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Toward a Low Hysteresis Helical Scale Jamming Interface Inspired by Teleost Fish Scale Morphology and Arrangement

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Abstract— Inspired by teleost fish scale, this paper investigates the possibility of implementing stiffness control as a new source of robots dexterity and flexibility control. Guessing about the possibility of biological scale jamming in real fish, we try to understand the possible underlying actuation mechanism of such behavior by conducting experiments on a Cyprinus carpio fish skin sample. Bulking tests are carried out on an encapsulated skin sample, in thin latex rubber, for unjammed and vacuum jammed cases. For the first time, we observed biological scale jamming with very small hysteresis due to the unique scale morphology and jammed stacking formation. We call this unique feature "Geometrical Jamming" where the resisting force is due to the stacking formation rather than the interlocking friction force. Inspiring by this unique morphology and helical arrangement of the scale, in this research, we investigate different possible design and actuation mechanisms for an integrable scale jamming interface for stiffness control of continuum manipulators. A set of curved scales are 3D printed which maintain a helix formation when are kept in place and jammed with two thin fishing steel wires. The non-self locking jagged contact surfaces replicate inclined stacking formation of the jammed fish scale resulting in the same reversible low hysteresis characteristics, in contrast to the available interlocking designs. The effectiveness of the designs are shown for uniaxial elongation experiments and the results are compared with similar research. The contact surfaces, in our design, can be lubricated for further hysteresis reduction to achieve smooth, repeatable and accurate stiffness control in dynamic tasks.
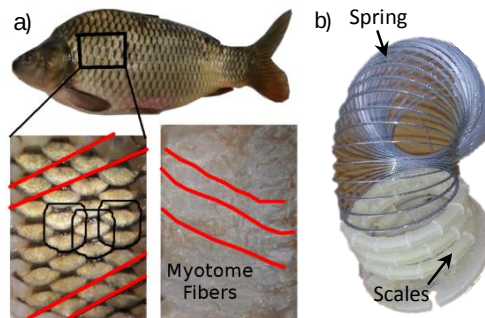
Fig. 1. (a) Skin sample surgery location on a Cyprinus carpio fish, helical myotome attachment sites and overlapping scales in relaxed state, (b) a sample scale jamming interface with curved interlocking scales on a low stiffness spring backbone.

I. INTRODUCTION

Fabrication of variable stiffness material [1] and variable stiffness soft manipulators, mostly inspired by octopus arms [2], as well as wearable robots have been widely investigated recently. They have numerous applications especially in soft surgeries where their deformable structure is beneficial to improve maneuverability, control and sensing [3], with less invasive interactions with organs [4], [5].

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Similar to Turgor Pressure, where the plasma membrane is pushed against the cell wall due to water pressure in a plant cell [6], the idea of jamming has been used to design variable stiffness endoscope for medical applications through increasing the friction in-between rigid segments [7], [8], [9], granular media [10], [11], [12], layers [13], [14] and wires [15], on which a through review is recently presented by L. Blanc, et. al. [16]. Granular jamming, being investigated more widely in the recent years due to their flexibility and easy implementation of different designs, is bulky and not appropriate for wearable applications. Layer jamming, which recalls birds feathers, is the only suitable choice for an integrable and wearable interface. However, they are hard to design, fabricate and model with low deformability due to their multilayer structure, necessary for resisting buckling forces, and the long flap length, required to achieve large deformations [14], [17]. Most segment locking designs are driven by tendons while the vacuum or internal pressure are used mainly for other types of jamming. A tendon driven jamming is more suitable for micro-scale fabrication and has new applications such as in-space exploration where pressurization is not possible. However, the routing and tendon-structure friction are the problems with this type of actuation [18]. The hysteresis loss, lack of local stiffness control and low repeatability are also inevitable with jamming based stiffening. While usually the normal forces on the jammed surfaces are controlled for stiffening, in our recent works, we investigated the idea of using low melting point composite [19] and active Velcro attachment mechanisms between the jamming media [20] to achieve higher stiffness range with simpler and smaller actuation mechanism for local stiffens control [16]. A tendon driven design is favorable for its controllability and robustness against environment uncertainties.

In this research, we investigate the idea of an integrable jamming interface for continuum manipulators. Such design has the advantages of easy integration on different manipulators with minimum added complexities due to separate fabrication procedure and actuation path, where directional stiffness control is possible by inhomogeneous modulation of the stiffness along the manipulator circumference. As a biological instance for wearable stiffness controllable interfaces, animals' skins and scales in nature show stiffness regulation in response to irritation or penetrating forces. Many animal species such as fish, turtles, armadillos and snakes have a hard scale or osteoderms as flexible armor and a means of friction regulation in contact with the environment [21] (Fig. 1.a). Mechanical properties of scale as a biological composite material is optimized for maximizing protection providing unique natural features such as unusual stiffness, toughness and strength [22]. Chemical compound of fish scales, especially the surface material, have been investigated to better understand the scales' different directional friction coefficient in snakes [23] and the turbulent-flow regime drag reduction effects due to riblet overlapping structure in fish, i.e. shark [24]. Fish scale properties differ considerably from one point to another on the animal body and are shown to be very sensitive to the scale hydration level. While the overall contribution of the scales material in the fish body stiffness is investigated [25], [26], to the best of our knowledge, no study has investigated the jamming property of the stacking scales and their possible stiffening effects.

Scale-like jamming has been investigated by Wall [13] and zuo [27] recently. In [13], the rigid scales, implemented on a soft silicone base, are packed together in an inclined orientation. The inclined orientation minimizes the design resistance against tension since part of the external pressure works in favor of the external force. In [27], rigid scales, with jagged contact surfaces for increased interlocking force, are integrated as an external layer on a hard backbone which makes it the most similar design to our work. Similar to layer jamming [14], both of these designs suffer from large hysteresis and low deformation range due to their bulky volume of the overlapping scales and short size of the straps. In our previous work, we presented an early version of a tendon-driven scale jamming design (Fig. 1.b) inspired by the helical arrangement and morphology of the fish scales to control torsional stiffness of a helical interface cross-section. A static model using LuGre friction model was presented for the deformation cycle of the jammed interface showing how the bio-inspired jagged design of the scale surface reduces the cyclic hysteresis of the jammed media. As a result, we achieved a simpler design and actuation method which, for the first time, provides better wearability, linear behavior, higher axial stretch and lower hysteresis [28] compared to the previous granular [5] and layer [14] jamming designs.

In this research, different variation of such scale jamming design is investigated. First, we chose Cyprinus carpio scales, as a good example of the most common type of teleost scales in modern fish species [29], to conduct experiments on the jamming characteristics of real fish scales in section II.
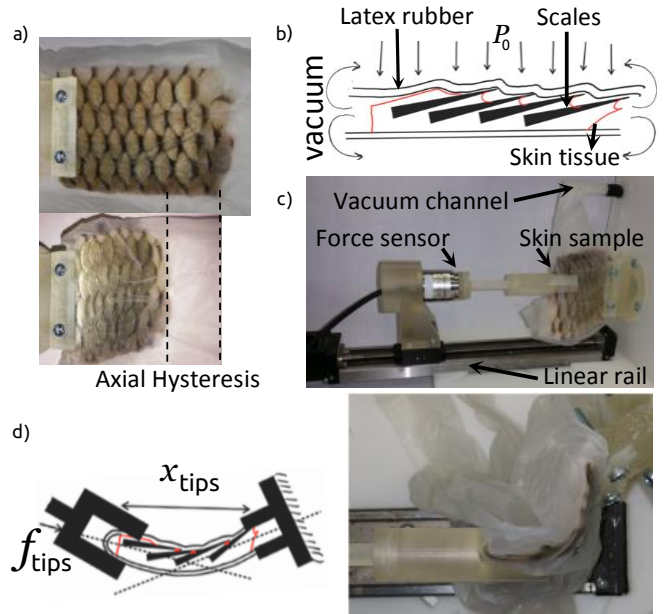

Fig. 2. (a) The experimental sample of the fish skin enclosed in latex rubber layer before and after uniaxial compression tests, (b) schematic of inclined stacked arrangement of the scales, (c) real test setup, (d) bulking test schematic and test setup.

Then, two scale jamming designs are introduced in section III in which 3D printed curved scales with jagged contact surfaces are placed in a helical formation. The stiffness of the interface is controlled through interlocking of the scales that regulates the torsional shear force on the cross-section of the helical structure. The inclination of the jagged surfaces is chosen to be smaller than the contacting material coefficient of friction that mimics the functionality of biological scale special geometry. As a result, for the first time in a jamming design, a very low hysteresis is achieved even after relative movement of the contacting surfaces (plastic deformations). We call this unique feature "Geometrical Jamming" where the resisting force is due to the stacking formation rather than the interlocking friction force. We chose this name to emphasis on the importance of the scales geometry and the stacking morphology in the observed behavior. This can be seen as an instance of morphological computation, the idea of exploiting the embodied intelligence or morphological computation of the available physical hardware to fulfill a task [30], [31], [32]. Placing the scales in a helix formation guarantees their face-to-face contact even in large deformations, despite their small size, and an easy to integrate low volume design. To our best knowledge, a design combining these ideas was not previously investigated for stiffening purposes in robotics. It should be noted that biomimicry is not our objective in this study. Rather, we aim to test the hypothesis that contact friction/locking control using scales is a viable method for stiffness control of exoskeletons for soft robots. The proposed helical interface is going to be integrated on a continuum manipulator to control the stiffness matrices of the elements along the backbone by adjusting the

torsional stiffness of the helix cross-section. The experiential results are discussed in section V where our model is verified for the simple elongation test. Finally, the advantageous and shortcomings of the proposed designs are addressed in comparison with similar recent research in section VI, followed by a conclusion in section VII.

II. BIOLOGICAL SCALE MORPHOLOGY AND JAMMING

We choose Cyprinus carpio scales in our experiments which is a teleost scale commonly used in similar research [21] (Fig. 1.a). Theoretically, the stiffness of a biological tissue with scales should change from the low stiffness of the underlying soft tissue (almost negligible) in the unjammed state to the rigidity of the scales ($E \approx 850$ [MPa], $\sigma_{\mathrm{yield}} \approx 30$ [MPa] [21]) in the fully jammed state. However, the maximum value of the stiffness is determined by the inter-scale coefficient of friction, which is very low because of an intermediate skin that prevents the direct contact of the scales.

A 62.55×50.14 [mm] ($width \times length$) sample of the skin with 4 by 7 arrangement of the scales is cut and sealed in a low stiffness latex glove (Fig. 3.a,b). The scales have an average size of 21×19.5 [mm] and the overall sample thickness (including the latex glove layers) is 1.06 [mm] with three overlapping scales. The sample is placed in a force measurement setup with an ATI Nano-17 force sensor (Fig. 2.c). Three cycles of test with stroke of 10 [mm] are carried out in quasi-static condition. Experimental data are collected at 0.01 [s] intervals and smoothened using Matlab software 'smooth' function based on a moving average filter with the step of 15. The sample is tested for uniaxial bulking (Fig. 2.d) as the most realistic deformation since the natural scales are attached with an offset from the fish vertebrae, as the neutral axis of the body curvature in bending, and undergoes longitudinal as well as bending deformations. The longitudinal deformation amplifies the jamming by pushing the scales against the inclined stacking formation of the jamming state. The scale jamming limits the skin curvature as well as preventing penetration by stacking together. Scales are placed on the bent inward direction and the reported results are the change in the blocking force, stress at the middle of the sample and equivalent modulus of elasticity in the jammed (vacuumed) and unjammed states. Scales do not jam if placed on the outer side of the bent. The results of the first test cycle, which we call the warm-up cycle, are noticeably different from the next cycles and hence, are neglected. The latex glove contribution in the jamming due to capillary forces is neglected too. The elasticity modulus is found based on a simple Euler-Bernoulli beam model.

The test results are presented in Fig. 3 and 4. A 30% increase in the stiffness is observed in this case but with a noticeable $\approx 0.1.7$ [N] resisting force and in a reversible manner with low hysteresis due to the small relative movement of the scales and overall bulking stroke (10 [mm]). The small inter-scale friction reduces the hysteresis, but results in immediate sliding of the scales where only the dynamic friction coefficient is important. A linear stiffness is
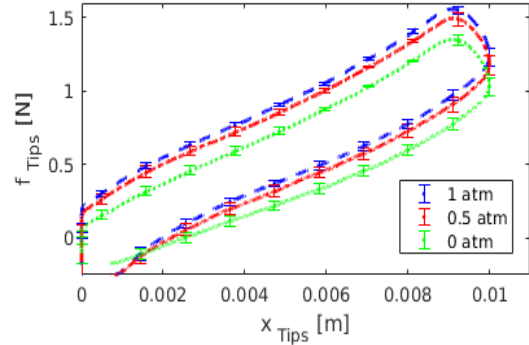

Fig. 3. Resisting force (f_{Tips}) vs. curve hypotenuse deformation (x_{Tips}) for different vacuum pressures in the bulking test on a real fish skin sample with jammed scales.
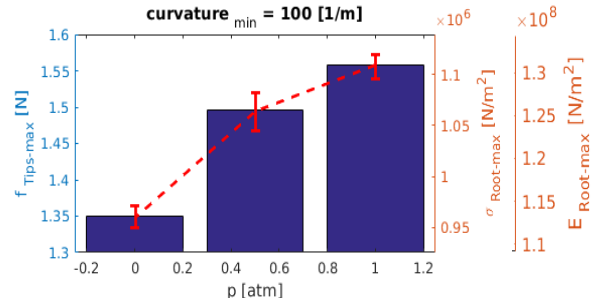

Fig. 4. Maximum tip force (f_{Tips}), stress ($\sigma_{\mathrm{Root-max}}$) and Euler-Bernoulli equivalent beam elasticity modulus ($E_{\mathrm{Root-max}}$) vs. vacuum pressure in the bulking test on a real fish skin sample with jammed scales and curvature 100 [1/m].

observed w.r.t. curvature and vacuum pressure. Considering the low friction tissue between the scales, we suspect that the stiffness increase in the bulking test is mainly due to the inclined stacking formation of the scales.

It seems that the scales are designed for not jamming together, because a multi-layer armor with small inter-layer friction, 1000 times less than the scale stiffness, results in a 50% increase in the protection against penetration [21]. However, a linear low hysteresis jamming behavior with good reversibility is observed which results in 18-80% increase in the stiffness mainly due to the inclined stacking formation of the jammed scales. The linear reversible jamming, due to low friction coefficient and inclined staking formation, and the helical formation, that preserves the stiffness in a large deformation, can inspire a design for jamming media surface and arrangement to achieve the same linear reversible performance for a large deformation range. These are beneficial for the design of an integrable interface for continuum manipulators. However, this is not clear if a similar jamming actually contributes to a real fish skin stiffness variation, and if so, what may causes it. As a guess, the fish may use the myotome attachment fibers and the inter-layer dermis for active jamming (similar to our tendon-driven design), or external hydrostatic pressure, due to swimming depth or turbulent flow hydro-dynamic pressure, as means of passive jamming.

III. Bio-Inspired Scale Arrangement and Design

Inspired by the real fish scales' morphology, helical arrangement and inclined stacking formation when are jammed, we propose a scale jamming interface in which the torsional stiffness of a helical interface cross-section is increased through controlling scales' interlocking friction (Fig. 5). The helical interface provides large axial and bending deformations and regional and directional stiffness controllability by having multiple points of stiffness adjustment on each ring of the helix. Tendons are used to jam the jagged surfaces of two scales with carefully selected slope angle that replicates the stacking of the biological scales in jamming. The contact surfaces push together and move apart by sliding up the slopes as a result of any relative rotation of the helical cross-section (Fig. 6). The tendon initial tension controls the interface stiffness by regulating the normal force acting on the surfaces and adjusting the pre-tension of the wire that undergoes a further tension due to the relative upward movement of the scales as in Fig. 6. This results in an increase in the jamming friction and wire tension. We call this "geometrical jamming", in which the contact surfaces can be lubricated for better reversibility and smooth operation with the same stiffening properties. In contrary to the conventional friction-based jamming, our design benefits from reversibility, higher stiffness range, low hysteresis and small surface wear. Two scale designs are presented to further investigate this idea.

1) A helical scale with smaller circular contact surface, with no need for a low stiffness spring backbone, where the tangential force resulting from tensioning the wire pushes the surfaces together (Fig. 5.a,b).
2) A scale like design where the reduced length of the wire due to the tension results in a radial force that pushes the scales together (Fig. 5.c,d).

IV. Scale Jamming Interface Integrated Mechanics

Local stiffness regulation along a continuum manipulator backbone enables simultaneous task space impedance and configuration control as well as disturbance rejection. Each full turn, in the proposed helical interface, adjusts the stiffness coefficient matrix of an element along the continuum manipulator backbone by the actuation of stiffness controllable joints. Similar to our previous thermoactive helical interface design in [19], we may use Castigliano's method to model each full turn stiffness matrices (K_v and K_u), to be used for the manipulator Variable Curvature kinematics as in [33]. The joints' torsional stiffness can be modeled using LuGre friction model for which a simple derivation is presented in our earlier work [28]. We plan to present a unified modeling framework in a future publication, as our main goal in this draft is to investigate and identify the advantages and limitation of different possible scale jamming designs.
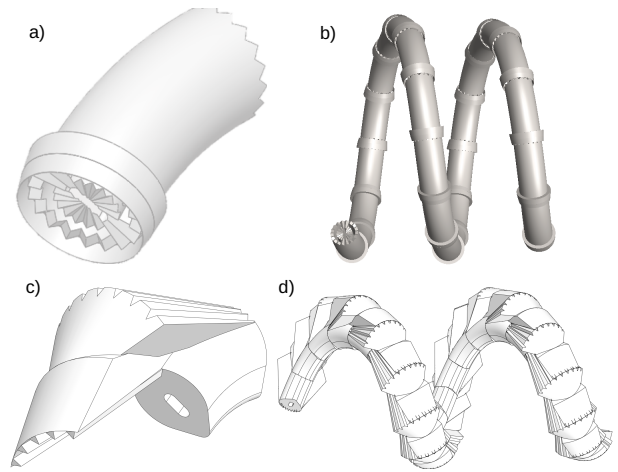

Fig. 5. Bio-inspired scale designs with, (a,b) tangential and (c,d) radial jamming force and (b,d) their arrangement forming a helical interface.
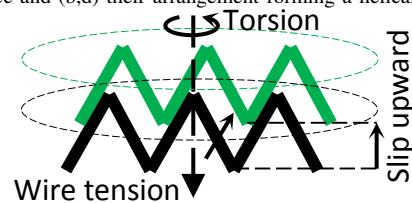

Fig. 6. Schematic of the jagged contact surfaces inspired by inclined stacking formation of natural fish scales showing an upward movement and increasing tension in the wire due to relative slip of jamming surfaces.

V. Experiments and Numerical Simulations for Different Designs

Two different scale designs are 3D-printed and tested in simple tension tests. Similar to our previous work [28], for a smaller design with better geometrical consistency with the helix backbone, a curved cylindrical design was introduced ($r_{j1} = 0.8, r_{j1} = 2.35$ routing and outer radius, $\alpha = 25$ [deg], $\phi_{sc} = 30$ [deg]), with contact surfaces perpendicular to the helix backbone, and actuated based on the tendon tangential force (Fig. 7). The tendon is connected to the last scale and the actuation tangential force is propagated through the interface from the last scale as well as through the tendon routing friction We showed, adding a low stiffness spring backbone is advantageous for smooth uniform operation of the interface; however, it reduces the blocking force, increases the tendon-routing friction and adds shape memory (a unique resting shape) and, as a result, a bias stiffness value to the system. A similar design with $\phi_{sc} = 90$ [deg] for increased joint effective rotation, cone-like surface for stronger teeth design, three roller bearings for friction reduction and without spring backbone is introduced to address these issues (Fig. 7). For simple tension tests of a sample with four turns and $l_0 = 40$ [mm], a linear, reversible and low hysteresis stiffness increase (f_{tip} =0.2-3.9 [N], 20 times increase) for different tendon tensions (f_t =0-17 [N]) is observed which has 278% larger blocking force (371% larger stiffness considering the different number of helix turns), compared to the previous design, with full stiffness range approximately as small as zero. However, larger hysteresis,

small load cycle fluctuations and less reversible results are observed compared with the version with a spring backbone in [28]. The new design does not present the same maximum blocking force in all the actuation cycles; however, the load cycles become more reversible after the first few warm-up cycles. This emphasizes the importance of a uniform relative movement which can be enforced using a low stiffness spring backbone. For tension forces higher than 17 [N], the hysteresis is increased without a noticeable change in the blocking force.

The second design which is more similar a fish scale, actuated with radial tendon force, needs a backbone spring with low axial but high radial stiffness to oppose the tendon force as a base (Fig. 8). To guarantee the jamming, the tendon route is designed so that the scale touches the next scale before contacting the backbone spring. We used a springy helix with rectangular cross section (1.2×0.2 [mm] dimension, $E_{\text{sp}} = 60$ [GPa], $r_{\text{sp}} = 19.2$ [mm] diameter, $\phi_{\text{sc}} = 30$ [deg]) as the backbone which satisfies our requirement. In a simple tension test for one turn of the radial scales (Fig. 8), a smooth 3.9 times increase in the resisting force (1.8-7 [N]) and stiffness is observed for 4 [N] wire tension. For higher tension values and up to 22 [N], the deformation profile is not smooth, with large hysteresis and only 60% increase in the blocking force. However, the scale has a bulky design to prevent the breakage of the thin unsupported contact surface at the scale tip. As a result, the deformation happens only in the elastic region. The scales are actuated by the tendon direct radial force which makes this design less sensitive to the tendon routing friction. The contact surface curvature center is not on the spring wire and the surface needs to slide as well as rotate to adjust to any change in the helix lead angle. As a result, large hysteresis and fluctuations are observed despite the good reversibility.

VI. DISCUSSION AND COMPARISON WITH OTHER JAMMING SOLUTIONS

The first scale design (Fig. 5.a,b) is considered as the best choice for a smaller design with better geometrical consistency and repeatable results; however, the second design (Fig. 5.c,d) may have advantages if considering the tendon routing friction in a longer design. In a future study, we plan to investigate the challenges with fabrication of a long helical interface, e.g. tendon routing friction and interface weight with both designs. The results from the experiments on the first design are compared with similar stiffening solutions in literature. Our design provides up to 3.6 times increase in the bending [28] and up to 20 times increase in the elongation tests, featuring a low hysteresis highly reversible load cycle. The maximum bending stiffness increase is on the average of similar jamming designs (granular jamming 0.5-15, layer jamming 0.7-7, wire jamming 3 times) and less than the segment locking designs (6-50 times) in literature [16] This value falls in the lower range of similar design stiffness range when the inner module is not active. The stiffness range in elongation tests is not reported. However, the scale jamming interface is easily integrable on any continuum ma-
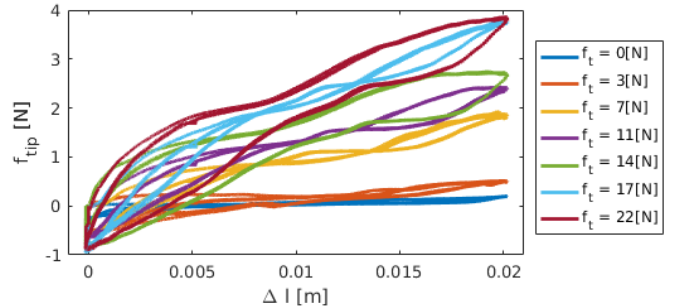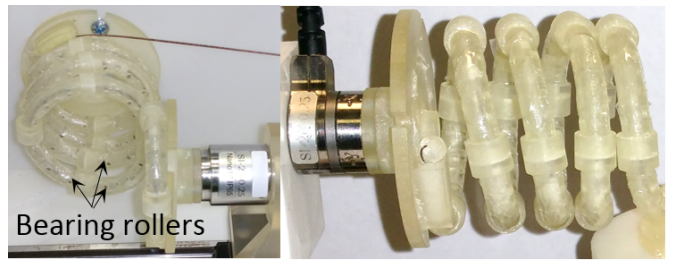

Fig. 7. (top) Scale jamming interface with tangential actuation force (Fig. 5.a) and roller bearings for friction reduction, (bottom) resisting force-elongation ($f_{\text{tip}} - \Delta l$) plot from uniaxial tension test (bottom). The jagged surface has 10 teeth with 0.45 [mm] height and 45 [deg] slope on a 77 [deg] cone-shape surface.
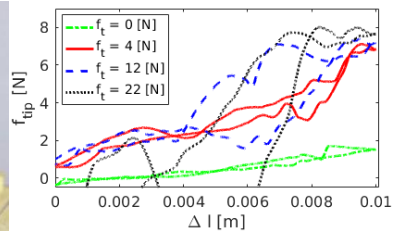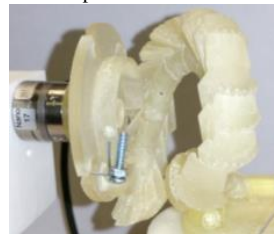

Fig. 8. Scale jamming interface with radial actuation force (Fig. 5.b) in experiments and results in uniaxial tension test. The jagged surface has 9 teeth with 1 [mm] height and 72 [deg] slope on a 40 [deg] cone-shape surface.

nipulator while the other designs need to be fabricated with the manipulator structure. We believe that the introduced geometrical jamming increases the stiffness control range and repeatability, and reduces the load cycle hysteresis and contact surface wear. However, the load bearing limitation of a helical interface is noticeable for long manipulators. Using tougher materials, e.g. using metal 3D-printed parts, and miniaturization of the scale design helps using multiple interfaces to act in parallel and cover more of the manipulator surface. In addition, a helix in full contracted configuration presents a higher stiffness that can be considered where a higher blocking force is needed.

VII. CONCLUSION

In this paper, for the first time, we briefly tested the idea of vacuum scale jamming on a real Cyprinus carpio fish skin. The results show an elastic deformation region with small hysteresis which we called "Geometrical Jamming" and believe is because of the special curved and jagged morphology of the biological scales. It is not clear whether the scale jamming happens for a real fish, and if so, what causes it. Two scale jamming interfaces are designed, by taking

inspiration from the morphology and helical arrangement of biological fish scales, to control the stiffness of continuum manipulators. The stiffness is controlled by changing the torsional stiffness and damping of the helical interface cross-section. We showed that the jagged contact surface reduces the hysteresis and increases the linear behavior range. Compared to the tendon stiffing, granular and layer jamming in the literature, we introduce a lighter and easily integrable design with shape locking capability, higher reversibility and stiffness variation ratio, and smaller hysteresis, volume and complexity. Relatively lower maximum blocking force of this design can be addressed by using multiple helical interfaces in parallel around a manipulator.

REFERENCES

[1] I. K. Kuder, A. F. Arrieta, W. E. Raither, and P. Ermanni, "Variable stiffness material and structural concepts for morphing applications," *Progress in Aerospace Sciences*, vol. 63, pp. 33–55, 2013. 00000.

[2] C. Laschi, M. Cianchetti, B. Mazzolai, L. Margheri, M. Follador, and P. Dario, "Soft Robot Arm Inspired by the Octopus," *Advanced Robotics*, vol. 26, no. 7, pp. 709–727, 2012.

[3] N. Sornkarn, M. Howard, and T. Nanayakkara, "Internal impedance control helps information gain in embodied perception," *Proceedings - IEEE International Conference on Robotics and Automation*, pp. 6685–6690, 2014. 00000.

[4] N. G. Cheng, M. B. Lobovsky, S. J. Keating, A. M. Setapen, K. I. Gero, A. E. Hosoi, and K. D. Iagnemma, "Design and analysis of a robust, low-cost, highly articulated manipulator enabled by jamming of granular media," *Proceedings - IEEE International Conference on Robotics and Automation*, pp. 4328–4333, May 2012.

[5] A. Jiang, G. Xynogalas, P. Dasgupta, K. Althoefer, and T. Nanayakkara, "Design of a variable stiffness flexible manipulator with composite granular jamming and membrane coupling," in *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*, (Vilamoura-Algarve, Portugal), pp. 2922–2927, IEEE, Oct. 2012.

[6] L. Tadrist and B. Darbois-Texier, "Are leaves optimally designed for self-support? An investigation on giant monocots," *Journal of Theoretical Biology*, vol. 396, pp. 125–131, May 2016.

[7] A. Degani, H. Choset, A. Wolf, and M. Zenati, "Highly articulated robotic probe for minimally invasive surgery," in *Proceedings 2006 IEEE International Conference on Robotics and Automation, 2006. ICRA 2006.*, pp. 4167–4172, IEEE, 2006.

[8] R. H. Sturges and S. Laowattana, "A Flexible, Tendon-Controlled Device for Endoscopy," *The International Journal of Robotics Research*, vol. 12, pp. 121–131, Apr. 1993.

[9] Y. J. Kim, S. Cheng, S. Kim, and K. Iagnemma, "A Stiffness-Adjustable Hyperredundant Manipulator Using a Variable Neutral-Line Mechanism for Minimally Invasive Surgery," *IEEE Transactions on Robotics*, vol. 30, pp. 382–395, Apr. 2014.

[10] M. Cianchetti, T. Ranzani, G. Gerboni, T. Nanayakkara, K. Althoefer, P. Dasgupta, and A. Menciassi, "Soft Robotics Technologies to Address Shortcomings in Today's Minimally Invasive Surgery: The STIFF-FLOP Approach," *Soft Robotics*, vol. 1, no. 2, pp. 122–131, 2014.

[11] R. M. Letts and D. A. Hobson, "The vacuum splint: an aid in emergency splinting of fractures," *Can Med Assoc J*, vol. 109, pp. 599–600, Oct. 1973.

[12] Y. Wei, Y. Chen, T. Ren, Q. Chen, C. Yan, Y. Yang, and Y. Li, "A Novel, Variable Stiffness Robotic Gripper Based on Integrated Soft Actuating and Particle Jamming," *Soft Robotics*, vol. 3, pp. 134–143, July 2016.

[13] V. Wall, R. Deimel, and O. Brock, "Selective Stiffening of Soft Actuators Based on Jamming," *2015 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 252–257, May 2015. 00006.

[14] Y.-J. J. Kim, S. Cheng, S. Kim, and K. Iagnemma, "A novel layer jamming mechanism with tunable stiffness capability for minimally invasive surgery," *IEEE Transactions on Robotics*, vol. 29, pp. 1031–1042, Aug. 2013.

[15] M. S. Moses, M. D. M. Kutzer, H. Ma, and M. Armand, "A continuum manipulator made of interlocking fibers," pp. 4008–4015, 2013.

[16] L. Blanc, A. Delchambre, and P. Lambert, "Flexible Medical Devices: Review of Controllable Stiffness Solutions," *Actuators*, vol. 6, p. 23, July 2017.

[17] J. L. C. Santiago, I. D. Walker, and I. S. Godage, "Continuum robots for space applications based on layer-jamming scales with stiffening capability," in *2015 IEEE Aerospace Conference*, pp. 1–13, IEEE, Mar. 2015.

[18] J. Jung, R. S. Penning, N. J. Ferrier, and M. R. Zinn, "A modeling approach for continuum robotic manipulators: Effects of nonlinear internal device friction," in *Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference on*, pp. 5139–5146, IEEE, 2011.

[19] S. M. H. Sadati, I. D. Walker, L. Sullivan, K. Althoefer, and T. Nanayakkara, "Three-Dimensional-Printable Thermoactive Helical Interface with Decentralized Morphological Stiffness Control for Continuum Manipulators," *IEEE Robotics and Automation Letters*, vol. PP, no. 99, 2018.

[20] H. Afrisal, S. Sadati, and T. Nanayakkara, "A Bio-Inspired Electro-Active Velcro Mechanism Using Shape Memory Alloy for Wearable and Stiffness Controllable Layers," in *Information and Automation for Sustainability (ICIAfS), 9th Int. Conf. on*, pp. 1–6, IEEE, 2016.

[21] D. Zhu, C. F. Ortega, R. Motamedi, L. Szewciw, F. Vernerey, and F. Barthelat, "Structure and mechanical performance of a "modern" fish scale," *Advanced Engineering Materials*, vol. 14, no. 4, 2012.

[22] R. K. Chintapalli, S. Breton, A. K. Dastjerdi, and F. Barthelat, "Strain rate hardening: A hidden but critical mechanism for biological composites?," *Acta Biomaterialia*, vol. 10, no. 12, pp. 5064–5073, 2014. 00006.

[23] X. Xiang, F. Long, A. Narkar, R. E. Kinnunen, R. Shahbazian-Yassar, B. P. Lee, and P. A. Heiden, "Is there value in chemical modification of fish scale surfaces?," *Journal of Applied Polymer Science*, vol. 133, no. 3, pp. n/a–n/a, 2016. 00000.

[24] B. Dean and B. Bhushan, "Shark-skin surfaces for fluid-drag reduction in turbulent flow: a review," *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, vol. 368, pp. 4775–4806, Oct. 2010.

[25] J. Long, M. Hale, M. Mchenry, and M. Westneat, "Functions of fish skin: flexural stiffness and steady swimming of longnose gar, Lepisosteus osseus," *Journal of Experimental Biology*, vol. 199, pp. 2139–2151, Oct. 1996.

[26] J. H. Long Jr. and K. S. Nipper, "The importance of body stiffness in undulatory propulsion," *American Zoologist*, vol. 36, no. 6, pp. 678–694, 1996. 00000.

[27] S. Zuo, K. Iijima, T. Tokumiya, and K. Masamune, "Variable stiffness outer sheath with Dragon skin structure and negative pneumatic shape-locking mechanism," *Int J CARS*, vol. 9, pp. 857–865, Sept. 2014.

[28] S. M. H. Sadati, Y. Noh, S. E. Naghibi, A. Kaspar, and T. Nanayakkara, "Stiffness Control of Soft Robotic Manipulator for Minimally Invasive Surgery (MIS) Using Scale Jamming," in *Intelligent Robotics and Applications*, Lecture Notes in Computer Science, pp. 141–151, Springer, Cham, Aug. 2015.

[29] A. Khayer Dastjerdi and F. Barthelat, "Teleost fish scales amongst the toughest collagenous materials," *Journal of the Mechanical Behavior of Biomedical Materials*, vol. 52, pp. 95–107, 2015. 00000.

[30] R. Pfeifer and J. Bongard, *How the Body Shapes the Way We Think: A New View of Intelligence*. MIT Press, Oct. 2006. Google-Books-ID: EHPMv9MfgWwC.

[31] H. Hauser, A. J. Ijspeert, R. M. Fchslin, R. Pfeifer, and W. Maass, "Towards a theoretical foundation for morphological computation with compliant bodies," *Biol Cybern*, vol. 105, pp. 355–370, Dec. 2011.

[32] H. Hauser, H. Sumioka, R. M. Fchslin, and R. Pfeifer, "Introduction to the Special Issue on Morphological Computation," *Artificial Life*, vol. 19, pp. 1–8, Nov. 2012.

[33] S. M. H. Sadati, S. E. Naghibi, I. D. Walker, K. Althoefer, and T. Nanayakkara, "Control Space Reduction and Real-Time Accurate Modeling of Continuum Manipulators Using Ritz and Ritz-Galerkin Methods," *IEEE Robotics and Automation Letters*, vol. 3, pp. 328–335, Jan. 2018.