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Unleashing Soft Modular Robots by means of a Bio-inspired Connection Strategy

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***Abstract*— Untethering can allow soft modular robots to move from the laboratory test bench into realistic environments and commercial use. However, today's state of the art soft modular robots remain electrically connected to external power sources and controllers. The reason for this is that current electrical connections between modules induce rigidity into the soft robot, eliminating the advantages of being soft or can have high electrical resistance making communication and power exchange among modules impractical. To overcome this, we present a new bio-inspired inter-module connection strategy that connects soft modules mechanically and electrically without sacrificing the high deformability of the robot nor the low electrical resistance. We show that our strategy allows connected modules to retain stiffness in the same order of magnitude as individual modules while providing low electrical resistance. This enabled us to develop two untethered soft modular tensegrity robots, a gripper capable of holding two times its body weight and grasp objects of different shapes and a crawler that can move up to 4.5cm/min.**

I. Introduction

For a long time researchers have been investigating the idea of developing universal reconfigurable machines able to carry out diverse missions by assuming task-specific morphologies [1]. The idea led to the foundation of the modular robotics field. Modular robots are versatile robotic systems made of simple subunits that can be assembled into task-specific morphologies [2].

Rigid modular robots are capable of untethered movement by using inter-module connection strategies that allow the transfer of mechanical loads as well as power and communication signals between the modules [3]. These strategies involve rigidly connecting the faces of neighboring modules with, mechanical latches [4] or magnets [5] to transfer mechanical loads and electrical plugs [3-5] to transfer communication signals and power. Being untethered frees modular robots to navigate complex environments without risking entanglement with obstacles. Furthermore, the presence of external tethers from each module can limit the set of possible connections among modules and, therefore, the set of potential morphologies [3].

Inspired by multi-cellular biological systems, researchers have recently investigated modular robots composed of soft modules [6]. These soft modular robots provide safer interaction with the environment and span a larger morpho-functional space [7].

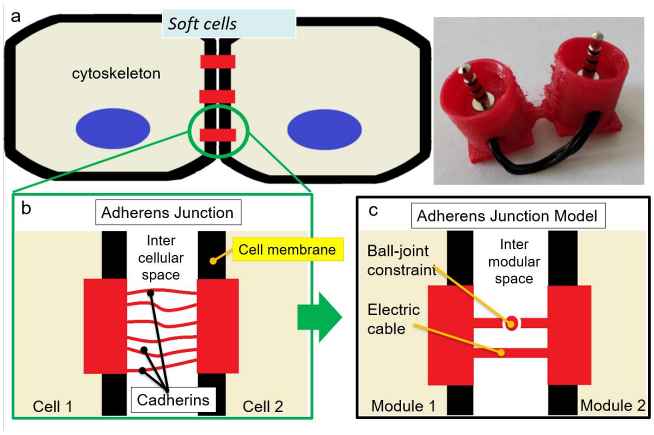

Figure 1. (a) A sketch of two living cells connected by adherens junctions. In red are three adherens junctions connecting the cell membranes (in black). In blue are the nuclei of the cells. (b) Zoomed in depiction of an individual adherens junction. In red the filiform cadherins proteins lie in the intercellular space and comprise the junction (c) Sketch of a mechanical and electrical model of the adherens junction. The junction (in red) can be modeled as a ball-joint constraint and an electric cable with zero bending stiffness in parallel.

However, current soft modular robots make use of connection strategies between their modules that only transfer mechanical loads [7-14] or have an electrical resistance that is too high to allow an efficient power and communication transmission [15-17].

Inspired by adheren junctions in soft pluricellular organisms, such as invertebrates and vertebrates' soft tissues, we propose a novel junctions connection strategy to not only transfer mechanical loads but also efficiently transfer power and communication signals using off-the-shelf copper wiring with low electrical resistance (i.e. $< 1\Omega$) . Moreover, our strategy preserves the high deformability of the soft modules after being connected. Differently from the strategy used for rigid and soft modular robots, the junction connection strategy consists in connecting single points of shared faces modules, instead of the entire faces.

The paper is organized as follows: in section II, the adherens junctions, and the bio-inspired junctions connection strategy for soft modular robots are presented. A hardware implementation of the connectors is also described. Section III describes the implementation of the connection strategy in a soft modular tensegrity robot platform and the results of the mechanical and electrical characterization of connected pairs of modules. In section IV, two untethered soft modular robots -a soft robotic gripper and a soft crawling robot- are presented to demonstrate the potential of the proposed connection strategy.

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II. BIO-INSPIRED BALL-JOINTS CONNECTIONS

In pluricellular organisms, cells in soft tissues are anchored to one another to transfer mechanical loads as well as to exchange energy and communication signals [18]. While connected, each cell preserves its own softness and ability to deform.

To achieve this, soft cells have evolved points of contact, called adherens junctions, distributed on their external membranes (Fig. 1a). These junctions consist of filiform cadherins proteins from each cell (Fig. 1b). Because they occupy only a small part of the external surface of the cell and are filiform structures that can easily bend, the adherens junctions do not hinder the overall ability of the joined cells to deform [18].

There are two types of specialized cadherins [18]. The first type is specialized in transferring mechanical loads. Being slender filiform structures, they only constrain relative translations between two membrane points while allowing relative rotations and can therefore be modeled as ball-joint constraints (Figure 1c) [19]. The second type of cadherins are specialized in transferring electrochemical energy and communication signals without hindering relative rotations between two membrane points. This type of cadherin can be modeled as a slack cable running in parallel to the ball-joint constraint (Figure 1c) [19].

The junctions connection strategy for soft modular robots, consists of anchored pairs of points on the external membranes of neighboring soft modules (Figure 2a). As with the biological counterparts, the novel junction connector is composed of two different cables. The first cable is stiff and short. It acts as a ball-joint constraint allowing the transfer of mechanical loads between modules. The second cable is a conductive electrical cable with low bending stiffness and low electrical resistance that allows transfer of power and communication signals between the soft modules (Figure 2b and d). A plug and socket attachment system on both cables enables the modules to be connected and disconnected (Figure 2b and d).

According to classical mechanics (chains law) [20] and its application on soft kinematic chains [21], for two three-dimensional modules to be considered connected, it is required that one or more connectors constrain all three relative rotations and all three relative translations between the modules at mechanical equilibrium [20]. An individual ball-joint constraint constrains three relative translations but still allows three relative rotations, while two ball-joint constraints would still allow one relative rotation between the modules, thus three ball joints are required to fully constrain two modules [21].

III. IMPLEMENTATION OF THE JUNCTIONS CONNECTION STRATEGY

We implemented the junctions connection strategy on a soft modular robotic platform composed of tensegrity modules [11] (Figure 2c-d). Each tensegrity module is composed of rigid struts enveloped in a flexible network of elastic cables (Figure 3) [15]. Two types of tensegrity modules are used in this work: an icosahedron module and a

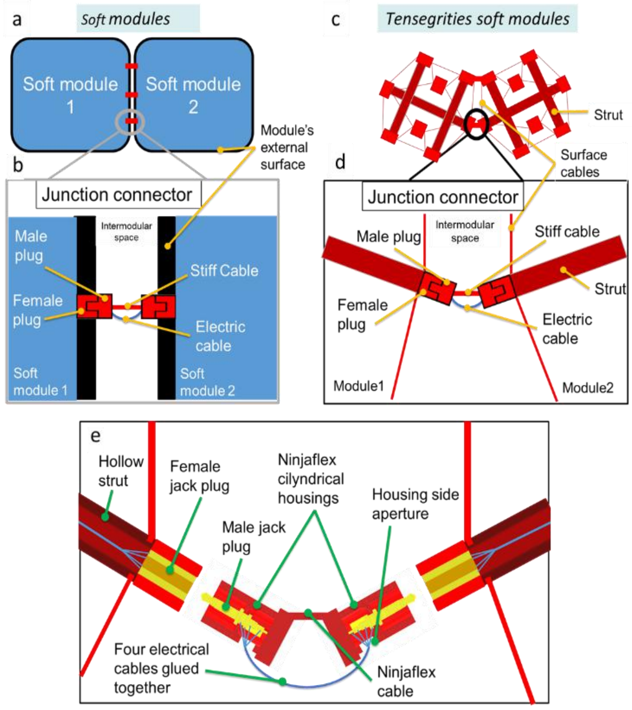

Figure 2. (a) Schematic representation of two generic soft modules with a membrane in black and connectors in red. (b) Zoomed in section of the junction connector inspired by biological adherens junctions, in red the plug and socket system and the stiff cable, in light blue the electrical conductive cable. (c) Schematics of two soft tensegrity modules connected at their struts vertices. (d) Zoomed in section of a junction connector connecting two tensegrity soft module vertices. (e) Detailed section of a hardware implementation of a junction connector. In yellow the plug and socket jack system, in light blue electric cables connecting the two jack plugs and in red structures 3D-printed in ninjaflex.

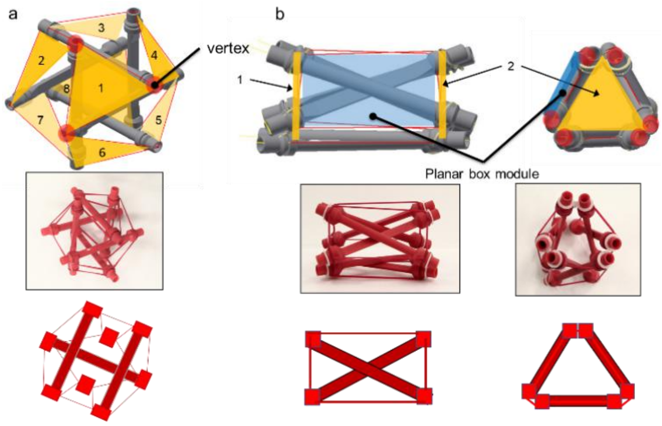

Figure 3. (a) Schematic representation of an icosahedron tensegrity module. The eight triangular faces displayed on the external surface are highlighted in yellow. Three circular red dots highlight the three vertices of one of one of the faces. Below, a photograph of one icosahedron module and its schematic representation used in the results section of the paper. (b) Schematic representation of a three-box tensegrity module in side view on left and front view on the right. The two triangular faces displayed on the external surface are highlighted in yellow. One of the rectangular surfaces is highlighted in light blue. Circular red dots highlight the six vertices of one of the faces. Below, a photograph of one of the modules and its schematic representation used in the result section of the paper.

Table 1. Experiment list

Exp.	Structure	Experiment Type	Measured Parameters	Max. Force [N]	Resistance [mΩ]
Fig. 4a	Icosahedron	Side compression 5 cm	Force	7	
Fig. 4b	Two connected icosahedrons	Longitudinal compression 5 cm	Force + Resistance	7	10.2 (σ ± 1.4)
Fig. 4d	Icosahedron	Side compression 5 cm	Force	7	
Fig. 4e	Two connected icosahedrons	Side compression 5 cm	Force + Resistance	13.8	8.7 (σ ± 1.7)
Fig. 4g	Three-box-prism	Side compression 2.5 cm	Force	5.2	
Fig. 4h	Two connected three-box-prisms	Side compression 2.5 cm	Force + Resistance	10.9	9.8 (σ ± 1.7)
Fig. 4l	Three-box-prism	Longitudinal compression 5 cm	Force	38	
Fig. 4n	Two connected three-box-prisms	Longitudinal to the connection 10 cm	Force + Resistance	38	11.3 (σ ± 1.8)

three-box-prism module (Figure 3 a-b). The icosahedron tensegrity module is composed of six struts and 24 cables. It has eight triangular faces all around its external surface (Figure 3a). Its face-to-face distance is about 10cm, and each strut has an approximate length of 9cm from vertex to vertex. The three-box-prism module is composed of three planar box tensegrity submodules [22-23] measuring 10cmx3.5cm (Figure 3b). The three planar box submodules are connected together along their longer side into a three-dimensional tensegrity prism (Figure 3b). The three-box-prism module is composed of six struts and 12 cables. It displays two opposite symmetric triangular faces on the external surface with the same dimensions as the icosahedron modules. Each soft module can be connected by means of three junction connectors, one at each corner of one of its triangular faces.

Each junction connector is composed of two cables and an off-the-shelf plug and socket jack connection system (Digikey - diameter 2.5mm) (Figure 2e). The stiff cable that transfers mechanical loads is 3D printed in ninjaflex with sufficiently large dimensions (2.5mmX2.5mm and length of 5mm) to exhibit around ten times the stiffness of the individual tensegrity module cables (31kN/m vs. 3kN/m). The stiff cable is 3D printed in a single print together with two cylindrical housings, one at each end of the cable. These housings contain the two jack plugs (Figure 2e). The bendable electrically conductive cable is composed of four low gage, and low electrical resistance wires glued together and soldered to the jack plugs. These cables pass through openings on the side of the cylindrical housings. The socket part of the jack plug system is glued to the tips of the vertices on the external surface of the tensegrity modules (Figure 2e).

IV. Results

To validate that our strategy does not reduce the deformability of the modular robot, we performed a set of experiments where we compared the deformability of individual modules with the deformability of pairs of connected modules. We compressed individual modules and pairs of modules in different directions (Table 1). The deformations of individual modules were then compared with pairs of connected modules in compression to assess how the connections affect deformability. During the experiments involving two connected modules, the electrical resistance of the connection was recorded to assess if an efficient transfer of energy and communication signals (i.e., low average electrical resistance) can be assured throughout the entire range of deformation.

In each experiment, the tested specimen was compressed to 50% of its length in the tested direction. Each experiment was repeated three times. An Arduino board was used to read and record electrical resistance during each experiment involving pairs of connected modules. The average resistance and a range of the minimum and maximum resistance recorded in the experiments are then presented.

The results of experiments with connected modules show that pairs of two connected modules require the same load as an individual module when compressed longitudinally (Figure 4 b-c and n-m) and approximately, double the load when compressed laterally (Figure 5 e-f and h-i). These results are in line with the equivalent springs law [20], where two identical modules compressed laterally behave as two identical springs in parallel and require double the load to compress 50% of their length, and two identical modules compressed longitudinally behave as two identical springs in series and require the same load to compress 50% of their length. Moreover, experiments 1-8 show an average electrical resistance of 10mΩ, a minimum of 8.6 mΩ and a maximum of 12.5mΩ throughout the entire range of deformation, showing that a stable and efficient electrical communication and power exchange can be maintained.

V. Soft Tensegrity Robot Demonstrator

Two robotic demonstrators have been developed to demonstrate the potential of the novel soft connection strategy: a soft untethered gripper and a soft untethered crawling robot. The two robots were assembled using a kit of

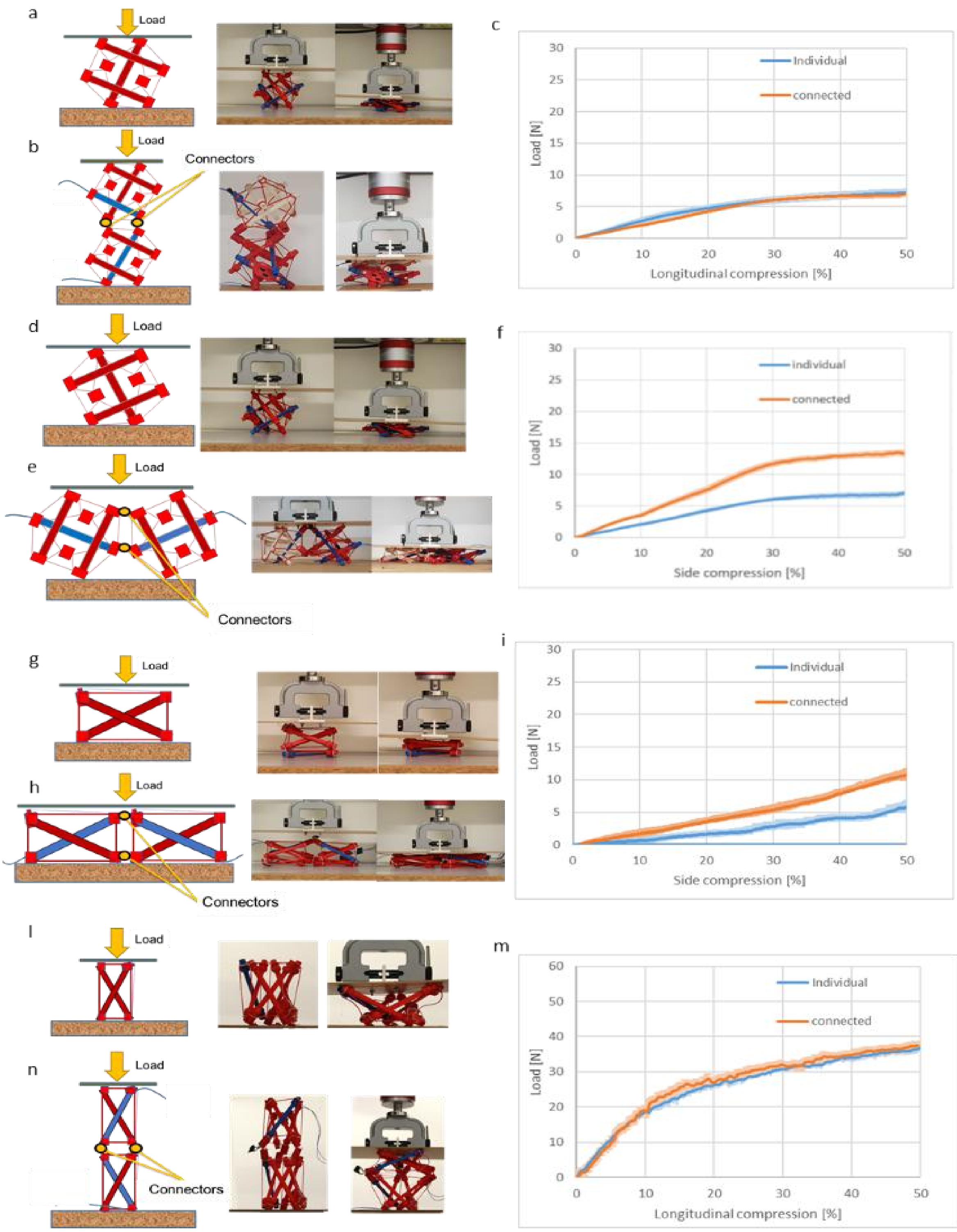

Figure 4. (a, b, d, e, g, h, l, n) On the left, diagrams of the specimens and experimental setup used in experiments 1 through 8; on the right photographs of the modules during experiment at rest and at 50% compression. In blue are represented the struts that contain the electric cables to pass communication and energy throughout the module; while the yellow dots represent the junction connectors to connect pairs of modules. (c) Comparison of experiment 1 and 2: individual vs two connected icosahedron modules compressed longitudinally. (f) Comparison of experiment 2 and 4: individual vs two connected icosahedron modules compressed from the side. (i) Comparison of experiment 5 and 6: individual vs two connected three-box-prism modules compressed from the side. (m) Comparison of experiment 7 and 8: individual vs connected two three-box-prism modules compressed longitudinally.

four different tensegrity modules. The kit consists of two types of icosahedron modules: a passive module with no additional components inside (Figure 5a) and a brain module equipped with a microcontroller and battery (Figure 5b). The kit also includes two types of three-box-prism modules: a passive module with no additional components inside (Figure 5d) and a bending module equipped with an actuation system (Figure 5e). These electronic components do not hinder the modules deformability because they are attached to the rigid struts [24-27].

The functionalized icosahedron has a TinyZero basic kit (TinyDuino) attached to one strut (Figure 5b). The TinyZero kit consists of a 3cmx3cm controller, two motor controller boards, and a battery (Figure 5b). The functionalized three-box-prism bending module has an actuation system consisting of a motor with pulley (Pololu, torque 2.6N/m) attached to one of its struts, and a tendon, running parallel to one of its edges, to control bending motion (Figure 5e).

The gripper consists of two fingers and was assembled using a brain module, four bending modules (two for each finger), and 18 junction connectors (Figure 5f). The gripper is controlled with a simple control signal which closes the two fingers by bending the four bending modules at the same time towards each other and opens the fingers after a set time when the microcontroller cuts off the current (Figure 5f). The two bending module vertices closest to the grasping point are equipped with two small 3D printed ninjaflex fingertips to increase the friction with the grasped object. The gripper is able to successfully grasp and hold up to two times its body weight and different object shapes (Figure 5h). Mechanical deformation tests were performed on the robot using the same test setup as in section III. These tests showed that the gripper deforms to 50% of its height with a maximum of 10N around 30% compression (Figure 5g).

The crawling robot was built using a brain module, a passive icosahedron module, a passive three-box-prism module, two bending modules, and 12 junction connectors (Figure 5i). The crawling robot is controlled with an oscillatory control signal at 0.5Hz frequency that deflects the two bending modules in the same direction pushing against the ground (Figure 5i). The vertices that push on the terrain have been equipped with the same ninjaflex pads used for the gripper fingertips to increase friction with the ground. The robot is able to achieve a speed of 4.5cm/min (Figure 5m) and is deformed to 50% of its height with 35N (Figure 5l). These results show that is it possible to use the connection strategy to assemble soft untethered modular robots.

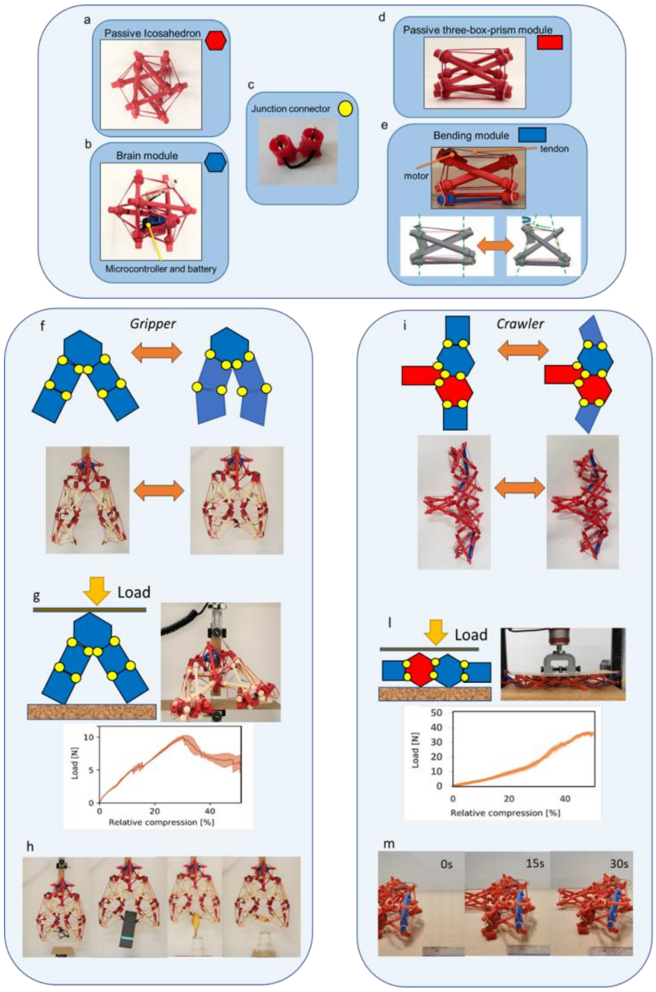

Figure 5. (a-e) Representation of the soft modular kit developed to demonstrate the connection strategy. (a) The passive icosahedron. (b) The brain module. (c) A junction connector. (d) The passive three-box-prism. (e) The bending module. At the bottom a sketch to show its deformation when actuated. (f) Schematic representation and photographs of the robotic gripper. On the left, the gripper in its configuration at rest, on the right, after closing its fingers. (g) Schematic representation of the experimental setup to test mechanical deformations of the gripper and the load-strain graph of the gripper. (h) Examples of the gripper grasping from left to right, a pair of glasses, a remote controller, a banana and a mandarin. (i) Schematic representation and photographs of the robotic crawler. On the left, the crawler in its configuration at rest, on the right, after it pushed its limbs backwards. (l) Schematic representation of the experimental setup to test mechanical deformations of the crawler. On the right a photograph of the experiment. At the bottom the load-strain graph of the crawler. (m) Sequence of images demonstrating movement of the crawler over time.

VI. CONCLUSION

This paper has presented and demonstrated a novel bio-inspired connection strategy for developing untethered soft modular robots. The results show that the connection strategy allows the transfer of mechanical loads as well as enables an efficient transfer of power and communication signals without hindering deformability of the individual modules.

We demonstrated the connection strategy on a tensegrity soft modular system. In the robots developed here, the junction connector connected vertices of rigid struts from neighboring modules together. However, some soft structures do not have rigid components or they do not connect at vertices. In these cases, the junction connectors can be incorporated into membranes or attached to elastic cables with 3d-printed housings on the external surface. Such flexibility in use also opens up the possibility of using the junction connectors for any modular robot, rigid or otherwise, as well as any electrical plug and socket that may be subjected to mechanical loading.

The junction connectors used in this project could be further improved by replacing the electrical cables with CANbus cables that can carry a significantly higher number of independent signal channels, thereby increasing the maximum number of modules in a robot. Moreover, in the future, the advancement of multi-material 3D printing [28] could allow the printing of the stiff cable, conductive cables, and the plug system at the same time in a unique component, making faster the manufacturing and more replicable the contact resistances given by manual soldering. In addition, future work will further explore the design space, investigating other potential designs that can be derived from the adheren junction inspired principle presented here.

We believe that the results presented in this paper demonstrate the remarkable potential that the junctions connection strategy has to be used in the future development of different untethered soft modular platforms and paves the way to foster research in the growing field of soft modular robotics.

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