Available online at www.sciencedirect.com
jmr&t
Journal of Materials Research and Technology
journal homepage: www.elsevier.com/locate/jmrt

Original Article

Applying Bio-Inspired hierarchical design to jamming technology: Improving density-efficient mechanical properties and opening application spaces

A.K. Matsushita [a,*], L.R. Garcia [a], Z.K. Liu [b], J. Doan [c], M.A. Meyers [a,d], J. McKittrick [a]

[a] Department of Mechanical and Aerospace Engineering and Materials Science and Engineering Program, USA
[b] Department of Chemical Engineering, USA
[c] Department of Neurophysiology, USA
[d] Department of Nanoengineering, University of California, San Diego, 9500 Gilman Dr., La Jolla, CA, 92093, USA

ARTICLE INFO

Article history:
Received 1 June 2020
Accepted 1 November 2020
Available online 5 November 2020

Keywords:
Jamming
Soft robotics
Bio-inspiration
Hierarchical architecture

ABSTRACT

In the soft-robotics field, bio-inspiration is often cited, pointing to the animal-like forms created—however, the concept of hierarchical architecture common to biological materials has yet to be applied effectively. Here, it is shown how that by considering the hierarchical structure of the medium (primary level), the organization of jamming media (secondary level), and the organization of jammers (tertiary level) new functionalities not possible with conventional jamming technology can be obtained. This is accomplished at the three layers enumerated above. At the primary level, optimal compositions of fibrous flakes and grains are identified to improve stiffness and strength per unit weight; fish-inspired ganoid scales are used to create flexible armors. At the secondary level, layers and grains are combined in the tensile and compressive faces of beams to maximize mechanical properties, while ganoid scales of different compositions are layered to create mechanical gradients, among other combinations of jamming media. Finally, at the tertiary level, the isotropy of triadically woven jammers is demonstrated relative to traditional biaxial jammers; a cylindrical "finger-trap" weave with adjustable radius is shown. The improved mechanical weight-efficiency, anisotropy control, mechanical property gradients, and other features enabled by considering hierarchical design in jamming promise new application spaces for an established field.

---

* *Corresponding author.*
E-mail address: akmatsus@eng.ucsd.edu (A.K. Matsushita).

https://doi.org/10.1016/j.jmrt.2020.11.002

1. Introduction & background

Unlike traditional hard contact robots, soft robots must be compatible with and adaptable to humans and human environments. Their compliance lets them safely interact with bodies while also navigating dynamic environments [1]. One such enabling technology is jamming, in which fluid-tight envelopes filled with loose media (e.g. grains, layers, wires, and other materials) are evacuated to bring the components into contact with one another and generate friction and device stiffness. The evacuation of the envelope provides the pressure which results in the frictional forces that impede the relative motion of internal components (the jamming media).

The earliest jammers used granular media, as demonstrated in 1965 by Fitzgerald et al. [2] who created polystyrene bead-filled membranes connected to a vacuum pump. A pilot would sit on the cushion-like device, and on evacuation, it hardened into a negative impression of the pilot's rear to create a mold for custom fiberglass seating. It was not until 2010 that Brown et al. [3] coined the term "jamming" and applied the technology to multifunctional robotic gripping and releasing devices, the idea being that an air-tight membrane filled with loose coffee grains could conform around any randomly shaped object (from plastic jacks to eggs), stiffen, and grip said object. Both Fitzgerald and Brown applied granular jamming to conform to physical objects, but Cheng et al. [4] made the leap to leverage its ability to assume any shape by designing a tentacle-like manipulator. Using a series of tension cables to control the shape of the tentacle while using granular jamming to stiffen and hold it, Cheng et al. demonstrated how jamming could be applied to soft-robotics for reversibly stiffening and highly articulated parts. Granular jamming, however, came against a fundamental limitation posed by beam bending mechanics: when bent, grains in the tensile face of the jammer unlocked and weakened the device. Furthermore, granular media could easily form "kinks" and create vertical columns of grain that easily buckled (analogous to a dislocation in a crystal structure). Bean et al. [5] formally elucidated these mechanisms in 2015 as responsible for plastic deformation in jammers, but even before their work it had become clear that granular jamming could only work in large-volume systems [6–8]. The limitation of granular jamming, combined with Cheng et al.'s reimagined application, inspired researchers to innovate jammer design to meet the need for high stiffness per unit weight and volume.

One approach to address granular jamming's limited efficiency was to confine it: Sridar et al. [9] adapted granular jammers to a load-bearing exoskeleton, but confined the jammers to pure axial compression, defeating the purpose of using a highly conformal material. Similarly, granular jamming-enabled vacuum splints have come to market, but rely on large, rigid, plastic boards within to provide the actual rigidity needed to stabilize patient limbs, thereby negating benefits of portability or complete adaptability to all geometries [10].

Another approach was to change the media entirely. In 2012, Kim et al. [11] developed a hollow endoscopic tube comprising several one degree-of-freedom joints. Each joint was surrounded by two rings of interleaving flaps of mylar or paper that could be jammed (coined "layer jamming"). Additional literature [12,13] continued to examine the use of fish-like scales to create jamming sheathes for surgical manipulators, in which scales generated frictional resistance by a high degree of overlap. The geometry, however, produced a surface of non-uniform thickness (preventing stacking of scales to generate greater stiffness), and restricted movement against the direction of overlap (limiting scale media to materials with a degree of flexibility) [13]. In 2013, Moses et al. [14] introduced interlocking fibers that formed a continuous hollow tube for use in surgical manipulators (later dubbed wire or fiber jamming [15,16]). In these new jammers the greater surface area-to-volume ratio of the layers/wires provided high stiffness in the direction parallel to the media length, thereby resisting the tensile forces in bending and improving performance compared to granular jamming [15]. As Narang et al. [8] elucidated, the bending behavior were determined by the number of layers, vacuum pressure, and friction coefficient of the media. A greater number of layers increased the initial loading regime's slope, while the vacuum pressure determined the deflection at which a second, weaker regime began. The yield behavior was caused by a cohesive bending of the layers giving way to a slipping between the interfaces, allowing high displacement. Therefore, friction coefficient of the media only influenced the slope of this second regime (explaining why Ou et al.'s initial investigation found that soft media with high friction coefficients did not result in stiffer jammers). Furthermore, longitudinal or laminar elements lack the conformality of granular jammers. Ou et al. [6,17] mitigated this problem using biaxial weaves of layer jammers whereby the porosity of the bulk structure provided malleability in the unjammed state. However, no mechanical characterization was performed on these structures comprising multiple jammers woven together.

Two major challenges in jamming technology are apparent: to obtain a device combining conformability and stiffness, and to achieve these properties while minimizing weight and volume. In this work, we applied bioinspired hierarchical structure to address these issues. Biological materials are able to combine disparate properties (such as strength and toughness) using minimal material through hierarchical architecture, or the combination of structural adaptations at multiple length scales [18–20]. Several previous jamming devices have cited bioinspiration: in the geometry of their jamming media (e.g. being scale-like [12,13]), the organization of their jamming media (e.g. inspired by eukaryotic flagellum [14]), or their general shape (e.g. being snake-like [7,21,22]). Our work, however, is the first to apply bioinspired hierarchical architecture rather than bioinspiration from a specific model organism (i.e. the Russian model of bioinspiration, or "BioTRIZ," which focuses on the abstract mechanisms of biology and their subsumption into engineering principles [23]).

To this end, we loosely borrowed from the vocabulary of protein hierarchical structure: the primary, secondary, and tertiary levels of structure. In our work, these terms described the constituent jamming media, their organization within a jamming unit, and the organization of several jamming units, respectively. An example is illustrated in Fig. 1: in (a), layers and grains are shown as the "ingredients" or primary level

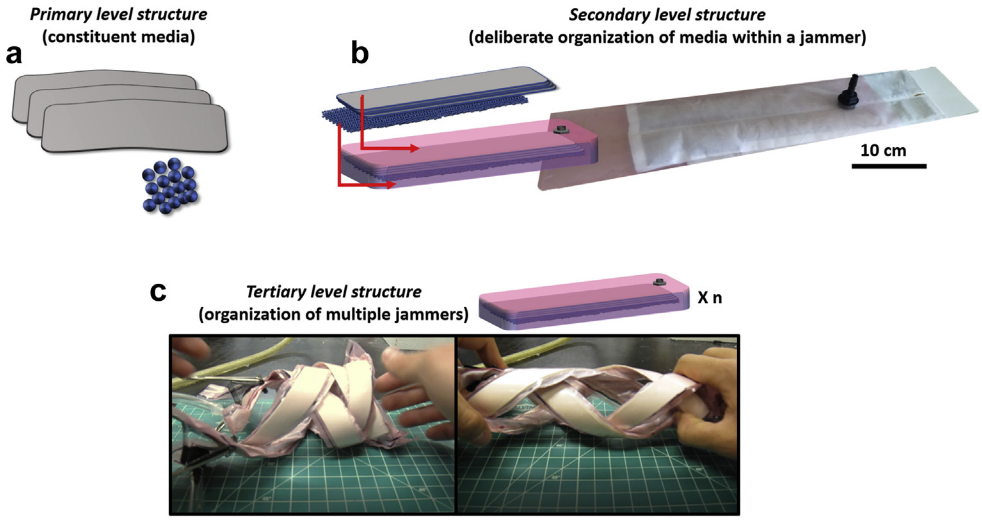

Fig. 1 – The hierarchical structure of jammer begins at (a) the primary level. This describes only the constituent media, which are here illustrated as layered and granular materials. (b) The secondary level of structure describes how the constituent media are organized with respect to one another within a single jammer. Here, the layered material are stacked on one face of the jammer, with the granular material confined by a sachet to the opposite face. The two components are inserted into a heat sealable high density polyethylene sleeve. (c) An assembly of multiple jammers forms a tertiary structure. Here, a finger-trap weave is illustrated.

structure. In (b), they are combined in a polyethylene membrane such that the layers are on top of the grains in a sewn sachet. With this secondary organization, the layers can resist tensile forces in beam bending while grains resist compression. In (c), multiple jammers of the structure in (b) are woven together into a finger-trap to form a loose cylinder that can expand and contract.

Recontextualizing the literature according to these hierarchical levels, it is clear that investigations have focused on the performance of different primary structures in jamming (granular, wire, and layer based) and their relative strengths and weaknesses [15], with some exceptions. Moses et al. [14] developed jammers comprising a primary structure of wire media arranged in a secondary structure of interlocking pieces forming a hollow culm, contained within the simple tertiary structure of a single, continuous jammer unit. This hierarchical architecture, however, was a byproduct of the need for a central cavity in the manipulator for surgical instruments, rather than the explicit goal of achieving unique mechanical properties. Though a thin-wall tube confers superior bending moment efficiency per unit weight to a dense column [24], Moses et al. made no mention of the fact. Ou et al. [6], on the other hand, investigated how a tertiary structure of biaxially woven layer jammers could be used to compensate for the primary structure's (sketch paper) lack of conformality. Furthermore, they demonstrated that by selectively evacuating only one set of jammers and not the orthogonal set, anisotropy could be achieved. The weave was a deliberate hierarchical architecture to achieve disparate mechanical properties (stiffness and conformality) and also a novel functionality (selective anisotropy).

A biaxial weave, however, is only the most basic of woven structures, and secondary architectures remain to be more fully explored. By taking a bioinspired approach and considering the primary, secondary, and tertiary structures of jammers, we have developed devices that combine disparate properties (stiffness and conformality), exhibit improved weight efficiency, and provide novel functionalities including mechanical property gradients, extended elastic regimes, and improved isotropy.

2. Materials & methods

In the literature, mechanical properties of jammers are not reported in a standardized way: for example, the bending stiffness of granular jammers are sometimes reported [15], but mechanical properties may also be reported as the compressive stress–strain of a cylinder [4,9]. On the other hand, the mechanical properties of layer jammers have been reported as the torque required to bend a single fixed-edge flap [6], or as the deflection of a beam in three-point bending with unreported dimensions [8], making comparisons difficult. Therefore, in this work, jammers from literature were reproduced to perform comparisons against our own unique devices in three-point bending. The membranes of all jammers were formed using heat-sealed high-density polyethylene (HDPE). Nylon hexagonal nuts and panel mount adaptors (U.S. Plastic Corp. Lima, OH) formed the air inlet joints.

2.1. *Primary level structure*

The goal of these experiments was to demonstrate how changes of the jamming media themselves altered the mechanical properties of devices. In one set of experiments, literature-typical granular jammers made from coarse coffee grounds (J.M. Smucker Co. Orville, OH) were compared against those containing a mixture of grounds and 6.35 mm chopped graphite fibers (Fibre Glast. Brookville, OH). Three jamming media mixtures containing 40 g of grounds (100 w.t.% coffee), 35 g of grounds and 5 g of fibers (13 w.t.% graphite fiber-87 w.t.% coffee), and 30 g of grounds and 10 g of fibers (25 w.t.% graphite fiber-75 w.t.% coffee) were prepared. Each mixture was sewn shut into identical cloth sachets to prevent media suction through the valve. The sachets were then placed into the HDPE jamming membranes (300 mm × 80 mm) and tested in three-point bending with 80 mm loading span. The thickness of a jammer containing grains is difficult to report due to the looseness—for the reader's consideration, coffee grounds were measured to have a density of roughly 333 kg/m^3 when poured into a beaker on a mass balance.

In a second set of experiments, 3D printed "ganoids" were tested as jamming media. Ganoids are a type of scale found in primitive fish such as gar [25] and bichir [26]. Unlike plasmoids fish scales, ganoids are chamfered to neatly fit against their adjacent neighbors rather than directly overlap with one another and produce a surface of uniform thickness. The much lower degree of imbrication improves the mobility of ganoids against the direction of overlap, and eliminates the weak interfaces that exist in scale arrangements [27]. To investigate their jamming ability, a design borrowed from Sherman et al. [25] was 3D printed using a Connex 3 Objet 500 printer (Stratasys. Eden Prairie, MN), using 100% Veroclear. The ganoids (50 mm × 15 mm x 6 mm) were then taped into their imbricating pattern onto a thin piece of fabric to prevent sliding and inserted into the HDPE membrane. To evaluate the ganoid jammer against a control granular jammer, cubic grains (1 mm × 1 mm × 1 mm) were printed with the same total mass of media as the array of ganoids. Both jammers formed a final dimension of 125 mm × 80 mm and were tested in three-point bending with 60 mm loading span, using a standard circular beam and an indentor tip to test the loss of stiffness.

2.2. *Secondary level structure*

Unlike the jammers described in section 2.1, these jammers comprised multiple types of jamming media deliberately arranged within a jamming membrane. For example, although the earlier graphite fiber-coffee jammers contained two types of media, they were randomly mixed with no order. In contrast, the first set of jammers tested for this section comprised layers and grain organized such that the former occupied the tensile face and the latter the compressive face. These layer-grain jammers were assembled from 12 layers of sketch paper (Pacon Corp. Appleton, WI) cut into 300 mm × 80 mm strips, totaling 25 g, combined with 25 g of coarse coffee grounds sewn into a sachet, to form a 300 mm × 80 mm jammer. These were compared against pure granular jammers using 50 g of coffee and pure layer jammers using 24 layers (or ~50 g) of sketch paper in three-point bending using 80 mm loading span.

A second type of jammer with secondary level structure using ganoids was qualitatively investigated. Two sets of 25 ganoids were printed: one with 80% Veroclear and 20% Tango Plus and another with 100% Veroclear. Each set was attached to a thin piece of fabric and arranged such that the stronger, more brittle 100% Veroclear ganoids lay atop the more flexible ganoids. The flexibility and ease of stacking were evaluated by bending the jammer in both directions and visual inspection.

2.3. *Tertiary level structure*

Here, multiple jamming units were combined to form woven structures. In the first set of experiments, a sparse biaxial weave was compared to an open triaxial weave in three-point bending with 160 mm loading span. Each structure comprised six layer jamming units (comprising five layers of sketch paper each cut to 15.5 mm × 220 mm) dimensions) arranged in a 3 × 3 pattern for the biaxial weave and 2 × 2 × 2 pattern for the open triaxial weave. In the open triaxial weave, three sets of jammers (A, B, and C) were interwoven such that jammers in set A always went under jammers of set B and over jammers of set C, resulting in an open hexagonal structure [28].

In a second set of similar experiments, a dense biaxial weave was compared to a dense bi-plain triaxial weave. Each structure comprised ten jamming units arranged in a 5 × 5 pattern and a 3 × 3 × 4 pattern, respectively. In the bi-plain triaxial weave, three sets of jammers (A, B, and C) were interwoven such that each jammer of set A went over (or under) at least one jammer from set B and under (or over) at least one jammer from set C [28].

To compare the bending properties of each weave, three-point bending was conducted in two different orientations. For the biaxial weave, three-point bending was conducted such that the axis of bending was at an angle of 0° (i.e. support pins parallel to one set of weaves and orthogonal to the other) and 45° (i.e. supports at a 45° angle relative to both sets of weaves). For the triaxial weaves, three-point bending was conducted such that the axis of bending was at an angle of 0° (i.e. supports in parallel to one set of the weaves and at a 60° angle relative to the other two sets of weaves) and 90° (i.e. supports orthogonal to one set of weaves and at a 30° angle relative to the other two sets of weaves).

Finally, a third device combining primary, secondary, and tertiary structures was qualitatively investigated. Graphite fibers and coffee were combined in a sachet and inserted into a layer-grain jammer, similar to those described in 2.2. Two of these jammers were then woven to form a cylindrical finger-trap weave. Here, two jammers (A and B) were interwoven such that one "arm" of A always went over one arm of B and the other arm of A always goes went the other arm of B.

3. Results

3.1. *Primary level structure*

The 100 w.t.% coffee jammer modeled off literature granular jammers (Fig. 2a) clearly exhibited an initial elastic regime followed by plastic deformation, characterized by the unlocking of grains in the tensile face and buckling of vertical grain columns that allowed high deformation at low load [5] (Fig. 2b, i). The transition occurred at approximately 1 mm of beam deflection, with a load of 7.1 N. The 13 w.t.% graphite fiber-87 w.t.% coffee jammer, on the other hand, exhibited a smooth continuous load curve. While the load at 1 mm of beam deflection was only marginally improved at 8.7 N, the

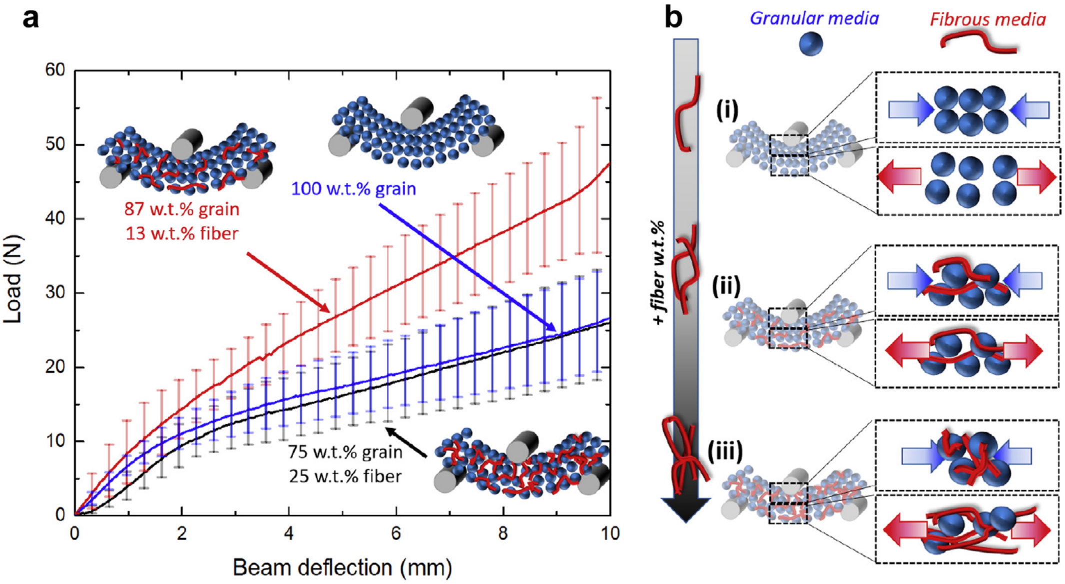

Fig. 2 – (a) Three jammers of identical mass and varying ratios of granular material (coffee grounds) and fibrous material (chopped graphite flakes) were tested in three point bending. (b) (i) Pure granular jammers suffered from the fact that grains in the tensile face simply separated from one another or formed kinks that caused buckled columns of grains, reducing the stiffness [5]. (ii) The addition of fibers caused entanglement between grains. Although compressively resistant elements were reduced, the prevention of grain separation and buckling (evidenced by a lack of "yield point" in the curve) allowed the jammer to outperform the literature-based pure granular jammer. (iii) An excess of fiber weakened the jammer but also delayed onset of the "yield point." While fibers provided a locking mechanism between grains, they were pliant themselves. Furthermore, fibers were more likely to entangle with one another rather than with grains that could anchor their position.

cumulative effect of preventing unlocking and buckling via entanglements (illustrated in Fig. 2b, ii) was significant: by 10 mm of deflection, the load of the mixed jammer (47 N) was nearly double that of the 100 w.t.% coffee jammer (27 N). The lack of abrupt transition to plastic behavior in these jammers was especially notable, and presents future applications in devices demanding robust behavior. The 25 w.t.% graphite fiber-75 w.t.% coffee jammer, however, exhibited diminished performance. While fibers provided a locking mechanism between grains, they were pliant themselves, therefore weakening the compressive resistance of jammer when added in excess. Furthermore, these fibers were far more likely to entangle with one another rather than with grains that could anchor their position, thereby diminishing their tensile resistance as well (similar to an epoxy-fiber composite with an excess of fiber [28]). Therefore, although the onset of plastic behavior was delayed from ~1 mm to ~ 2 mm compared to the 100 w.t.% coffee jammer, the stiffness was decreased by the smaller proportion of grains able to resist compression and providing entanglement anchors for resisting tension. These mechanisms are illustrated in Fig. 2b, iii.

The full range of fiber-grain ratios and combinations of different fiber and grain materials were not explored. Previous literature have demonstrated that different granular [4] and layer [6] materials result in different properties in their respective pure jammers, so it is likely that different material combinations in fiber-grain jammers (or entangled grain jammers, to avoid confusion with wire/fiber jamming) will similarly yield different properties. Nevertheless, these data show that an optimized ratio of grains and fibers can overcome the unlocking and buckling phenomena that limit granular jamming. This innovation was made possibly by fully considering the mechanism of the primary structure's stiffening.

Another innovation at the primary level was the use of arrays of abutting "ganoids" within the jamming membrane. In contrast to traditional scale jammers which could only use ductile materials such as sketch paper, the stiff Veroclear ganoids retained their flexibility and were able to conform to curves (Fig. 3a, b) while also stiffening (Fig. 3c). The armor flexibility was decoupled from the material properties. In three-point bending (Fig. 3d), the ganoid assembly resisted a peak load 40% greater than the granular jammers made of the same material and exhibited more consistent mechanical behavior between tests. Granular jammers are prone to bunching, which can produce uneven jamming media distribution and inconsistent behavior. The ganoids avoid this by their chamfered geometry. Tests were also conducted with a small, sharp indenter subjecting the jammers to bending instead of the traditional cylinder. The peak-load strength of both the ganoid and grain jammers was reduced to about 60% of their normal three-point bending value: it was hypothesized that the granular jammer's mechanical properties would be reduced to a greater extent because the more locally applied load may push aside grains, even under vacuum. However, the reduction in mechanical properties was consistent for both jammer types. Repeating this experiment in the future with ceramic ganoids and grains may provide greater insight into how bulk vs. local stiffness and strength are affected by the different jamming media, if at all. It should

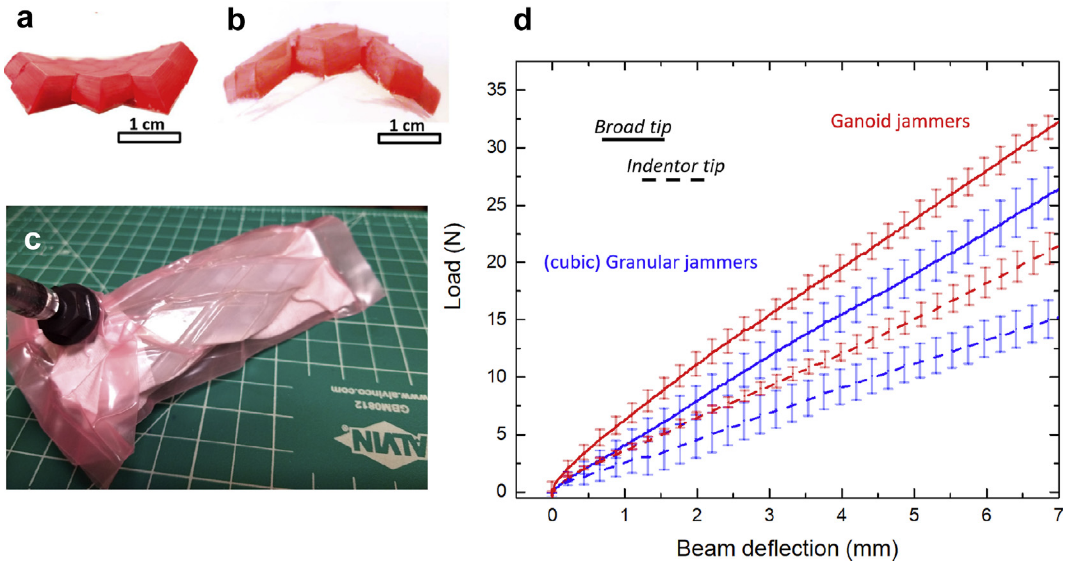

Fig. 3 – Ganoids, unlike traditional scales, can provide a high degree of flexibility (a) against and (b) with the direction of overlap, regardless of the stiff material used. (c) 3D printed ganoids form a ganoid jammer. (d) Jammers using identical mass and volume of Veroclear ganoids and cubic grains were compared in three point bending. Due to geometric locking effects, neither jammer transitioned to a weaker bending mode brought on by tensile unlocking or buckling. (a)–(b) adapted from [25].

also be noted that unlike other granular jamming experiments performed using literature-typical coffee grounds (see Figs. 2a and 4b) and behaviors observed in literature [4,5,9], no transition to plastic behavior was exhibited within the comparable loading regime. This may be attributed to the fact that the 3D printed grains were cubic (1 mm × 1 mm × 1 mm) unlike the irregularly shaped and finer coffee grounds. The stiffening mechanism therefore combined grain jamming as well as segment locking (geometric jamming), allowing continuous deformation across the jammer and stiffer behavior [15] and preventing the buckling mechanism discussed in the introduction.

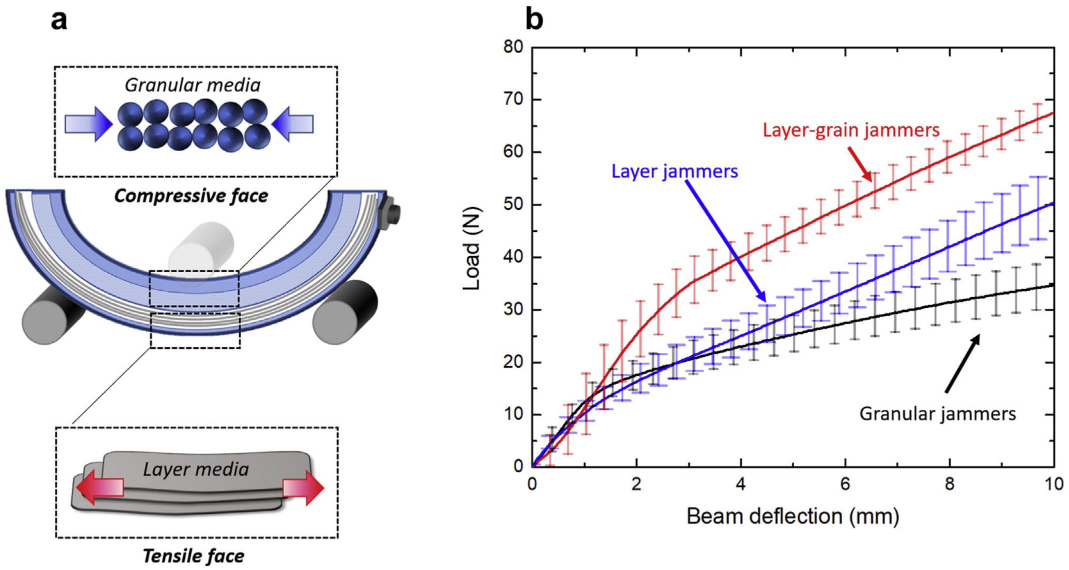

Fig. 4 – (a) A layer-grain jammer uses both layers and grains as jamming media. By placing layers in the tensile face and grains in the compressive face of bending, the efficiency of mechanical properties per unit weight is greatly improved, (b) as shown in three point bending of jamming units of equal mass and similar volume. An early transition to weaker bending behavior was observed in both pure granular jammers and layer jammers, caused by grain unlocking and buckling and layer bending, respectively. In the layer-grain jammer, weakening was delayed by the secondary structure: (1) grains were restricted to the compressive face and lessened the likelihood of unlocking and buckling, and (2) compressively resistant grains impeded local layer bending.

3.2. *Secondary level structure*

As previously discussed, grains generate compressive resistance while layers generate tensile resistance when the jammers are evacuated. The assembled layer-grain jammers therefore maximized the efficiency of the grain and layer components with their secondary level structure, illustrated in Fig. 4a. When compared to pure granular jammers and pure layer jammers constructed according to literature, layer-grain jamming offered marked improvements for the same mass of jamming materials (Fig. 4b). The granular jammer exhibited an initial linear regime of $m = 12.5$ N/mm, but on reaching 1 mm of beam deflection transitioned to its plastic regime of weaker behavior, caused by unlocking and buckling of grains. The slope of this second regime was dramatically reduced to $m = 2.5$ N/mm. The layer jammer exhibited a similar initial slop as the granular jammer, but at only 0.5 mm of displacement transitioned from bulk bending to a weaker local bending mode near the loading pin caused by slipping between the layered media. The reduction of slope ($m = 4.5$ N/mm) was not as dramatic as in the granular jammer, however, and after greater displacement allowed the layer jammer to overtake the granular jammer. The layer-grain jammer exhibited similar initial and secondary slopes as the layer jammer, but was able to extend its initial regime to 2.5 mm of displacement. This suggested that granular material's unlocking and buckling were significantly delayed, but that weakening caused by layer slipping eventually led to layer-dominated behavior. We emphasize that this improvement in mechanical properties was achieved using the same amount of jamming media in mass (and near same amount in volume). Furthermore, the combination with conformality of grain jamming (on one surface) makes the applications of wearables and furniture proposed by Ou et al. [6,17,29] a far more attractive prospect.

A secondary structure of stacked ganoids was also qualitatively explored. In Fig. 5a, an arrangement of 100% Veroclear layers atop 80% Veroclear-20% TangoPlus ganoids is shown. As illustrated in Fig. 5b, the ganoids produced uniformly thick surfaces that remained flush even when conforming to curvature. Using materials such as silicon carbide as an interface defeating material and a ductile polymer as a shock absorbent material, layered armor with gradients of mechanical properties can therefore be produced (reminiscent of the mechanical property gradients used by animals such as boxfish for protection [19]). These would retain the flexibility of a single layer of ganoids while also combining disparate properties. The integration of the secondary structure into a jammer is illustrated in Fig. 5c, as well as its ability to bend in the opposite direction (Fig. 5d) of that shown in Fig. 5b. Ganoids can also be easily layered atop other jamming materials and fully accommodate their motion, as shown when paired with wires (Fig. 5e) to form an armored wire jammer (Fig. 5f).

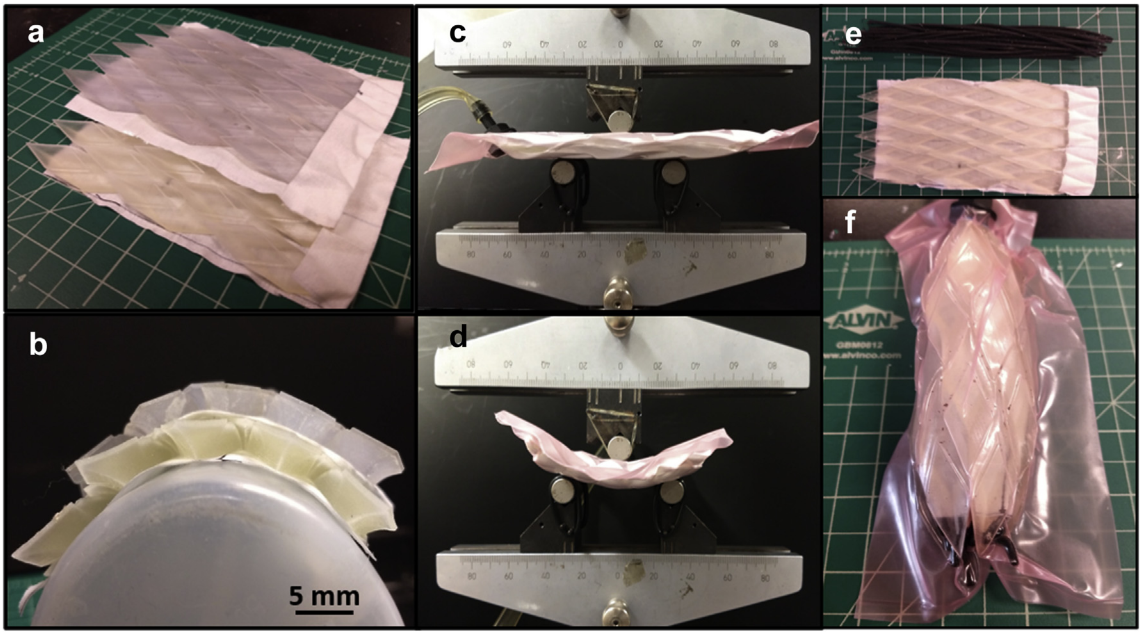

Fig. 5 – (a) Ganoids were 3D printed in two compositions: 100% Veroclear and 80% Veroclear, 20% Tango Plus. The 100% Veroclear ganoids on top serve as a strong and stiff layer suitable for penetration resistance and interface defeat. The 80% Veroclear 20% Tango Plus ganoids below serve as a ductile, back-face deformation dampening layer. (b) The unique imbrication of ganoids creates surfaces of uniform thickness which can be layered flush while retaining flexibility. (c) Once sealed, the two ganoid layers can create a jammer with mechanical gradient properties. (d) Three-point bending demonstrates equal flexibility in the opposite direction as shown in (b). (e) Wires and ganoids can be assembled together (f) to form a tube with a wire core and a ganoid exterior. The result is a jammer that can bend in any direction with high stiffness.

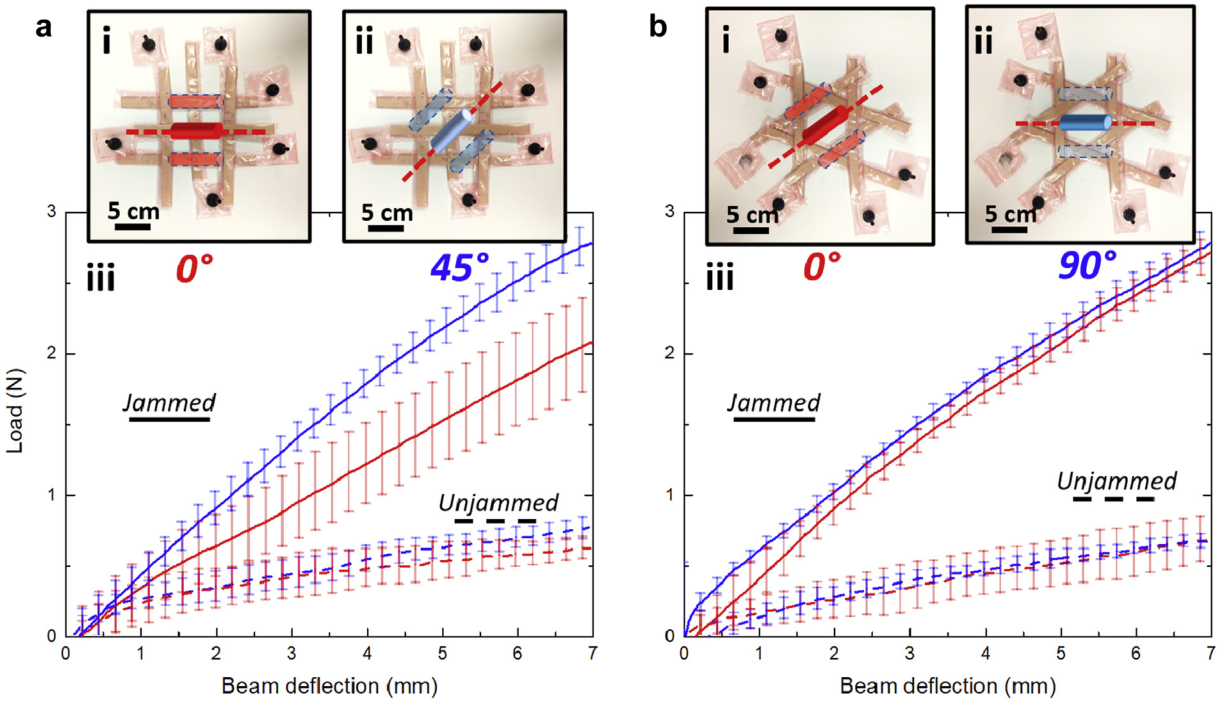

Fig. 6 — (a) The plain biaxial weave was tested in three-point bending in two orientations. (i) In the first, one set of jammers was parallel to the bending axis. (ii) In the second, neither set was parallel. (iii) The weave was significantly less stiff in the first orientation as the parallel set of jammers was not recruited in bending resistance. (b) A triaxial weave using the same number of jamming units was similarly tested in two orientations such that (i) one set of jammers was parallel to the bending axis (ii) and no jammers were parallel to the bending axis. (iii) Unlike in the plain biaxial weave, the behavior was isotropic.

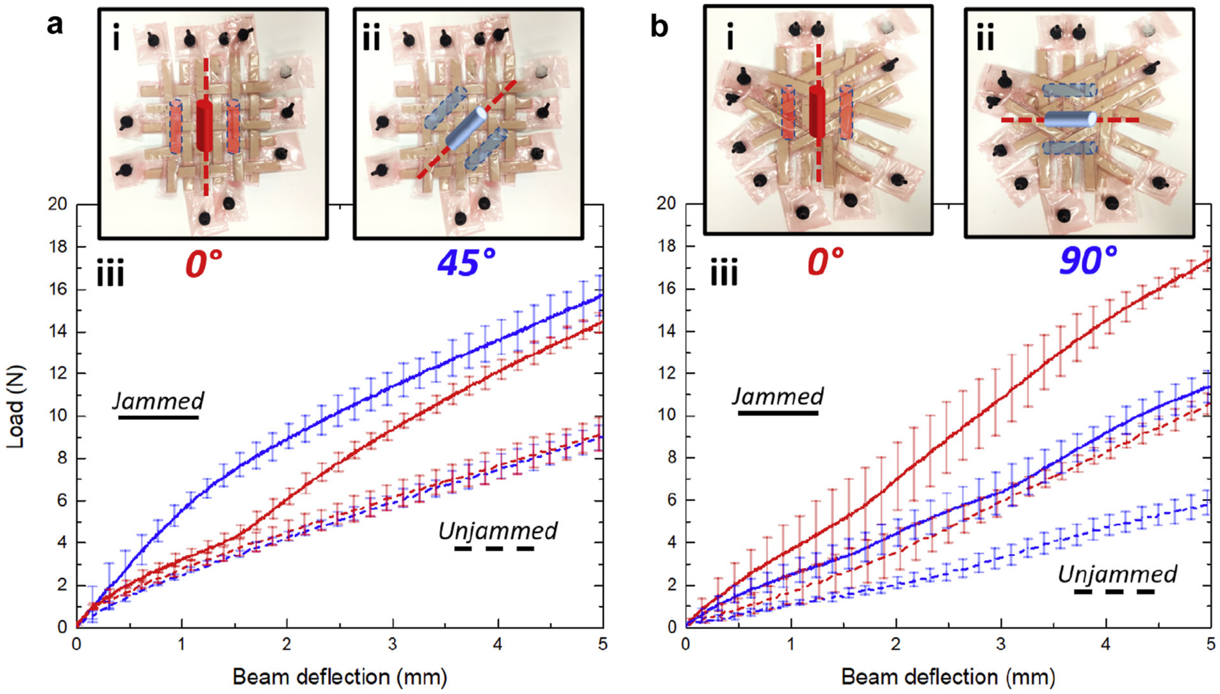

Fig. 7 — (a) A dense biaxial weave was tested in three-point bending in two orientations. (i) In the first, one set of jammers was parallel to the bending axis. (ii) In the second, neither set was parallel. (iii) Unlike the open biaxial weave (Fig. 6a), the dense biaxial exhibited a second stiffening regime when bent in the parallel direction due to crowding of the parallel jammers. (b) A bi-plain triaxial weave using the same number of jamming units was similarly tested in (i, ii) two orientations. (iii) The lower frequency of intertwining of jammers resulted in fewer interactions between differently oriented sets, leading to far more ductile behavior in the bending orientation normal to one set of jammers.

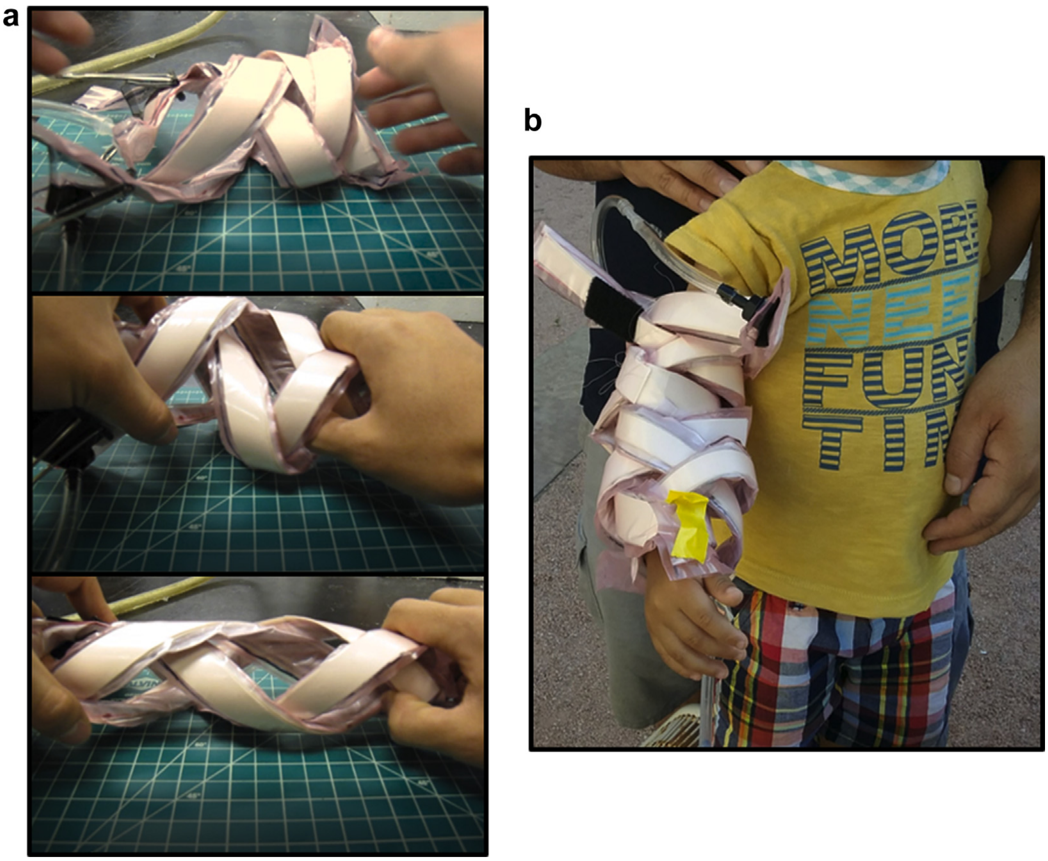

Fig. 8 – (a) Two mixed media jammers are woven into a finger trap, demonstrating the relationship between extension and diameter. (b) A larger finger trap jammer is fitted around the arm of a child, demonstrating a potential application as an emergency brace.

3.3. *Tertiary level organization*

Unjammed, the sparse weaves (Fig. 6) performed similarly to one another in both orientations indicating comparable conformability. When jammed, however, the biaxial weave as constructed from Ou et al. showed marked anisotropy with diminished stiffness and strength in the 0° orientation as half the jamming units were effectively doing nothing to resist deformation. The plain triaxial weave exhibited near isotropic performance, potentially allowing for more robust applications in wearable technologies: not only in that there are three degrees of stiffness tuning rather than just two, but in that there are no dramatically weak directions of bending that can negatively impact usability.

A bi-plain triaxial weave was also tested in another set of experiments against a different plain biaxial weave of equal mass and jamming unit composition (Fig. 7). Like the sparse biaxial weave, the dense biaxial weave exhibited anisotropic behavior when jammed. Stiffness and strength were improved in the 45° orientation, in which both sets of orthogonal jammers were able to provide bending resistance. In the 0° orientation parallel to one set of jammers, the initial mechanical behavior of the jammed biaxial weave was undistinguishable from the unjammed behavior—however, at 1.75 mm of deflection there was a stiffening response, and the peak load at 5 mm deflection approached that of the 45° orientation. This was caused by “crowding” of the jamming units being pushed together as the deflection became more pronounced, and may be used deliberately to compensate for the anisotropy of biaxial weaves. Unlike the open triaxial weave, the bi-plain triaxial weave exhibited high anisotropy in both the unjammed and jammed states. In the 0° orientation parallel to one set of jammers, the bi-plain triaxial weave exhibited high stiffness in both the unjammed and jammed states, with a peak load of 10 and 17 N, respectively. In the 90° orientation orthogonal to one set of jammers, the jammed peak load at 12 N was only marginally greater than the unjammed 0° peak load. This significant anisotropy was unexpected [28], and may be due to the fact that in this weave pattern, a warp does not weave through wefts as often as in the dense biaxial weave for the same amount of material. Therefore, even with the same number of identical jammers, one cannot create a tertiary structure with as many complete “unit cells” so to speak. We can conclude bi-plain triaxial weaves were not as robust and more sensitive to the specifications of jamming units

Another unique weave explored was that of the finger trap constructed from two layer-grain jammers. In this configuration, like a finger trap, the woven hollow tube can decrease in radius by elongating and increase in radius by contracting

(Fig. 8a). Such a device could provide a reinforcing for actuating mechanisms of length-change in soft robots, be used as an emergency brace (as envisioned in Fig. 8b around a child's arm), or a new type of gripper like commercially available snake grippers or wire mesh grips. Each level of structure contributed in this embodiment: the primary level comprised grains of coffee mixed with graphite fibers to provide high stiffness efficiency combined with conformality to wrap around complex body contours. At the secondary level, these coffee-graphite fiber media were leveraged by being positioned towards the user arm, but combined with layer media facing outward to improve bending stiffness of each jamming unit even further while retaining conformality. Finally, two jamming units were combined to form a cylindrical but adjustable shape. In other words, hierarchical architecture helped maximize mechanical properties per unit weight and volume while retaining conformality, all the while forming an adaptive shape that could instantly stiffen. In an application such as casting in which comfort, lightness, high stiffness and strength, and a brief cure time are important characteristics [30], one may easily imagine future hierarchical jamming devices.

4. Conclusions

Although jamming is an established technology, new functionalities were inspired by the principle of hierarchical structures of nature. We demonstrated how changes to the jamming media (primary level), the organization of jamming media within a membrane (secondary level), and the woven structure of jammers (tertiary level) can enhance mechanical properties per unit weight, robustness, and protective functionality.

- At the primary level, jammers using a mixture of grains and fibers, jammers using ganoids (rhombohedra inspired by primitive fish scales), and jammers using cubic grains were tested in three point bending. The major finding was that unlocking and buckling in granular jamming can be overcome.
  - When added to grains, fibers provided an entangling mechanism for grains to resist unlocking and buckling, and improved mechanical properties per unit weight. When added in excess, fiber pliancy and the diminished number of grains around which to entangle reduced beam bending stiffness.
  - Unlike irregularly shaped coffee grounds or round glass beads explored in previous literature, granular media with regular geometries can be densely packed to delay buckling and unlocking, exhibiting no weakening behavior in a comparable loading regime.
  - Ganoid jammers compared to granular jammers of identical jamming media mass and volume exhibited superior stiffness in three point bending. This was due to the segment locking effect which caused a continuous response along the jammer.
- At the secondary level, jammers using layers and grains and jammers comprising ganoids of different compositions were constructed. The major findings were that conformality and high mechanical properties could be achieved without compromising either, and that ganoids are a highly versatile alternative to scales due to decoupling of flexibility from material properties.
  - Layer-grain jammers exhibited a marked improvement in mechanical properties—although the stiffness of the jammers was comparable to layer jammers, the initial linear regime was significantly extended by the addition of grains to add a more compressively resistant element.
  - Layers of ganoids of different materials can be stacked flush atop one another, unlike traditional scales. Their unique imbrication allows flexible armors (able to bend with and against the direction of overlap) and mechanical property gradients. The versatility of ganoids was further demonstrated by combining ganoids with wires to create a column-geometry jammer with a protective layer.
- At the tertiary level, open plain triaxial and dense bi-plain triaxial weaves were compared to sparse and dense biaxial weaves, respectively. The shape changeability of a tertiary cylinder assembled by a finger-trap weave was also demonstrated
  - Plain triaxial weaves were shown to be highly isotropic in both the unjammed and jammed states, suitable for more robust applications than conventional biaxial weaves.
  - Bi-plain triaxial weaves were shown to be surprisingly anisotropic—this was due to the low frequency of intertwining in this specific weave pattern. For the same number of identical jammers as a comparable biaxial weave fewer points of interaction between differently oriented jammers is achieved.
  - A cast constructed from layer-entangled grain jammer woven into a finger trap illustrated new potential applications enabled by hierarchical jamming. The ability to combine stiffness and strength, light-weight, conformability, and shape change are critical properties for wearables.

Hierarchical jamming is not limited to the embodiments shown in this work: it is an open framework by which to construct devices and overcome the limitations of traditional jammers, as we have illustrated. In the manner of how analytical and finite element models have contributed to improved understanding of the jamming mechanics (e.g. as by Narang et al. [8] for layered media), the same may be done in the future for mixtures of different media with these hierarchical architectures. With the improvements of hierarchical jamming and a more complete understanding of its principles, applications such as exoskeletons—previously deemed unfeasible with—may be revisited with the next generation of jamming technology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the NSF Innovation-Corps Seed Fund as provided through the Institute for the Global Entrepreneur at University of California, San Diego and the Jacobs Fellowship research fund; Dr. Michael Tolley for use of the Connex 3 Objet 500 3D printer.

REFERENCES

[1] Li Y, Chen Y, Yang Y, Wei Y. Passive particle jamming and its stiffening of soft robotic grippers. IEEE Trans Robot 2017;33(2):446–55. https://doi.org/10.1109/TRO.2016.2636899.

[2] Fitzgerald JG, Sharp MC, Barwood AJ. A rapid method of casting body contours. 1965.

[3] Brown E, Rodenberg N, Amend J, Mozeika A, Steltz E, Zakin MR, et al. Universal robotic gripper based on the jamming of granular material. Proc Natl Acad Sci Unit States Am 2010;107(44):18809–14. https://doi.org/10.1073/pnas.1003250107.

[4] Cheng NG, Lobovsky MB, Keating SJ, Setapen AM, Gero KI, Hosoi AE, et al. Manipulator enabled by jamming of granular media. In: Proceedings of 2012 IEEE International Conference on Robotics and Automation (ICRA); 2012. p. 4328–33.

[5] Thompson-Bean E, Steiner O, McDaid A. A soft robotic exoskeleton utilizing granular jamming. IEEE/ASME international conference on advanced intelligent mechatronics, AIM 2015;2015-August:165–70. https://doi.org/10.1109/AIM.2015.7222526.

[6] Ou J, Yao L, Tauber D, Steimle J, Niiyama R, Ishii H. jamSheets: thin interfaces with tunable stiffness enabled by layer jamming. In: Proceedings of the 8th international conference on tangible, embedded and embodied interaction - TEI '14; 2014. p. 65–72. https://doi.org/10.1145/2540930.2540971.

[7] Kim YJ, Cheng S, Kim S, Iagnemma K. A novel layer jamming mechanism with tunable stiffness capability for minimally invasive surgery. IEEE Trans Robot 2013;29(4):1031–42. https://doi.org/10.1109/TRO.2013.2256313.

[8] Narang YS, Vlassak JJ, Howe RD. Mechanically versatile soft machines through laminar jamming. Adv Funct Mater 2018;28(17):1–9. https://doi.org/10.1002/adfm.201707136.

[9] Sridar S, Majeika CJ, Kaan C, Popovic M. Design and control of HydroBone – an approach to variable stiffness structures using jamming of granular media. MA: Worcester; 2016.

[10] Williams GR. US 2012/0277644 A1. Vacuum splint; 2011.

[11] Kim YJ, Cheng S, Kim S, Iagnemma K. Design of a tubular snake-like manipulator with stiffening capability by layer jamming. In: IEEE/RSJ international conference on intelligent robots and systems; 2012. p. 4251–6.

[12] Zuo S, Iijima K, Tokumiya T. "Variable stiffness outer sheath with ' Dragon skin ' structure and negative pneumatic shape-locking mechanism. International Journal of Computer Assisted Radiology and Surgery 2014;(9):857–65. https://doi.org/10.1007/s11548-014-0981-4.

[13] Sadati SMH, Naghibi SE, Althoefer K, Nanayakkara T. Toward a low hysteresis helical scale jamming interface inspired by teleost fish scale morphology and arrangement. 2018 IEEE international conference on soft robotics (RoboSoft) 2018:455–60. https://doi.org/10.1109/ROBOSOFT.2018.8405368.

[14] Moses MS, Kutzer MDM, Ma H, Armand M. A continuum manipulator made of interlocking fibers. IEEE international conference on robotics and automation 2013:4008–15. https://doi.org/10.1109/ICRA.2013.6631142.

[15] Blanc L, Delchambre A, Lambert P. Flexible medical devices: review of controllable stiffness solutions. Actuators 2017;6(3):23. https://doi.org/10.3390/act6030023.

[16] Brancadoro M, Manti M, Grani F, Tognarelli S, Menciassi A, Cianchetti M. Toward a variable stiffness surgical manipulator based on fiber jamming transition. Frontiers Robotics AI 2019;6(MAR):1–12. https://doi.org/10.3389/frobt.2019.00012.

[17] Ou Jifei, Yao L, Tauber D, Ishii H. US 2015/0107233 A1: methods and apparatus for layer jamming. 2014.

[18] Fratzl P, Weinkamer R. "Nature's hierarchical materials. Prog Mater Sci 2007;52(8):1263–334. https://doi.org/10.1016/j.pmatsci.2007.06.001.

[19] Naleway SE, Porter MM, Mckittrick J, Meyers MA. "Structural design elements in biological Materials : application to bioinspiration. Adv Mater 2015;27(37):5455–76. https://doi.org/10.1002/adma.201502403.

[20] Wegst UGK, Bai H, Saiz E, Tomsia AP, Ritchie RO. Bioinspired structural materials. Nat Mater 2015;14(1):23–36. https://doi.org/10.1038/nmat4089.

[21] Jiang A, Xynogalas G, Dasgupta P, Althoefer K, Nanayakkara T. Design of a variable stiffness flexible manipulator with composite granular jamming and membrane coupling. IEEE International Conference on Intelligent Robots and Systems 2012:2922–7. https://doi.org/10.1109/IROS.2012.6385696.

[22] Degani A, Choset H, Zubiate B, Ota T, Zenati M. Highly articulated robotic probe for minimally invasive surgery. In: Proceedings of the 30th annual international conference of the IEEE engineering in medicine and biology society, EMBS'08. Personalized Healthcare through Technology; 2008. p. 3273–6.

[23] Vincent JFV. Biomimetics - a review. Proceedings of the institution of mechanical engineers, Part H: journal of engineering in medicine 2009;223(8):919–39. https://doi.org/10.1243/09544119JEIM561.

[24] Dixon PG, Gibson LJ. The structure and mechanics of Moso bamboo material. J R Soc Interface 2014;11(99):1–12. https://doi.org/10.1098/rsif.2014.0321.

[25] Sherman VR, Quan H, Yang W, Ritchie RO, Meyers MA. A comparative study of piscine defense: the scales of Arapaima gigas, Latimeria chalumnae and Atractosteus spatula. Journal of the Mechanical Behavior of Biomedical Materials 2016;73(May 2016):1–16. https://doi.org/10.1016/j.jmbbm.2016.10.001.

[26] Duro-Royo J, Zolotovsky K, Mogas-Soldevila L, Varshney S, Oxman N, Boyce MC, et al. A hierarchical computational model for design and fabrication of biomimetic armored surfaces. CAD Computer Aided Design 2015;60:14–27. https://doi.org/10.1016/j.cad.2014.05.005.

[27] Yang W, Gludovatz B, Zimmermann EA, Bale HA, Ritchie RO, Meyers MA. Structure and fracture resistance of alligator gar (Atractosteus spatula) armored fish scales. Acta Biomater 2013;9(4):5876–89. https://doi.org/10.1016/j.actbio.2012.12.026.

[28] Mallick PK. Fiber-reinforced composites. 3rd ed. Boca Raton, FL: Taylor & Francis Group; 2008.

[29] Niiyama R, Yao L, Ou J, Follmer S, Ishii H. Method and apparatus for shape control. 2014. US 20140314976 A1.

[30] Wytch R, Mitchell CB, Wardlaw D, Ledingham WM, Ritchie IK. Mechanical assessment of polyurethane impregnated fibreglass bandages for splinting. Prosthet Orthot Int 1987;11(3):128–34. https://doi.org/10.3109/03093648709078195.