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 contraction, bending and bulking experiments on a vacuum jammed Cyprinus carpio fish skin sample, encapsulated in thin latex layers. For the first time, we observed biological scale jamming with very small hysteresis due to the unique scale morphology and jammed stacking formation rather than the interlocking friction force, which we call "Geometrical Jamming". Inspired by this observation, we investigate the contact surface modeling and different possible designs of an integrable scale jamming interface for stiffness control of continuum manipulators. A set of 3D-printed curved scales with non-self-locking jagged contact surfaces, that replicates the inclined stacking formation of the jammed fish scale, maintain a helix formation when are kept in place and jammed with two thin fishing steel wires. As a result, we achieve very reversible low hysteresis, in contrast to the available interlocking designs. The effectiveness of the designs are shown in numerical simulation and simple elongation and bending experiments, when integrated on a continuum actuator module, and compared with available stiffening solutions in literature. The challenges with tendon routing friction in a long design investigated by adding roller bearings and possible lubrication of the contact surfaces for further hysteresis reduction and smooth, repeatable and accurate dynamic stiffness control.**

Demonstration Description: **We plan to showcase a multi-strand interface with directional stiffening properties, and a long single strand interface with dynamic regulation of the stiffness in our demonstration.**

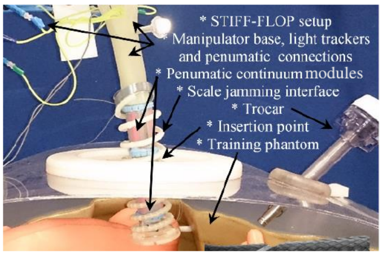

Fig. 1. Integration of a scale jamming interface on a STIFF-FLOP continuum module with application in Minimal Invasive Surgery.

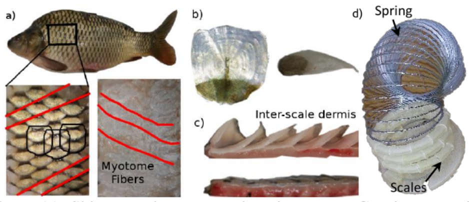

Fig. 2. (a) Skin sample surgery location on a Cyprinus carpio fish, helical myotome attachment sites and overlapping scales in relaxed state, (b) top and side view of a scale used in the experiments, (c) side view of a sample skin without scales showing the intermediate dermis preventing direct contacts of the scales, (d) a sample scale jamming interface with curved interlocking scales on a low stiffness spring backbone.

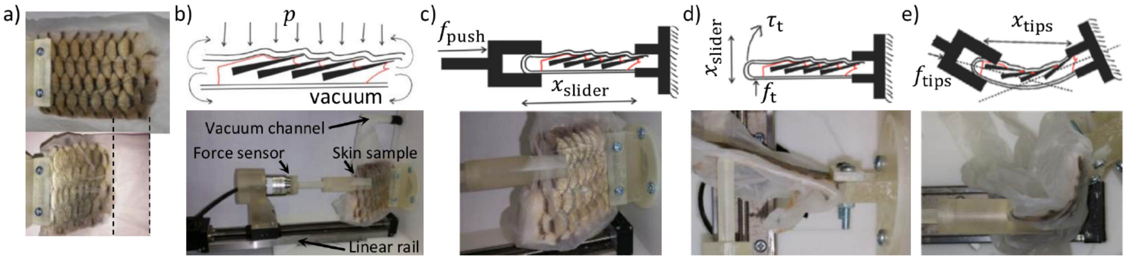

Fig. 3. (a) The fish skin sample enclosed in thin latex rubber layers before and after uniaxial compression tests. Schematic of (b) inclined stacking arrangement of the scales and the real test setup, (c) axial compression test, (d) bending test and (e) bulking test.

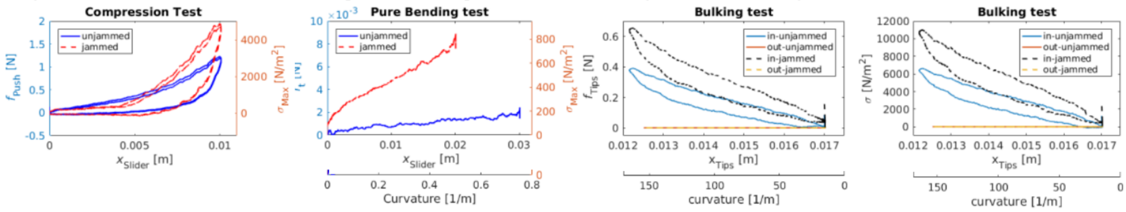

Fig. 4. The experimental results of vacuum jamming of a real fish skin sample: resisting force (f), maximum stress (σ_{Max}) and equivalent Euler-Bernoulli beam elasticity modulus (E) vs. linear deformation (x) and bending curvature in compression, simple bending and bulking tests. Tests are carried out twice, with scales on inward and outward side of the bend.

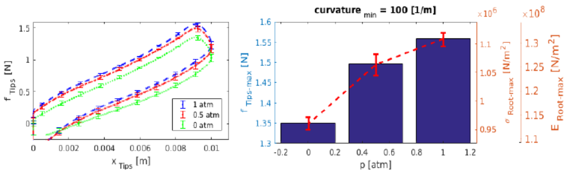

Fig. 5. Bulking test with larger than natural curvature, left: resisting force (f_{Tips}) vs. curve hypotenuse deformation (x_{Tips}) for different vacuum pressures, and right: maximum tip force (f_{Tips}), stress ($\sigma_{\mathrm{Root-max}}$) and equivalent Euler-Bernoulli beam elasticity modulus ($E_{\mathrm{Root-max}}$) vs. vacuum pressure for curvature 100 [1/m].

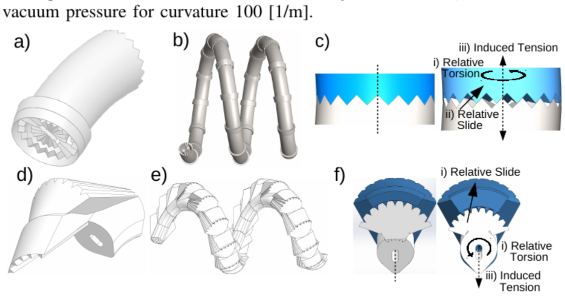

Fig. 6. (a-c) Bio-inspired inter-locking scale designs with tangential and (d-f) radial jamming force, (a,d) scale designs with two jagged contacting surfaces on both ends and a central hole for passing the actuation tendon and a low stiffness spring backbone if needed, (b,e) helical arrangement of the scales, (c,f) jagged contact surfaces inspired by inclined stacking formation of jammed biological scales. Relative axial (for the scales with tangential jamming force) and radial (for the scale with radial jamming force) movement of the scales due to relative slip of the jagged surfaces (white and blue) and the resulting increase in the wire tension.

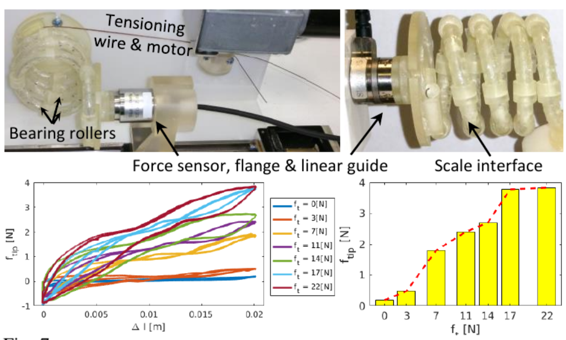

Fig. 7. Top: Scale jamming interface with tangential actuation force (Fig. 6.a-c) with roller bearings for friction reduction, bottom: resisting force-elongation ($f_{\mathrm{tip}} - \Delta l$) plot from simple tension test.

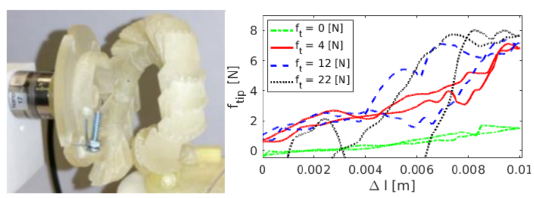

Fig. 8. Left: cale jamming interface with radial actuation force (Fig. 6.d-f), and right: results for simple tension test.