting three double-spirals with 2 mm thickness and then three double-spirals with 3 mm thickness, we formed medium and high stiffness structures, respectively. We also developed the structure with adaptive stiffness by connecting three double-spirals each having a different thickness. Regarding the function of the developed structures, we extended all models to their maximum length (245 mm) at a rate of 1 mm/s and unloaded them at the same rate to investigate their loading-unloading behavior (Fig. 5b, Fig. S1).

To compare the potential of the four developed structures in impact absorption, their behavior under tensile forces was quantified (Fig. S2). The area between the loading and unloading force-displacement curves was calculated and considered as the amount of energy dissipated due to the deformation of each structure in response to a specific force value (Fig. 5c, Table S3).

While each of low, medium, and high stiffness structures are highly efficient only for objects of a limited range of masses, the structure with adaptive stiffness could absorb a considerable amount of energy in response to the collision of objects of various masses. The adaptive stiffness structure benefits from the combination of double-spirals with different thicknesses and deforms under a wide range of forces.

Furthermore, to investigate the impact of loading rate on the mechanical behavior of the developed impact absorbers, we conducted the same tensile tests on them at a rate of 10 mm/s and quantified the resulting energy dissipation (Table S3). Although the values of displacement and dissipated energy vary with the loading rate, comparing the performance of structures leads to the same conclusion: The adaptive stiffness structure extends in response to a large variety of force values and absorbs more energy.

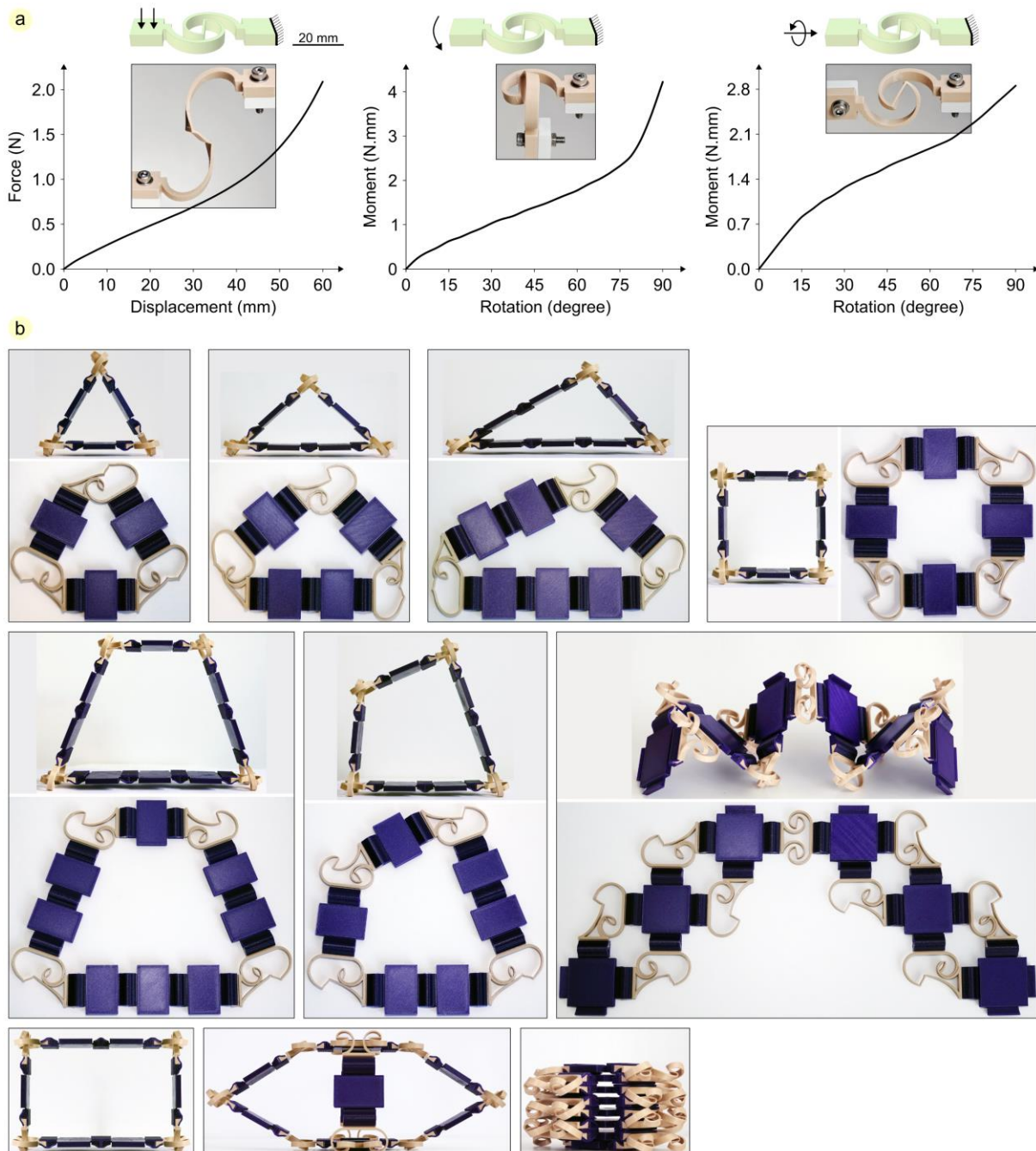


**Fig 5.** Adaptive impact absorber. a) Using three double-spirals with different thicknesses to develop structures with low, medium, high, and adaptive stiffness. b) Force-displacement graphs resulted from experimental tensile tests conducted on the four developed structures at a rate of 1 mm/s. c) Comparing the amount of dissipated energy resulting from the deformation of four developed structures when subjected to the same tensile forces at a rate of 1 mm/s.

### 3.5. Compliant planar joint

Double-spiral is used here as a monolithic compliant joint which allows in- and out-of-plane displacement and rotation of interconnected parts. Taking advantage of the fixed cross-sectional profile of double-spiral, its extrusion height can be simply tuned to meet our requirements. We design-

ed a double-spiral with 5 mm extrusion height. This is a small extrusion height to facilitate out-of-plane deformation of the double-spiral. We then 3D printed two specimens to quantify their mechanical behavior when subjected to out-of-plane sliding, rotation, and torsion. We tested each specimen three times and presented the average force-displacement graphs (Fig. 6a). We then used the double-spirals as compliant joints to connect stiff plates to each other and developed modular structures with different shapes and mechanical behavior (Fig. 6b, Video S3).



**Fig 6.** Compliant planar joint. a) Quantifying the mechanical behavior of the 3D printed double-spiral under out-of-plane sliding, rotation, and torsion. b) Using compliant double-spiral joints and stiff plates to make different modular structures. The developed structures can be easily deformed and switched between 3D spatial and planar states.

Numerous structures can be developed by assembling different numbers of 3D printed double-spiral joints and plates. Desired shapes and deformation patterns are exploitable by reconfiguring the arrangement of the constituent modules. The high deformability of the double-spiral joints enables us to easily fold/unfold the plates and combine them in different spatial orientations. Moreover, the assembled structures are bistable, and we can easily switch them from a 3D spatial state to a planar state. Similar to the mechanical behavior of double-spiral in response to planar loading scenarios that was studied before [14,18], design variables can be used to manipulate the out-of-plane behavior of the joints. By assembling rationally designed double-spiral modules with specific spatial arrangements, desired properties are achievable.

## 4. Discussion

Nowadays, the increased accessibility of advanced equipment and machines across various fields has significantly accelerated scientific and technological progress. Consequently, traditional engineering solutions are frequently rendered obsolete as technological advances raise further requirements. Many conventional materials and structures fail to meet the demands of modern systems, necessitating the replacement of outdated designs with novel and innovative alternatives. Modern structures have higher efficiency, durability, and unprecedented tunable properties. These novel structures possess the ability to adjust stiffness, change shape, adapt to different conditions, and perform multiple tasks or functions. Therefore, in many technological applications, they offer advantages over conventional materials and structures, which possess fixed mechanical properties tailored to limited tasks. Hence, efforts must be focused on promoting low-cost and easily accessible solutions for the development of engineering designs with huge potential [47-49].

In this study, we first developed the Double-Spiral Design software as a tool that facilitates the design of double-spirals with diverse geometries. The software enables users to design double-spirals consisting of four different either logarithmic or Archimedean spiral curves, to have a higher control over the geometry of their designs and achieve desired mechanical behavior, as previous studies have indicated the significant influence of the design variables on the mechanical behavior of double-spirals [14,18]. We then used double-spirals in different structures and investigated their performance in practice. The possibility of adapting double-spirals to obtain properties that allow for a variety of applications has been demonstrated. As a mechanical element designed to regulate the functionality of a structure in a passive way, achieving substantial control over the mechanical behavior of the double-spiral using only a few design parameters is an exquisite feature.

When designing structures, there are instances where conflicting objectives need to be met, necessitating the identification of a trade-off point. In this study, we address one of these contradictory scenarios with the introduction of a highly extensible enveloping gripper (section 3-2). On the one hand, a double-spiral comprising thinner coils offers greater compliance, enabling better adaptation to objects of various shapes and increasing the contact area. On the other hand, a double-spiral with thicker coils can exert more force on the gripped objects, which is crucial for establishing static friction between the gripper and the objects. An optimal compromise between such contradictory objectives can be reached in future studies utilizing evolutionary algorithms.

Thermoplastic polyurethane (TPU) is a material suitable for the fabrication of flexible parts in various engineering fields [50]. Consisting of hard and soft segments, TPU has a two-phase microstructure and demonstrates strong hysteresis, rate dependence, and softening when subjected to mechanical loads. The frictional interactions between hard segments, and the interactions between the soft and hard segments are the source of energy dissipation arising from the microstructure of the material [51,52]. However, when compliant double-spirals are employed for impact absorption, both the constituent material and the structure are crucial for ensuring effective performance.

The large extension of double-spirals limits the transfer of high forces to the protected objects by increasing the duration of impact, even in a scenario where the deformation is perfectly elastic. However, energy dissipation enhances the process of impact absorption by reducing the unwanted oscillations of objects following impact [53]. The contacts occurring between the coils of double-spirals serve as a structural energy dissipation mechanism [54]. Desired frictional behavior can be achieved by controlling the surface roughness through the fabrication process. In FDM 3D printing, specifically, adjusting the height of layers and printing orientation are two well-known methods for manipulating the roughness of printed surfaces [55,56].

Future studies can take advantage of other structural and material strategies to enhance the efficiency of double-spirals. (i) The highly extensible enveloping gripper (section 3-2) might grip objects better if a structural strategy is used to increase the adhesion or surface friction between the double-spirals and objects [43,57]. (ii) The mechanical interlocking structure developed in this study (section 3-3) is an example showing how we can modify the geometry of a double-spiral to improve its functionality for a specific goal. (iii) Regarding the equations of spirals (equations 1 and 2), reducing the thickness of the coils of a double-spiral is a simple method to decrease its stiffness. However, manufacturing precision determines the minimum possible dimensions of parts. In such cases, porosity can be used as a strategy to control the mechanical behavior of a double-spiral [58]. (iv) The fabrication of double-spirals using other materials, such as composite filaments composed

of TPU and PLA [59,60] or TPU and wood flour [61] is another possibility that could be useful for the development of spiral-based structures with higher efficiency.

The main purpose of this article was to showcase the versatility of compliant double-spirals as an element in various structures to attain specific mechanical characteristics. Detailed investigations using theoretical and experimental methods are required for each of the developed structures to explore optimized double-spirals and ensure predictability in their behavior. Furthermore, the performance of the developed spiral-based structures can be compared with other designs that are currently being used in engineering systems for similar purposes in future studies.

## 5. Conclusion

Compliant double-spiral is a design based on highly deformable natural spirals. It is mainly designed for being programmed to transmit motion or force via its elastic deformation and meet specific requirements by manipulating its geometry. Using a few design variables, its non-linear behavior in different directions can be tuned to obtain a broad range of properties. When embedded in engineering systems, a single double-spiral or the combination of double-spirals in specific configurations can offer enhanced adaptability suited to our technical needs. This study contributes to the exploration of new ideas and concepts surrounding double-spirals, paving the way for their utilization in innovative engineering applications.

## Supplementary materials

The first part of the supplementary data that support the findings of this study are available online at: <https://zenodo.org/doi/10.5281/zenodo.10880672>

- **Double-Spiral Design software.** Please download “Software.zip” using the link and run the file “DSD.exe” to open the Double-Spiral Design software. You can develop your own double-spiral models with this software.
- **Models.** 3D models of the spiral-based structures presented in this study.
- **Video S1.** Freeform passive gripper being used for grasping objects of different shapes and masses. We added small magnets to the outer surface of the double-spiral loop and made a magnetic gripper for picking up five random objects.

- **Video S2a.** High reversible extension of the three-jaw enveloping gripper. The area inside the gripper can be remarkably increased, and when released, the double-spiral gripper returns to its original coiled state.
- **Video S2b.** Highly extensible enveloping gripper being used for gripping objects of various shapes and masses.
- **Video S3.** Mechanical behavior of the spiral-based interlocking structure. The results show that the pulling force is more than 40 times the pushing force.
- **Video S4.** Deformation of the spiral-based modular structures under different loading scenarios. Double-spirals were used as compliant joints to develop modular structures with different shapes and mechanical behavior.

## Tables

**Table S1.** 3D printing settings.

Filament	Thermoplastic polyurethane (Flexfill TPU 98A)	Polylactic acid (PLA)
Produced by	Filamentum 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	0.3
Fill pattern	Gyroid	Gyroid
Fill density (%)	20	50

**Table S2.** The values of design variables defined for the design of double-spirals in this study.

Developed Mechanical systems	Design variables			
	Polar slope	Initial thickness ( $n_{0,2} - n_{0,1}$ ) [mm]	Angle of rotation [rad]	Extrusion height [mm]
Freeform passive gripper	0.20	1.5 (7.0-5.5)	$1.5\pi$	20
Highly extensible enveloping gripper	0.07	2.0 (15.0-13.0)	$2.5\pi$	40
Mechanical interlocking structure	0.10	1.4 (11.6-10.2)	$3.0\pi$	20
	0.10	4.8 (13.7-8.9)	$3.0\pi$	20

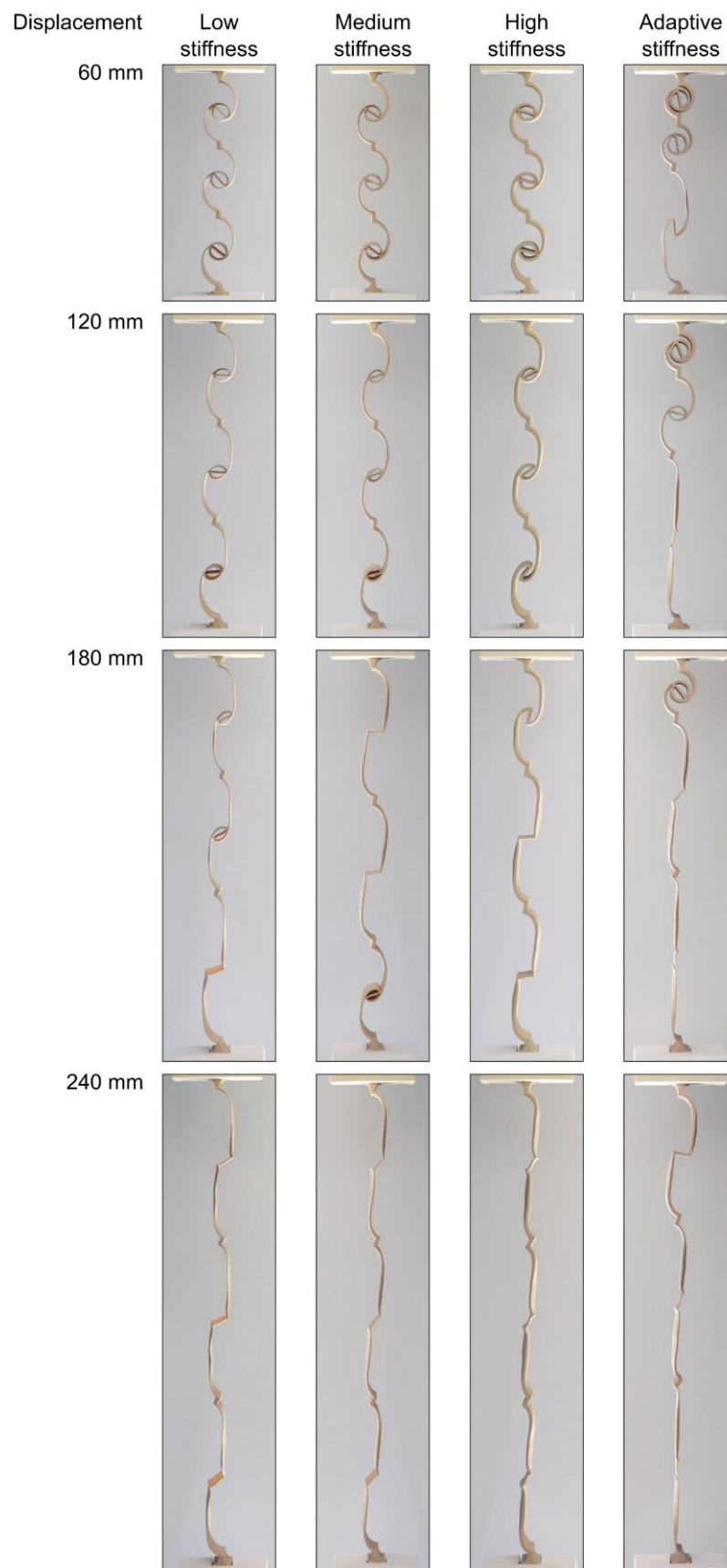
Adaptive impact absorber	0.10	1.0 (12.0-11.0)	$2.0\pi$	20
	0.10	2.0 (12.0-10.0)	$2.0\pi$	20
	0.10	3.0 (12.0-9.0)	$2.0\pi$	20
Compliant planar joint	0.20	2.5 (15.0-12.5)	$1.5\pi$	5

**Table S3.** Extension of the low, medium, high, and adaptive stiffness structures under tensile forces, along with the corresponding energy dissipation due to their deformation.

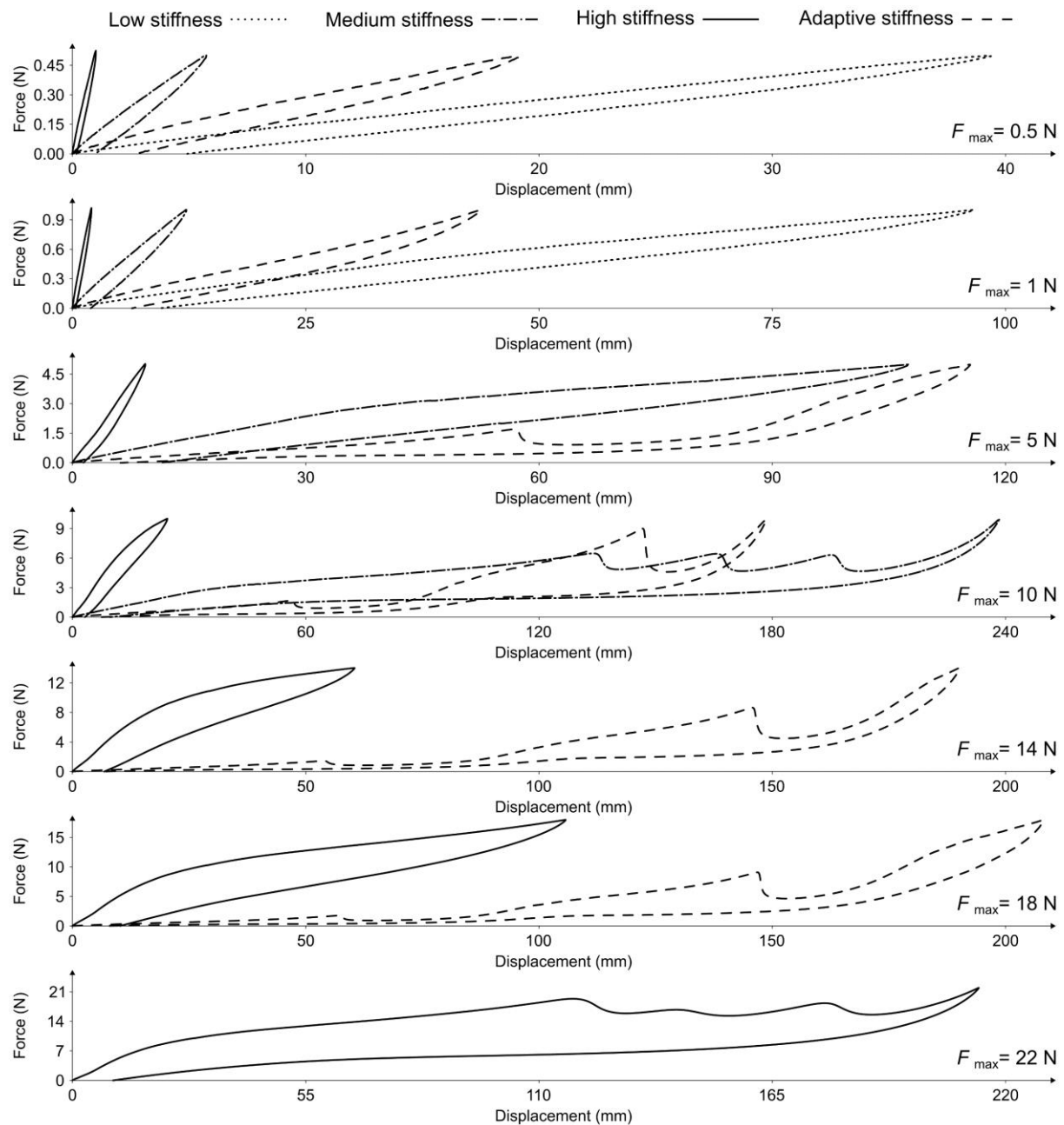
Loading rate: 1 mm/s								
Measured parameter	Developed structure	Applied force (N)						
		0.5	1.0	5.0	10.0	14.0	18.0	22.0
Extension (mm)	Low stiffness	39.37	96.49					
	Medium stiffness	5.74	12.20	107.68	238.70			
	High stiffness	1.00	2.04	9.38	24.40	60.45	105.68	213.73
	Adaptive stiffness	19.13	43.74	115.50	178.68	190.34	208.09	
Dissipated energy (N.mm)	Low stiffness	7.67	39.00					
	Medium stiffness	1.02	4.41	210.85	543.73			
	High stiffness	0.18	0.72	16.12	96.54	362.77	750.17	1403.28
	Adaptive stiffness	3.57	14.38	107.38	298.15	380.16	547.74	
Loading rate: 10 mm/s								
Measured parameter	Developed structure	Applied force (N)						
		0.5	1.0	5.0	10.0	14.0	18.0	22.0
Extension (mm)	Low stiffness	30.25	72.46					
	Medium stiffness	4.20	8.09	51.03	232.41			
	High stiffness	1.35	2.15	7.65	16.75	31.22	65.13	100.29
	Adaptive stiffness	12.52	28.79	100.60	139.33	181.71	191.19	
Dissipated energy (N.mm)	Low stiffness	5.58	27.56					
	Medium stiffness	0.81	2.88	96.24	605.41			
	High stiffness	0.34	0.87	12.27	59.41	165.53	464.32	811.31
	Adaptive stiffness	2.23	10.45	88.62	249.80	379.14	456.13	



## Figures



**Fig S1.** Tensile behavior of four structures consisting of geometrically different double-spirals. The figure compares the deformation of the low, medium, high, and adaptive stiffness structures when extended to the same lengths.



**Fig S2.** Mechanical behavior of the low, medium, high, and adaptive stiffness structures under tension. Force–displacement curves illustrate the viscoelastic behavior of compliant double-spirals when subjected to tensile forces at a rate of 1 mm/s.

## References

- [1] Farzaneh, H.H. and Lindemann, U., 2018. *A practical guide to bio-inspired design*. Berlin, Heidelberg, Germany: Springer Vieweg Verlag.  
DOI: 10.1007/978-3-662-57684-7
- [2] Vincent, J.F., Bogatyreva, O.A., Bogatyrev, N.R., Bowyer, A. and Pahl, A.K., 2006. Biometrics: Its practice and theory. *Journal of the Royal Society Interface*, 3(9), pp. 471-482.

- DOI: 10.1098/rsif.2006.0127
- [3] Lenau, T.A., 2009. Biomimetics as a design methodology-Possibilities and challenges. In *Proceedings of the International Conference on Engineering Design (ICED), Palo Alto, CA, USA, 24-27 August*, pp. 121-132.
- [4] Bar-Cohen, Y., 2006. Biomimetics—Using nature to inspire human innovation. *Bioinspiration & Biomimetics*, 1(1), pp. P1-P12.  
DOI: 10.1088/1748-3182/1/1/P01
- [5] Bhushan, B., 2009. Biomimetics: Lessons from nature—An overview. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 367(1893), pp. 1445-1486.  
DOI: 10.1098/rsta.2009.0011
- [6] Cook, T.A., 1979. *The curves of life: Being an account of spiral formations and their application to growth in nature, to science, and to art: With special reference to the manuscripts of Leonardo da Vinci*. New York, NY, USA: Dover Publications.
- [7] Tsuji, K. and Müller, S.C. (eds.) 2019. *Spirals and vortices: In culture, nature, and science*. Cham, Switzerland: Springer.  
DOI: 10.1007/978-3-030-05798-5
- [8] Yuan, X. and Wang, Y., 2023. Nonlinear stretching mechanics of planar Archimedean-spiral interconnects for flexible electronics. *Thin-Walled Structures*, 185, 110568.  
DOI: 10.1016/j.tws.2023.110568
- [9] Rehman, M.U. and Rojas, J.P., 2017. Optimization of compound serpentine–spiral structure for ultra-stretchable electronics. *Extreme Mechanics Letters*, 15, pp. 44-50.  
DOI: 10.1016/j.eml.2017.05.004
- [10] Du, R., Xie, L., Du, R. and Xie, L., 2013. The mechanics of the spiral spring. In *The mechanics of mechanical watches and clocks*. Berlin, Heidelberg, Germany: Springer Vieweg Verlag, pp. 89-113.  
DOI: 10.1007/978-3-642-29308-5\_4
- [11] Georgiev, N. and Burdick, J., 2017. Design and analysis of planar rotary springs. In *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Vancouver, Canada, 24–28 September*, pp. 4777-4784. IEEE.  
DOI: 10.1109/IROS.2017.8206352
- [12] Scarcia, U., Berselli, G., Palli, G. and Melchiorri, C., 2017. Modeling, design, and experimental evaluation of rotational elastic joints for underactuated robotic fingers. In *IEEE-RAS International Conference on Humanoid Robots (Humanoids), Birmingham, UK, 15–17 November*, pp. 353-358. IEEE.  
DOI: 10.1109/HUMANOIDS.2017.8246897

- 
- [13] Ahmad, B., Barbot, A., Ulliac, G. and Bolopion, A., 2022. Remotely actuated optothermal robotic microjoints based on spiral bimaterial design. *IEEE/ASME Transactions on Mechatronics*, 27(5), pp. 4090-4100.  
DOI: 10.1109/TMECH.2022.3145646
- [14] Jafarpour, M., Gorb, S. and Rajabi, H., 2023. Double-spiral: A bioinspired pre-programmable compliant joint with multiple degrees of freedom. *Journal of the Royal Society Interface*, 20(198), 20220757.  
DOI: 10.1098/rsif.2022.0757
- [15] Li, S. and Yang, J., 2021. Topological transition in spiral elastic valley metamaterials. *Physical Review Applied*, 15(1), 014058.  
DOI: 10.1103/PhysRevApplied.15.014058
- [16] Cimolai, G., Dayyani, I. and Qin, Q., 2022. Multi-objective shape optimization of large strain 3D helical structures for mechanical metamaterials. *Materials & Design*, 215, 110444.  
DOI: 10.1016/j.matdes.2022.110444
- [17] Dong, L., Wang, D., Wang, J., Jiang, C., Wang, H., Zhang, B., Wu, M.S. and Gu, G., 2022. Modeling and design of periodic polygonal lattices constructed from microstructures with varying curvatures. *Physical Review Applied*, 17(4), 044032.  
DOI: 10.1103/PhysRevApplied.17.044032
- [18] Jafarpour, M., Gorb, S.N. and Rajabi, H., 2023. Double-spirals offer the development of pre-programmable modular metastructures. *Advanced Engineering Materials*, 25(13), 2300102.  
DOI: 10.1002/adem.202300102
- [19] Liang, L., Wang, M., Wang, X., Peng, P., Liu, Z., Chen, G. and Sun, G., 2022. Initiating a stretchable, compressible, and wearable thermoelectric generator by a spiral architecture with ternary nanocomposites for efficient heat harvesting. *Advanced Functional Materials*, 32(15), 2111435.  
DOI: 10.1002/adfm.202111435
- [20] Li, Q., Wang, X., Dong, L., Liu, C. and Fan, S., 2019. Spirally deformable soft actuators and their designable helical actuations based on a highly oriented carbon nanotube film. *Soft Matter*, 15(47), pp. 9788-9796.  
DOI: 10.1039/C9SM01966A
- [21] Wang, D., Li, L., Serjouei, A., Dong, L., Weeger, O., Gu, G. and Ge, Q., 2018. Controllable helical deformations on printed anisotropic composite soft actuators. *Applied Physics Letters*, 112(18), 181905.  
DOI: 10.1063/1.5025370

- [22] Farhan, M., Klimm, F., Thielen, M., Rešetič, A., Bastola, A., Behl, M., Speck, T. and Lendlein, A., 2023. Artificial tendrils mimicking plant movements by mismatching modulus and strain in core and shell. *Advanced Materials*, 35(22), 2211902.  
DOI: 10.1002/adma.202211902
- [23] Chen, E., Yang, Y., Li, M., Li, B., Liu, G., Mu, W. and Yin, R., 2023. Bio-mimic, fast-moving, and flippable soft piezoelectric robots. *Advanced Science*, 10(20), 2300673.  
DOI: 10.1002/advs.202300673
- [24] Mu, W., Li, M., Chen, E., Yang, Y., Yin, J., Tao, X., Liu, G. and Yin, R., 2023. Spiral-shape fast-moving soft robots. *Advanced Functional Materials*, 33(35), 2300516.  
DOI: 10.1002/adfm.202300516
- [25] Neebha, T.M., Andrushia, A.D. and Durga, S., 2020. A state-of-art review on antenna designs for ingestible application. *Electromagnetic Biology and Medicine*, 39(4), pp. 387-402.  
DOI: 10.1080/15368378.2020.1821707
- [26] Uppalapati, N.K. and Krishnan, G., 2018. Towards pneumatic spiral grippers: Modeling and design considerations. *Soft Robotics*, 5(6), pp. 695-709.  
DOI: 10.1089/soro.2017.0144
- [27] Li, H., Yao, J., Zhou, P., Chen, X., Xu, Y. and Zhao, Y., 2019. High-load soft grippers based on bionic winding effect. *Soft Robotics*, 6(2), pp. 276-288.  
DOI: 10.1089/soro.2018.0024
- [28] Tapre, R.W. and Kaware, J.P., 2015. Review on heat transfer in spiral heat exchanger. *International Journal of Scientific and Research Publications*, 5(6), pp. 376-380.
- [29] Aresti, L., Christodoulides, P. and Florides, G., 2018. A review of the design aspects of ground heat exchangers. *Renewable and Sustainable Energy Reviews*, 92, pp. 757-773.  
DOI: 10.1016/j.rser.2018.04.053
- [30] Huffard, C.L., 2006. Locomotion by *Abdopus aculeatus* (Cephalopoda: Octopodidae): Walking the line between primary and secondary defenses. *Journal of Experimental Biology*, 209(19), pp. 3697-3707.  
DOI: 10.1242/jeb.02435
- [31] Luger, A.M., Ollevier, A., De Kegel, B., Herrel, A. and Adriaens, D., 2020. Is variation in tail vertebral morphology linked to habitat use in chameleons?. *Journal of Morphology*, 281(2), pp. 229-239.  
DOI: 10.1002/jmor.21093
- [32] Klimm, F., Speck, T. and Thielen, M., 2023. Force generation in the coiling tendrils of *Passiflora caerulea*. *Advanced Science*, 10(28), 2301496.  
DOI: 10.1002/advs.202301496

- [33] Krenn, H.W., 2010. Feeding mechanisms of adult Lepidoptera: Structure, function, and evolution of the mouthparts. *Annual Review of Entomology*, 55, pp. 307-327.  
DOI: 10.1146/annurev-ento-112408-085338
- [34] Matsumura, Y., Yoshizawa, K., Machida, R., Mashimo, Y., Dallai, R., Gottardo, M., Kleinteich, T., Michels, J., Gorb, S.N. and Beutel, R.G., 2014. Two intromittent organs in *Zorotypus caudelli* (Insecta, Zoraptera): The paradoxical coexistence of an extremely long tube and a large spermatophore. *Biological Journal of the Linnean Society*, 112(1), pp. 40-54.  
DOI: 10.1111/bij.12260
- [35] Matsumura, Y., Jafarpour, M., Reut, M., Shams Moattar, B., Darvizeh, A., Gorb, S.N. and Rajabi, H., 2021. Excavation mechanics of the elongated female rostrum of the acorn weevil *Curculio glandium* (Coleoptera; Curculionidae). *Applied Physics A*, 127, pp. 1-11.  
DOI: 10.1007/s00339-021-04353-8
- [36] Vasco, A., Moran, R.C. and Ambrose, B.A., 2013. The evolution, morphology, and development of fern leaves. *Frontiers in Plant Science*, 4, 345.  
DOI: 10.3389/fpls.2013.00345
- [37] Ma, Y., Feng, X., Rogers, J.A., Huang, Y. and Zhang, Y., 2017. Design and application of 'J-shaped' stress-strain behavior in stretchable electronics: A review. *Lab on a Chip*, 17(10), pp. 1689-1704.  
DOI: 10.1039/C7LC00289K
- [38] Trivedi, D., Rahn, C.D., Kier, W.M. and Walker, I.D., 2008. Soft robotics: Biological inspiration, state of the art, and future research. *Applied Bionics and Biomechanics*, 5(3), pp. 99-117.  
DOI: 10.1080/11762320802557865
- [39] Burgner-Kahrs, J., Rucker, D.C. and Choset, H., 2015. Continuum robots for medical applications: A survey. *IEEE Transactions on Robotics*, 31(6), pp. 1261-1280.  
DOI: 10.1109/TRO.2015.2489500
- [40] Gladun, D. and Gorb, S.N., 2007. Insect walking techniques on thin stems. *Arthropod-Plant Interactions*, 1, pp. 77-91.  
DOI: 10.1007/s11829-007-9007-2
- [41] Büscher, T.H., Becker, M. and Gorb, S.N., 2020. Attachment performance of stick insects (Phasmatodea) on convex substrates. *Journal of Experimental Biology*, 223(17), jeb226514.  
DOI: 10.1242/jeb.226514
- [42] Winand, J., Gorb, S.N. and Büscher, T.H., 2023. Gripping performance in the stick insect *Sungaya inexpectata* in dependence on the pretarsal architecture. *Journal of Comparative Physiology A*, 209(2), pp. 313-323.  
DOI: 10.1007/s00359-022-01570-1

- [43] Winand, J., Büscher, T.H. and Gorb, S.N., 2022. Learning from nature: A review on biological gripping principles and their application to robotics. In Monkman, G. J. (ed.) *Soft Robotics*. Singapore: Bentham Science Publishers, pp. 21-59.
- [44] Gorb, S.N., Sinha, M., Peressadko, A., Daltorio, K.A. and Quinn, R.D., 2007. Insects did it first: A micropatterned adhesive tape for robotic applications. *Bioinspiration & Biomimetics*, 2(4), S117. DOI: 10.1088/1748-3182/2/4/S01
- [45] Gorb, S.N., 2008. Biological attachment devices: Exploring nature's diversity for biomimetics. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 366 (1870), pp. 1557-1574. DOI: 10.1098/rsta.2007.2172
- [46] Büscher, T.H. and Gorb, S.N., 2021. Physical constraints lead to parallel evolution of micro- and nanostructures of animal adhesive pads: A review. *Beilstein Journal of Nanotechnology*, 12(1), pp. 725-743. DOI: 10.3762/bjnano.12.57
- [47] Wagg, D., Bond, I., Weaver, P. and Friswell, M. (eds.) 2008. *Adaptive structures: Engineering applications*. Chichester, West Sussex, UK: John Wiley & Sons.
- [48] Su, M. and Song, Y., 2021. Printable smart materials and devices: Strategies and applications. *Chemical Reviews*, 122(5), pp. 5144-5164. DOI: 10.1021/acs.chemrev.1c00303
- [49] Khaheshi, A. and Rajabi, H., 2022. Mechanical intelligence (MI): A bioinspired concept for transforming engineering design. *Advanced Science*, 9(32), 2203783. DOI: 10.1002/advs.202203783
- [50] Desai, S.M., Sonawane, R.Y. and More, A.P., 2023. Thermoplastic polyurethane for three-dimensional printing applications: A review. *Polymers for Advanced Technologies*, 34(7), pp. 2061-2082. DOI: 10.1002/pat.6041
- [51] Qi, H.J. and Boyce, M.C., 2005. Stress-strain behavior of thermoplastic polyurethanes. *Mechanics of Materials*, 37(8), pp. 817-839. DOI: 10.1016/j.mechmat.2004.08.001
- [52] Wang, Y., Ma, R., Li, H., Hu, S., Gao, Y., Liu, L., Zhao, X. and Zhang, L., 2022. Effect of the content and strength of hard segment on the viscoelasticity of the polyurethane elastomer: Insights from molecular dynamics simulation. *Soft Matter*, 18(21), pp. 4090-4101. DOI: 10.1039/D2SM00463A
- [53] Stronge, W.J., 2018. *Impact mechanics*, 2nd ed., Cambridge, UK: Cambridge University Press. DOI: 10.1017/9781139050227

- 
- [54] Lazan, B.J., 1968. *Damping of materials and members in structural mechanics*. Oxford, UK: Pergamon Press.
- [55] Buj-Corral, I., Domínguez-Fernández, A. and Durán-Llucià, R., 2019. Influence of print orientation on surface roughness in fused deposition modeling (FDM) processes. *Materials*, 12(23), 3834. DOI: 10.3390/ma12233834
- [56] Ferretti, P., Leon-Cardenas, C., Santi, G.M., Sali, M., Ciotti, E., Frizziero, L., Donnici, G. and Liverani, A., 2021. Relationship between FDM 3D printing parameters study: Parameter optimization for lower defects. *Polymers*, 13(13), 2190. DOI: 10.3390/polym13132190
- [57] Shao, Y., Dou, H., Tao, P., Jiang, R., Fan, Y., Jiang, Y., Zhao, J., Zhang, Z., Yue, T., Gorb, S.N. and Ren, L., 2022. Precise controlling of friction and adhesion on reprogrammable shape memory micropillars. *ACS Applied Materials & Interfaces*, 14(15), pp. 17995-18003. DOI: 10.1021/acsami.2c03589
- [58] Al-Maharma, A.Y., Patil, S.P. and Markert, B., 2020. Effects of porosity on the mechanical properties of additively manufactured components: A critical review. *Materials Research Express*, 7(12), 122001. DOI: 10.1088/2053-1591/abcc5d
- [59] Tao, Y., Shao, J., Li, P. and Shi, S.Q., 2019. Application of a thermoplastic polyurethane/polylactic acid composite filament for 3D-printed personalized orthosis. *Materiali in Tehnologije*, 53(1), pp. 71–76. DOI: 10.17222/MIT.2018.180
- [60] Jafari Horastani, S., Karevan, M. and Ghane, M., 2022. Structural, thermal, and viscoelastic response of nanoclay reinforced polylactic acid/thermoplastic polyurethane shape-memory nanocomposites of low transition temperature. *Polymers for Advanced Technologies*, 33(9), pp. 2720-2735. DOI: 10.1002/pat.5727
- [61] Bi, H., Ren, Z., Guo, R., Xu, M. and Song, Y., 2018. Fabrication of flexible wood flour/thermoplastic polyurethane elastomer composites using fused deposition molding. *Industrial Crops and Products*, 122, pp. 76-84. DOI: 10.1016/j.indcrop.2018.05.059



## Chapter 5:

### Discussion

#### 1. Double-spiral: Design, fabrication, and function

The first step in the design of a mechanical element is a thorough understanding of its intended tasks and functions [1,2]. Knowing the purpose of design, the path to innovation sometimes begins with the recognition of structures existing in nature or previously produced by humans. These structures, when viewed with a different perspective, can be utilized for entirely new purposes after the required modifications are implemented [3,4]. Double-spiral is a prominent example of a modification applied to an existing design, i.e., spiral, to provide an advantage over it and enhance its functionality towards our needs. A planar double-spiral, consisting of two interconnected spirals, has two outer ends that are free and can be easily connected to other objects, whereas a single spiral has only one outer end and its inner end is not accessible in a planar framework [5]. With this specific design, double-spirals could be utilized as joints to interconnect various components or connected to other double-spirals as the modules of spiral-based metastructures [5-18].

The double-spirals developed in this thesis have a 2D planar design. In other words, their cross-sectional profile is fixed along their depth, and 3D models of double-spirals can be made using the simple out-of-plane extrusion technique. This feature offers some advantages in numerical analysis, manufacturing, and the functionality of double-spirals:

- In the case of numerical analysis, the planar design simplifies both modeling and simulation process. On the one hand, this simplification reduces computational costs significantly and increases the efficiency of simulations. On the other hand, it increases computational errors [19,20]. Hence, the obtained results should be validated against experimental data to ensure that they are accurate and reliable. Comparing the numerical and experimental results, the validity of simulations in this study was verified, demonstrating that 2D models can be used to predict the mechanical behavior of double-spirals with reasonable accuracy.
- From a manufacturing perspective, the double-spiral model with a fixed cross-sectional profile offers considerable benefits. It is highly compatible with a wide range of fabrication methods, from formative and subtractive manufacturing to various additive manufacturing technologies

[5,7,12,14-18]. This flexibility in manufacturing is advantageous due to the large variety of materials available for the fabrication of double-spirals. Moreover, choosing between different types of manufacturing techniques suitable for production in small or large volumes can be done considering the cost-effectiveness and accessibility [21,22]. It was shown in this thesis that a low-cost, easily accessible, single-nozzle fused deposition modeling (FDM) 3D printer can efficiently produce the double-spiral with a straightforward layer-by-layer extrusion, resulting in a mechanical component with the desired characteristics. Printing the double-spiral without the necessity of using support structures reduces material waste, minimizes the likelihood of defects, ensures printing consistency, and accelerates the manufacturing process [22].

- In terms of functionality, the fixed cross section of the double-spiral simplifies its integration into other structures, making it practical and suitable for various applications. Leveraging this feature, the extrusion height of the double-spiral can be easily adjusted to meet specific requirements. As demonstrated in this thesis, the double-spiral can be suitable for a wide range of in-plane and out-of-plane deformations. When it is subjected to planar loading scenarios, an extrusion height close to the other dimensions of the double-spiral can prevent unwanted out-of-plane deformation and buckling [23-25]. Reducing the extrusion height of the double-spiral when it is under out-of-plane loads decreases the undesirable contacts between coils, resulting in a more predictable and stable behavior [18,26]. However, contacts between the coils of double-spirals can be potentially desirable in specific applications, including where friction forces are needed as a solution for energy dissipation [27,28]. Hence, further studies are required to investigate these contacts and quantify the parameters affecting them.

The basis of this study and one of the most important characteristics of compliant double-spirals is their high reversible extensibility. Fabricating double-spirals with thermoplastic polyurethane (TPU) was the strategy used here to achieve large deformations while having negligible plasticity and damage in the developed structures. Owing to the remarkable flexibility and durability of TPU, 3D printed parts can withstand different types of repeated mechanical loads without losing their structural integrity and functionality [29,30]. TPUs are copolymers consisting of hard and soft segments in varying proportions. The interactions between these hard and soft segments result in a certain degree of viscoelasticity [31,32]. Previous studies have revealed that the process of 3D printing and the defined configurations can affect the viscoelastic properties of the fabricated TPU parts [33,34]. Therefore, a smart selection of manufacturing settings and configurations can enhance the viscoelastic behavior of double-spirals in line with their intended functions.

While both geometry and material composition could be investigated as key factors for manipulating the mechanical behavior of double-spirals, this study specifically examined the impact of

geometrical parameters on their functionality. Logarithmic spiral curves were employed to develop double-spiral models. The simple equation of logarithmic spirals provides a concise and clear method for the design of double-spirals. It creates a predictable and repeatable framework, facilitates the modification of design variables, and reduces potential errors [35,36]. Meanwhile, the simplicity of this design approach does not limit the variety of double-spirals that can be achieved.

Although employing both Archimedean and logarithmic spirals in the Double-Spiral Design software increases the number of design variables, it also provides the possibility of developing double-spirals with more diverse geometries. Plotting four independent spiral curves gives us higher control over the variation of thickness and the curvature of spiral coils within a double-spiral. As a result, the thickness of a coil can be constant, decreasing, or increasing from its outer end to its inner end. The reason behind the importance of having a higher number of geometrically distinct double-spirals lies in the possibility of achieving a wider range of mechanical properties.

The mechanical behavior of the double-spiral under different loading scenarios can be categorized and correlated with its geometry. This makes the behavior of the double-spiral predictable, allowing us to passively control its deformations under mechanical loads. Design variables can be used to manipulate the number, density, curvature, and thickness of the coils of double-spiral, thereby allowing precise adjustment of its mechanical behavior. When employing the double-spiral in a specific application, understanding the relationship between its geometry and function becomes crucial, especially where multiple objectives need to be met.

This study promotes the utility of double-spirals by showing that when rationally designed and combined in various configurations, they can exploit more desired properties. When multiple double-spirals are linked to each other as the modules of a mechanical metastructure, their spatial arrangement and the interactions between them are as important as the characteristics of each module. Engineered deformation of all double-spirals together determines the behavior of the entire structure under different boundary conditions and loadings [37-39].

In this thesis, metastructures with different forms and arrangements of double-spirals were developed, including configurations such as a row, triangle, rectangle, circle, and cube, each designed for a specific function (see Chapters 3 and 4). The results demonstrated the potential of double-spirals as an efficient, yet simple solution for creating structures with adjustable mechanical properties. The non-linear behavior of these spiral-based structures in different directions is tunable and they can transform into predictable shapes and deformation patterns in response to mechanical loads. Taking advantage of their inherent compliance, double-spirals effectively transmit motion or force through elastic deformation to achieve desired functions.

Most of the characteristics of compliant double-spirals observed as in this study, such as anisotropic and asymmetric behavior, high extensibility, variable stiffness, and multiple degrees of freedom, may not always be desirable for an engineering structure. Depending on the intended function of the structure, each of these characteristics can be considered either an advantage or disadvantage. However, having precise control over these features is a significant benefit [40-43]. In situations where the tunability of mechanical behavior is required, compliant double-spirals can be valuable elements.

## 2. Outlook

In this thesis, the design of compliant double-spirals was carried out with a focus on comprehending various features of geometrically distinct models, and the experiments were conducted with the aim of providing a proof of concept. Future research could be dedicated to exploring the characteristics required for specific applications and developing double-spirals optimized for each application. Moreover, comparing the performance of the developed double-spirals with other designs that are currently being used in engineering systems for similar purposes, their advantages and disadvantages can be evaluated.

Simple mathematical equations of spiral curves may facilitate the optimization of the double-spiral. Increasing the number of independent curves and introducing additional design variables in the design of double-spirals enhances the diversity of achievable geometries and mechanical properties. However, it simultaneously leads to increased computational costs and optimization time [44]. Finding a trade-off between the richness of design possibilities and computational efficiency is a crucial consideration in optimizing double-spirals.

Double-spirals with varying extrusion heights were designed and employed in this thesis, with a brief discussion on how this height can impact the performance of spiral-based structures. However, no comprehensive investigation on this matter was conducted here. Future studies should delve into exploring the scalability of the double-spiral and quantifying the relationship between its stiffness and extrusion height to determine the conditions required for obtaining high stability in its behavior and controlling it efficiently. Furthermore, using a higher number of double-spirals in the development of complex aperiodic structures needs to be studied as a factor that could hinder their coherent and predictable performance [45,46].

As mentioned earlier, the high elastic deformability of TPU filament is the key strategy employed here to achieve reversible large deformations in double-spirals [29,30]. On the other side, however,

natural deformable spirals often have hierarchical designs, leveraging various mechanisms at different length scales to achieve the desired mechanical properties for their specific tasks and functions [47-51]. It might be worthwhile to focus on implementing diverse design strategies in the development of double-spirals and investigating their behavior when fabricated using materials with different mechanical properties.

## References

- [1] Sydenham, P.H., 1981. Mechanical design of instruments: 3: Fundamental concepts of systems nature (Part A). *Measurement and Control*, 14(1), pp. 5-10.  
DOI: 10.1177/002029408101400101
- [2] Sturges Jr, R.H., O'Shaughnessy, K. and Reed, R.G., 1993. A systematic approach to conceptual design. *Concurrent Engineering*, 1(2), pp. 93-105.  
DOI: 10.1177/1063293X9300100202
- [3] Farzaneh, H.H. and Lindemann, U., 2018. *A practical guide to bio-inspired design*. Berlin, Heidelberg, Germany: Springer Vieweg Verlag.  
DOI: 10.1007/978-3-662-57684-7
- [4] Lenau, T.A., 2009. Biomimetics as a design methodology-Possibilities and challenges. In *Proceedings of the International Conference on Engineering Design (ICED), Palo Alto, CA, USA, 24-27 August*, pp. 121-132.
- [5] Ahmad, B., Barbot, A., Ulliac, G. and Bolopion, A., 2022. Remotely actuated optothermal robotic microjoints based on spiral bimaterial design. *IEEE/ASME Transactions on Mechatronics*, 27(5), pp. 4090-4100.  
DOI: 10.1109/TMECH.2022.3145646
- [6] Racu, C.M. and Doroftei, I., 2018. Compliant mechanism for ankle rehabilitation device. Part II: Optimization and simulation results. *IOP Conference Series: Materials Science and Engineering*, 444(5), 052015.  
DOI: 10.1088/1757-899X/444/5/052015
- [7] Hendrich, N., Wasserfall, F. and Zhang, J., 2020. 3D printed low-cost force-torque sensors. *IEEE Access*, 8, pp. 140569-140585.  
DOI: 10.1109/ACCESS.2020.3007565
- [8] Tian, Y., Zhou, C., Wang, F., Lu, K. and Zhang, D., 2020. A novel compliant mechanism based system to calibrate spring constant of AFM cantilevers. *Sensors and Actuators A: Physical*, 309, 112027.  
DOI: 10.1016/j.sna.2020.112027

- 
- [9] Zolfagharian, A., Gharai, S., Gregory, J., Bodaghi, M., Kaynak, A. and Nahavandi, S., 2022. A bioinspired compliant 3D-printed soft gripper. *Soft Robotics*, 9(4), pp. 680-689.  
DOI: 10.1089/soro.2020.0194
- [10] Xiang, C., Li, Z., Wang, F., Guan, Y. and Zhou, W., 2023. A 3D printed flexible electroadhesion gripper. *Sensors and Actuators A: Physical*, 363, 114675.  
DOI: 10.1016/j.sna.2023.114675
- [11] Lv, C., Yu, H. and Jiang, H., 2014. Archimedean spiral design for extremely stretchable interconnects. *Extreme Mechanics Letters*, 1, pp. 29-34.  
DOI: 10.1016/j.eml.2014.12.008
- [12] Alcheikh, N., Shaikh, S.F. and Hussain, M.M., 2019. In-plane deformation mechanics of highly stretchable Archimedean interconnects. *AIP Advances*, 9(1), 015224.  
DOI: 10.1063/1.5053967
- [13] Yuan, X. and Wang, Y., 2023. Nonlinear stretching mechanics of planar Archimedean-spiral interconnects for flexible electronics. *Thin-Walled Structures*, 185, 110568.  
DOI: 10.1016/j.tws.2023.110568
- [14] Dong, L., Wang, D., Wang, J., Jiang, C., Wang, H., Zhang, B., Wu, M.S. and Gu, G., 2022. Modeling and design of periodic polygonal lattices constructed from microstructures with varying curvatures. *Physical Review Applied*, 17(4), 044032.  
DOI: 10.1103/PhysRevApplied.17.044032
- [15] Liu, J., Guo, H., Liu, H. and Lu, T., 2023. Designing hierarchical soft network materials with developable lattice nodes for high stretchability. *Advanced Science*, 10(8), 2206099.  
DOI: 10.1002/advs.202206099
- [16] Zarrinmehr, S., Eftehad, M., Kalantar, N., Borhani, A., Sueda, S. and Akleman, E., 2017. Interlocked archimedean spirals for conversion of planar rigid panels into locally flexible panels with stiffness control. *Computers & Graphics*, 66, pp. 93-102.  
DOI: 10.1016/j.cag.2017.05.010
- [17] Chen, R., Turman, C., Jiang, M., Kalantar, N., Moreno, M. and Muliana, A., 2020. Mechanics of kerf patterns for creating freeform structures. *Acta Mechanica*, 231, pp. 3499-3524.  
DOI: 10.1007/s00707-020-02713-8
- [18] Darnal, A., Mantri, K., Shahid, Z., Kalantar, N. and Muliana, A., 2023. The influence of inelastic materials on freeform kerf structures. *Thin-Walled Structures*, 193, 111292.  
DOI: 10.1016/j.tws.2023.111292
- [19] Smith, M., 2009. *Abaqus/standard user's manual, version 6.9*. Dassault Systèmes Simulia Corp, Providence, RI.

- 
- 
- [20] Lee, H.H., 2023. *Finite element simulations with ANSYS Workbench 2023: Theory, applications, case studies*. Mission, Kansas, USA: SDC publications.
- [21] Kalpakjian, S. and Schmid, S., 2022. *Manufacturing engineering and technology*, 8th ed., London, UK: Pearson.
- [22] Redwood, B., Schfffer, F. and Garret, B., 2017. *The 3D printing handbook: Technologies, design and applications*. Amsterdam, Netherlands: 3D Hubs.
- [23] Fan, Z., Zhang, Y., Ma, Q., Zhang, F., Fu, H., Hwang, K.C. and Huang, Y., 2016. A finite deformation model of planar serpentine interconnects for stretchable electronics. *International Journal of Solids and Structures*, 91, pp. 46-54.  
DOI: 10.1016/j.ijsolstr.2016.04.030
- [24] Su, Y., Ping, X., Yu, K.J., Lee, J.W., Fan, J.A., Wang, B., Li, M., Li, R., Harburg, D.V., Huang, Y.A., Yu, C., Mao, S., Shim, J., Yang, Q., Lee, P.-Y., Armonas, A., Choi, K.-J., Yang, Y., Paik, U., Chang, T., Dawidczyk, T.J., Huang, Y., Wang, S. and Rogers, J.A., 2017. In-plane deformation mechanics for highly stretchable electronics. *Advanced Materials*, 29(8), 1604989.  
DOI: 10.1002/adma.201604989
- [25] Alcheikh, N., Shaikh, S.F. and Hussain, M.M., 2018. Ultra-stretchable Archimedean interconnects for stretchable electronics. *Extreme Mechanics Letters*, 24, pp. 6-13.  
DOI: 10.1016/j.eml.2018.08.005
- [26] Zhang, W., Neville, R., Zhang, D., Yuan, J., Scarpa, F. and Lakes, R., 2023. Bending of kerf chiral fractal lattice metamaterials. *Composite Structures*, 318, 117068.  
DOI: 10.1016/j.compstruct.2023.117068
- [27] Zhang, Z., Scarpa, F., Bednarczyk, B.A. and Chen, Y., 2021. Harnessing fractal cuts to design robust lattice metamaterials for energy dissipation. *Additive Manufacturing*, 46, 102126.  
DOI: 10.1016/j.addma.2021.102126
- [28] McCrary, A., Hashemi, M.S. and Sheidaei, A., 2022. Programmable bidirectional mechanical metamaterial with tunable stiffness and frictional energy dissipation. *Advanced Theory and Simulations*, 5(7), 2200135.  
DOI: 10.1002/adts.202200135
- [29] Desai, S.M., Sonawane, R.Y. and More, A.P., 2023. Thermoplastic polyurethane for three-dimensional printing applications: A review. *Polymers for Advanced Technologies*, 34(7), pp. 2061-2082.  
DOI: 10.1002/pat.6041
- [30] Fillamentum, and addi(c)tive polymers. 2019. Flexfill TPU 98A technical data sheet.
- [31] Qi, H.J. and Boyce, M.C., 2005. Stress-strain behavior of thermoplastic polyurethanes. *Mechanics of Materials*, 37(8), pp. 817-839.

- DOI: 10.1016/j.mechmat.2004.08.001
- [32] Wang, Y., Ma, R., Li, H., Hu, S., Gao, Y., Liu, L., Zhao, X. and Zhang, L., 2022. Effect of the content and strength of hard segment on the viscoelasticity of the polyurethane elastomer: Insights from molecular dynamics simulation. *Soft Matter*, 18(21), pp. 4090-4101.  
DOI: 10.1039/D2SM00463A
- [33] Pelayo, F., Blanco, D., Fernández, P., González, J. and Beltrán, N., 2021. Viscoelastic behaviour of flexible thermoplastic polyurethane additively manufactured parts: Influence of inner-structure design factors. *Polymers*, 13(14), 2365.  
DOI: 10.3390/polym13142365
- [34] Gumus, O.Y., Ilhan, R. and Canli, B.E., 2022. Effect of printing temperature on mechanical and viscoelastic properties of ultra-flexible thermoplastic polyurethane in material extrusion additive manufacturing. *Journal of Materials Engineering and Performance*, 31(5), pp. 3679–3687.  
DOI: 10.1007/s11665-021-06510-9
- [35] Tsuji, K. and Müller, S.C. (eds.) 2019. *Spirals and vortices: In culture, nature, and science*. Cham, Switzerland: Springer.  
DOI: 10.1007/978-3-030-05798-5
- [36] Goldman, R., 2009. *An integrated introduction to computer graphics and geometric modeling*. Boca Raton, Florida, USA: CRC Press.  
DOI: 10.1201/9781439803356
- [37] Yang, N., Zhang, M., Zhu, R. and Niu, X.D., 2019. Modular metamaterials composed of foldable obelisk-like units with reprogrammable mechanical behaviors based on multistability. *Scientific Reports*, 9(1), 18812.  
DOI: 10.1038/s41598-019-55222-7
- [38] Liu, W., Jiang, H. and Chen, Y., 2022. 3D programmable metamaterials based on reconfigurable mechanism modules. *Advanced Functional Materials*, 32(9), 2109865.  
DOI: 10.1002/adfm.202109865
- [39] Mao, J.J., Wang, S., Tan, W. and Liu, M., 2022. Modular multistable metamaterials with reprogrammable mechanical properties. *Engineering Structures*, 272, 114976.  
DOI: 10.1016/j.engstruct.2022.114976
- [40] Xu, S., Shen, J., Zhou, S., Huang, X. and Xie, Y.M., 2016. Design of lattice structures with controlled anisotropy. *Materials & Design*, 93, pp. 443-447.  
DOI: 10.1016/j.matdes.2016.01.007
- [41] Zhang, Y., Sun, L., Ren, X., Zhang, X.Y., Tao, Z. and Xie, Y.M., 2022. Design and analysis of an auxetic metamaterial with tuneable stiffness. *Composite Structures*, 281, 114997.



- DOI: 10.1016/j.compstruct.2021.114997
- [42] Fleisch, M., Thalhamer, A., Meier, G., Fuchs, P.F., Pinter, G., Schlögl, S. and Berer, M., 2022. Asymmetric chiral and antichiral mechanical metamaterials with tunable Poisson's ratio. *APL Materials*, 10(6), 061105.  
DOI: 10.1063/5.0091756
- [43] Wang, H., Lyu, Y., Bosiakov, S., Zhu, H. and Ren, Y., 2023. A review on the mechanical metamaterials and their applications in the field of biomedical engineering. *Frontiers in Materials*, 10, 1273961.  
DOI: 10.3389/fmats.2023.1273961
- [44] Haupt, R.L. and Haupt, S.E., 2004. *Practical genetic algorithms*, 2nd ed., Hoboken, New Jersey, USA: John Wiley & Sons.  
DOI: 10.1002/0471671746
- [45] Coulais, C., Teomy, E., De Reus, K., Shokef, Y. and Van Hecke, M., 2016. Combinatorial design of textured mechanical metamaterials. *Nature*, 535(7613), pp. 529-532.  
DOI: 10.1038/nature18960
- [46] Yang, N. and Silverberg, J.L., 2017. Decoupling local mechanics from large-scale structure in modular metamaterials. *Proceedings of the National Academy of Sciences*, 114(14), pp. 3590-3595.  
DOI: 10.1073/pnas.1620714114
- [47] Krenn, H.W., 2010. Feeding mechanisms of adult Lepidoptera: Structure, function, and evolution of the mouthparts. *Annual Review of Entomology*, 55, pp. 307-327.  
DOI: 10.1146/annurev-ento-112408-085338
- [48] Shear, W.A., 2015. The chemical defenses of millipedes (Diplopoda): Biochemistry, physiology and ecology. *Biochemical Systematics and Ecology*, 61, pp. 78-117.  
DOI: 10.1016/j.bse.2015. 04.033
- [49] Luger, A.M., Ollevier, A., De Kegel, B., Herrel, A. and Adriaens, D., 2020. Is variation in tail vertebral morphology linked to habitat use in chameleons?. *Journal of Morphology*, 281(2), pp. 229-239.  
DOI: 10.1002/jmor.21093
- [50] Kier, W.M., 2016. The musculature of coleoid cephalopod arms and tentacles. *Frontiers in Cell and Developmental Biology*, 4, 10.  
DOI: 10.3389/fcell.2016.00010
- [51] Matsumura, Y., Kovalev, A.E. and Gorb, S.N., 2017. Penetration mechanics of a beetle intermittent organ with bending stiffness gradient and a soft tip. *Science Advances*, 3(12), eaao-5469.  
DOI: 10.1126/sciadv.aao5469

## Chapter 6:

### Conclusion

This study was devoted to understanding the mechanical behavior of compliant double-spirals and investigating their potential as highly deformable mechanical elements. The conclusions derived from the obtained results are as follows.

- Inspired by the coiling-uncoiling behavior of highly deformable natural spirals, the compliant double-spiral has been designed to serve as a mechanical element with tunable mechanical properties potentially desirable in engineering fields such as soft robotics.
- By leveraging the simple equations of spirals and adjusting a few design parameters, one can easily manipulate the geometry of the double-spiral, adjust its mechanical behavior, and achieve a broad range of properties. Increasing the number of design variables, double-spirals with more diverse geometries and a broader range of properties are accessible.
- Anisotropic and asymmetric behavior, multiple degrees of freedom, reversible non-linear extensibility, and variable stiffness are among tunable characteristics that can be achieved through the elastic deformation of a single double-spiral or multiple interconnected double-spirals with rationally designed geometries, under specific boundary conditions and loading.
- The fixed cross-sectional profile of the double-spiral and its planar design simplifies its modeling and the numerical simulation of its behavior, accelerates the manufacturing process, and facilitates its integration into different structures.
- Among available manufacturing technologies, an easily accessible FDM 3D printer is a suitable tool for the rapid and cost-effective fabrication of double-spiral using a single material.
- The exploration of the double-spiral as a bio-inspired mechanical element aims to contribute to the ongoing efforts in developing simple yet versatile and efficient systems. The vision is for the double-spiral to serve as a foundational element in the development of various technical structures, such as soft grippers, continuum manipulators, compliant robot foot, impact absorbers, deployable structures, etc.

## Declaration

Hereby, I declare that the present dissertation, apart from the supervisor's guidance, is all my own work. The thesis has not been submitted, either partially or wholly, as part of a doctoral degree to another examining body. The essential parts of the work have been published in scientific journals. This thesis is in compliance with the Rules of Good Scientific Practice of the German Research Foundation. I also declare that no academic degree has ever been withdrawn from me.

Kiel,

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Mohsen Jafarpour Kourka