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Review

A Review of Jamming Actuation in Soft Robotics

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Abstract: Jamming is a popular and versatile soft robotic mechanism, enabling new systems to be developed that can achieve high stiffness variation with minimal volume variation. Numerous applications have been reported, including deep-sea sampling, industrial gripping, and use as paws for legged locomotion. This review explores the state-of-the-art for the three classes of jamming actuator: granular, layer and fibre jamming. We highlight the strengths and weaknesses of these soft robotic systems and propose opportunities for further development. We describe a number of trends, promising avenues for innovative research, and several technology gaps that could push the field forwards if addressed, including the lack of standardization for evaluating the performance of jamming systems. We conclude with perspectives for future studies in soft jamming robotics research, particularly elucidating how emerging technologies, including multi-material 3D printing, can enable the design and creation of increasingly diverse and high-performance soft robotic mechanisms for a myriad of new application areas.

Keywords: jamming actuation; granular jamming; layer jamming; fibre jamming; soft actuators; soft robotics; stiffness-tuneable mechanisms

1. Introduction

Soft robotics is a subfield of robotics focused on the use of flexible and adaptive materials, which draws heavily on biological inspiration. A notable area of soft robotics research focuses on exploiting the jamming transition as a means of achieving stiffness tuneability. There are three distinct types of jamming that have been employed in soft robotics: granular jamming, layer jamming and fibre jamming. Granular jamming is the natural phenomenon of transitioning a compliant, low-density packing of granular matter, such as sand, coffee, or gravel, into a rigid, high-density packing via externally applied stress. Loose, unjammed packings of grains function as fluids, and rigid, jammed packings behave as solids [1]. Jamming is not restricted to granular matter: planar sheet packings and bundles of threads can also phase-transition from compliant packings to rigid structures, as layer and fibre jamming, respectively, however neither function as fluids when unjammed. Granular jamming was the first type explored in soft robotics applications and is still the most prevalent. Jamming holds particular promise for soft robotics for two main reasons: (i)considerable stiffness variation can be achieved with minimal volume variation, and (ii) jamming structures are relatively free-form in their possible instantiations, meaning that this stiffness variability can be easily adapted towards different soft robotics applications, e.g., for gripping, locomotion, shock resistance as a limb, end effector and body.

In the context of robotics, jamming is typically used as an actuator and belongs to a class of stiffness-tuneable mechanisms including:

- Electro active polymers (EAPs) (which deform under electric field);
- Fluidic actuators (e.g., McKibben actuators, PneuNets);
- Shape memory materials (SMMs) (which can be alloys or polymers);
- Electro- and magneto-rheological materials (ERMs and MRMs, can be fluid or elastomers), which use embedded magnetic/electric particles that actuate under magnetic/electric field to orient and build chains (stiffen);
- Low Melting Point Materials (LMPMs, alloys or polymers which display rapid stiffness change with varying temperature).

Jamming can provide a higher maximum stiffness than fluidic actuation, SMM, EAP, ERM and MRM mechanisms, but typically requires attachment to a vacuum pump, which is an additional payload. Other actuation mechanisms have their own drawbacks: EAPs and ERMs require electric fields, MRMs necessitate magnetic fields, SMMs and LMPMs engender complex temperature modulation, and some LMPMs are toxic. Combined, these factors may limit applicability to particular tasks and environments. Jamming is safe to biological lifeforms and, like fluidic actuation, does not require complex interactions or expensive auxiliary systems to enact stiffness transitions. SMMs and LMPMs have slow stiffness transitions due to cooling requirements, whereas jamming, fluidic actuation, EAPs, ERMS and MRMs are generally expedient. Granular and fibre jamming systems are mostly unrestrained by size or shape, unlike the other stiffness-tuneable mechanisms, which generally require stiff framing structures, however, layer jamming systems are restricted to planar structures.

The three jamming mechanisms have their own respective characteristics when applied to Soft Robotics. Layer jamming and fibre jamming typically require less volume and are lighter than granular jamming systems (a benefit of their planar and long, tubular designs, respectively) but their stiffness-tuneable range and passive, unjammed deformations are not as large, as they do not function as fluids when unjammed. Layer jamming, in particular, is the least deformable in any context, and its restriction to non-fluidic planar sheets can more easily result in internal damage to the jamming structure when under stress, rendering parts of it incapable of unjamming. Jamming actuators can simply force a phase-transition, often via state-switching a vacuum pump, however the unpredictability of a packing's constituent grains, sheets or fibres introduces complexity. Granular jamming in particular suffers from this, with the unpredictability of grain rearrangement and the variable density range over which granular jamming can occur for a given material leading to reduced stability, controllability and repeatability. Layer and fibre jamming, while generally more stable in their arrangement due to not functioning as fluids when unjammed, still introduce complexity from undesired rearrangements via changes in pressure. Additionally, the pumps that are often used to enact jamming add weight to the system and can result in a dependence of the maximum achievable stiffness on environmental pressure. Granular jamming may further require a significant volume of potentially weighty grains. For a full comparison of the various stiffness-tuneable mechanisms, we refer the interested reader to a recent review [2].

The first jamming gripper was presented in 1978 [3], and was designed as a simple jaw-shaped gripper filled with (unspecified) granules which deform against objects and evacuate pneumatic fluid to enable grasping. The detailed mechanism behind its function was not rigorously understood at the time. There was relatively little further work in the field until much more recently, when the potential of this approach became better understood. In this review, we will focus on the more modern work that has taken place since 2009, that has sought to understand the physics behind the jamming mechanisms employed in these systems and their effective utilisation in real-world applications. This has lead to a resurgence of interest and publications on this topic (more than 60 since 2009).

To obtain the literature analyzed in this review, we performed combinations of (i) searching Web of Science and Google Scholar databases using the search terms "jamming actuation", "jamming actuator", "jamming mechanism", "granular jamming", "particle jamming", "layer jamming", "laminar jamming", "fibre jamming", "thread jamming", "soft robotic jamming", "jamming robot", "jamming grippers", "jamming paws", (ii) reference searching any literature found through databases for the new literature and search terms. Through this technique, we identified 62 papers on jamming related to soft robotics applications in the period of 2009–2020. The first work in this period detailed a granular locomotive soft robot, with two further studies on this topic being reported since this work (2009–2017) [4–6]. Jamming grippers have been the clear major area of research interest, with approximately half of the publications considered being on this topic (29 papers in total, including recent works on swarm grippers) [7–35]. Layer jamming grippers have also received considerable attention, with seven studies published between 2012 and 2020 [36–42], one study comparing granular vs. layer grippers (2015) [43], and two studies focusing on the hybridization of granular and layer, or fibre, jamming in grippers (2019) [44,45]. Granular grippers have been the majority research interest in jamming soft robots in all explored years except 2009, 2013, 2014 and 2019 (where they tied with layer jamming grippers). The period of 2019 shows the beginnings of interest in the hybridization of jamming mechanisms to mimic human hands, and 2020 has seen the first examples that incorporate swarm robotics into granular grippers. Studies between 2013 and 2014 focused on the effects of granular jamming in a soft robotics context [46–48]; one study in 2018 focused on fibre jamming effects [49]. Granular jamming was explored in studies between 2013 and 2019 for minimally invasive surgery (MIS) tools [50–53], with more recent interest in fibre jamming (2019) [54]. We define jamming MIS tools, and differentiate them from simple jamming grippers by their intended use as jamming manipulators for surgical applications. These MIS tools have design specifications including the capacity to function with trocar ports for single access surgery, multidirectional bending, elongation, minimization of organ damage, material compositions that are not human allergens, potential for embedding devices or tools for laparoscopic or endoscopic procedures, high precision stiffness controllability, and considerable force for organ displacement and/or retraction. Jamming exoskeletons have also been a popular topic, with three studies on layer jamming (2014–2019) [55–57] and one on granular jamming (2015) [58]. Researchers have shown particular interest in granular paws since 2016 [59–63] and there have been interesting studies on layer jamming's application for support (2016) [64], and damping effectors for UAVs (2017) [65]. This spread is shown in Figure 1.

In recent years, there has been a great increase in the diversity of the types of jamming robots studied; from 2009 to 2014, at most, two types were explored per year, 2015–2018 showed three to four, while 2019 had seven. There has also been a general upward trend in the number of jamming soft robot studies. Figure 2 displays various robots found throughout the literature.

In these studies, the soft robotic jamming of grains, layers or fibres stored within membranes, was induced using seven different mechanisms. Table 1 lists the mechanisms used per jamming type throughout the literature.

Table 1. Frequency of jamming actuation mechanism per jamming type.

	Granular	Layer	Fibre
Evacuate interstitial air via vacuum	[6–20,23,26–29,33,35,44,46–48,50–53,55–63,65]	[36,37,39,41,42,44]	[49,54]
Evacuate interstitial liquid	[14,17,22,28,46]	-	-
Inflate a neighbouring cavity	[21,25,31,43,45]	[38,43]	[45]
Compress interior volume via cable drive	[34]	[64]	-
Compress membrane via external force	-	[40]	-
Transmit grains via piston injection	[30]	-	-
Link grains via string and pull	[32]	-	-

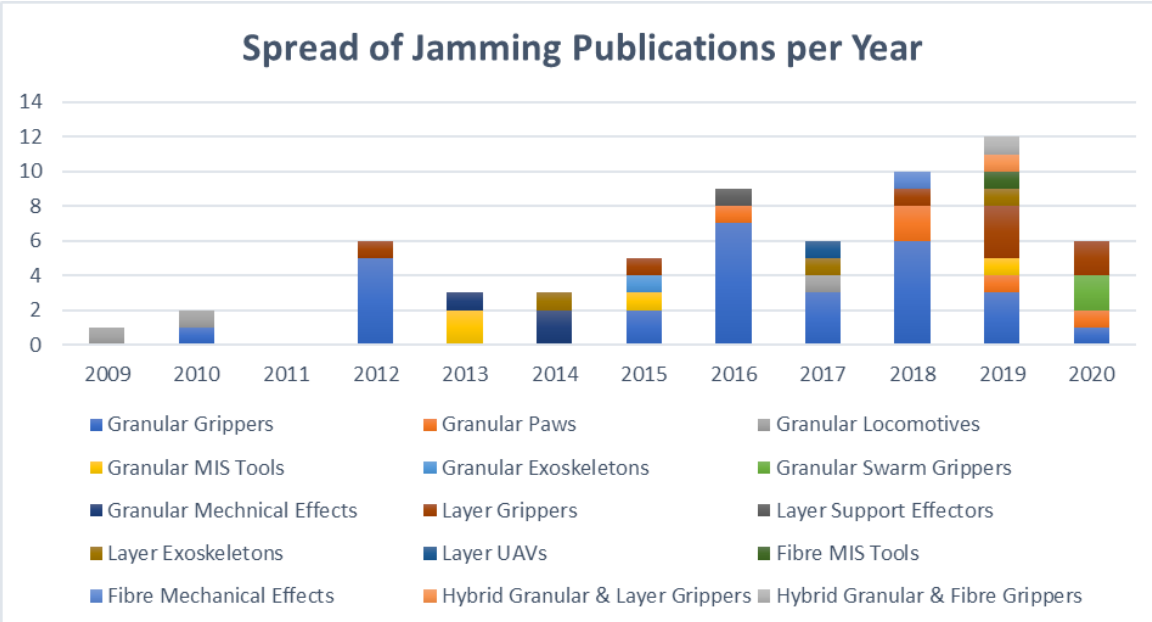

Figure 1. The spread of found soft robotic jamming publications from 2009 to 2020.

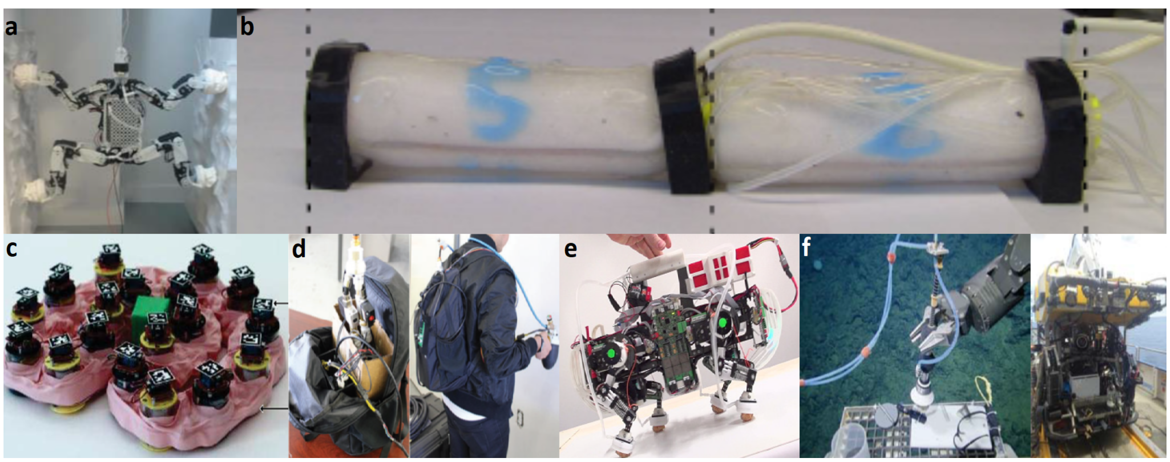

Figure 2. A diverse array of jamming actuated soft robots designed for unique environments and applications. From left to right, top to bottom: (**a**) a locomotive, humanoid, rigid robot using granular jamming paws to vertically ascend a rigid shaft via exploiting the jamming transition to increase compliance and friction against irregularly shaped walls [60], (**b**) a wormbot that crawls via bending moments created by combinations of McKibben actuation and jamming cells [5], (**c**) an ant-bioinspired granular jamming swarm gripper comprising of independently controllable sub-robots capable of surrounding a target object, jamming to grasp it and transporting it via wheeled leg locomotion [35], (**d**) a prostheses device incorporating a granular jamming bag gripper which was designed to assist amputees with daily living tasks including object grasping and manipulation [18], (**e**) a rigid four-legged locomotive robot utilizing granular paws with rubber cube packings with goals to increase damping and terrain compliance, and reduce slippage, during locomotion on smooth and rough surfaces [59], and (**f**) a remotely operated underwater vehicle capable of grasping and manipulating delicate deep-sea objects through a hydraulically actuated granular jamming gripper which engenders stronger grasps as environmental pressure increases [28].

The remainder of this review is structured as follows: Section 2, Materials and Designs, focuses on the constituent materials used and their fabrication. Section 3, Jamming Soft Robot Applications, details the current and historical application cases of jamming actuated robots. Section 4, Jamming Soft Robot Evaluation, explores the performance evaluation experiments and metrics used to quantify jamming soft robot performance. Section 5, Jamming Soft Robot Modelling, showcases the state-of-the-art of modelling practices. We finish in Section 6, Discussion and Perspectives, with a discussion and perspectives on the future of jamming soft robots.

2. Materials and Designs

The constituent materials, device geometries and fabrication method employed all play critical roles in determining the final performance of jamming robots. There are two distinct areas where material choices must be made: firstly for the constituent jamming elements (grains, sheets, or fibres), and secondly for the containing membrane or vessel. These together comprise a jamming actuator, which functions as its own entity. Grain, sheet and fibre shapes, materials and packing arrangement (such as how bulk grains are dispersed, sheets are patterned, or fibres are bundled) within a membrane all affect a range of factors for the combined actuator. These include the jammed stiffness (generally through inter-grain/sheet/fibre interactions, including their frictional properties), ability to deform against objects or surfaces when unjammed, the compressive or tensile Young's modulus and yield strength, and the total required volume (and mass). Similarly, the membrane's materials and geometry affect all stated factors, as well as the capacity for the actuator to perform its planned function, e.g., having a finger vs. a paw geometry.

2.1. Grains, Layers and Fibres

A large variety of materials and geometries (morphologies) have been explored for the grains, sheets, and fibre materials used in jamming soft robots. This spread of grain materials and morphologies is listed in Table 2.

There are two main types of grains used for granular jamming: naturally occurring (coffee, corn, gravel, rice, pepper, salt, sugar) and man-made (including plastic, glass or rubber materials of spherical, cubic or cylindrical geometries). Naturally occurring grains have wide variations in shape and size distribution that are not strictly controlled a priori, while man-made grains offer the ability to exactly control constituent morphologies and size distributions (though generally, in studies to date, homogeneous monodisperse sets of grains have been used). Ground coffee is the most widely used type of grain, however, other natural grains have also been employed. Glass spheres are the most common man-made grain, and are generally used due to their ready availability, and the removal of complexities of grain shape, which enables easy modelling. Rubber cubes have also often been used in paws and have been found to have benefits in terms of controllability and force dissipation properties. Sheet materials are listed in Table 3.

Paper, polyethylene terephthalate and sandpaper are the only sheet materials used in multiple studies. The different fibre materials employed are listed in Table 4.

Table 2. Frequency of various grain materials and geometries.

Grain	References	Count
Acrylic demi-spheres	[46]	1
Calcium chloride desiccants	[31]	1
Coffee powder	[24,27,29,33,50]	5
Corn	[31]	1
Crushed coffee	[13]	1
Glass spheres	[5,7,17,21,22,25,28,30,44,47,63]	11
Gravel	[29]	1
Ground coffee	[6,7,9–13,18–20,23,23,43,52,53,60,63]	17
Hollow plastic spheres	[35]	1
Hollow rubber cubes	[8]	1
Pepper	[53]	1
PLA cubes	[32]	1
Plastic cubes	[8,48]	2
Plastic spheres	[8,15,29,31,45,48,51,63]	8
Plastic assorted shapes	[48]	1
Polystyrene spheres	[13,56]	2
Rice	[26,29]	2
Rubber-coated plastic cubes	[8]	1
Salt	[53]	1
Solid rubber cubes	[8,59,61]	3
Sugar	[53,58]	2
Unspecified material cylinders	[34]	1
Unspecified material spheres	[16,62]	2
Wooden cubes	[56]	1

Table 3. Frequency of various sheet materials.

Sheet	References	Count
Elastomer	[40]	1
Leather sealed	[39]	1
Paper	[37,39,41,44,56,65]	6
Photopolymer	[38]	1
PLA	[57]	1
Polyester film	[42]	1
Polyethylene terephthalate	[36,43]	2
Sandpaper	[39,55]	2
Tyvek sealed in vinyl-pane clear plastic	[39]	1
View foil	[64]	1

Table 4. Frequency of various fibre materials.

Fibre	References	Count
Leather	[49]	1
Nylon	[49]	1
Polypropylene	[45]	1
Polytetrafluoroethylene	[49]	1
Polyvinyl chloride	[49]	1
Silicone	[49]	1
Waxed cotton	[49,54]	2

Fibre jamming in soft robotics has only been explored for the past two years, and thus material trends in this area are yet to emerge.

2.2. Membranes

The spread of membrane materials is listed in Table 5 below:

Table 5. Frequency of use of various membrane materials.

Membrane Material	References	Count
Braided mesh	[64]	1
Elastomers	[12,14,18,20,25,32,40,41,62]	9
Elastomer film	[65]	1
Ineslatic textile ice pack	[63]	1
Latex rubber	[7,8,10,11,13,17,19,22,24,28,33,34,36,42,46–49,52,56,59–61]	23
Nitrile	[47]	1
Photopolymer	[38]	1
Polythene	[47,55]	2
Pongee fabric	[45]	1
PVC	[51]	1
"Rubber"	[26]	1
Silicone rubber	[5,6,9,15,16,21,23,27,29–31,37,39,43,44,50,53,54,57,58]	20
Vinyl	[35,47]	2

The most ubiquitous membrane materials are elastomers, specifically silicone and latex rubbers, which are also the most commonly used materials in other soft robotic grippers [2]. The only commercialised gripper used a custom polychloroprene to improve durability over more standard membrane materials. Silicone is preferred to latex for surgical applications due to potential allergic reactions. Jamming actuator geometries are listed in Table 6.

Table 6. Frequency of use of jamming actuator geometries.

Membrane Geometry	References	Count
Beams	[37,39,53,55,57,58]	6
Cylinders	[8,36,46–49,53,56,64]	9
Fingers	[26,29,30,37,40–42,45]	8
Icosahedron cells	[5]	1
Nubbed bags	[10]	1
Multi-chambered cylinders	[6,15,38,50,52,54]	6
Multi-chambered fingers	[16,21,25,31,32,43,44]	7
Octopus sucker	[24]	1
Segmented cylinders	[9,23,51]	3
Simple bags	[7,10–14,17,18,22,28,33,59–61,63]	15
Simple bags & active robotics	[19]	1
Spined bags	[62]	1
Tori swarms	[34,35]	2
Variable volume bags	[20,27]	2

There has been a move away from simple granular bag grippers to more complex granular and layer fingers/multi-fingered designs, and multi-chamber constructs combining jamming to control stiffness and pneumatics to provide bending (independently controllable). Jamming paws are a relatively nascent study area and have not progressed beyond bags. Surgical tools tend towards long and slender tubular cylinders, utilizing jamming for stiffening and force generation. Recent developments have incorporated locomotive swarm robotics into tori membranes [34,35], or designed bioinspired human fingers through hybridizations of grains and layers or fibres, mimicking muscles, joints and bones [44,45].

2.3. Fabrication

Additive manufacturing has been increasingly employed to create complex gripper membrane geometries. Membrane fabrication methods per geometry are listed in Table 7.

Table 7. Frequency of Fabrication Methods for Membranes.

Fabrication Method	Bags	Beams	Cylinders	Fingers	Internal Skeletons
Cast moulds	-	[53]	[50,53]	-	-
3D printed cast moulds	[10]	[57,58]	[54,56]	[16,21,29–32,43,44]	-
Dip moulds	[14]	-	-	-	-
Direct 3D prints	-	-	-	[25,38,40]	[15,42]

Aside from purchasing commercially available membranes (e.g., latex balloons), cast moulding is the most common approach to fabricating a membrane. Cast moulding consists of filling a pre-fabricated (recently via 3D printing) mould with a formula (such as liquid silicone—ecoflex and dragonskin are popular brands) and waiting until a solid membrane is formed via setting. Almost all finger-shaped grippers used 3D-printed moulds, with these methods increasingly becoming the norm. Direct printing is rare but increasing in popularity, as cast moulding is a complex, multi-step and slow process in comparison. Direct 3D prints allow for comparatively greater stiffness variation through a broader range of potential materials, higher control over the fidelity of the final design, rapid prototyping, and smaller variations between individual actuators. However, additive manufacturing techniques such as functional gradation and complex, multi-material builds are yet to be fully exploited in the search for increased actuator performance. Figure 3 displays some of the various fabrication methods found throughout the literature.

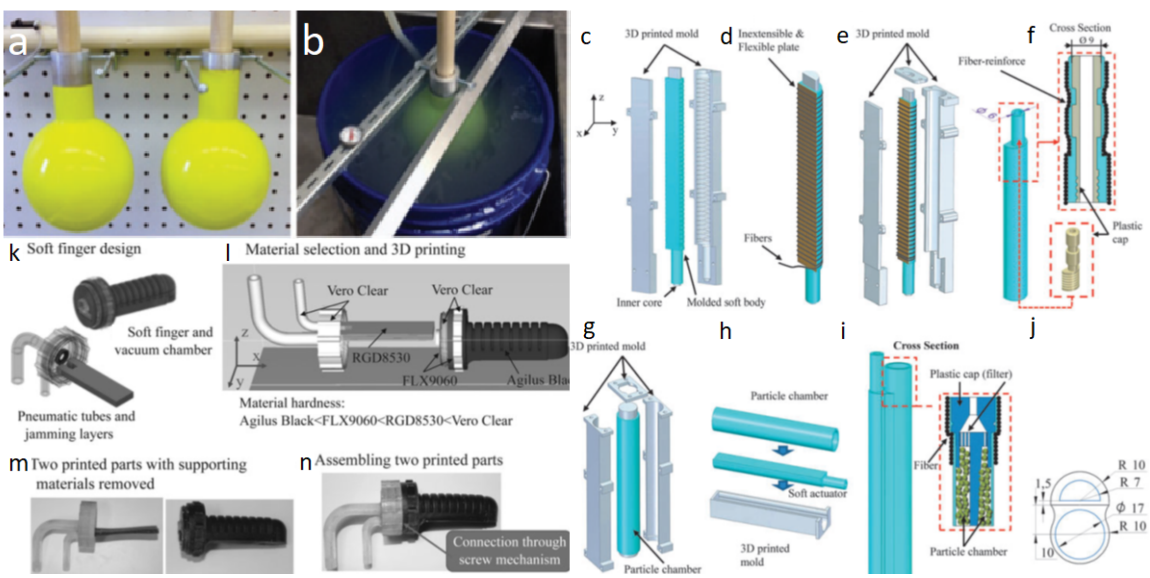

Figure 3. A selection of soft jamming robot fabrication methods. Clockwise from top-left; (**a**,**b**) show the dip moulding process of commercialized ellipsoidal bag grippers composed of a custom polychloroprene formula, whereby mandrels are dipped into the formula and left to dry (**a**) and subsequently warmed in a hot water bath to allow the removal of the membrane (**b**) [14]. (**c**–**j**) display the application of 3D-printed cast moulds in the complex, multi-step manufacturing process of a silicone rubber soft jamming finger.

This process utilized a 3D printed cast mould to fabricate the molded soft body (**c**) which was then encased in an in extensible but flexible plate and wrapped in winding fibres along the grooves (**d**). Another 3D printed cast mould was utilized to lock the fibres and plate within a thin layer of silicone (**e**), and a 3D printed rigid cap was then inserted into the bottom of the structure (**f**). An additional cast mould was used to fabricate the particle chamber (**g**). The soft finger and particle chamber were joined with silicone via a final 3D printed cast mould (**h**), and the particle chamber filled with sphere granules and sealed (**i**). (**j**) shows the cross sectional measurements of the prototype [16]. (**k**–**n**) is a visualization of the streamlined manufacturing process of a fully multi-material, direct 3D-printed, soft layer jamming finger. The two distinct CAD models of the pneumatic tubes and jamming layers and the soft finger and vacuum chambers respectively are shown in (**k**), a visualization of the printing environment and the materials selected for the fabrication process (**l**), the two printed parts with their support materials removed (**m**), and the connection of the parts via a screw mechanism to finalize the prototype (**n**) [38].

Most studies use commercially purchased grains, sheets or fibres, with rare examples of 3D printing [38,40,48,57]. Thus, the majority of the literature has been restricted to commercially available sizes of common simple shapes, e.g., cubes and spheres ranging from 1.5 m to 8 mm, or sheets, e.g., paper or PET.

3. Jamming Soft Robot Applications

While the research has predominantly focused on grippers, the last eleven years have shown a versatile range of testing scenarios and real-world applications for soft jamming robots. The frequency of Soft Jamming Robots per application domain is listed in Table 8.

Table 8. Frequency of soft jamming robots per application domain.

Application Domain	References	Count
Aerial Robotics	[65]	1
Deep-sea Missions	[22,28]	2
Haptic Feedback Wearables	[55,56]	2
Independent Living Devices	[18,57,58]	3
Industrial	[14,19,33]	3
Object Transportation	[13,34,35]	3
Surgical Devices	[50–54]	5
Terrain Locomotion	[4–6,23,24,34,35,59–61]	10

This section details which environments and use-cases jamming soft robots have recently been applied to, their performance at given tasks and trends in their use.

3.1. Grippers

While grippers have been the predominant focus of research in jamming soft robots, the only clear trend in their usage is in grasping, stiffness or strain testing in controlled laboratory conditions, and (often) a subsequent lack of translation to a specific, complex application domain. Despite this, a collection of studies have utilized grippers in more unconventional scenarios. This section explores these usages and the state-of-the-art of jamming grippers in real-world applications.

Jiang et al. [12] utilized their jamming gripper alongside computer vision and a grasp learning algorithm to ascertain if hardware-agnostic grasps could be learnt for a jamming gripper, and bypass physical modelling. Their learning algorithm increased grasp success by 18% on unseen objects versus a heuristic algorithm which was programmed to always grasp the centroid of an approximated region of the object. Both algorithms performed similarly on smaller, stable objects such as pens. The learning algorithm outperformed the heuristic algorithm on objects where the centroid of the approximated region did not align with the true centre of the object, or aligned with an area poorly suited for grasping (e.g., the cable of a phone charger). Both algorithms performed poorly on unstable objects, such as a horizontally aligned martini glass, however, even manual control of the gripper struggled with these grasps. Similarly, D'Avella et al. [33] attempted to reduce the complexity of robotic pick and place tasks of multiple types of geometrically complex objects, e.g., bin picking. They used a single universal jamming gripper and a corresponding perception algorithm in an attempt to create a universal perception gripper and algorithm to circumvent a typical industry approach requiring multiple, object specific grippers and algorithms. Their prototype was tested across a variety of objects, including a smooth ceramic cup, a porous brush box, chewing gum, and a rubber duck toy. It achieved an approximately 75% success rate, however, it struggled with porous objects, such as the brush box, due to reduced material adherence. It also struggled with objects that were larger than the diameter of the balloon. These are common problems with jamming grippers using balloon membranes. Their perception algorithm was able to correctly identify correct grasping poses while achieving equal, or better, computation times compared to two benchmark algorithms. The gripper and perception algorithm combination displayed the capacity to pick and place objects from various industries, however, approximations of industry-specific domain conditions reduced the capacity for direct comparisons against standard industry solutions. These combinations of perception algorithms and universal jamming grippers [12,33] are novel and useful approaches for specific industrial applications, however, they are dependent on the quality of the perception algorithms.

Valenzuela et al. [13] attached their simple latex balloon and ground coffee universal gripper onto an omni-directional mobile platform to explore the capacity of using a mobile jamming gripper to grasp and place fragile objects. Their platform was capable of grasping and transporting diverse objects, e.g., coins, Styrofoam cubes and spheres, through intricate passages, and exerted small activation forces on the test objects, however, key metrics such as the holding force were not measured.

Cheng et al. [18] sought to employ a latex balloon and ground coffee universal jamming gripper as part of a prosthetic device for amputees, and used real-world trials of their prototype against commercial products, with amputees as operators, in a variety of common tasks. Their prototype was slower than the commercial counterpart due to its pneumatic actuation, and users reported additional fatigue from having to push the gripper into objects. Despite this, users were able to complete the tasks, and the researchers state that the discomfort can be minimized via exploring higher performing and lighter, granular materials and optimizing the size and morphology of the membrane.

Harada et al. [19] used a ground coffee and latex balloon universal jamming gripper alongside four active robotic fingers in approximated assembly line experiments. The active robotics fingers determined the pose of the object before grasping. This allowed the gripper to adapt to the various shapes of objects "passed to it", theoretically reducing the number of required gripper types on an assembly line to one. Their prototype was capable of grasping various male and female parts of a plastic object, and assembling them together. However, the introduction of rigid components reduces the compliance benefits typically associated with soft robotic systems.

Licht et al. 2017, 2018 [22,28] deployed their hydraulic actuated, latex balloon and glass sphere jamming grippers on deep-sea missions on a remote-operated, underwater-vehicle in order to grasp objects of variable geometries and potentially fragile compositions at depth. Their goals were to reduce damage from the recovery of valuable biological and cultural deep-sea items and expeditionary costs from at-depth tool changes. The grippers were found to have increased holding force at depth, and a gripper with a lower fill level was more successful at retrieving items off laboratory controlled soft substrates than a gripper filled to the highest volume that did not cause elastic membrane deformation due to partial fill levels allowing increased envelopment of target objects and the minimization of displacing the objects further into the soft sediment. Due to budgetary constraints, the hydraulically actuated, partially filled gripper could only be tested on four objects on a rigid deep-sea surface, and was entirely successful at this task.

Fujita et al. [27] demonstrated that their Silicone rubber multi-chambered cylinder and coffee powder gripper was not only capable of grasping objects, but also complex manipulation of a switch door via pressing its button to unlock it, then grasping and pulling the handle to open the door. The gripper was capable of generating enough force to activate the button when oriented upwards, downwards and sideways. This is a novel demonstration of the capacity of soft jamming grippers to perform multiple different tasks, including complex object manipulation beyond grasping.

Zhu et al. [38] showed that their two-fingered layer jamming gripper was capable of maintaining high stiffness and grasps on a target object (lemon) at various high accelerations. Grasping robustness was tested through mounting the gripper to a robotic arm, grasping the object, and then accelerating the arm and gripper horizontally. The results showed 100% grasp success at accelerations of 2 m/s^2 and 0.75 m/s maximum speed, and 40% success at 8 m/s^2 and 1.5 m/s maximum speed. This is the first application showing the benefits of a jamming gripper in a highly dynamic scenario and raises further research questions around variations in vacuum pressure, gripper orientation and possible target objects.

Tanaka et al. [34] designed a swarm gripper with a torus-shaped membrane that contained eight sub-robots interconnected by chains and laterally standing cylinders as its granular packing. The sub-robots could independently actuate their connected membrane subsection via shortening their chain linking, thereby compressing the membrane. Each sub-robot had a differential drive system for locomotion. They used their locomotive gripper to grasp cylinder objects and pulled them in a straight line. Karimi et al. [35] also designed a locomotive swarm gripper with a torus-shaped membrane, however, they exploited vacuum pressure to enact jamming. Their grasping strategy was bioinspired from ants, whereby a sub-robot approached a target object and acted as a center of rotation for the aggregate swarm to engulf the object. Their grasping test consisted of the swarm engulfing a cube object and then pulling the object away in two configurations: jammed and unjammed. The jammed configuration achieved holding forces 50% greater than unjammed. While there are open questions with respect to object grasping and transportation over harsh terrains, the computational programmability of the constituent grains is a novel and intriguing consideration of both jamming grippers, and jamming robotics as a whole.

Amend et al. [14] commercialized their Versaball gripper in 2012. Industrial robotics had the strongest interest, generally in using the grippers on robotic arms for pick and place tasks, and the creators reported that the interest spread was 25% plastics, 20% consumer products, 15% automotive kitting and assembly, 15% packaging, 10% collaborative robot applications, 10% food products, and 5% consumer electronics [14]. The product specifications that were vital to sales and customer retention within this sector were primarily sensing grip confirmation, membrane durability, maintenance requirements, breakage detection, maximum payload, required activation force, actuation speed, placement precision, air consumption and supply requirements, chemical resistance, and safe operating temperature range. The company eventually closed, and our literature search returned no other attempts to commercialize.

Granular jamming is the only variant of jamming to be utilized in a soft robotic gripper outside of laboratory tests. Layer and fibre jamming are newer jamming technologies and have not had the opportunity to fully expand beyond laboratory testing. Recent laboratory controlled research on granular jamming grippers, which primarily focused on grasping, strain or stiffness testing, trended towards designing complex, multi-chambered finger or cylinder grippers with man-made monodisperse, higher controllability grains (e.g., glass spheres) in order to maximize evaluation metrics. Despite this increase in design complexity for laboratory-based tests, real-world (or laboratory approximated) applications of soft jamming grippers still chiefly utilize simple bag morphologies and naturally occurring grain packings that engender no explicit control over grain morphology, e.g., latex balloons filled with ground coffee. These applications are often attempting to simply demonstrate the transferability of

Brown et al.'s [7] universal jamming gripper to a specific application domain. While there are general durability and repeatability concerns inherent to bag style grippers versus traditional industry grippers, there is evidence that this can be ameliorated via material research and modularity. For instance, Amend et al.'s [14] commercialization process demonstrates research-driven increases in gripper life-cycle, starting with an average of 1000 grips and ending with 50,000. Real-world applications are often constrained by environmental factors which complicate tests and lead to simplifications, such as the number of membrane or grain compositions experimented with (if modified at all) or abstracting the true environmental conditions (such as deep-sea soft sediment surfaces), thus increasing the difficulty in ascertaining the optimality of the final prototype. Given the comparatively simple design specifications, advanced material fabrication techniques, such as functional gradation and programmed deformations in multi-material builds, have yet to be exploited for real-world applications of soft jamming grippers as they have been for other soft robotics systems.

3.2. Paws

Jamming paws for legged robots are a nascent but promising area of research. Contemporary legged robots typically require complex multi-layered control strategies, especially in non-smooth terrains, and contact the terrain through simple ball- or cylindrical-shaped feet, with limited damping, which can cause detrimental control oscillations, jolts, and slippage. Recent studies use granular jamming paws to increase locomotion ability over rough terrains through material compliance, simultaneously offering a route towards simpler control strategies.

Hauser et al. 2016, 2018A [59,61] ascertained whether the damping properties of cubic granular packings could increase the damping of their robot's paws. Three variants were tested: default ball-shaped feet, and unjammed, and jammed granular membranes. Both studies dropped the variants onto stationary [59] or moving [61] surfaces. Unjammed variants had the greatest damping, followed by all jammed variants, and the original foot had the least damping. Hauser et al. 2016 study [59] showed jamming paws having higher plastic deformation and lower elastic deformation than the default foot.

Hauser et al. 2016, 2018B [59,60] tested their granular paws on various surfaces to ascertain their ability to reduce slippage. Hauser et al. 2016 [59] measured the friction across a smooth plastic-coated wood surface and found the orignal foot's ground adherence > unjammed paw > jammed paw, but all variants achieved similar friction. Hauser et al. 2018B [60] measured the friction between a surface and their wall-climbing paw across four vacuum pressures, 1000 mbar (atmospheric), 800, 500 and 200, compared against a rubber cast ball and a spherical sponge. Two sets of walls were used, smooth and rough. The rubber ball had the highest frictional force on the smooth wall, then jamming paws, then the sponge. The 200 mbar jamming paw had the highest friction on rough walls, then the rubber ball, then the 500 mbar paw. The jamming effectors used the irregularities to increase frictional force. Jamming can be used to enhance performance and reduce slippage of robotic end effectors, with particular beneficial effects on rough terrains.

In similar research, Fujita et al. [24] used their ground coffee and latex membrane grippers as wall climbing end effectors for a four armed robot. It scaled a mortar wall and a plasterboard ceiling. Ruotolo et al. [62] constructed a prototype hand with spined underactuated fingers for grasping convex shapes, and a spined compliant granular jamming paw for conforming to irregular surfaces, with eventual applications in a climbing quadruped robot.

As well as damping and slippage, locomotion speed has also been studied. Hauser et al. [59] recorded forward and backward locomotive speed on a smooth linoleum surface. All variants considered had similar forward speeds, with jammed paws having the highest backwards speed. The authors determined that jamming enabled better ground contact through a half cylindrical shape being formed from elastic deformation of the soft rubber cubes. Static gaits were used across all feet. Jammed paws were generally as capable of forward and backward ascending steep slopes as the original foot. Hauser et al. separately [61] tested their variants on four terrains: flat smooth, flat rough, 3° inclined rough, and 5° inclined rough. No jamming variant was better than the original foot on smooth terrain. All jamming variants were better than the original foot on flat rough terrain and inclined surfaces. A simple switching control strategy allowed the paw to switch between jammed and unjammed states at different phases of the gait cycle providing enhanced performance: landing unjammed allowed for additional compliance, subsequent jamming allows for improved force transmission.

Overall, jamming paws demonstrated superior ground compliance versus traditional end effectors during locomotion, specifically over the types of rough, rugged terrains where traditional robotic feet tend to struggle. Geometric jamming of non-rigid (e.g., rubber) cubic packings is used extensively in jamming paws compared to jamming grippers. These packings are demonstrably useful for damping and locomotion [59–61] versus traditional rigid robotic feet. Despite these successes, soft jamming paws are nascent and under-explored compared to soft jamming grippers. All paw membranes are variations of simple bag membranes, often simple latex balloons which tear and disfigure during use, and are set to unvaried morphologies and sizes per study. The majority of studies also focused on just single-grain materials, sizes, morphologies and fill levels. The additive manufacturing of paw membranes or grains is yet to be exploited in this jamming robot domain. The great potential for merging soft jamming paws with soft jamming grippers is only beginning to be explored, with the best examples to date in vertical wall climbing robots [24,60]. Layer and fibre jamming are yet to be applied in any context to soft jamming paws, and as these successful, yet simplistic, granular paws are abstractions of animal paws, there is obvious potential for bioinspired hybrid jamming paws or feet akin to bioinspired hybrid jamming fingers [44,45]. Further, the paws in these studies were tested in laboratory environments, with man-made and approximated rough terrain, and have not been tested in the rigorous, real-world conditions that rigid robotic feet are commonly subjected to. Researchers are yet to significantly apply computational modelling methods (such as FEM or DEM) to granular jamming paws, likely due to their slower uptake in application compared to jamming grippers and the increased complexity of interactions between paws and non-uniform surfaces. This offers a significant future research avenue in computational design to optimise the jamming process in these soft robotic systems.

3.3. Other Diverse Jamming Robots

A key strength of jamming as a soft actuation mechanism is the potential diversity of application areas; here, we summarise other work not related to grippers or paws.

Jamming soft robotics researchers have conceptualized jamming soft surgical tools for minimally invasive surgery, with the goal of reducing damage to patients through use of softer utensils, minimizing surgical complexity engendered from rigid surgical tools whilst improving dexterity and providing sufficient stiffness and force generation when required [50–54]. Jiang et al. [51] embedded a laparoscopic camera into their stiffness-tuneable bending manipulator, however, it was not trialled in any experiments. Cavallo et al. [53] successfully demonstrated the potential of their ferromagnetic and granular jamming tissue retraction tool in vivo on a porcine intestine, showing stable retraction and acceptable organ grasping. They state that a more rigorous validation process, under the oversight of medical doctors, will be required for further advancements. Ranzani et al. [52] used their granular jamming tool to wrap and retract an 800 g water-filled balloon, however, the potentially problematic on-board pneumatic pumps render it as a proof-of-concept rather than a realized tool for minimally invasive surgery. Brancadoro et al. [54] created two novel fibre jamming variants of the commonly-used "STIFF-FLOP" manipulator. Both variants displayed increased force when jammed vs. the original, and recovered their initial position once unjammed. However, their Module A removes the internal free lumen of the STIFF-FLOP manipulator and renders it incapable of use for instrument insertion, and module B was restricted to 1 DOF and required the use of a supporting rod for omnidirectional bending, severely reducing maneuverability. Minimally invasive surgery necessitates an extremely high level of repeatability, controllability and safety, and while these tools have not yet been rigorously tested in enough comparable scenarios, granular or fibre jamming appear to be promising avenues for augmenting performance in these forms of surgery.

In other works, Santiago et al. [64] created a layer jamming kangaroo tail for a kangaroo toy. It complied to surfaces when soft, and was a successful support structure when rigid. It showed linear and bending stiffness increases of 4-fold and 1.5-fold, respectively. Narang et al. [65] sought to reduce the impact from landing for their UAV, and applied layer jamming structures as impact response landing gear for a UAV. They experimented with soft and hard landings, and they reasoned that at a given landing velocity, there was a jamming pressure to "minimize peak forces on the UAV while also preventing its chassis from bottoming out" [65]. The results supported the hypothesis; for a given landing velocity, there were unique decay rates, frequencies and oscillation amplitudes, and ideal pressures existed for given velocities.

Steltz et al. 2009, 2010 [4,5] created high degree of freedom jamming, locomotive soft robots that circumvented the complexity in extracting environmental work endemic to other soft actuators. The Jamming Skin Enabled Locomotion (JSEL) icosahedron robot had 20 independently activatable triangle faces, and a fluid centre as an actuator. It locomoted by jamming and unjamming subsets of faces and inflating the fluid cavity, creating a "rolling gait". A locomotive "wormbot" was created from two Jamming Modulated Unimorphs (JMU), which are McKibben actuators surrounded by three jamming cells. Pressuring an actuator and jamming a cell creates a bending moment away from the cell, and jamming two creates a moment towards the unjammed cell. The wormbot was capable of crawling from combinations of jamming and actuation. Miao et al. [6] designed a four-legged, locomotive, and grasping, granular jamming robot. More recent work [23] employs a similar modular design, using jamming to locomote a worm-like robot that uses a quick, cheap fabrication strategy. Granular jamming based locomotion shows promise in reducing both the complexity of design and the requirements for environmental work compared to other forms of soft actuation.

An emerging research area is the investigation of jamming exoskeleton gloves to reduce size, weight and compliance issues, and increase usage versus rigid, non-compliant exoskeletons. Thompson et al. [58] created assistive jamming gloves for physically impaired persons. The prototype provided support to fingers and locked them in position, however, the jammed force could not restrict minor finger movements. A qualitative questionnaire of 10 people showed high scores in comfort, weight and unrestrictiveness. Zubrycki et al. [56] theorized teleoperational gloves that would jam when a multi-fingered robot touched an object, preventing further teleoperator hand movement and providing kinaesthetic feedback. Their prototype was 20% lighter than a comparable rigid exoskeleton, however, its force resistance for 5 mm displacement was 7 compared to 12 N. It was not tested in a teleoperation scenario, but they detail how it could be applied in this way. Simon et al. [55] designed a garment-integrated, layer jamming mitten for haptic feedback. A qualitative study showed "positive outcomes with all participants indicating there was a detectable haptic sensation that felt realistic" [55]. Choi et al. [57] created a sliding linkage-based layer jamming mechanism to increase yaw movement whilst displaying similar linear stiffness to conventional layer jamming. The authors reported a approximately 100-fold stiffness increase in the linear direction when jammed, and approximately 60-fold stiffness increase for yaw. The authors highlight potential applications as a wearable spine assistant, wrist protector, and smart elbow sleeve. Jamming shows potential in exoskeleton applications, with increased usage being observed and augmented functional capacity compared to purely rigid devices.

4. Jamming Soft Robot Evaluation

This section details the performance evaluation methods that are commonly applied for jamming soft robots and a summary of the results obtained in a range of studies. Grippers comprise a majority of the literature and, thus, grasp tests form a significant component of the discussion that follows.

Most studies physically test jamming robots to evaluate performance. The three primary physical evaluations are:

- Object grasping for jamming grippers;
- Bending stiffness tests for jamming actuators;
- Compressive or tensile strain tests for jamming actuators.

Grasping is tested to quantify a gripper's capacity for holding an object, robustness to grasping objects of varying shapes/sizes, and the force exerted upon an object during grasping (important for fragile objects). Common grasping metrics are the holding force, maximum pulling force on a grasped object before losing grasp, and maximum force applied to an object during grasping; they are typically measured via load-cells and scales. Bending stiffness is a measure of external force versus bending deformation for a jamming soft robot (generally cylindrical or finger shaped), which is important for a variety of applications such as surgical tools or finger grippers. Researchers quantify bending stiffness through load vs. displacement (LvD), bending hysteresis, actuated bending angle, applied moment, rotational stiffness, and range of motion. Compressive or tensile strain measures the elastic and plastic deformation of a jamming soft robot, with some robots benefiting from elastic deformation (such as paws on certain surfaces) and some benefiting from none at all (grippers once jammed around an object). Strain is quantified through stress vs. strain curves, the Young's Modulus and yield stress. Table 9 lists the frequency of the performance metrics throughout the literature.

Table 9. Frequency of performance metrics.

Metric	References	Count
Holding force	[7,10,11,14,17,22,25,27,28,34,35]	11
Activation force	[10,11,13,17,20,27,28,30,40,50]	10
Load vs displacement	[8,9,15,16,26,29,32,37,38,40,42,44–47,49,50,52,54,56–58,65]	23
Bending hysteresis	[8,30,38,46,47]	5
Actuated bending angle	[6,21,25,31,38,50]	6
Applied Moment	[15,16,21,23,26,32,44,64]	8
Rotational stiffness	[21,25,30,31]	4
Range of motion	[30]	1
Compressive strain	[9,24,39,47,48,52,53,60]	8
Tensile strain	[47]	1

Figure 4 displays a selection of the experimental set ups for some of the more common tests throughout the literature.

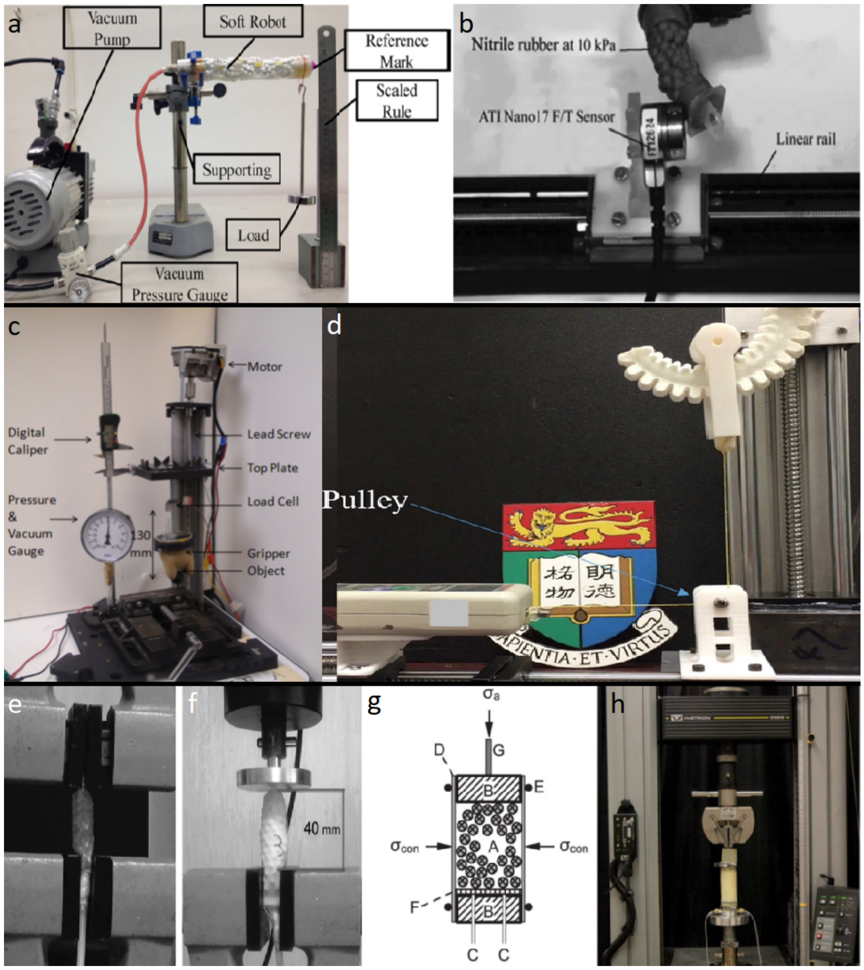

Figure 4. A selection of photos of various laboratory controlled experiments performed to ascertain jamming actuator performance. Note a lack of standardisation in testing—cantilever-beam tests are conducted with differing orientations, for example. From left to right, top to bottom, (**a**,**b**) shows two cantilever beam tests to assess stiffness through load vs. displacement via measuring the force required to displace the tip of the beam a certain distance ([15,47]), (**c**,**d**) visualize two pull-out tests to assess the holding force of a gripper via grasping an object and measuring the force required to pull it from the grasp ([10,25]), and (**e**–**h**) display a tensile test (**e**), a compression test (**f**) [47] and another compression test (**g**,**h**) [48] used to ascertain the compressive or tensile stiffness of a jamming actuator via measuring the load required to evoke a predetermined level of strain.

Researchers often isolate and vary one of eight parameters to ascertain the effect on a metric:

- Multiple actuation pressures (AP);
- Multiple grain, layer or fibre sizes (GS), (LS), (FS);
- Multiple grain, layer or fibre geometries (GG), (LG), (FG);
- Multiple grain, layer or fibre materials (GM), (LM), (FM);
- Multiple membrane sizes (MS);
- Multiple membrane geometries (MG);
- Multiple membrane materials (MM);
- Multiple fill levels/packing fractions (PF).

These eight categories generally comprise the modifiable parameters of a jamming actuator's stiffness-tuneability, and researchers seek to quantify how the isolation and variation in one will affect the overall stiffness of the unjammed or jammed actuator. Tables 10–12 visualize the spread of varying isolated granular jamming, layer jamming, and fibre jamming parameters per metric, respectively:

Table 10. Frequency of varying granular jamming parameters per metric.

	AP	GS	GG	GM	MS	MG	MM	PF
Holding force	[7,10,22,25]	[14]	-	-	-	[10,14,25]	-	[24,27,28]
Activation force	-	[13]	[13]	[13]	-	-	-	[20,27,28,30]
LvD	[8,15,16,26,44–47,50,52]	[8,15,56]	[8]	[8,29,56]	[58]	[8,15]	[47]	-
Hysteresis	[30,47]	[8]	[8]	[8]		[8]	[47]	[30]
Bending angle	[6,21,25,31,50]	-	-	-	-	[25]	-	-
Applied Moment	[15,16,21,26,44]	-	-	-	-	-	-	-
Rotational stiffness	[21,25,30,31]	[21,30]	-	[31]	[21,30,31]	[25,30]	[30]	[30]
Range of motion	[30]	[30]	-	-	[30]	[30]	[30]	[30]
Compressive strain	[24,47,60]	-	[48]	[53]	-	[53]	[47,53]	-
Tensile strain	[47]	-	-	-	-	-	[47]	-

Table 11. Frequency of varying layer jamming parameters per metric.

	AP	LS	LG	LM	MS	MG	MM	PF
Holding force	-	-	-	-	-	-	-	-
Activation force	[40]	-	[40]	-	-	-	-	-
LvD	[37,38,40,42,44,56,57,65]	[40]	[40]	[56]	-	-	-	[37]
Hysteresis	-	-	-	-	-	-	-	-
Bending angle	[38]	-	-	-	-	-	-	-
Applied Moment	[44,57]	-	-	-	-	-	-	-
Rotational stiffness	-	-	-	-	-	-	-	-
Range of motion	-	-	-	-	-	-	-	-
Compressive strain	-	-	-	-	-	-	-	-
Tensile strain	-	-	-	-	-	-	-	-

Table 12. Frequency of varying fibre jamming parameters per metric.

	AP	FS	FG	FM	MS	MG	MM	PF
Holding force	-	-	-	-	-	-	-	-
Activation force	-	-	-	-	-	-	-	-
LvD	[45,49]	-	[49]	[49]	-	[54]	-	[54]
Hysteresis	-	-	-	-	-	-	-	-
Bending angle	[54]	-	-	-	-	[54]	-	[54]
Applied Moment	-	-	-	-	-	-	-	-
Rotational stiffness	-	-	-	-	-	-	-	-
Range of motion	-	-	-	-	-	-	-	-
Compressive strain	-	-	-	-	-	-	-	-
Tensile strain	-	-	-	-	-	-	-	-

4.1. Grasp Testing

A significant portion of jamming robot studies have used grippers to grasp various objects, which are listed in Table 13.

Table 13. Frequency of grasped objects.

Grasped Object	References	Count
Bolts	[29]	1
Chairs	[14]	1
Cubes	[7,11,13,15,18,24,31,35]	8
Custom fabricated objects	[16,17]	2
Cutlery	[18]	1
Cylinders	[6,7,10,11,13,17,20,22,24–30,33,34,41]	18
Disks (incl. coins)	[7,11,13,17,28]	5
Foam ear plugs	[7]	1
Gears	[13]	1
Hemispheres	[11,14,17]	3
Jacks	[7,11]	2
Lightbulbs	[7,28,40]	3
Mugs	[9,12,29,31,33,66]	6
Raw eggs	[11,31,40,42]	4
Rectangular prisms	[6,7,10,11,24,29,33,41,42]	9
Robotic assembly parts	[19]	1
Sea shells	[28]	1
Solid foodstuffs	[7,9,21,29,38,40,41]	7
Spheres	[7,10,11,13,15,24,26,37]	8
Springs	[7,11]	2
Switchboard door handles	[27]	1
Tetrahedrons	[7,11,24]	3
Various hardware/office items	[7,21,30,40,42,44]	6
Various household items	[6,12,17,18,24,26–33,41]	14
Water bottles	[15,16,21,24,29,32,41]	7

Most studies used simple shapes such as spheres, cubes or cylinders, of diverse sizes and materials (from elastomers to metals). Researchers chose the remaining grasped objects based on the objective for their gripper. Raw eggs or sea shells were chosen for demonstrating a fragile object manipulation, coins or foam ear plugs for overcoming standard soft gripper limitations, and various household or hardware items to demonstrate universality. Grippers rarely grasp objects in cluttered environments [18,33], multiple objects at once [11], or near-human-sized objects [14].

Early work ascertained the key mechanisms for jamming gripper object grasping, finding that granular jamming bag grippers deform around objects and then jam to grasp objects via one of three main grasping mechanisms [7]:

- Geometric constraints from interlocking between gripper and object surfaces;
- Static friction from normal stresses at contact;
- Additional suction effect, if the gripper membrane can create a seal .

The authors note that jamming grippers are unlikely to reliably have interlocking or seal grasps; the main mechanism is static friction.

Table 14 lists the spread of granular jamming grasping mechanisms on objects.

Table 14. Frequency of detailed grasp mechanisms.

Grasping Mechanism	References	Count
Interlocking	[7,10,17,22,28,34,35]	7
Static friction from contact	[7,11,17,28]	4
Suction from a formed seal	[7,17,28]	3

These mechanisms were rarely exploited for specific goals. Kapadia et al. [10] coated a target sphere with water; this strengthened the seal and doubled the holding force for their latex balloon membrane. Amend et al. [11] chose target objects with surface textures too coarse to permit seals. Licht et al. [17] created custom target objects that only allowed for specifically desired grasping mechanisms.

Jamming pressure is the most commonly modified metric across all tests (likely due to most researchers using pneumatic actuation, which allows for simple pressure variation). Numerous studies [7,10,21,22,25,31] showed the holding force, or maximum held weight, increasing alongside actuation pressure, from 0 to 450 kPa, across diverse grain, membrane and actuation compositions. Kapadia et al. [10] found that the holding force was independent of ambient pressure across two orders of magnitude, and tests at various ambient pressures showed the holding force was more sensitive to increases in actuation pressure between 30 and 85 kPa than 85 and 450 kPa. Amend et al.'s 2016 [14] large hydraulic cylinder quadrupled the holding force compared to pneumatic actuation. Amend et al.'s 2012 [11] positive pressure resets of grain packings increased the holding force on larger objects but decreased it on smaller objects. They reasoned that the greater flowability increased contact angle on large objects but displaced grains to the side of small objects. Kapadia et al. [10] created fluidized grain beds within their two gripper geometries, which lead to greater holding forces vs. non-fluidized for 23 out of 34 test sets, across nine distinct objects and four activation forces. They deliberated that the fluidization caused further expansion and increased contact areas on objects. These collective results show that the holding force on target objects can be varied via modifying jamming pressure or surrounding ambient pressure for fluidic actuation methods.

Grain size, material properties and morphology all affect inter-grain interaction during jamming, and two researchers [13,14] measured how such variations would affect the holding or activation forces. Amend et al.'s 2016 [14] 35–60 mesh grains generated higher holding forces than 12–20 and 60–100 mesh. Valenzuela et al.'s [13] 1.2 mm Styrofoam sphere grains obtained greater grasp success percentages on five out of six distinct objects compared against 2.5 mm, but required higher activation forces in 60% of cases. The 2.5 mm grains were incapable of grasping a Styrofoam sphere. Their crushed coffee grains successfully grasped three of six objects, and crushed coffee grasped one, but with a smaller activation force. Styrofoam balls always generated smaller activation forces than coffee grains. It is evident that modifications to these parameters have an effect on the holding or activation force of a jamming gripper.

While no studies modified membrane sizes or materials during grasping tests, a few modified the geometry of their grippers to measure the effect on holding or activation forces. Kapadia et al. [10] used a nubbed bag that enabled holding forces up to 1000 times greater than their simple bag for certain sized and oriented objects, due to increased contact area. However, nubbed grippers were worse on some of the objects/orientations considered. Li et al. [25] designed three pressure pack finger gripper variants, two with granular jamming and one without. The granular jamming pair approximately doubled the holding force vs. the non-jamming variant on an object when grasped from the same bending angle. However, at equal air pressures, the non-jamming variant outperformed the jamming pair, and the jamming variant with the most grains had the lowest holding force. They inferred that the increased air pressure, from less grains, enabled a larger contact angle and caused increased holding forces. These combined studies suggest that complex geometrical modifications of gripper membranes can lead to increases in holding force.

The effect on holding force of the relative sizes of bag grippers and objects, and the given contact angles, has been investigated by a number of studies. Amend et al. 2016 [14] stated that there is a linear relationship between holding force and object envelopment for their ellipsoidal grippers, and that the grip efficiency has a strong dependence on the relative sizes between the target object and the gripper. Brown et al.'s [7] gripper's holding force increased alongside contact angle, and they found that a 45° contact angle was critical; however, Kapadia et al. [10] observed that holding force generally did not increase alongside contact angle. Amend et al. 2012 [11] found that grasping success rate sharply decreased as a hemisphere object's diameter went beyond approximately 65% to 75% of their grippers' diameter. Amend et al. 2016 [14] disclosed that holding force is maximized when object diameter is approximately 50% of a gripper's diameter, and gripping reliability is maximized when object diameter is within 30% and 70%. These results are not rigorously supported by empirical results, and are partially contradictory, however, there is obvious merit in further investigation, especially with non-spherical objects.

The fill level (volume of granular material within a membrane) is both easily modifiable and an important design factor. Minimizing volume required without losing holding force translates into a lower weight requirement for a jamming robot. Several studies tested their bag grippers at various fill levels. Li et al. 2019 [30] showed that the activation force consistently increased alongside total injected grain volume. Fujita et al. 2018A [27] increased coffee fill level four times and each increase resulted in an increase in activation and holding forces on a vertical standing cylinder, as well as reducing variability in grip strength. Licht et al. 2018 [28] used three fill levels of glass beads. Holding force increased alongside fill level for disk and vertical standing cylinder objects, but not for a horizontally standing cylinder. Activation pressure generally increased similarly. Fujita et al. [24] used 50% and 80% fill levels. The 50% fill gripper achieved higher holding forces on a 10 mm ball, horizontally standing pipe, and cone objects, and lower for 8 mm ball, cube, and horizontally standing cylinder objects. These combined results suggest that there is a trade-off between decreasing activation force versus increasing holding force for certain objects, while other objects have decreased holding forces with increased fill levels. The differences in fill level increase vs. holding force for horizontally standing cylinders are likely due to the significant design differences between grippers for the two studies. Further investigation of fill level vs. holding or activation force is warranted.

A specific research interest has been the ratio between holding and activation forces. Kapadia et al. [10] showed that the holding force was generally independent of the activation force between 10 and 25 N for both balloon grippers and their non-fluidized nubbed gripper. They reasoned that the three grippers were at maximum deformation over objects before 10 N. Licht et al. 2016 [17] found maximum holding force and maximum activation force correlated for activation forces from 0 to 4.5 N. They required up to 10-fold fewer activation forces to achieve holding forces between 5 and 10 N compared to Kapadia et al. [10] due to use of fluid in place of air. Licht et al. 2018 [28] provided quantitative evidence that the primary determinant for the holding force to activation force ratio for interstitial fluid jamming is the combined volume of grains and fluid.

4.2. Stiffness Testing

As with grasping tests, actuation pressure was the most modified parameter during bending stiffness tests. All pertinent studies showed that stiffness increased alongside jamming actuation pressure for granular, layer and hybrid jamming. This was across load vs. displacement [8,15,16,26,37,38,40,42,44–47,56,57,65], bending angle [6,21,25,31,38], applied moment [15,16,21,26,38,44,57] and rotational stiffness tests [21,25,30,31]. Studies commonly positioned beam, cylindrical, and finger actuators as cantilever beams [8,9,15,26,32,38,46,47,58]. Al et al. [26] found that decreases in air pressure at lower vacuum pressures caused greater stiffness than at higher pressures. Jiang et al. 2019 [31] used a differential pressure jamming finger to pressurize two distinct chambers: one with grains and pressure P_g, and one with air and pressure P_a where $P_a \geq P_g$. They measured the rotational stiffness for a range of P_g and five differential pressures, whereby a differential pressure $P_d = P_a - P_g$. As P_g and P_a increased the rotational stiffness increased for all constant P_d, and each P_d caused greater stiffness than any lower P_d. Setting $P_d = P_a$ caused rapid stiffness increases. Li et al. 2019 [30] compared the rotational stiffness when injecting grains, water or air to the same range of motion. Grain injection achieved 1.5- and 2-fold stiffness compared to water and air, respectively. The gripper's range of motion with grain injection increased as injected grain volume increased. Jiang et al. 2014 [47] found that hysteresis increased alongside jamming actuation pressure for three of five tested membrane materials, and one material had an inverse relationship. Overall, the results suggest that actuation pressure is a key determinant in the bending stiffness of a jamming actuator.

Grain or layer sizes were another commonly modified parameter, and several studies tested how variations would affect the bending stiffness of actuators. Wei et al., Jiang et al. 2012 [12,15] used 4, 6 and 8 mm plastic spheres, and Jiang et al. 2012 [8] also used 1.5, 2 and 4 mm plastic cubes, in load vs. displacement tests across several pressures. Wei et al.'s [15] 6 mm spheres were the stiffest, followed by 4 and 8 mm. Jiang et al. 2012's [12] 4 mm spheres were the stiffest and had the lowest variability, followed by 8 and 6 mm. Wei et al.'s [15] ball and socket spine render comparisons non-ideal. Jiang et al. 2012's [8] 4 mm spheres had the highest hysteresis, followed by a tie. The 2mm cubes were the stiffest and least variable, followed by 1.5 and 4 mm. The 1.5 mm cubes had the highest hysteresis, followed by 2 and 4 mm. Hysteresis generally decreased as grain size increased. A comparison between 4 mm solid rubber cubes in a latex membrane and a 10 mm solid block showed that the rubber block required an approximately 33% greater force to displace. They noted the "force-deflection profile of many of the tests display a plateau effect, where the measured force no longer increases as the system is further deflected" [8]. This may be caused by shifts causing loss of contact with adjacent grains. Wei et al. [15] showed force rise alongside displacement up to displacements 4-fold those of Jiang et al.'s 2012 [8]. Li et al. 2017, 2019 [21,30] utilized 2, 3 and 4 mm diameter glass spheres and found rotational stiffness increased with sphere diameter across multiple actuation pressures. Elgeneidy et al. [40] discerned that stiffness increased with layer sheet density. The granular jamming results suggest that grain size affects the bending stiffness, and the two factors do not always increase (or decrease) alongside each other due to local (or global) maximums.

Due to their having a distinct effect on a variety of factors (such as volume, density, and grain interactions), several papers tested how modifying grain or layer geometry would affect the bending stiffness. Jiang et al.'s 2012 [8] 1.5, 2 and 4 mm plastic cube packings caused consistently less stiffness variability than 4, 6 and 8 mm plastic spheres. The 4 mm cubes had the best stiffness linearity. Spheres and cubes had similar force ranges. The 4 mm plastic spheres achieved the highest displacement force. Elgeneidy et al.'s [40] results show that stiffness increased with layer sheet angle. Zubrycki et al. [56] assessed the LvD for a latex cylinder over two granular and two layer packings: wooden cubes, polystyrene spheres, 64 layers of 90 g paper with three foam layers and 112 layers of 90 g paper. The 112 layers was stiffest by a distinct margin, followed by 64 layers, wooden cubes, and polystyrene beads. The results show that distinct grain or layer geometries can produce different maximum stiffnesses and variability in stiffness linearity, and that layer jamming versus granular jamming with respect to bending stiffness deserves further investigation.

Grain or fibre material is a direct determinant of inter-grain/fibre friction in a packing, and certain researchers quantified how various materials would affect the bending stiffness of an actuator. Jiang et al. 2012 [8] used 4 mm plastic, solid rubber, hollow rubber and rubber-coated plastic cube packings. Rubber granules were less stiff than plastic, but had lower hysteresis and variability. They discerned that this was due to the decreased probability of shear between individual granules. Four millimetre, rubber-coated plastic cubes had better stiffness than rubber ones, and better linearity and hysteresis than all others. Jiang et al. 2019 [31] tested corn, calcium chloride and plastic sphere packings within their differential pressure jamming finger. Corn had the highest rotational stiffness, followed by calcium chloride. They hypothesized that the smoothness and shape regularity of the plastic spheres caused a lower friction coefficient, and the calcium chloride's larger diameter caused a lower packing fraction, leading to lower stiffness than corn. Mizushima et al. [29] used four grain materials: coffee powder, plastic spheres, rice, and gravel. Rice was stiffest, followed closely by both gravel and plastic spheres, and then coffee powder. Brancadaro et al. [49] compared six fibre materials: PTFE, PVC, Nylon, Silicone, Waxed Cotton, and Leather. Each had two packing methods: bundle, with an average fill level 0.25–0.37, and comb, with

0.22–0.31, in a cylindrical latex membrane. All variations were stiffer jammed vs. unjammed. Nylon had the highest jammed stiffness, in part due to its inherent increased rigidity. Cotton achieved the highest unjamed vs. jammed stiffness variation. Their maximum stiffness variations of 300–400% align with granular findings from Jiang et al. 2012 [8]. Comb packings had higher stiffness variations for all except Nylon, and generally increased from 15 to 212% between packing types. This was attributed to a more structured and organized arrangement of the fibers in the CT joint. The stiffness variation of the comb packings increased alongside surface roughness. The combined results show that grain/fibre surface roughness and deformability are key determinants of the bending stiffness of a jamming actuator.

Certain researchers quantified whether increasing membrane thickness, or overall size, would affect the bending stiffness of a jamming actuator. Li et al. 2017, 2019, and Jiang et al. 2019 [21,30,31] tested Silicone rubber membranes of varying thickness for their finger actuators, Li et al. 2017 [21] 3, 4 and 5 mm, Jiang et al. 2019 [31] 1.5, 2 and 2.5 mm, Li et al. 2019 [30] 2, 3 and 4 mm. Increased membrane thickness always decreased rotational stiffness. Li et al. 2019 [30] showed no significant increase in range of motion as membrane thickness increased. Thompson et al. [58] tested the LvD of three sizes of sugar filled Silicone rubber beam membranes—large (15 × 15 × 85 mm), medium (15 × 12 × 85 mm) and small (15 × 9 × 85 mm)—and compared them against a solid beam of Silicone rubber. Deflection decreased as chamber size increased, and the solid rubber beam was least stiff. They found evidence suggesting that the relationship between chamber size and deflection is non-linear. Error bars showed that jamming beams were unpredictable compared to the solid beam. At separate points for each jamming beam, a sharp gradient increase occurred, suggesting changes in the jamming structure of the granules as more weight or deflecting force is applied to the beam. These collective results suggest that increasing membrane thickness when using a given material will generally decrease finger-shaped jamming actuator bending stiffness.

Three researchers experimented with how modifying either the internal structure of their membranes would affect the inter-grain interactions and overall bending stiffness of their granular actuators. Jiang et al. 2012 [8] embedded 4 mm half-spheres into a latex membrane. This increased stiffness linearity and decreased hysteresis vs. the simple latex membrane with 4 mm plastic sphere packings. Neither the stiffness variability nor the peak force were improved. Wei at al.'s [15] granular jamming ball-and-socket gripper achieved higher rigidity and stiffness between pressures than the non-jamming version. Li et al. 2018's [25] two granular jamming grippers achieved vastly greater rotational stiffness than their non-jamming gripper. Their two jamming variants exchanged dominance at certain pressures for both planar and lateral rotational stiffness. Their joint findings provide quantification that minor or extensive modifications to membrane geometry can affect the bending stiffness of a granular actuator.

Much like grain–grain material interactions, the membrane–grain material interactions play a part in the inter-grain interactions of a jamming actuator, and researchers sought to quantify this effect. Jiang et al. 2014 [47] used Latex, Nitrile, Vinyl, Vitrile, and Polythene cylindrical membranes, each with 4 mm glass sphere packings at approximately 0.61 packing fractions across a range of pressures. The polythene membrane had the highest stiffness and variability. Its high hysteresis was explicated to be due to plastic deformation from membrane–granule and granule–granule interactions. Nitrile and Latex were the next stiffest materials, with similar results for force, hysteresis and variability. Vinyl and Vitrile were the least stiff and had similar variability to Latex and Nitrile. Pairwise Mann–Whitney U-Tests found that the variability between the unjammed actuators was always significantly different. They reasoned that since the peak stiffness of the unjammed state depends primarily on the membrane stiffness, there was a base level difference in the bending stiffness because of the different types of membranes used. Some pairs lost their significant differences in stiffness variability at 10 kPa, which the authors found to imply that there is an interaction effect between the type of membrane and the level of vacuum. An n-way ANOVA test found a significant effect on the stiffness from the pressure, the membrane material and the interaction between the pressure and membrane material. Li et al. 2019 [30] used three Silicone rubber shore D hardness variants, 0, 5 and 10D, across a range of injected grain volumes. Rotational stiffness decreased as hardness increased. Range of motion increased alongside hardness when the injected grain volume was beyond a threshold. These results show that the membrane material has a significant effect on the bending stiffness of a granular jamming actuator.

Few research has directly compared granular vs. layer jamming; however, two researchers quantified comparative bending stiffness across the jamming types. Wall et al. [43] compared two granular jamming and two layer jamming PneuFlex finger variants. G1's coffee grains were in a cylindrical compartment, G2's in a conical. L1 stacked 10 interleaved polyester sheets in a compartment, L2 reduced the distance between sheets and incorporated an elastic top layer. L2 achieved the highest averaged stiffening factor, followed by L1, G2 and G1. Yang et al. [44] designed a hybrid layer and granular jamming finger with bioinspiration from human hands. It had a pneumatic actuator, mimicking muscles and tendons, three chambers of layer jamming sheets, functioning as bones, and two granular jamming chambers, acting as joints. Each compartment was independently actuatable. It was tested against two variants: all chambers containing grains, and all chambers containing layers. The solely layer jamming variant was the stiffest, followed closely by the hybrid, and the granular stiffness was approximately half of either. The authors noted that with more controllable pneumatic chambers, their proposed hybrid jamming finger could not only realize variable stiffness capability but also possess bending shape controllability, giving greater versatility compared to pure granular or layer jamming fingers. This suggests that layer jamming may enable greater bending stiffness than granular jamming for the same approximate total allowed volume.

4.3. Strain Testing

Actuation pressure was the most modified parameter in strain testing. Fujita et al. 2018 [24] showed a coffee-powder-filled latex membrane actuator increasing in compressive hardness alongside actuation pressure. Hauser et al.'s [60] latex bag, containing rubber cubes, showed its compressive load vs. displacement decrease and Young's Modulus increase as jamming pressure increased. Their results show that the compressive hardness of a jamming actuator increases alongside jamming pressure.

Jiang et al. 2014 [47] quantified how the membrane–grain material interactions would affect the compressive and tensile stiffness of their actuators, using multiple membrane materials over multiple actuation pressures. They used Latex, Nitrile, Vinyl, Vitrile, and Polythene cylindrical membranes, each with 4 mm glass sphere packings at approximately 0.61 packing fractions across a range of pressures. They recorded the peak stress, hysteresis, variability (MPa) and E (MPa) were recorded for up to 20% compressive and tensile displacements across 101 kPa (15 PSI-A), 55 kPa (7.5 PSI-A), and 10 kPa (1.5 PSI-A). The compressive peak stress and E always increased with jamming pressure, and hysteresis was persistently different at vacuum vs. atmospheric. Peak tensile stress was greater at 55 kPa than 10 kPa, except for vinyl ,which was constant. Tensile E increased with jamming pressure for all except vinyl and nitrile, which decreased beyond 55 kPa and stagnated beyond 55 kPa, respectively. Polythene always had the highest compressive E and variability, and was significantly superior in all pairings at all pressures, except vinyl at 10 kPa. Vinyl had the largest compressive stiffness range, followed closely by latex. A total of 20% compressive strain caused permament deformation to vitrile and polythene actuators. All actuators had similar compressive hysteresis. Pairwise Mann–Whitney U-Tests for peak compressive stresses showed all pairs were significantly different at 101 kPa, latex, nitrile and vinyl were not significantly different at 55 kPa, and at 10 kPa, all pairs were significantly different. Mann-–Whitney U-tests for compressive stress vs. strain showed that all pairs were significantly different at 101 kPa, and all but vinyl and vitrile at 10 kPa. Membrane-only tensile tests showed that latex, vinyl and vitrile cylinders had linear stress vs. strain with small hysteresis. Nitrile and polythene had high tensile hysteresis; they theorized that polythene's was from permanent deformation from testing. Polythene had peak tensile stress and E values approximately 10-fold greater than all others. Pairwise Mann–Whitney U-Tests found that all except latex–vinyl and nitrile–vitrile were significantly different. At 101 kPa, all packed actuators except polythene were similar to the empty membranes. The authors noted that without jamming, the tensile strength of the actuator is limited by the membrane, with the unjammed grains having little effect. Polythene had four-fold greater peak tensile stress and E than all other actuators, and underwent further deformation, leading to the highest hysteresis. Nitrile, vinyl and vitrile decreased in E beyond 55 kPa; polythene and latex linearly increased in stiffness. Pairwise Mann–Whitney U-Tests on peak tensile stress showed that all pairs were significantly different at 101 and 10 kPa, except nitrile–vinyl at 101 kPa. Pairwise Mann–Whitney U-Tests on stress vs. strain showed that all pairs were significantly different at 101 and 10 kPa, except latex–nitrile at 101 and 10 kPa, or latex–vinyl and nitrile–vinyl at 10 kPa. Their results show that membrane material can significantly affect the compressive or tensile stiffness of a granular jamming actuator, and that jamming has a strong affect on the stiffness of an actuator.

Athanassiadis et al. [48] studied the mechanical response of granular packings for a range of convex and non-convex grain shapes. They compression tested 14 distinct geometric shaped grain packings, including eight convex shapes and six non-convex shapes, in cylindrical latex membranes. They tested all packings first at confining pressure σ_{con} 0.08 MPa, and then a range of σ_{con}. Stress vs. strain curves deduced the Young's Modulus E under compression, and compressive yield stress σ_y. E and σ_y always correlated, and their ratio was not determined by convex vs. concave packings. $E \propto (\sigma_{con})^n$ across all packings, and n generally increased with packing sphericity. E and σ_y increased with confining stress for several orders of magnitude. E was affected by the combination of σ_{con} and shape. The grain shape was determined σ_y by approximately one order of magnitude and was largely independent of σ_{con}. σ_{con} determined σ_y for certain packings. Faceted Platonic solid packings had increased strain, and increased stress for plastic deformation vs. sphere packings. Stress beyond yielding correlated well with sphericity. High packing density did not correlate with rigidity. Compact packings had nearly perfectly linear plastic failure. Packings with sharp points or lengthy protrusions had stress increased in stress beyond yielding. The interpenetrative packing did not result in an increased E from increased σ_{con}. The authors noted that, at small strains, the stress increased approximately linearly. For larger strains, the stress smoothly transitioned into a plastic failure regime.

Cavallo et al. [53] compression tested the jammed vs. unjammed compressive stiffness of two silicone rubber membranes filled with equally distributed ground coffee: one with a single chamber and one with three. The single chamber had the greatest compressive stiffness variation. They tested three Silicone hardness variants: shores 10, 30 and 50. The Shore hardness 10 variant had the largest compressive stiffness variation, however, it engendered excessive effort for use and was unstable. It was followed by the 30 and 50 variants. Pepper, salt, sugar, and ground coffee were tested in a single-chambered shore 30 membrane. Salt achieved the highest compressive stiffness variation and the highest standard deviation. Coffee was next highest, followed by pepper with a similar standard deviation to coffee, and sugar with little deviation. A high-resolution microscope was used to quantify the size and shape of the materials, and the better coffee performance in terms of stiffness variation was attributed to its significant surface roughness and irregular shape. Their results show that membrane geometry or material hardness and grain geometry or surface roughness can be determinants of a beam-shaped granular actuator's compressive strength.

5. Jamming Soft Robot Modelling

Computational Models can be used in conjunction with physical experimentation to simulate the detailed interactions between individual constituent elements within a gripper, the membrane and the environment to obtain information not readily obtainable in experiments and to test new materials and designs in silico prior to potentially more costly and time consuming physical experimentation. The Discrete Element Method (DEM) and Finite Element Method (FEM) have been extensively used. The frequency of modelling methods is listed in Table 15.

Table 15. Frequency of soft jamming robot modelling per method.

Modelling Method	References	Count
Discrete Element Method	[7,15,21,30,31,34,44,46]	8
Finite Element Method	[8,32,36,45,53,58]	6

Modelled metrics that have been studied include the holding force [7], grasp mechanisms [7], activation force [10], Young's Modulus of granular actuators [8], load vs. displacement [44–46,58], bending angle [15,21,31,45], the moment [15,32,67], rotational stiffness [21,30,31,67], range of motion [30], and various stresses vs strains [36].

Notable simplifications include assuming material deformation obeys Hooke's law [7,15,30], grains are restrained [15,46], granular actuators are ideal cantilever beams [8,58], incompressible materials [31,32], uniform cross-sections at certain grain volumes [30,45], ignoring grain weight [21], and ensuring that grains are packed in a hexagonal close packing [44]. Broad approximations are observed in the literature, for example, approximating demi-spherical grains as full spheres, with a noted impact on model quality. All models accounting for grain interactions, and all but two physical tests corroborating models [11,32] used spherical grains.

Brown et al. [7] DEM modelled various physical properties of bag-shaped jamming grippers, including the holding force on objects and the three grasp mechanisms. They further theorized that the holding force would rise alongside contact angle, however, Kapadia et al. [10] demonstrated that this needs further investigation. Jiang et al. 2012 [8] showed the bending profiles of their modelled ideal cantilever beam and the experimental results were approximately the same; however, Thompson et al. [58] reported opposing results. Jiang et al 2013. [46] accounted for inter-grain interactions during their cantilever beam test modelling, however, their simulation used whole spheres versus real spheres for the real tests, and they reported different results between them. Wei et al. 2016 [15] found that the bending moment for their ball-and-socket spine and granular jamming robot was discernibly lower and less linear than their DEM modelled results. Li et al. 2017's [21] DEM modelled results generally aligned well with their experiments, however, at a certain higher pressure they noted a noticeable deviation in experimental results from the models. They believed that this may be due to reaching the threshold of frictional work from the grains. Jiang et al. 2019's [31] experimental results showed that their DEM model could effectively predict the stiffness of the actuator, however, the experimental results were slightly larger than the model's. They reasoned that this was partially from granular jamming's capacity to transform external pressure into friction appearing to have an upper-limit. Li et al. 2019's [30] experimental results showed discernibly less stiffness than the DEM model's, however, the model generally predicted the trends. Yang et al.'s [44] DEM model for their hybrid gripper produced notably higher stiffness results for displacement tests than experimental ones. They reasoned that this may have been from incorrect assignments to variables, such as coefficients of friction, and from assumptions made during modelling. Kim et al.'s [36] FEM model generally aligned with their experimental results for torsional stress vs. strain. Most stiffness modelling shows some level of deviation from reality, especially due to the granular actuator deformation limits or grain friction modelling simplifications, but the trends generally hold.

While the benefits of modelling have been demonstrated in studies to date, there remains a strong need for more complex computational models that are capable of taking in to account the detailed inter-grain interactions between variously shaped grains combined with a realistic deformable material model to simulate the membrane.

6. Discussion and Perspectives

In this review, we analysed the state of the field of jamming as a soft robotics technology. The modern story of granular jamming began with the promise of diversity—jamming was positioned early on (2010) as an 'enabling technology' for soft robotics [5], capable of providing locomotion, gripping, and shock absorption, amongst others. The popular 'Universal Gripper' paper was published in the same year [7], and its success led to a more narrow focus on gripping applications using simple bag geometries. In recent years, we have seen an expansion in materials, grain types, geometries, and subsequent use cases. Rather than just granular mechanisms, the modern literature shows diverse implementations of three main jamming mechanisms, primarily granular jamming, but also, more recently, layer and fibre jamming. The results demonstrate that each technology has its own strengths and weaknesses, and the decision to employ a specific mechanism should be informed by specific use cases. As an example of how recent advances can unlock this promise of jamming as an enabler for soft robotics, we note that early work showed a strong interest in granular jamming for legged locomotion, however, (paws aside) there has been little recent interest. The long, slender bundles of threads in fibre jamming could potentially lead to thin, agile legs, capable of great bending and deformation during locomotion, compliance through rough terrain, and astounding stiffness variation when required.

There is a large degree of variation in the literature in terms of material selection: grain/layer/fibre and membrane sizes, geometries and materials. However, it is unclear how principled the design of many jamming actuators in the literature are, or how many alternative options were tried before a final design was settled on. Soft robotics is a nascent field, and one observation (and criticism) is that the design of soft robots more closely resembles an art than a science. Jamming is no different, and, specifically, granular jamming is very hard to generate accurate models for. One takeaway is, therefore, that the design space of possible granular actuators is under-explored, and that two key advances are required to drive the development of increasingly capable, optimised jamming actuators.

First, advances are required in the computational modelling of jamming mechanisms. Current modelling places limits on the design, often enforcing spherical grain shapes to achieve reasonable veracity. The broader field of granular materials research uses a wider variety of shapes, e.g., ellipsoids, and mixtures of different grains, which, to date, have not been accurately brought into a model in a robotics context. Increasing modelling veracity can be achieved through advances in DEM, or through the adoption of data-driven approaches, facilitating a move away from spheres into a wider range of shapes, while reducing the effects of the reality gap and making modelling more applicable to the field. Improved modelling increases the chances of finding a globally optimal solution for the problem under consideration. Furthermore, a combination of modelling and physical experimentation can uncover fundamental design rules for jamming systems, which are not well understood and subject to various local and global behaviours induced by grain–grain, grain–membrane, and gripper–environment interactions. Although difficult to model, these complexities may enable a wide variety of potentially useful behaviours which have not yet been exploited for soft robotics. Surveying the literature shows some conflicting results, which may be due to differences in experimental procedure, or an actual phenomenon associated with granular material.

Second, jamming must adopt modern manufacturing techniques to support a noted trend towards more complex structures with inner geometries, multiple chambers, and hybrid actuation mechanisms. As with all printed soft robotics, the performance of printed jamming systems critically depends on available printable materials (which will improve with time), however, printing offers a route towards simpler fabrication that readily incorporates techniques including functional gradation and multi-material builds, whilst allowing precise control over final geometries (i.e., membrane thickness), again to embody diverse behaviours in the robot. A key advantage of jamming actuators is that they can form a substantial part of the structure of the robot, scale well, and can be realised in relatively free-form geometries (moreso for granular jamming). As such, one could envisage a soft robot constructed with multiple jamming systems throughout its morphology, combined with other soft robotic technologies where appropriate. To date, the JSEL [4] is the only (simple) robot almost entirely made of jamming components. Hybrid jamming fingers, bioinspired from humans, [44,45] showed the versatility and effectiveness of following a hybrid approach. Creating further bioinspired hybrid jamming effectors, e.g., paws, tentacle manipulators or deformable wings, could further demonstrate the utility of jamming in soft robotics, and potentially better mimic animals than the state-of-the-art.

As the range of possibilities for realising jamming robots increases, care should be taken to standardise testing procedures, such that jamming can be rigorously compared both within itself, and to other approaches in the literature. Standardizations for metrics used to assess the bending, compressive or tensile stiffness of a gripper are lacking, and methods to measure a given metric are diverse. For instance, cantilever beam tests vary, from linear rails and robotic arms to hooked weights, and are conducted from various angles. Grasp tests in particular lack homogeneity. Future research into a standardized set of target objects (we suggest a benchmark used in other settings such as YCB), and easily reproducible test procedures would be particularly valuable to the field, give a clearer picture of the state of the art, and provide a route towards wider acceptance in the soft robotics community.

Whilst standard laboratory tests serve a useful purpose (with caveats mentioned in the above paragraph), the true utility of jamming must be measured in its applications. With some notable exceptions (e.g., deep-sea sampling, actual deployments into surgery), real-world applications are scarce. Recent research in jamming paws shows that the benefits of the technology increase as the environment gets more challenging, and it is our contention that jamming grippers could find a useful niche in gripping, picking, and manipulating in unstructured environments, which would also fuel innovation and future research in the area as the field rises up to meet the challenge.

In terms of target applications, jamming grippers are readily transferable to industries such as search and rescue, recycling, automation, medical sciences, aerospace, food production, and assembly lines. The medical sciences display an acute need for soft, deformable tools capable of exerting high force, and future research should aim for in vivo human trials. Only one commercialization attempt was found, and despite choosing to discontinue, their simple bag grippers had a measurable level of real-world success and adoption.

Overall, jamming has shown significant progress since the first jamming gripper in 1978 [3], and has the potential to fill a fundamental role as a stiffness-varying structural material for diverse applications in soft robotics. Technological advances in modelling, design, and fabrication heralds a bright future for jamming as a enabling technology [5] to empower diverse future soft robots across a range of challenging application areas.

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