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The JamHand: Dexterous Manipulation with Minimal Actuation

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Abstract

From using chopsticks to grab items off a plate, to snapping together two LEGO bricks in one hand, common manipulation tasks are easy for humans. However, grasping and dexterous manipulation still rank among the principal grand challenges in robotics. A key challenge is the complex interaction between hand biomechanics and motor control, leading to humanoid hands that remain too complex and costly for use in daily tasks. Here, we bypass this challenge by offering an alternative approach based on multi-finger material phase transition effects. By limiting our focus to dexterous manipulation, we are able to design a robotic hand that can achieve six fundamental dexterous manipulations as well as precision and power grasps, all with only two actuators. We further demonstrate our system on a range of real-world grasping and manipulation challenges. Besides practical application, these results suggest that leveraging the phase transition of granular materials is a viable technique for reducing the hand complexity required for performing daily tasks.

Keywords: soft manipulation, soft interaction, highly deformable robots

Introduction

Engineers have endeavored to replicate the human hand since at least 202 BC, at first only aesthetically, and later with increasing functionality.[1–4] For the vast majority of this time, efforts were focused only on prosthetic devices, but starting in the late 1960s, concurrent advancements in electronics, computers, and robotics opened the door for research into some of the first dexterous hands for robots as well.[5–9] The competence of the human hand is one of the central evolutionary advantages that humans possess[10]; thus, restoring this functionality for amputees and furthering these capabilities in robots are important goals.

The central challenges for both prosthetic and robot hands are to achieve human-level grasping—restraining of objects[11]; and dexterous manipulation—the movement of a grasped object within the workspace of the hand.[12] Since robot hands are not subject to the many design constraints of prosthetics (weight, size, power, controllable degrees of freedom [DOF]), they have served as the primary platform for recent grasping and dexterous manipulation research.

Dexterous manipulation is a task-centric concept, meaning that a hand can be classified as *dexterous* through the demonstration of certain in-hand manipulations of an object. Exactly what these requisite manipulation tasks entail, however, is a topic of considerable uncertainty. The two prevailing metrics for evaluating *dexterous robotic manipulation* are:

(1) Demonstrations from among several basic classes of in-hand movements,[12,13] recently separated into six fundamental classes for robots[14]: regrasping, in-hand manipulation, finger gaiting, pivoting, rolling, and sliding.
(2) Demonstration of a sufficiently broad set of real-world tasks that are typically some combination of those proposed in: the Activities of Daily Living,[15] Cutkosky's taxonomy of manufacturing grasps,[16] the DARPA ARM-H project announcement challenge tasks,[17] or other tasks contrived to illustrate the capabilities of a particular hand.

In 1984, while describing the seminal Utah/MIT dexterous robot hand, Jacobsen *et al.*[18] articulated the viewpoint that had been (and which has largely remained) the longstanding sentiment of researchers in the field: "The natural manipulation system found in humans is complex. … It should be expected

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that the construction of an artificial counterpart will also include significant complexity.'' The human hand has 22 DOF,[19] and as a result, many proposed robot hands have been designed with a similar level of complexity. For those robot hands that do not adhere to anthropomorphism so strictly, designs are typically based on the work of Salisbury,[20] who found that under certain conditions a minimum of three fingers and nine DOF are needed to perform arbitrary manipulations.

The operation and control of robotic hands with nine or more DOF can be a difficult task, as evidenced by the large body of work that exists in grasp algorithm and planning research.[21–23] Some recent work, however, has put forth the view that human-level grasping and manipulation can perhaps be achieved with fewer DOF and fewer actuators by taking advantage of synergies that exist between the actuators,[24] and through underactuated mechanical designs.[25] Indeed, several recent underactuated hands have had success grasping a wide variety of objects with four DOF or fewer,[26–29] but relatively little progress has been made in the area of dexterous manipulation. Later in Table 2, we compare the reported performance of some of the most well-known robot hands to illuminate the state of the art in this area.

In this article, we present the JamHand, a simple two-fingered design that incorporates pockets of granular material in the fingertips, and builds on previous work with individual jamming grippers.[30,31] The sections that follow include: a description of the JamHand's design and control approach, the derivation of an analytical model to describe the JamHand's gripping behavior; results from experimental manipulation testing; and finally, some conclusions. Our focus in this article is to present a mechanical design for a robotic hand that has maximum dexterous manipulation capabilities with minimal actuation complexity. We do not focus here on the grasping capabilities of jamming grippers, which has been previously covered.[30,31] Using just two motors for motion control and two three-position valves for air pressure control in the fingertips, we achieve: multiple precision and power grasps, six fundamental dexterous manipulations, and the demonstration of real-world grasping and manipulation challenges. Besides practical application, these results suggest that leveraging the phase transition of granular materials is a viable technique for reducing the hand complexity required for performing daily tasks.

JamHand Design and Control

The JamHand design is shown in Figures 1 and 2. It is a simple two-fingered configuration with pockets of granular material in the fingertips. This design enables each of the fingertips to be used separately as independent jamming grippers[30,31] or to be used together in a manner similar to an opposable jawed gripper. To achieve this, the hand has an asymmetric design, with one ''finger'' and one ''thumb.'' Together, these represent the only two continuous DOF in the hand. The finger and the thumb are each driven by a separate servomotor such that the finger can move along a fixed path prescribed by a four-bar linkage and the thumb can rotate about its base. The four-bar linkage is a crank-rocker mechanism with link lengths of 3.46-cm, 4.57-cm, 5.72-cm, and 6.86-cm. A more detailed mechanical drawing of the JamHand is provided in Appendix Figure A1.

Most of the components for our JamHand prototype are 3D printed by using an Objet Connex 500 machine and Objet's FullCure720 photopolymer material. The four-bar linkage in the finger is printed as one monolithic mechanism and, therefore, does not require any post-printing assembly. The fingertips of the JamHand each consist of 250-mL of ground Colombian coffee encased in a latex party balloon. We drive the fingers by using Dynamixel RX-28 servo motors, chosen for their strength and ease of use. The thumb is able to rotate 180° about its base, whereas the finger makes a more complex motion, as shown in Figure 2. With this design, we achieve a maximum gap opening of 6.4-cm between the fingers. The Dynamixel RX-28 motors enable actuation times of 0.5-s for the 180° rotation for the thumb and 0.6-s for the full range of motion of the finger. Maximum pinch force exerted by the fingertips is 80-N, which was experimentally measured by pinching a 2-cm thick digital scale between the two fingertips until motor stall.

The air pressure within each of the two fingertips is controlled by a separate three-position valve so that the interstitial space can be evacuated, positively pressurized, or

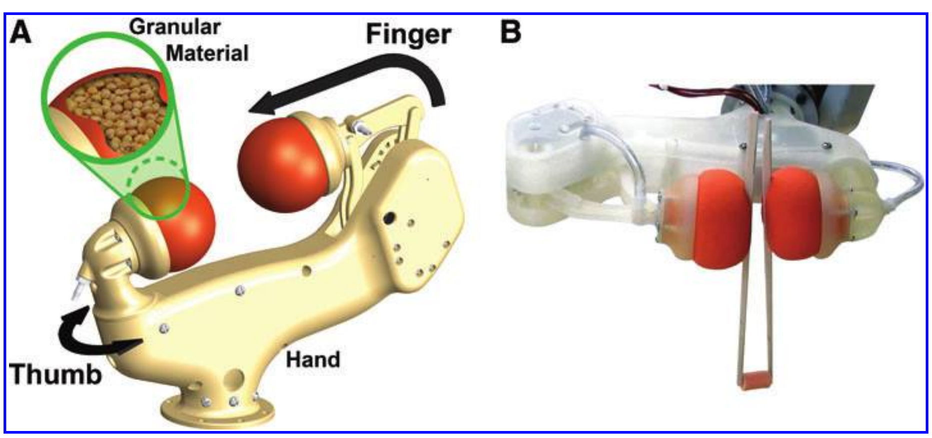


FIG. 1. **(A)** The JamHand has two fingers, each controlled by one motor, permitting the finger motions shown. The ''thumb'' can rotate about its base. The ''finger'' moves along a path prescribed by a four-bar linkage. The fingertips each contain a mass of granular material that can be hardened or softened by controlling the air pressure within, and each fingertip can separately be used as an independent gripper. **(B)** The JamHand can perform real-world manipulation tasks like utilizing chopsticks to move small items. Color images available online at www.liebertpub.com/soro

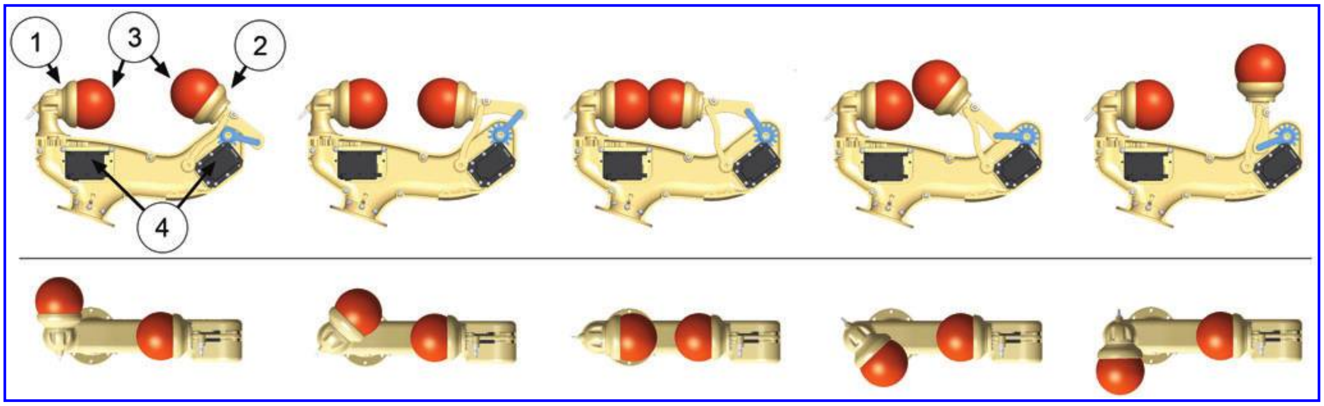


FIG. 2. Illustration of the JamHand with parts (1) thumb, (2) finger, (3) jamming gripper fingertips, and (4) drive motors. The travel path of the finger is show at the *top*, with the crank link of the four-bar mechanism highlighted in *blue*. The 180° rotation of the thumb is shown at the *bottom*. Color images available online at www.liebertpub.com/soro

neutralized with the atmosphere. These valves are not contained within the hand, but rather are located on the robot arm to which the JamHand is mounted. We employed a CRS A465 robot arm for demonstrating and testing the JamHand. Positive pressure air was provided at 620 kPa, and vacuum was achieved with pump rated for a maximum vacuum of 25 μm. We were able to control the robot arm, valves, and hand motors through a single control program written in C++. A system diagram of the setup is shown in Figure 3. The total cost for this JamHand prototype (including motors, valves, and 3D printed components) is approximately US $1000.

In demonstrating the JamHand, we use the open loop position control as a proof of concept. There is a significant opportunity for additional control work in the future, for example, through the addition of embedded sensors and feedback.

JamHand Analysis

When the fingertips of the JamHand are used separately, as independent jamming grippers, their behavior obeys the analytical analysis of Brown *et al.*,[30] as well as the experimental analysis of Amend *et al.*[31] A single jamming gripper has been shown to retain objects by a combination of friction, geometric interlocking, and vacuum suction forces.[30] Each contributes separately to the total holding force, which is, therefore, calculated as the sum of these independent contributions:

$F_H = F_F + F_I + F_S$, where F_H is the total holding force, F_F is the contribution from friction, F_I is the contribution from interlocking, and F_S is the contribution from vacuum suction. This type of gripping is illustrated in Figure 4A.

We can adapt the analysis of a single jamming gripper's performance for the opposable two-fingered design of the JamHand, such that:

$$F_{H2} = F_{F2} + F_{I2} + F_{S2} \quad (1)$$

This type of grasp is illustrated in Figure 4B. When a single jamming gripper is evacuated, it produces a pinching contact region similar to an o-ring on the gripped object.[30] The object is pinched with an applied stress σ over an area A, as illustrated in Figure 4A. In the most basic case, if we consider the gripped object to be a hemisphere, we can describe the pinch as a distributed normal force $F_N = \sigma A \sin\theta$, where θ is the contact angle between the gripper and the hemisphere. With further knowledge of the radius of the gripped hemisphere R and the width of the contact area d, we can calculate $F_N = \sigma d(2\pi R \sin^2\theta)$. Applying the coefficient of static friction between the object and the gripper membrane, we can then calculate the contribution from F_N to the friction based holding force.

$F_F = F_N(\mu\sin\theta - \cos\theta)$.[30] However, we must turn this single gripper 90° to modify this calculation for an opposable two-fingered grip. Accounting for the combined holding force of two separate grippers as well as any additional pinch force that the fingers may provide, the contribution from friction becomes:

$$F_{F2} = 2\ \mu F_N(\sin\theta - \cos\theta) + \mu F_P \quad (2)$$

where F_P is the pinch force. For a two-fingered grip, if the contact angle $\theta > 0$, then an additional contribution to holding force from geometric interlocking develops. This force results from the combined bending and stretching that the bulk granular material must undergo for a gripped object to be removed. Here, because the degree of interlocking can be expected to be

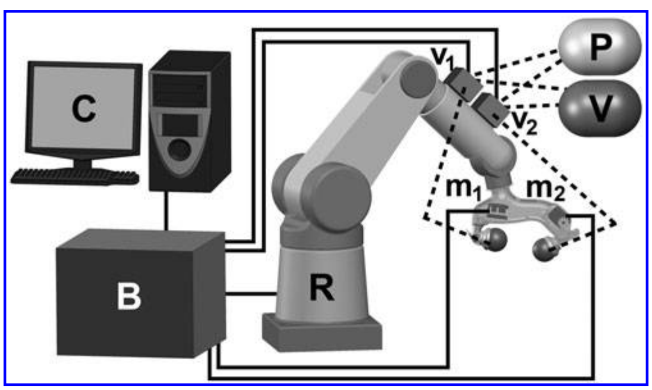


FIG. 3. System diagram of the JamHand installed on a robot arm. *Solid lines* show electrical communication between the controlling computer (C), the robot's control box (B), the robot (R), valves (v_1 and v_2), and motors (m_1 and m_2). *Dotted lines* show pneumatic communication between the pressure source (P), the vacuum source (V), valves (v_1 and v_2), and the jamming fingertips.

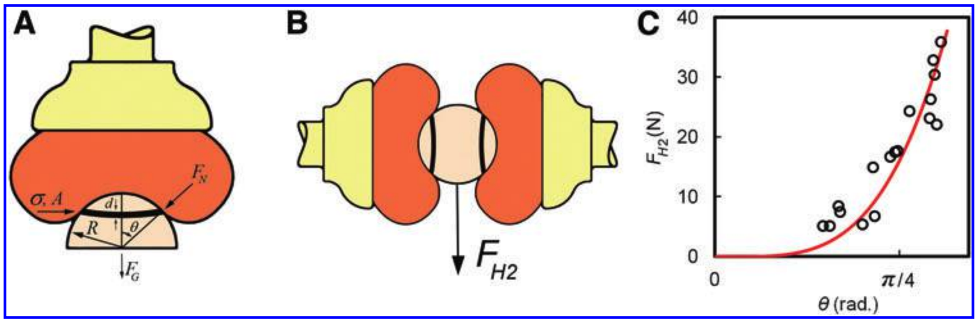


FIG. 4. **(A)** Variables related to grip strength shown on a single jamming gripper. **(B)** Two-fingered power grip achieved with opposable jamming grippers as on the JamHand, and the experimentally measured holding force F_{H2}. **(C)** Experimental holding force data overlaid with a theoretical model. Color images available online at www.liebertpub.com/soro

very high compared with the amount usually found in a single gripper, we can utilize the equation provided by Brown *et al.* for interlocking dominated by the bending component:

$$F_I = (\pi/2)ER^2(t/l)^3(\theta - \pi/2)^3 \quad (3),$$

where t is the thickness of the gripper section responsible for the interlocking, l is the length of the bending arm, and E is the modulus of the granular material. Only an approximate value can be given for the contribution from interlocking, however, because l is not predetermined and t is typically nonuniform. To arrive at an equation for a two-fingered gripper, we must consider that geometric interlocking may not occur on all sides of the gripped object, and also that each gripper is turned 90°. This gives:

$$F_{I2} = \sin\theta(\pi/4)ER^2(t/l)^3\theta^3 \quad (4)$$

Finally, for smooth objects on which the gripper is able to achieve an air-tight seal, a vacuum suction force can develop and contribute to the total holding force. Brown *et al.* gives the suction force as $F_S = P_G A^*$, where P_G is the pressure in the gap between the object and the gripper, and A^* is the cross-sectional area of the sphere at θ, which we can calculate to be $A^* = \pi R^2 \sin^2\theta$. The maximum gap pressure depends on the friction force at which slip will occur at the contact between the gripper and the object, and it can, therefore, be calculated as $P_G = F_{F2}/A$. When the gripper is turned 90° as in the two-fingered grip of Figure 4B, the suction force is perpendicular to the measured holding force, so its contribution becomes an addition to the frictional force through multiplication by μ. Therefore, for our two-fingered gripper:

$$F_{S2} = \mu^2 R\sin\theta((4\sigma\pi R\sin\theta)(\sin\theta - \cos\theta) + F_P/d) \quad (5)$$

To confirm this model, holding force experiments in the configuration shown in Figure 4B were conducted by using a 3D printed sphere as a test object. To execute a test, the sphere was first grasped by the JamHand in the manner shown in Figure 4B, while both fingertips were vented to the atmosphere. To achieve the most symmetrical grasp on the test object, the spheres were presented elevated from the table on a thin pillar. Next, both fingertips were evacuated, and then the sphere was lifted from the pillar. Maximum pullout force was measured by using a digital load cell as the test sphere was pulled downward out from the gripper. Throughout the experiment, θ was varied while F_H was measured; all other variables were held constant. Results are shown in Figure 4C, where the expected value of F_{H2} is plotted along with experimental data.

To calculate the expected value of holding force in Figure 4C, we use $\sigma = 50$-kPa, $d = 1.07$-mm, $E = 7.4$-MPa, and $\mu = 1.0$.[30] For our specific test setup $R = 14$-mm, $F_P = 1.96$-N, $F_G = 0.14$-N, $t = 20$-mm, and $l = 20$-mm. The calculated line is scaled by a factor of 0.14 to fit the data. This scaling factor is a free parameter that accounts for approximations in the model such as non-uniform thickness in the gripper cross section, or spatial variations in the bending modulus. The value of 0.14 is compatible with the findings of Brown *et al.*[30] The test object used to measure the holding force was not smooth enough for the fingertips to achieve an air-tight seal, so F_{S2} is not included in the calculation of F_{H2}. Likewise, based on the experimental confirmation of F_{H2} and the significant coverage devoted to this model in Ref.[30] we have left the independent confirmation of F_{I2} and F_{S2} as a potential area of future work, preferring instead to focus more effort here on experimental manipulation testing.

Spherical objects were utilized to develop and evaluate this model, whereas the majority of real-world objects are non-spherical. The contact relationship between the gripper and non-spherical objects is much more difficult to describe. One of the key takeaways from this simplified model is that gripper holding force can be maximized by increasing both the engagement with the object (θ), and the applied stress (σ, which develops from confining pressure). Indeed, in real-world testing, we find that the best performance is achieved when we can drive an object far into the granular material and also reach a deep vacuum within the membrane. Because our vacuum pump is sufficient to reach more than 90% vacuum during a grip cycle and θ values between $\pi/4$ and $\pi/2$ are common, we can expect upper limit payloads for the JamHand to be around 2.5-kg, when it is employed as a two-fingered gripper.

Manipulation Testing

With just two continuous DOF in the finger joints—each driven by a separate servomotor—and two three-position valves to control the air pressure within the fingertips, the JamHand is able to achieve: multiple precision and power grasps, six fundamental dexterous manipulations, and the demonstration of real-world grasping and manipulation tasks. Demonstrations of these tasks can be seen in Figure 5 and Supplementary Video S1 (Supplementary Data are available online at www.liebertpub.com/soro). In addition, we have experimentally tested the JamHand for open loop repeatability of the six basic manipulations, as well as its tolerance for error in the location of the target object. Table 1 shows the results of these experiments.

The repeatability and error tolerance tests reported in Table 1 were performed on our CRS A465 robot arm by using position control and open loop routines. The specific manipulations tested were those shown in Figure 5E–J. Each

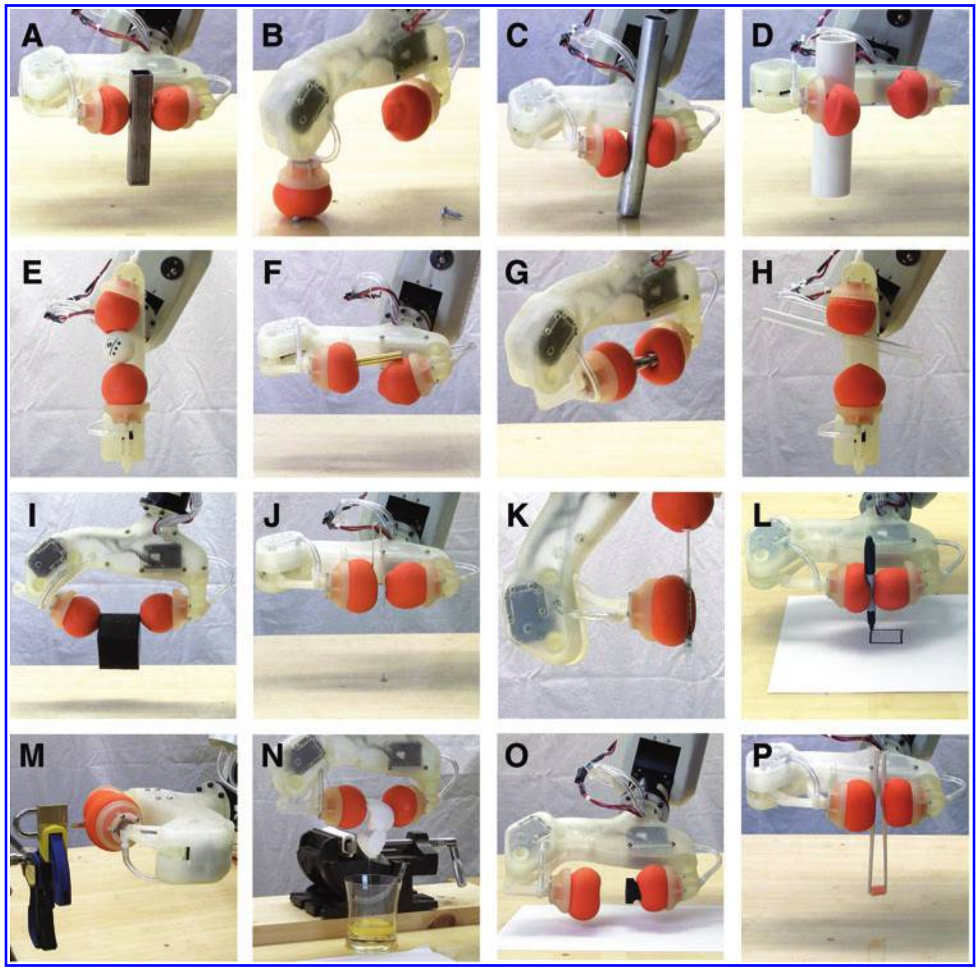


FIG. 5. The JamHand can achieve multiple precision and power grasps, and it can perform all six basic dexterous manipulations (in addition to other real-world grasping and manipulation tasks). Here, in screen shots taken from Supplementary Video S1, the JamHand performs: **(A)** precision grasping, **(B)** a second precision grasp, **(C)** power grasping, **(D)** a second power grasp, **(E)** rolling, **(F)** sliding, **(G)** regrasping, **(H)** finger gaiting, **(I)** pivoting, **(J)** in-hand manipulation, **(K)** operating a syringe, **(L)** writing with a pen, **(M)** opening a lock with a key, **(N)** cracking an egg, **(O)** assembling two LEGOs in-hand, and **(P)** using chop sticks. Color images available online at www.liebertpub.com/soro

manipulation was attempted 100 times to generate the values for the first two columns of the Table. In each test, the hand attempted the given manipulation once, and if successful, it would continue to perform that manipulation until failure.

The first column in Table 1 reports the one-time success rate for each manipulation, which is to say when the hand performs the manipulation, it will succeed at least once on the reported percentage of attempts. The second column in Table 1 reports the maximum repetitions of a single manipulation, which is to say that if the hand successfully completes the open loop manipulation once, then it can go on to successfully repeat that manipulation the given number of times before failure. The reported range on this value represents the 95% confidence interval.

In the third column of Table 1, error tolerance indicates the ability of the hand to complete the intended manipulation when the target object is located some distance away from its expected pick-up position on the work surface. The distance range for error tolerance reported in Table 1 indicates the range within which the hand is still able to complete the intended manipulation at least 95% of the value reported in the first column of Table 1. To find the tolerable error distance, we first moved the object away from its intended location on the work surface by the same amount in each of the four main directions (along the length and width axes of the hand). We then performed repeated tests at a variety of distances to determine in which direction the hand had the least tolerance for error in object location. Next, we chose a distance in that worst-case direction, tested 10 manipulations at that distance, and iterated until the maximum distance was found for which the one-time repeatability did not fall below 95% of the value reported for the case without error.

From Table 1, we can read, for example, that in open loop the JamHand can complete the pivoting manipulation at least once on 81% of attempts; when successful on the first try, it can then

Table 1. Results from Open Loop Testing of the JamHand's Manipulation Repeatability

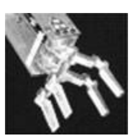
Manipulation	*One-time success rate (100 trials), (%)*	*Maximum repetitions (95% confidence)*	*Object location error tolerance* (mm)
Regrasping	100	8 ± 4	± 11
In-hand manipulation	84	>100	± 9
Finger gaiting	41	2 ± 1	± 0.5
Pivoting	81	4 ± 3	± 2
Rolling	100	8 ± 3	± 4
Sliding	100	>100	± 5

TABLE 2. COMPARISON OF ROBOTIC HANDS

Hand	*Image*	*No. of fingers*	*No. DOF at joints*	*No. of actuators*[a]	*Grasps achieved*	*Fundamental manipulations achieved*[b]	*Real-world dexterous manipulation achievements*
JamHand (this article)		2	2	2[c]	Precision and power grasps	1,2,3,4,5,6	Operating tweezers, depressing a syringe, writing with a pen, opening a lock with a key, cracking an egg, assembling two LEGOs in-hand, using chopsticks
BarrettHand[26]		3	7	4	Precision and power grasps	Unreported	Some manipulation capabilities assumed but not specifically demonstrated
DEKA Luke Arm[36–38]		5	Unreported	Unreported	Precision and power grasps	2	Pouring a grasped measuring cup, operating fingernail clippers, plucking a grape, pouring water, more capabilities assumed
DLR Hit Hand II[39]		5	15	15	Human-like grasping assumed	Unreported	Manipulation capabilities assumed but not specifically demonstrated
Gifu Hand[40]		5	16	16	Human-like grasping assumed	Unreported	Manipulation capabilities assumed but not specifically demonstrated
Harada Hand[41]		5	14	5	Precision and power grasps	2	Operating wire cutters, depressing trigger on a grasped cordless drill, more capabilities assumed
High Speed Hand[42–48]		3	8	5	Precision and power grasps	1,2,5	Knotting a flexible rope, dribbling a ball, spinning a thin rod between fingers, operating tweezers, folding cloth

(*continued*)

Table 2. (Continued)

Hand	*Image*	*No. of fingers*	*No. DOF at joints*	*No. of actuators*[a]	*Grasps achieved*	*Fundamental manipulations achieved*[b]	*Real-world dexterous manipulation achievements*
iHY Hand[49]		3	8	5	Precision and power grasps	1,2,4,5,6	Rolling, sliding, and pivoting to transition from pinch to power grasps; opening a lock with a key; using a cordless drill
KITECH Hand[50]		4	16	16	Precision and power grasps	2,5	Rolling and reorienting various objects
Meka H2 Hand[51]		4	12	5	Precision and power grasps	Unreported	Manipulation capabilities assumed but not specifically demonstrated
Robonaut2 Hand[52–54]		5	12	18	Precision and power grasps	Unreported	Flipping switches, pressing buttons, rotating knobs, handling cloth, operating an air flow meter, operating a cordless drill, operating a portable x-ray device, more capabilities assumed
SARAH[27,55,56]		3	10	2	Precision and power grasps	None demonstrated	No manipulation capabilities demonstrated or assumed
Schunk SDH[57]		3	7	7	Precision and power grasps	Unreported	Some manipulation capabilities assumed but not specifically demonstrated
SDM Hand[28,58,59]		4	8	1	Precision and power grasps	None demonstrated	No manipulation capabilities demonstrated or assumed

(*continued*)

Table 2. (Continued)

Hand	*Image*	*No. of fingers*	*No. DOF at joints*	*No. of actuators*[a]	*Grasps achieved*	*Fundamental manipulations achieved*[b]	*Real-world dexterous manipulation achievements*
Shadow Hand[60–62]		5	20	20 or 40[d]	Human-like grasping assumed	Unreported	Manipulation capabilities assumed but not specifically demonstrated
SRI Hand[29]		4	13	5[e]	Precision and power grasps	1,2	Operating a flashlight, more capabilities assumed
Stanford/JPL Salisbury Hand[20,63]		3	9	10	Precision and power grasps	1,2,4,5	Pivoting, rolling, and reorienting grasped objects; more capabilities assumed
Utah/MIT Dexterous Hand[18,64]		4	16	32	Human-like grasping assumed	Unreported	Manipulation capabilities assumed but not specifically demonstrated

[a]Only actuators are counted, simpler activators[65] are addressed with footnotes.
[b]Inferred where possible: (1) regrasping, (2) in-hand manipulation, (3) finger gaiting, (4) pivoting, (5) rolling, (6) sliding.
[c]Plus two three-position valves.
[d]20 motors or 40 air muscles.
[e]Plus separately controlled brakes at each joint.
DOF, degrees of freedom.

go on to repeat that manipulation 1–7 times; and for an error of ±2 mm in any direction on the table, it can still successfully complete that manipulation at least once on 77% of attempts.

Conclusion

Grasping and dexterous manipulation rank among the principal grand challenges in robotics. Proposed solutions are typically complex robot hands that take inspiration from the human hand, often with nine or more independent DOF. Greater than 100 different robot hand designs have been proposed by researchers in the past 40 years,[32–34] and great strides have been made in grasping, but the achievement of human-level manipulation by robots has remained elusive. In Table 2, we compare the performance of the JamHand with the reported performance of some of the most well-known robot hands in the literature to illuminate the state of the art in robotic dexterous manipulation.

The survey in Table 2 is by no means exhaustive. Among the many robot hands that have been proposed in the literature, the focus of their accompanying publications has most often been on the design, manufacturing, and control strategies that are implemented in the given prototype. Relatively few papers present quantitative performance data, and often, terms like *dexterous manipulation* are often used liberally or are simply assumed without explicit demonstration. Most of these robot hands are singular prototypes produced for research purposes and cannot be obtained for further testing. Therefore, in Table 2, the columns indicating achieved grasps and manipulations were inferred, where possible, if they could not be found specifically reported. It is our hope that this article's quantitative, performance-centric approach to comparing the state of the art will help provide some new benchmarks for future work in this field.

The focus of this article is on achieving dexterous manipulation with minimal actuation. Few existing hands have been designed for the same goal. Therefore, other evaluation metrics (e.g., grasp force/strength, grasp size, speed, robustness, etc.), had they been of interest to this discussion, could have painted a different picture in Table 2. Likewise, we also recognize that there are many tasks that other hands may be able to perform that the JamHand cannot, and these capabilities may not be considered in an analysis dealing with only hand complexity and dexterous manipulation. It is clear, though, that the JamHand represents a significant step forward in the pursuit of low-complexity dexterous robotic manipulation. Although the JamHand is ill suited for manipulation tasks that are designed specifically around the human hand, such as operating a hand drill or typing on a keyboard, its simple design and wide range of capabilities indicate that leveraging the phase transition of granular materials is a viable technique for reducing the hand complexity required for performing daily tasks. It has long been predicted that artificial hands and the tools they use may undergo coevolution to their mutual benefit,[35] much as we have seen with human hands and our modern tools.[10] High-functioning non-anthropomorphic designs that are easy to implement are a first step toward achieving this goal.

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Author Disclosure Statement

No competing financial interests exist.

References

1. Wilson AB Jr. Limb prosthetics—1967. Artif Limbs 1967;11:1.
2. Klopsteg PE, Wilson PD. Human Limbs and Their Substitutes. New York, NY: Hafner, 1968.
3. Vanderwerker EE. A Brief Review of the History of Amputations and Prostheses. Inter-Clin Info Bull 1976;15:15–16.
4. Monkman GJ, Hesse S, Steinmann R, Schunk H. Robot Grippers. Weinheim, Germany: John Wiley & Sons, 2007.
5. Tomovic R. A new model of the Belgrade hand. In Proc. 3rd Int. Symp. on External Control of Human Extremities. Dubrovnik, Croatia: Yugoslav Committee for Electronics and Automation, 1969.
6. Lundström G. Industrial robot grippers. Ind Robot An Int J 1974;1:72–82.
7. Skinner F. Designing a multiple prehension manipulator. Mech Eng 1975;97:30–37.
8. Okada T, Tsuchiya S. On a versatile finger system. In Proceedings of the 7th International Symposium of Industrial Robots. Tokyo, Japan: Japan Industrial Robot Association, 1977.
9. Crossley FE, Umholtz FG. Design for a three-fingered hand. Mech Machine Theory 1977;12:85–93.
10. Napier J. The evolution of the hand. Sci Am 1962;207:56–62.
11. Bicchi A, Kumar V. Robotic grasping and contact: a review. In Proceedings of International Conference on Robotics and Automation. Piscataway, NJ: IEEE, 2000, pp. 348–353.
12. Bicchi A. Hands for dexterous manipulation and robust grasping: a difficult road toward simplicity. In Proceedings of International Conference on Robotics and Automation. Piscataway, NJ: IEEE, 2000;16:652–662.
13. Okamura AM, Smaby N, Cutkosky MR. An overview of dexterous manipulation. In Proceedings of International Conference on Robotics and Automation. Piscataway, NJ: IEEE, 2000 (Vol. 1, pp. 255–262).
14. Ma RR, Dollar AM. On dexterity and dexterous manipulation. In Proceedings of International Conference on Advanced Robotics. Piscataway, NJ: IEEE, 2011, pp. 1–7.
15. Lawton MP, Brody EM. Assessment of older people: self-maintaining and instrumental activities of daily living. Gerontologist 1969;9:179–186.
16. Cutkosky MR. On grasp choice, grasp models, and the design of hands for manufacturing tasks. In International Conference on Robotics and Automation. Piscataway, NJ: IEEE, 1989;5:269–279.
17. Pratt G. Autonomous Robotic Manipulation Hardware Track (ARM-H). DARPA-BAA-10-29. 2010.
18. Jacobsen SC, Wood JE, Knutti DF, Biggers KB. The UTAH/MIT dextrous hand: work in progress. Int J Robot Res 1984;3:21–50.
19. Agur AM, Dalley AF. Grant's Atlas of Anatomy. Baltimore, MD: Lippincott Williams & Wilkins, 2009.
20. Mason MT, Salisbury JK Jr. Robot Hands and the Mechanics of Manipulation. Cambridge, MA: MIT Press, 1985.
21. Shimoga KB. Robot grasp synthesis algorithms: a survey. Int J Robot Res 1996;15:230–266.
22. Miller AT, Knoop S, Christensen HI, Allen PK. Automatic grasp planning using shape primitives. In Proceedings of International Conference on Robotics and Automation. Piscataway, NJ: IEEE, 2003 (Vol. 2, pp. 1824–1829).
23. Saxena A, Driemeyer J, Ng AY. Robotic grasping of novel objects using vision. Int J Robot Res 2008;27:157–173.

24. Brown CY, Asada HH. Inter-finger coordination and postural synergies in robot hands via mechanical implementation of principal components analysis. In International Conference on Intelligent Robots and Systems. Piscataway, NJ: IEEE, 2007 (pp. 2877–2882).
25. Birglen L, Laliberté T, Gosselin CM. Underactuated Robotic Hands. Berlin, Germany: Springer-Verlag, 2008.
26. Townsend W. The BarrettHand grasper-programmably flexible part handling and assembly. Ind Robot 2000;27:181–188.
27. Laliberté T, Birglen L, Gosselin C. Underactuation in robotic grasping hands. Machine Intell Robot Control 2002;4:1–1.
28. Dollar AM, Howe RD. A robust compliant grasper via shape deposition manufacturing. IEEE Trans Mech 2006;11:154–161.
29. Aukes D, Kim S, Garcia P, Edsinger A, Cutkosky MR. Selectively compliant underactuated hand for mobile manipulation. In Proceedings of International Conference on Robotics and Automation. Piscataway, NJ: IEEE, 2012 (pp. 2824–2829).
30. Brown E, Rodenberg N, Amend J, Mozeika A, Steltz E, Zakin MR, *et al.* Universal robotic gripper based on the jamming of granular material. Proc Natl Acad Sci U S A 2010;107:18809–18814.
31. Amend JR Jr, Brown E, Rodenberg N, Jaeger HM, Lipson H. A positive pressure universal gripper based on the jamming of granular material. IEEE Trans Robotics 2012;28:341–350.
32. Boubekri N, Chakraborty P. Robotic grasping: gripper designs, control methods and grasp configurations-a review of research. Integr Manuf Syst 2002;13:520–531.
33. Kato I, Sadamoto K. Mechanical Hands Illustrated. Washington, DC: Hemisphere Publishing, 1987.
34. Mason MT. Mechanics of Robotic Manipulation. Cambridge, MA: MIT press, 2001.
35. Cutkosky MR. Robot Grasping and Fine Manipulation. Norwell, MA: Kluwer, 1985.
36. DEKA Arm. Available: www.dekaresearch.com/deka_arm.shtml Accessed June 13, 2016.
37. Kamen D. The emotion behind invention. Available: www.ted.com/talks/dean_kamen_the_emotion_behind_invention Accessed June 13, 2016.
38. Resnik L. Research update: VA study to optimize the DEKA Arm. J Rehabil Res Dev 2010;47:ix–x.
39. Liu H, Wu K, Meusel P, Seitz N, Hirzinger G, Jin MH, *et al.* Multisensory five-finger dexterous hand: The DLR/HIT Hand II. In Proceedings of International Conference on Intelligent Robots and Systems. Piscataway, NJ: IEEE, 2008, pp. 3692–3697.
40. Mouri T, Endo T, Kawasaki H. Review of gifu hand and its application. Mechanics Based Design of Structures and Machines 2011;39:210–228.
41. Keymeulen D, Assad C. Investigation of the Harada robot hand for space. In International Conference on Humanoid Robotics. 2001 Tokyo.
42. Namiki A, Imai Y, Ishikawa M, Kaneko M. Development of a high-speed multifingered hand system and its application to catching. In Proceedings of International Conference on Intelligent Robots and Systems. Piscataway, NJ: IEEE, 2003 (Vol. 3, pp. 2666–2671).
43. Shiokata D, Namiki A, Ishikawa M. Robot dribbling using a high-speed multifingered hand and a high-speed vision system. In Proceedings of International Conference on Intelligent Robots and Systems. Piscataway, NJ: IEEE, 2005, pp. 2097–2102.
44. Furukawa N, Namiki A, Taku S, Ishikawa M. Dynamic regrasping using a high-speed multifingered hand and a high-speed vision system. In Proceedings of International Conference on Robotics and Automation. Piscataway, NJ: IEEE, 2006, pp. 181–187.
45. Yamakawa Y, Namiki A, Ishikawa M, Shimojo M. One-handed knotting of a flexible rope with a high-speed multifingered hand having tactile sensors. In Proceedings of International Conference on Intelligent Robots and Systems. Piscataway, NJ: IEEE, 2007, pp. 703–708.
46. Mizusawa S, Namiki A, Ishikawa M. Tweezers type tool manipulation by a multifingered hand using a high-speed visual servoing. In Proceedings of International Conference on Intelligent Robots and Systems. Piscataway, NJ: IEEE, 2008, pp. 2709–2714.
47. Senoo T, Yamakawa Y, Mizusawa S, Namiki A, Ishikawa M, Shimojo M. Skillful manipulation based on high-speed sensory-motor fusion. In Proceedings of International Conference on Robotics and Automation. Piscataway, NJ: IEEE, 2009, pp. 1611–1612.
48. Yamakawa Y, Namiki A, Ishikawa M. Motion planning for dynamic folding of a cloth with two high-speed robot hands and two high-speed sliders. In Proceedings of International Conference on Robotics and Automation. Piscataway, NJ: IEEE, 2011, pp. 5486–5491.
49. Odhner LU, Jentoft LP, Claffee MR, Corson N, Tenzer Y, Ma RR, *et al.* A compliant, underactuated hand for robust manipulation. Int J Robot Res 2014;33:736–752.
50. Bae JH, Park SW, Park JH, Baeg MH, Kim D, Oh SR. Development of a low cost anthropomorphic robot hand with high capability. In Proceedings of International Conference on Intelligent Robots and Systems. Piscataway, NJ: IEEE, 2012, pp. 4776–4782.
51. Meka Robotics. Meka H2 Compliant Hand. Available: www.youtube.com/watch?v=9EQJ845nLxU Accessed June 13, 2016.
52. Diftler MA, Mehling JS, Abdallah ME, Radford NA, Bridgwater LB, Sanders AM, *et al.* Robonaut 2-the first humanoid robot in space. In Proceedings of International Conference on Robotics and Automation. Piscataway, NJ: IEEE, 2011, pp. 2178–2183.
53. Diftler MA, Ahlstrom TD, Ambrose RO, Radford NA, Joyce CA, De La Pena N, *et al.* Robonaut 2—initial activities on-board the ISS. In IEEE Aerospace Conference. Piscataway, NJ: IEEE, 2012, pp. 1–12.
54. Bridgwater LB, Ihrke CA, Diftler MA, Abdallah ME, Radford NA, Rogers JM, *et al.* The robonaut 2 hand-designed to do work with tools. In Proceedings of International Conference on Robotics and Automation. Piscataway, NJ: IEEE, 2012, pp. 3425–3430.
55. Laliberté T, Gosselin CM. Underactuation in space robotic hands. In International Symposium on Artificial Intelligence, Robotics and Automation in Space, Montréal, Canada. 2001, pp. 18–21.
56. Rubinger B, Brousseau M, Lymer J, Gosselin CM, Laliberté T, Piedboeuf JC. A novel robotic hand-SARAH for operations on the international space station. In Proceedings of ASTRA Workshop 2002 November Paris: European Space Agency, 2002.
57. SCHUNK GmbH. SDH Robotic Hand. http://mobile.schunk-microsite.com/de/produkte/produkte/servoelektrische-3-finger-greifhand-sdh.html, Accessed June 13, 2016.
58. Dollar AM, Howe RD. Simple, robust autonomous grasping in unstructured environments. In Proceedings of International Conference on Robotics and Automation. Piscataway, NJ: IEEE, 2007, pp. 4693–4700.

59. Dollar AM, Howe RD. The SDM hand as a prosthetic terminal device: a feasibility study. In Proceedings of International Conference on Rehabilitation Robotics. Piscataway, NJ: IEEE, 2007, pp. 978–983.
60. Tuffield P, Elias H. The shadow robot mimics human actions. Ind Robot Int J 2003;30:56–60.
61. Kochan A. Shadow delivers first hand. Ind Robot Int J 2005; 32:15–16.
62. Shadow Robot Company. Dexterous Hand. Available: www.shadowrobot.com/products/dexterous-hand Accessed June 13, 2016.
63. Salisbury JK. Salisbury Robotics Hand. Available: www.youtube.com/watch?v=Q2z8pJMN1dM Accessed June 13, 2016.
64. Jacobsen SC, Iversen EK, Knutti DF, Johnson RT, Biggers KB. Design of the Utah/MIT dextrous hand. In Proceedings of International Conference on Robotics and Automation. Piscataway, NJ: IEEE, 1986 (Vol. 3, pp. 1520–1532).
65. Steltz E, Mozeika A, Rembisz J, Corson N, Jaeger HM. Jamming as an enabling technology for soft robotics. In SPIE Smart Structures and Materials Nondestructive Evaluation and Health Monitoring 2010 Mar 25 (p. 764225).

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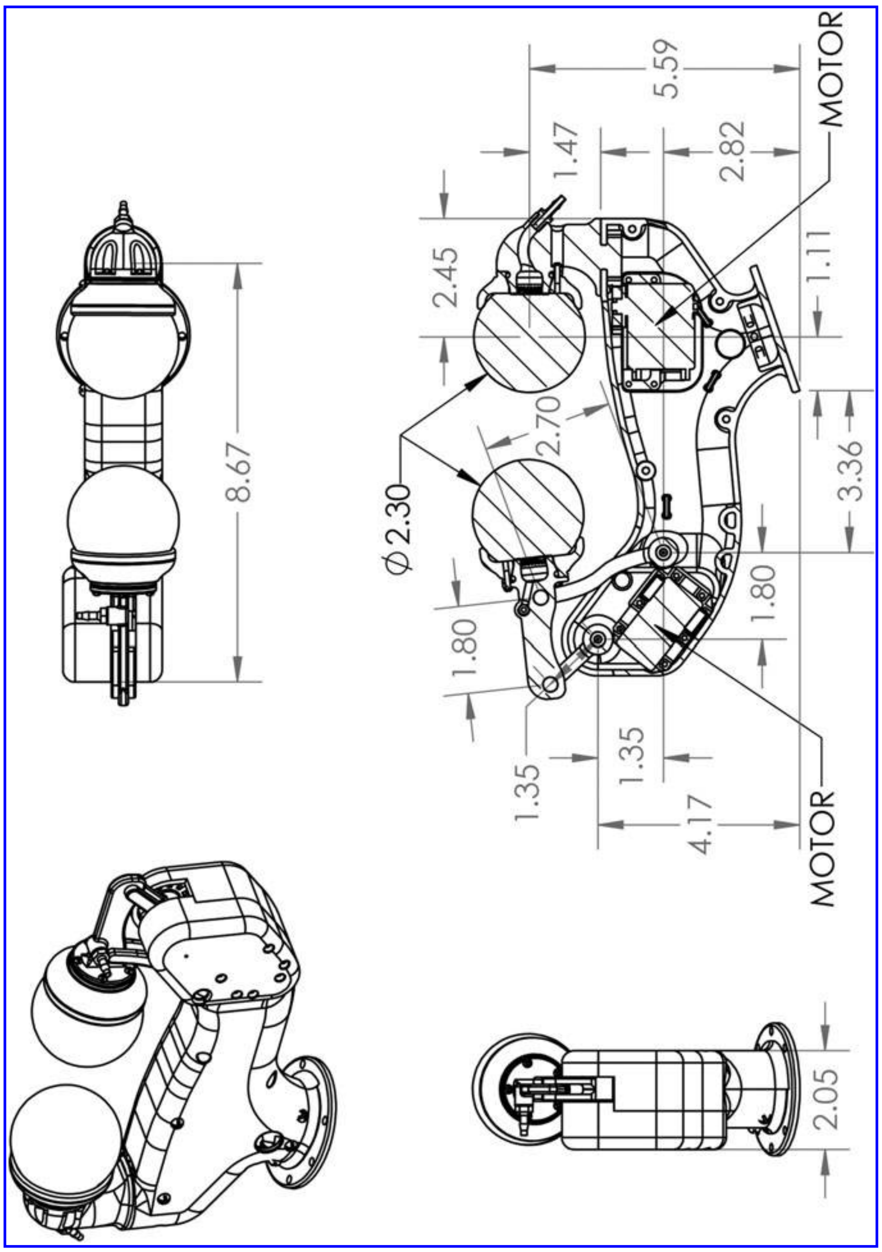

APPENDIX FIG. A1. Mechanical drawing of the JamHand (dimensions in inches).

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1. C. Piazza, G. Grioli, M.G. Catalano, A. Bicchi. 2019. A Century of Robotic Hands. *Annual Review of Control, Robotics, and Autonomous Systems* **2**:1, 1-32. [Crossref]
2. Li Haili, Yao Jiantao, Zhou Pan, Chen Xinbo, Xu Yundou, Zhao Yongsheng. 2019. High-Load Soft Grippers Based on Bionic Winding Effect. *Soft Robotics* **6**:2, 276-288. [Abstract] [Full Text] [PDF] [PDF Plus] [Supplementary Material]
3. S P Murali Babu, Ali Sadeghi, Alessio Mondini, Barbara Mazzolai. Antagonistic Pneumatic Actuators with Variable Stiffness for Soft Robotic Applications 283-288. [Crossref]
4. An Mo, Wenzeng Zhang. 2019. A novel universal gripper based on meshed pin array. *International Journal of Advanced Robotic Systems* **16**:2, 172988141983478. [Crossref]
5. Fei Yanqiong, Wang Jiangbei, Pang Wu. 2019. A Novel Fabric-Based Versatile and Stiffness-Tunable Soft Gripper Integrating Soft Pneumatic Fingers and Wrist. *Soft Robotics* **6**:1, 1-20. [Abstract] [Full Text] [PDF] [PDF Plus] [Supplementary Material]
6. Jun Shintake, Vito Cacucciolo, Dario Floreano, Herbert Shea. 2018. Soft Robotic Grippers. *Advanced Materials* **30**:29, 1707035. [Crossref]
7. Langer Marlene, Amanov Ernar, Burgner-Kahrs Jessica. 2018. Stiffening Sheaths for Continuum Robots. *Soft Robotics* **5**:3, 291-303. [Abstract] [Full Text] [PDF] [PDF Plus]
8. Wang Wei, Ahn Sung-Hoon. 2017. Shape Memory Alloy-Based Soft Gripper with Variable Stiffness for Compliant and Effective Grasping. *Soft Robotics* **4**:4, 379-389. [Abstract] [Full Text] [PDF] [PDF Plus] [Supplementary Material]
9. Licht Stephen, Collins Everett, Mendes Manuel Lopes, Baxter Christopher. 2017. Stronger at Depth: Jamming Grippers as Deep Sea Sampling Tools. *Soft Robotics* **4**:4, 305-316. [Abstract] [Full Text] [PDF] [PDF Plus]
10. Seppe Terryn, Joost Brancart, Dirk Lefeber, Guy Van Assche, Bram Vanderborght. 2017. Self-healing soft pneumatic robots. *Science Robotics* **2**:9, eaan4268. [Crossref]