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Review

Recent Improvements in the Development of Soft Grippers Capable of Dexterous Manipulation

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Abstract: Soft grippers perform various handling tasks using passive conformability. This article reviews the improvements in their capabilities of dexterous manipulations, including how they achieve dexterity and how their performance could be evaluated. This article particularly points out the correlations between potential and real dexterity, and the relationship between the space of degrees of freedom and the corresponding dexterity level. Our main contribution is the proposition of a uniform framework for the characterization of soft grippers and their performance. We first present an introduction to soft grippers and those capable of in-hand manipulation. We emphasize their hybridization by combining soft and rigid materials or using several active materials. Next, we define and discuss the manipulation tasks and how to achieve dexterity, making a distinction between stable grasping and stable in-hand manipulation. We finally discuss the means to achieve assessment and how the performance can be evaluated, and we develop a general exploitable approach for characterizing soft grippers and their dexterous performance based on their architecture, DOF space, and physical performance.

Keywords: soft grasping; hybridization; soft manipulation; dexterity level; dexterous evaluation

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1. Introduction

Since robots are constructed to perform human or animal-like tasks, it is essential for them to be capable of grasping and manipulating objects of various shapes in order to interact with their environment. To achieve this, the development of robotic hands has been long-term in progress. The first to be produced were made of rigid materials with rigid links and kinematic joints, integrating a large number of sensors and actuators, e.g., refs. [1–3]. According to [4], this technology has resulted in a limited number of everyday applications. To respond to some of the challenges faced by this kind of technology, such as safety for humans, adaptability to the environment, the manipulation of fragile objects, cheaper cost of fabrication, etc., soft compliant materials have lately been used in the development of grippers or robotic hands in various reported works.

For example, the work in [5] presents a review of soft grippers, with the main illustration being the picking up of objects. Their article focuses on the different grasping technologies and the various materials used to develop soft grippers. They present a comparison of gripping performance and discuss the sensing technologies in soft grippers. Reference [6] is another paper that reviews soft grippers to assess actuation methods, sensors, and materials and methods used in their development. They also discuss the fabrication technologies and the morphology of soft robotic grippers.

The present article focuses on dexterity and dexterous manipulations. Our main contribution is the proposal of a uniform framework for the characterization of dexterous soft grippers and their performance, based on the existing benchmarks. We discuss how to achieve dexterity for soft grippers, the primitive movements that dexterous soft grippers can perform, and their evaluation. We also discuss hybridization strategies and their impact on gripper performance. A review of various dexterous soft grippers found in the literature is made, including their performance, morphology, and assessments. Before discussing the aforementioned points, we present soft grippers and different grasping techniques, the materials used, the main sensors, and the manufacturing methods.

Focusing on recent work, the different articles reviewed in this article were selected from the works reported in the past decade (2014–2023). However, our review includes older research works that provide foundational methodologies and historical perspectives that are still relevant today. The articles were selected from leading journals and conferences in the field of robotics and automation, through keyword-based searches in the usual search engines and in the search engines of various publishers. The keywords for the article selection included dexterous grasping, dexterous manipulation, soft fingers, soft grippers, stiffness variation, and dexterity evaluation. Some of these keywords were combined in the research process. Since our article does not aim to report every single work published in this domain within the last decade, we selected the articles which, according to us, show the potentiality of dexterous capabilities thanks to the arrangements of their DOFs, towards the proposition of a uniform framework for dexterity evaluation.

This article's structure is as follows: in Section 2, we discuss soft grippers and those capable of in-hand manipulation, different actuation, sensing, manufacturing techniques, and hybridization strategies. Section 3 presents dexterous manipulations and the primitive movements that can be achieved by dexterous soft grippers and the methods applied in the literature to achieve dexterity. In this section, we also discuss performance evaluation for various soft grippers found in the literature, and we propose a uniform re-usable approach for the characterization of a dexterous soft gripper and its performance. Finally, Section 4 summarizes the article, and in Section 5, we suggest prospects for improvements in the development of soft dexterous grippers.

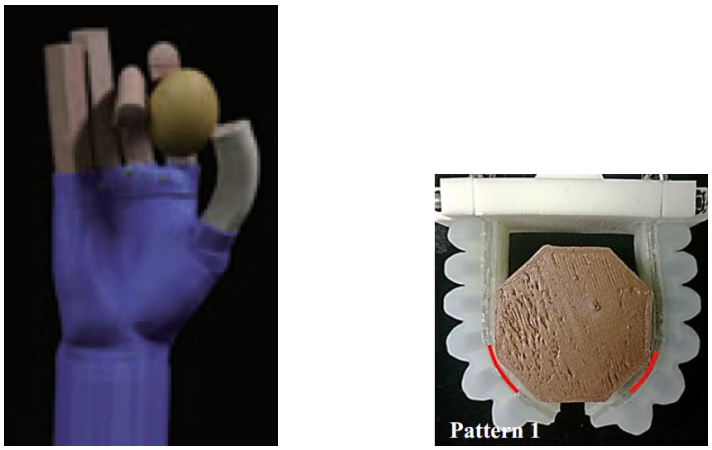
2. Soft Grippers

Soft robotics was born in response to the disadvantages of poly-articulated robotics and can be understood as a logical evolution [7]. Hence, soft grippers are a possible evolution of the classical rigid grippers towards creating soft robotic hands intended for general objects (of various shapes) with a safe interface for the human being within the surrounding workspace [6]. Soft grippers are designed, fabricated, and controlled with the same technologies applied to common soft robots, and they potentially exploit the same perception technologies.

2.1. Architecture

Concerning the architectures of soft grippers, there are two main types: anthropomorphic (Figure 1a) and non-anthropomorphic (Figure 1b). The anthropomorphic ones have a structure which is very close to the human hand. They generally have a thumb and three to four other fingers. Anthropomorphic soft grippers are normally made in the interest of performing manipulation tasks from inside the hand (dexterous manipulation). These are more desirable for service robots or robots that do human-like tasks [8]. On the other hand, non-anthropomorphic grippers can also perform dexterous manipulation tasks. Their structure is mostly made of equal fingers, between 2 and 4, that are fixed to a central palm. Their applications are rather directed to the transport and handling of goods.

In general, anthropomorphic soft grippers are intended for medical applications, notably in the development of prostheses, in rehabilitation or in assistance. Non-anthropomorphic grippers, on the other hand, are generally used in the industry for pick-and-place and object handling tasks. For example, ref. [9] presents a review of soft grippers applied to agriculture. However, other applications can be considered for soft grippers and dexterous soft grippers.



(**a**) (**b**)

Figure 1. Figure showing the different architectures of soft grippers. (**a**) Anthropomorphic soft gripper [10]; (**b**) Non-anthropomorphic soft gripper [11].

Soft grippers capable of in-hand manipulation are also anthropomorphic or non-anthropomorphic. The grippers in [12–15] all have three or four fingers and a thumb that give them a human-like shape. The authors in [16] present a soft gripper that has only one finger and one human-like thumb, making it anthropomorphic. On the other hand, the grippers in [15,17–25] have a non-anthropomorphic shape. The number of fingers varies from one work to the other based on the design parameters chosen by the authors but always lies between two and five. One sub-type of robotic hands that has been identified in the literature, falling under non-anthropomorphic hands, is the spherical hand with a two-finger hand topology, [26]. In this topology, the axis that describes the displacement of the grasped object intersects at the same point relative to the palm.

2.2. Actuation and Sensing

The common actuation techniques used are fluidic elastomeric actuators (FEAs), and the most used FEAs are soft pneumatic actuators (SPAs). Other actuators used are shape memory alloys and polymers (SMAs and SMPs); electroactive polymers (EAPs); tendon-driven actuators and external motors associated with the grippers' passive structures. On the other hand, semi-active actuation consists of manipulating actuators in an indirect way, i.e., the actuation is based on the mechanical properties of the materials; examples of semi-active actuation technologies are jamming, electro, and magneto-rheological materials (ERMs and MRMs), and low melting point alloys and polymers (LMPAs and LMPPs) [5,7], whose stiffness varies when they are subjected to an electric or magnetic field.

The main sensing technologies used are resistive ionic sensors (force, pressure, and strain); soft electronics (pressure); piezoelectric-resistive-capacitive sensors (strain); capacitive sensors (strain); thermoplastic resistive conductive sensors (strain); sensing fabrics and fibers (strain); and optical sensors (deformation) [5,6,27].

Some soft dexterous grippers rely uniquely on fluidic actuation, [13,15,17,22,24,28,29], while others combine fluidic actuation with motor actuation [23], or some others combine FEAs with motor actuation and other actuation like a suction cup or particle jamming [21]. In [30], FEAs

are embedded with low-melting-point alloys. Some of the studied dexterous soft grippers did not integrate FEAs but rather exploited tendon-driven actuation, ref. [12], combined with motor actuation, ref. [20] and motor actuation combined with particle jamming [16]. A combination of SMA actuators with electromagnets and DC motors is presented in [31].

The introduction of sensors into the functioning loop of soft grippers confers them with desirable dexterous performances as discussed in Section 3.2.2. Pressure sensors are the most commonly used [13,15,17,21–24,29,32]. Other sensors, such as tactile sensors, are used in [21,33]. A six-axis force/moment sensor is introduced in [34].

2.3. Design, Fabrication, and Modeling

Soft grippers are a subgroup of soft robots. As a result, they are designed and fabricated through soft robotics techniques. The manufacturing methods generally rely on additive manufacturing and 3D printing [6,27,35]. The soft actuators can either be casted using 3D-printed molds or directly fabricated using additive manufacturing techniques such as material extrusion, material jetting, VAT polymerization, as explained in [36]. The prototyping of soft robots is generally a faster process than for classical rigid robots, since the main methods used are said to be rapid and adaptable [27]. The simulation of soft robots is a growing field and its development could ease the design of prototypes for testing. The primary materials used in soft robotics have a Young's modulus ranging approximately between 10 kPa (e.g., gels and foams) and 1 GPa as noted in [37], and can be shaped with different topologies. Among them are found rubber, silicone, other elastomers, fabrics, foam, etc.

A model of the system is often needed to study the behavior. Generally, the techniques of physical models for soft robots are constant curve approximation (CCA) [38] and exact geometric models [39]. When it comes to soft grippers, in order to characterize some parameters like the bending angle, the grasping performance, the actuation time, or the deformation with respect to the geometry and material properties, various modeling techniques have been used in the literature. For example, in [40], an analytical model of the gripper is constructed using a chain composite model of each pneumatic finger, the computation of strain energy and work performed by pressure, the gripper geometry, and coordinate transformation to analyze the grasping performance. In [41], they use the forward kinematics of the pneumatic actuator and homogeneous transformations to compute its displacement. The Neo-Hookean hyperelastic model is used to calculate material stretch moments. An approximative static mathematical model of the actuator can be derived based on the geometry and material properties, as performed in [42]. The Jacobian and neural network approaches are two methods of modeling tendon-driven actuators [6].

Once the models have been created, simulations can be performed using the finite element method (FEM) with frameworks like SOFA, for example, ref. [43], or soft-volumetric pixel (called voxels) models with VoxCAD [6]. Simulations can allow the control of the grippers. For soft pneumatic fingers, the low-level approach control, i.e., the control of the internal pressure or volume of the actuators, is commonly used in soft grippers. For motor-driven actuation, the direct control of the motors is often applied to control the grippers.

According to [5], soft grippers can be classified at the level of the grasping principle. This reference gives an idea of the principles with the different technologies applied: by actuation, by stiffness variation, and by adhesion. The reference also gives a general view of the performance of soft grippers by comparing the grasping principles in terms of the gripper/object weight relationship, the size of the gripper and the objects, the response time and the energy consumed, and the surface conditions required for the object.

2.4. Hybridization Strategies

In order to improve soft grippers' performance and overcome specific difficulties such as task repeatability, movement precision, and grasping force [6], different technologies have been used. Soft grippers could be developed using active materials and particle jamming technologies to overcome some of these difficulties. The combination of different existing technologies to exploit the best capabilities is considered a more promising approach to overcoming the aforementioned difficulties [5,27]. This approach, called hybridization, confers the grippers with properties such as stiffness variation, auto-perception, and others shown in Table 1. Hybrid soft grippers can either have a combination of rigid and soft structures like in [18,21], or a multi-material structure integrating several active materials. In the following works, [10,11,30,44–53], the stiffness variation of the soft grippers is achieved by integrating active materials such as LMPA, LMPP, SMP, SMA, and jamming approaches in actuators with FEAs or EAPs. Figure 2 shows hybrid soft grippers with variable stiffness. Some soft-rigid hybridization strategies have been found in the literature. The fingers of the gripper developed in [54] are McKibben muscles, whose stiffness is proportional to the air pressure inside them. Pneumatic muscle actuators are used in [18], with rigid articulable bones in each finger constituting the gripper. This confers the fingers with a length-constraining mechanism that allows them to conform to different object shapes and sizes, hence facilitating handling. The soft gripper in [55] uses tunable rigidity elastomers as ligaments. When electrically activated, the ligament's rigidity decreases by approximately 35×, causing more extension. The work in [21] is based on the use of a translating rod inside the finger to produce a movable bending point and, at the same time, modify the stiffness of the fingers as their effective length varies.

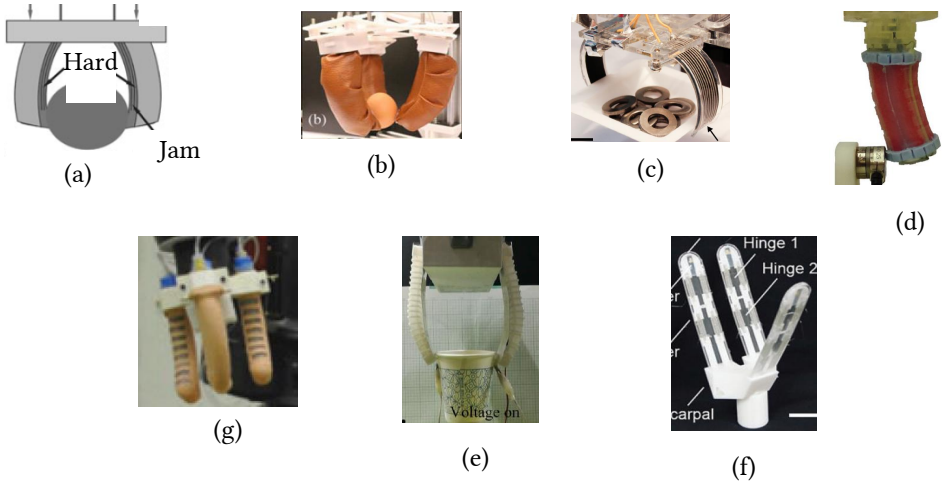


Figure 2. Different technologies for soft grippers integrating hybridization strategies. (**a**) Two-finger non-anthropomorphic soft gripper with FEA and layer jamming technologies [44]. (**b**) Three-finger non-anthropomorphic soft gripper with FEA and particle jamming technologies [45]. (**c**) Two-finger non-anthropomorphic soft gripper with DEA and LMPA technologies [46]. (**d**) Soft pneumatically actuated manipulator combined with tendon-driven actuation [47]. (**e**) Two-finger non-anthropomorphic soft gripper with FEA and electrostatic layer jamming technologies [48]. (**f**) Non-anthropomorphic soft gripper with 3 SMA fingers and 2 SMP per finger [49]. (**g**) Three-finger non-anthropomorphic soft gripper with FEA and particle jamming technologies [50].

Although hybridization considerably enhances the dexterous capabilities for soft grippers, the complexity of multi-material integration remains a major trade-off. Active materials, for example, can provide non-desired property shifting, producing challenges in fabrication. The modeling of active materials or combined rigid and soft structures remains underdeveloped. As a result, the control of hybrid soft grippers remains complex.

Table 1 shows some soft grippers that integrate hybridization strategies. Some of which are capable of dexterous manipulations. The table shows the impact of hybridization on the grippers' performance, from the maximum bending stiffness for some, through the maximum bending angle, and to the maximum pulling force for others.

Table 1. Functional properties resulting from different hybridization strategies. (DM stands for dexterous manipulations.).

Ref	Dexterity	Hybridization Strategy	Performance
[54]	DM	Use of pneumatic actuators surrounded with braided nylon (pneumatic muscles)	Bending stiffness increased by more than 150%
[30]	DM	Use of LMPA tubes to stiffen a cable-driven arm with the rigid phase	Capable of preventing vertical deflection with pulling force: 2N
[51]	No DM	Use of LMPA to stiffen an FEA actuator with the rigid phase	Stiffness increased 35 times 7 possible shapes
[11]	No DM	Use of SMP to stiffen an FEA actuator with the rigid phase	Maximum lifting load: 500 g 7 possible shapes
[21]	DM	Use of a translated rod that varies the bending point and the stiffness of the finger	Maximum bending angle: 90° Exerts up to 650 mN in less than 3 s
[55]	DM	Use of programmable ligaments (elastomers) whose stiffness varies	Twisting angle: 18° Complete twisting process in less than 15 s
[50]	No DM	Use of particle jamming; stiffening of an FEA actuator	Stiffness increased 10 times and gripping force from 0.18 to 1.8 N

3. Dexterous Manipulation

Dexterous manipulation has been defined in several ways in the literature. The two general approaches are anthropomorphic and object-centric manipulation. The former considers that having a shape or capabilities like the human hand on a gripper is the origin of dexterous manipulation. The latter considers that dexterous manipulation is

arbitrarily manipulating an object in space without considering the gripper's configuration or the strategy used to perform the movement [56]. These two approaches also define the gripper's architecture. Considering the diversity of forms and technologies that grippers can have, the object-centric approach is considered the most adequate since it facilitates a holistic view of the grippers and the manipulation itself. Thus, dexterous manipulation is a function carried out by animals and robots allowing the spatial manipulation of an object around its 6 degrees of freedom (DOFs) in an arbitrary way, starting and ending in stable grasping positions [56,57].

3.1. Primitive Movements

According to [56], dexterous manipulation can be subdivided into a number of primitive or basic movements resulting in the free motion of fingers, achieving optimal grasps, the redistribution of the finger, and the rotation of an abject about its axis. The types of primitive movements discussed in this article are in-grasp manipulation, finger gating, finger pivoting, finger rolling, and finger sliding. All are shown in Figure 3. With in-grasp manipulation, the object's position and orientation are slightly changed, while the contact is kept with the fingertips. In finger gating, some fingers grasp the object while others are free. Once the grasping fingers reach joint limits, they are replaced by free fingers and are then placed in other positions to replace the current grasping fingers during the object manipulation. As for finger gating, in finger pivoting, some fingers are free while others rotate the object. The free fingers guide the object's rotation about an established axis. Finger rolling combines the rotation and translation of the object. In [56], it is referred to as a non-prehensile manipulation that requires non-holonomic control and is mainly realized by the fingers of specific geometries [58]. Finger sliding on its part manipulates the object through controlled slip [56].

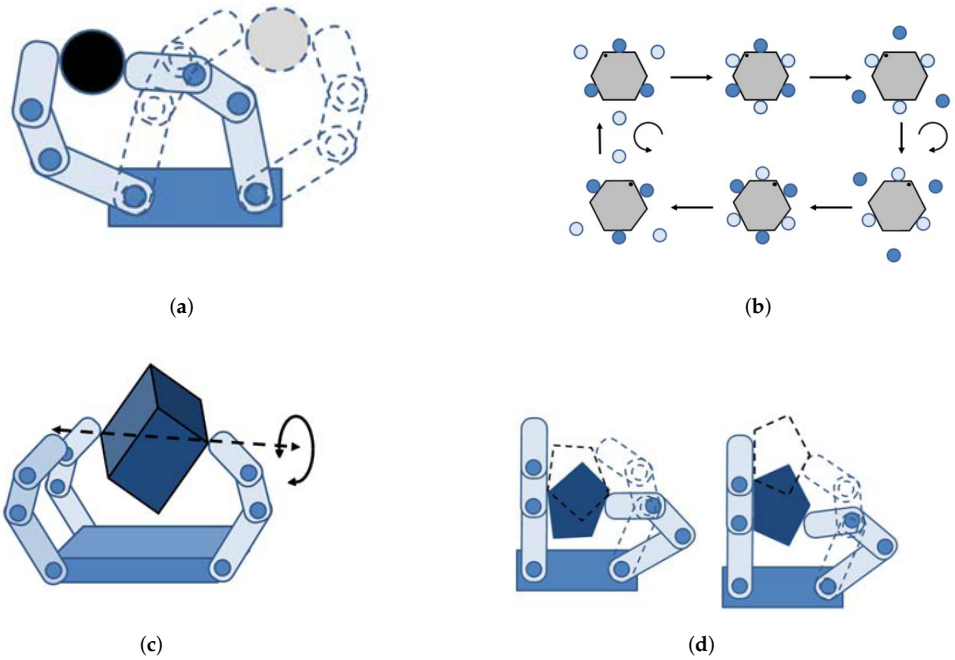


Figure 3. Primitive movements [56]. (**a**) In-grasp manipulation; (**b**) Finger gating; (**c**) Finger pivoting; (**d**) Rolling and sliding manipulations.

3.2. Achieving Dexterity for Soft Grippers

Dexterous manipulation remains a challenge for soft grippers as their structures are commonly under-actuated, making it challenging to perform complex manipulation tasks [59]. However, hand dexterity plays a significant role in both grasping patterns and

manipulation stability. This section discusses how to achieve dexterity for soft grippers, passing through stable or dexterous grasping.

3.2.1. Stable Grasping

To stably manipulate an object, the gripper must be able to grasp it stably. Various strategies have been implemented in order to ensure a stable grip. This part of the article presents some techniques reported in the literature.

Optimization is often a means to achieve dexterity for soft grippers. In [60], the design and performance are optimized by performing a characterization test on casted fingers and comparing the joint displacements with an equivalent simulation set up in the SOFA framework [43] for setup validation. Topology optimization is applied in [61,62] to design new soft fingers capable of grasping various objects. The grasping force and the loading capacity are other characteristics that can be optimized by investigating the effects of the design parameters as explained in [63].

The number of bending segments and, hence, the level of actuation play an important role in the type of grasps achieved. Achieving pinch grasps requires at least two independent bending segments, and actuating the proximal segment lets the fingers achieve precision grasps while uniform actuation, i.e., actuating both proximal and distal segments, allows for power grasps [64]. The fingers of the gripper in [65] contain two independently actuated sections that are aligned on the same axis, making them capable of complex deformations. Adaptive grasping is made possible for the gripper in [66], which also contains two-segment soft fingers. The self-adaptive fingers presented in [67] can adaptively grasp objects and achieve precise angle positioning. They are actuated by tendons which can move two joints independently by controlling two motors.

Soft grippers often integrate active palms that provide firm support and stabilize the grip, as discussed in [66]. The hand proposed in [68] has three actuators in its palm, which confers it with large range motions and force capability. The palm of the bionic soft hand in [69] is capable of mimicking the elongation of the muscles on the back of the human hand, thereby modifying its curvature.

Structure hybridization was previously presented as a way to improve grippers' performances in Section 2.4. The grippers in [62,63,70] combine soft and rigid structures to achieve stable grasping. The gripper in [70] integrates rigid fingernails. The authors proved their hypothesis that rigid fingernails improve precision grasping. The harder outer layers of the pneumatic actuators in [62] impose constraints on the grasped objects, allowing the gripper to perform various grasping tasks. The palm of the soft hand in [69] combines pneumatic actuation with particle jamming, making it capable of stiffness variation, hence improving grasp stability.

Fiber-reinforced air chambers whose cross-section has an ellipse shape reducing the material stress at their edges [65], making the gripper capable of reliably grasping objects of varied shapes and sizes while overcoming external disturbances. The flexion movement of the three palm actuators in [68] was enhanced and constrained with a proposed novel elastic fiber reinforcement.

A motion planning algorithm could also improve grasping stability. In [71], an autonomous motion planning algorithm which encapsulates the object shape and position allows the gripper to autonomously grasp and place a variety of objects at random positions in the system's workspace.

3.2.2. Stable In-Hand Manipulation

Once a gripper is capable of the stable grasping of various objects, some other techniques can be applied to ensure that it manipulates the objects without breaking contacts and that some standard known performances are achieved during manipulation.

According to [24], one reliable way of achieving dexterity with soft grippers is by increasing the DOF space of the end effector. The 3-DOF finger developed in [15] is said to substantially reach a larger area than single-chamber conventional soft actuators, making it capable of various grasping and in-hand manipulations. In addition, the passive compliance of most soft grippers adds a passive reachable area to the active workspace. This idea is better explained in [15]. For tendon-driven foam hands, the possibility of the tendon being routed anywhere along the hand's surface allows complex families of deformations and facilitates dexterous in-hand manipulation [12]. For pneumatically actuated grippers, one way of increasing the DOF space is by increasing the number of pneumatic chambers in the fingers, as explained in [72], where the bio-inspired soft anthropomorphic hand has 22 DOFs.

Dexterity could also be enhanced by the introduction of sensors in the actuator matrix. For example, the soft gripper in [33] uses tactile sensing and active shape-changing to achieve precise in-hand manipulation. The tactile sensors avoid object damage and provide the closed-loop control of the fingertips' positions. The grasping quality of the fingers developed in [21] is increased by the installation of the capacitive tactile sensor developed by the same authors in [73]. They use the sensors' data as feedback for the fingers' control. A force-feedback control method is also used in [32]. They adjust the joint angles or link lengths of their elongatable fingers based on the contact pressures measured by some hyperelastic soft sensors. According to [34], most grippers incorporate force sensors that only detect one direction force. As a result, they propose a six-axis force/moment sensor that detects the force and moment in three directions, i.e., Fx, Fy, Fz, Mx, My, and Mz. Detecting the force in the three directions allows the gripper to safely grasp random objects, while detecting the moment in the three directions allows the gripper to precisely detect the object's position with the gripper.

One other way to achieve dexterity is by setting the axis normal to the palm, parallel to the object's central axis, as explained in [1]. This allows the object rotation and translations to occur in the reference frame attached to the palm. In [26], it is explained that the grippers are configured such that the instantaneous screw axes always intersect at the same point relative to the palm, which produces an instant motion about this common point independent of the object geometry in a stable grasp.

The integration of hybridization strategies that enable attributes to change over time also improves the dexterous capabilities of soft grippers. Figure 4 shows a number of dexterous hybrid soft grippers that are capable of stiffness variation. In [31], the combination of different actuation systems is proven to overcome the weaknesses and shortcomings of soft grippers based on only one actuator system. They combine SMA actuators with DC motors and electromagnets to actuate a soft hand that is capable of grasping objects of different shapes and objects from inside, securing smaller objects, and a higher grip force. In [21], the authors proposed a dexterous finger whose dexterity is achieved by varying the bending point and the stiffness of its soft pneumatic actuator. They argue that the variable effective length of the fingers and their bending capability increases the hand's dexterity. The tunable rigidity elastomeric fingers that constitute the gripper in [55] confer the gripper with twisting manipulations, which enhances in-hand manipulation. The fingers contain programmable ligaments that are composed of conductive thermoplastic elastomers, whose stiffness varies when stimulated electrically or when heated. The LMPA-based soft robotic arm in [30] is omnidirectionally bendable and capable of performing dexterous opening and grasping operations with cable-driven fingers. The bio-inspired soft wrist developed in [74] was based on a

multi-cable jamming approach. The wrist can perform hybrid motion and stiffness control through the actuation of one same muscle. According to the authors, their work is the first one to achieve both motion and stiffness control by driving cables, as their work inherits the advantages of existing jamming methods and easy deployment. The soft–rigid hybrid gripper in [75] is inspired by the human metacarpophalangeal joint and was designed with eight independent muscles. The authors showed that adding this joint enabled the hybrid gripper to perform in-hand manipulation, lateral passive compliance, and new control modes. The gripper had three major control modes that allowed it to achieve a large grasping force, dexterous motions, and stabilized grasping. In [76], they use an algorithm to reposition the gripper's fingertips on the surface of a grasped object. They then search for an optimal grasp state on the object's surface using a manipulability-based metric. The two-finger hand designed in [77] was experimentally proven to be highly adaptable and capable of grasping and manipulating heavy objects, thanks to its reinforced fingers. The soft pneumatic fingers have an embedded rigid skeleton that increases the torsional stiffness up to 300%. According to [78], soft fingertips more efficiently maintain stable contact than some other deformation control strategies. In [79], deformable finger pad designs that have different inner solid structures are proposed. Ref. [80] presents a novel method to model the contacts of soft fingertips in dexterous manipulation. The results of their experiments demonstrate that soft fingertips allow better manipulation performance.

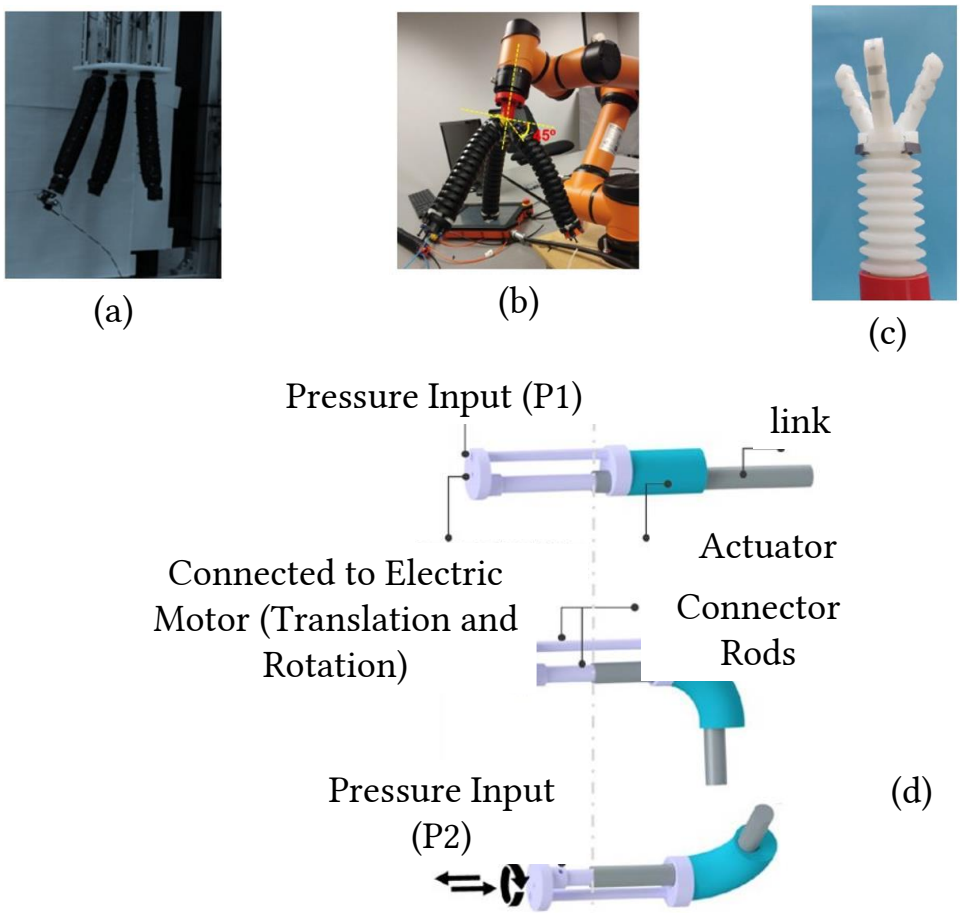


Figure 4. Soft dexterous grippers capable of stiffness variation: (**a**) Soft gripper with McKibben muscles for dexterous manipulations [54]; (**b**) Soft gripper with decoupled stiffness and shape control. Each finger has an articulable rigid backbone and is powered by pneumatic muscle actuators [18]; (**c**) Soft robotic manipulation system capable of stiffness variation and dexterous operations. The robotic arm is made of soft elastomers embedded with low melting point alloys [30]; and (**d**) Dexterous robotic finger with a sliding, rotating, and soft-bending mechanism that maximizes [21].

3.3. Performance Evaluations

For dexterous soft grippers, the most common attribute evaluated is their dexterity. Dexterity evaluation allows the comparison of the performances of different dexterous manipulation approaches and grippers, and even the comparison with the human hand. Since there is no global reference evaluation method to date, this is usually performed individually in each publication. Besides the dexterity evaluation, some other evaluations can be made to give users or readers an idea of the manipulation capabilities of the soft grippers. As shown in Table 2, the maximum force is one of the most reported performance features in the literature. Other evaluated criteria are the workspace, as seen in [15], the bending angle, and the effective length, as seen in [21]. The authors of [81] present an iterative framework that generates and evaluates hand designs for recorded tasks performed by the human hand.

3.3.1. Dexterity Evaluation

According to [57], dexterity evaluations can be classified into real dexterity evaluations that measure the ability of a gripper to perform dexterous manipulation tasks, e.g., opening a vial or manipulating a tool, and potential dexterity evaluations, that measure the elements that enable dexterous manipulation, e.g., the number of DOFs or the number of primitive motions achievable. Moreover, the evaluation of potential or real dexterity in a gripper is determined by what is makeable with its control system. Table 3 presents the dexterity and performance evaluations of different dexterous soft grippers.

Although there is no global reference evaluation method to date, some dexterity measures are common to different reported works. There is a total of 50 dexterity measures for the human hand, i.e., 33 grasp taxonomies (Feix tests), 11 Kapandji tests, and 6 in-hand manipulations (the primitive moments shown in Figure 3), [29].

The Kapandji and Feix tests are common to anthropomorphic hands, for the measurement of their potential dexterity [13,82,83].

Kapandji Test

The Kapandji was initially a test for humans after surgery. The human subject has to touch a set of easily identifiable locations on the fingers with the tip of the thumb [13]. In the evaluation of soft grippers' dexterity, 11 different hand postures are tested while using their thumb to reach the different target regions of the hand [29].

Feix Test

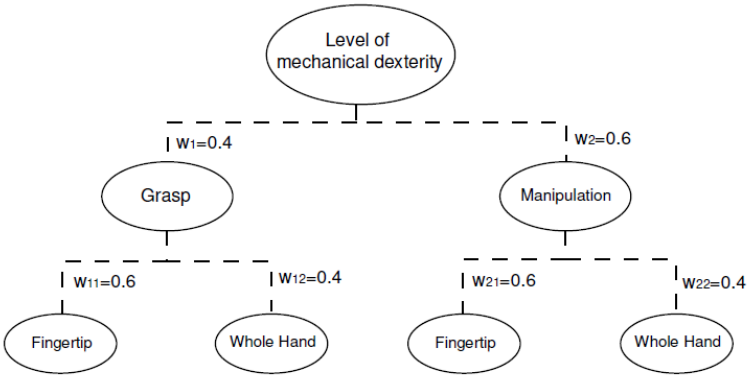
The Feix test [82] was also originally destined for humans. The test is based on the grasping of 33 objects of human daily life. Reference [13] presents the Feix test as the most comprehensive grasp taxonomy to date. The gripper is enacted to perform some or all of the Feix grasps, and can successfully or not make them.

3.3.2. Evaluation of Dexterous Soft Grippers

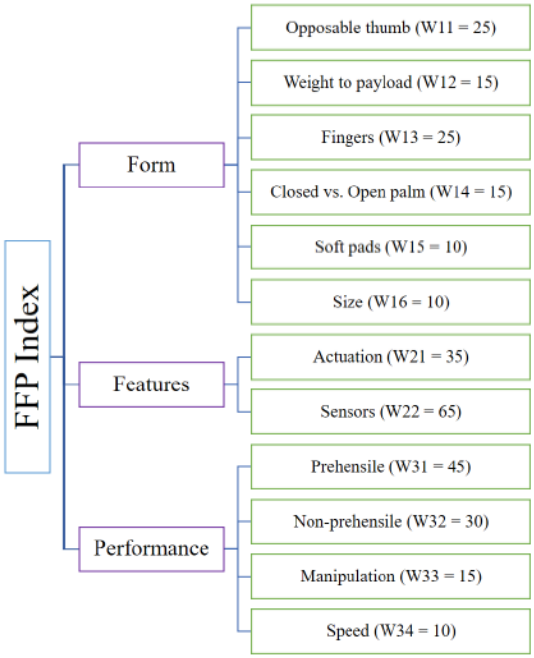
Dexterous grippers can be evaluated based on their level of dexterity, their shape, their characteristics, their performance, and even the control algorithms. The most significant evaluation methods proposed in the literature are as follows:

- Kinematic dexterity level [57]: it is an evaluation based on the grasping and manipulation capabilities of robotic hands. Depending on whether the grasping and manipulation are made with the fingertips or the whole hand, the dexterity is evaluated from 0 to 1, with the weighting shown in Figure 5a.

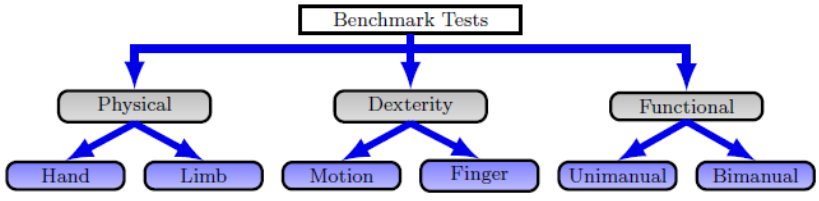
- FFP index [84]: it is an evaluation based on the shape or the form, the features, and the performance of robotic grippers. It evaluates dexterity from 0 to 300 based on the existence or absence of various characteristics. The weighting is shown in Figure 5b.
- Taxonomy of benchmark tasks [85]: it is an evaluation based on the ability of the grippers to perform tasks that measure physical, dexterity, and functional capabilities. The hierarchy of tasks is given in Figure 5c.
- Open grasp suite [86]: it is an evaluation focused on the control algorithms of classical grippers. It is based on simulations with software developed by the authors.



(**a**)



(**b**)



(**c**)

Figure 5. Evaluation of dexterous grippers. (**a**) Kinematics dexterity level [57]; (**b**) FFP index [84]; (**c**) Taxonomy of benchmark [85].

3.3.3. Other Evaluation Criteria

The article [87] presents a set of objects (including the Yale Carnegie Berkeley (YCB) object set) and a number of task protocols with experimental implementation. They chose objects that are frequently used in daily life but also in simulations and experiments. The authors designed a protocol and benchmarks for manipulation. In this protocol, they introduce five categories of information. For the definition of manipulation benchmarking, the authors introduced four information categories. The article also presents five YCB protocols and benchmarks, which include pouring a liquid from a container, doing the pick-and-place task, and others.

3.4. Framework for Characterizing Dexterous Soft Grippers and Their Performance

In this part of our article, we propose a uniform characterization of dexterous soft grippers and their performance based on the different reviewed works. We synthesized the various existing evaluation tests and benchmarks into our tables which can be used to report soft grippers' dexterous capabilities. The gripper characterization describes the gripper by its structural attributes, while the performance characterization precises the dexterity level and dexterous evaluation. In Figure 6, we present some dexterous soft grippers that we sorted based on their dexterity evaluation, the type of actuation, and their architecture.

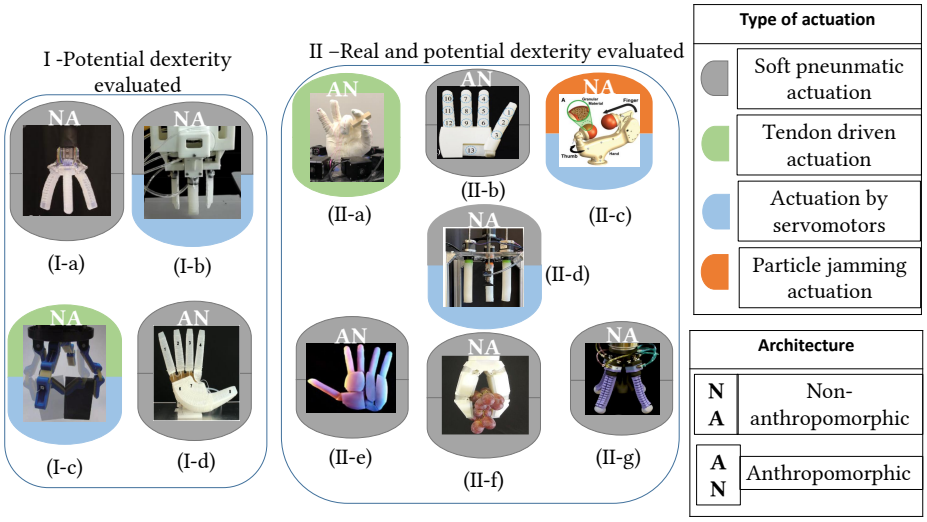


Figure 6. A review of dexterous soft grippers with their dexterity level. (**I-a**) Soft gripper actuated by FEAs, which have embedded ionogel sensors for somatosensitive manipulations [17]; (**I-b**) soft gripper actuated by servo motors and FEAs, with convertible grasping modes [16]; (**I-c**) underactuated soft gripper with tendons and motors for efficient finger-gaiting-based dexterous manipulations [20]; (**I-d**) soft robotic hand (RBO Hand 2) actuated by FEAs for dexterous grasping [13]; (**II-a**) foam hand driven by tendons for dexterous manipulations [12]; (**II-b**) soft robotic hand (BCL-13) actuated by FEAs for dexterous grasping and in-hand manipulations [15]; (**II-c**) the Jamhand actuated by servo motors and particle jamming for dexterous manipulations with minimal actuation [22]; (**II-d**) soft gripper with active palm and reconfigurable fingers actuated by SPAs and servo motors for dexterous in-hand manipulations [88]; (**II-e**) soft robotic hand (BCL-26) actuated by FEAs for dexterous in-hand manipulations [29]; (**II-f**) soft gripper (Edgy-2) actuated by SPAs for robust dexterous grasping [24]; (**II-g**) dexterous soft robotic hand actuated by FEAs for delicate in-hand manipulations [15]. The image shows the type of actuation of the grippers and their architecture.

3.4.1. Soft Gripper Characterization

We propose a selection of physical attributes to characterize a dexterous soft gripper. First, the gripper's architecture is usually a function of the targeted applications. Next, the number of degrees of freedom plays a significant role in dexterous performance, as reported in various works. We then precise the type of contact as it determines the grasp

type, and finally, we highlight the physical achievements of the gripper if assessed by the authors.

Our proposed gripper characterization can be made for any individual soft dexterous gripper, or for a number of soft dexterous grippers in order to compare them as in Table 2 where we selected a number of articles in which we could identify all or nearly all our chosen physical attributes.

Table 2. Characterization of different dexterous soft grippers.

Ref.	Architecture	DOF Space	Physical Performance	Type of Contact
[16]	AN fingers: One finger and one thumb with particle jamming bags in their tips	4-DOF	Maximum lifting mass: 2.5 kg	Fingertip
[12]	AN hands: Foam matrix wrapped by a glove with superficially sewn cables Cable routing depends on the hand fabricated	4–5-DOF	Sliding resistance force: 3.4–5.8 N Depends on the hand evaluated	Finger body
[13]	AN hand: 5 PneuFlex fingers without joints	7-DOF	Maximum lifting mass: 540 g Sliding resistance force: 8 N	Fingertip Finger body
[15]	AN: 4 fingers; rotating thumb base	13-DOF 3 per finger, 1 for the thumb base	Maximum gripping force of one finger: 8.5 N	Fingertip Finger body
[29]	AN hand: 5 fingers, 1 active palm	26-DOF 3 per finger, 11 for the palm	Maximum lifting force: 21.9 N	Finger body Fingertip
[24]	NA: 2 fingers; each finger with two flexible joints	4-DOF	Maximum joint force: 50 N Maximum grip force of one finger: 12 N	Fingertip Finger body
[18]	NA: 3 soft pneumatic fingers surrounded with a nylon mesh	4-DOF (verif) 2 per finger	Maximum lifting load: 5 kg	Finger body

Table 2. *Cont.*

Ref.	Architecture	DOF Space	Physical Performance	Type of Contact
[22]	NA: Three FEA fingers; each bi-articulated	6-DOF	Maximum finger force: 550 mN	Fingertip
[23]	NA: 4 fingers and a movable suction cup	7-DOF	—	Fingertip Adhesion by suction
[21]	NA: 3 fingers with an active changeable palm; suction cup, granular particles	7-DOF 2 per finger, 1 for the palm	Maximum blocking force: 650 mN Maximum bending angle: 90°	Fingertip
[17]	NA: 4 parallel fingers, each finger composed of two parallel chambers	8-DOF	Maximum finger force: 2.3 N on main direction, 1.2 N on laterals	Fingertip
[20]	NA: 2 pairs of fingers; 1 with flexion-based proximal joints the other with pin-base revolute proximal joints the movement of the thumb - Oscillation of a thin rectangular object	9-DOF	—	Fingertip Finger body

AN stands for anthropomorphic and NA stands for non-anthropomorphic.

3.4.2. Performance Characterization

Here, we propose a characterization of a soft dexterous gripper's performances based on the type of experiments carried out for its evaluation. We designed a table in which the authors could report the real and potential dexterity evaluations and any other evaluations performed.

Table 3 shows that simply grasping different objects of varied masses can also help to evaluate a soft gripper's performance, as it is done in [13]. Measuring the fingers' bending angle during actuation like in [88] is also interesting with regard to the gripper's performance. The bending stiffness (measured in $\mathrm{N\,m\,rad^{-1}}$) is evaluated in the variable stiffness gripper developed in [18].

Our proposed table can be made to characterize one gripper's performances, or for a number of grippers, as in Table 3.

Table 3. Performance characterization of dexterous soft grippers.

Ref.	Real Dexterity Evaluation	Potential Dexterity Evaluation	Other Evaluations
[17]	- Opening of a bottle and handling of the bottle and its lid. - Stabilization of the weight of the bottle with a horizontal grip.	Primitive movements that can be performed by hand	Measuring the blocked force during actuation
[16]	- Operating a syringe - Writing with a pen - Opening a padlock - Breaking an egg - Assembling two Lego bricks	Realization of the primitives described in [56].	Maximum object pullout force test
[12]	- Manipulation of objects from within the hand - Rotation between fingers of a piece of wood, a brush, and a cutter	- Possible gripping modes In-grasp manipulation	Maximum object pullout force test
[13]	No tests	- Kapandji test - Feix test	Grasping different objects of different masses Testing different force disturbances
[55]	No tests	- Grasping and twisting manipulation of different objects of different shapes and masses	Measurement of bending force and deflection of the fingertip
[20]	No tests	- Primitive movements that can be performed by hand	—
[21,88]	- Rotation of a Rubik's cube - Pouring from a cup	- Primitive movements that can be performed by hand	Measurement of the bending angle and blocking force under actuation Workspace analysis
[22]	No tests	- Possible gripping modes	Measuring the blocked force during actuation
[23]	No tests	- Four possible gripping modes	—
[29]	- Rotation and translation of a can in the 3 main axes - Writing - Oscillation of a thin rectangular object - Kapandji test - Feix test	- Kapandji test - Feix test	Maximum object pullout force test
[24]	No tests	- Four possible gripping modes In-grasp manipulation	Fingertip and joint forces measured under actuation

Table 3. *Cont.*

Ref.	Real Dexterity Evaluation	Potential Dexterity Evaluation	Other Evaluations
[15]	- Rotation of an object without releasing it - Movement of a ball with two fingers - Rotation of an object with the movement of the thumb - Oscillation of a thin rectangular object	- Kapandji test - Grasping various objects (sphere, cylinder, fruit, etc.)	Force measurement under actuation

4. Discussion

Soft grasping is a branch of soft robotics that allows the manipulation and handling of various objects. It is the evolution of classical grasping towards creating versatile devices for general objects' manipulation independent of their shape or deformability, with a safe interface for humans and the environment.

The most common actuation technology used in soft grippers is FEA followed by servo motor actuation, tendon-driven actuation, SMA actuation, and particle jamming. In the review, both anthropomorphic and non-anthropomorphic grippers appear. The sensors are mainly pressure sensors and some few grippers have tactile, flexion sensors, and force/moment sensors.

Due to the existing limitations in the modeling, control, perception, and manufacture of soft robots, soft grasping presents difficulties in task repeatability, movement precision, and grip force. An approach used to overcome these difficulties is the hybridization of existing technologies. It has been studied to vary soft actuators' stiffness or to improve perception by the introduction of sensors in the actuator matrix. Examples of hybridization strategies have been reviewed in Section 2.4, along with Figure 2 and Table 1. Different solutions have been reviewed in Section 2.4, Figure 2, and Table 1, which compare the performance of various hybrid grippers.

Soft grippers' dexterity depends on their capacity to manipulate an object in 6 DOFs. With this criterion, among the reviewed grippers, the BCL-26 developed in [29] stands out with its 26-DOF space, and its maximum lifting force of 21.9 N, making it a performant gripper.

For all the grippers, the reported achievements are normally related to maximum forces. Other achievements, such as the bending angle, the sliding resistance, and the workspace, are equally reported. Regarding dexterous manipulation, real dexterity is not evaluated in all cases, and is normally evaluated with real tasks. On the other hand, potential dexterity is mostly evaluated by performing the feasible primitive movements discussed in Section 3.1 and the evaluation techniques exposed in Section 3.3.1. In future works, it could be interesting to develop a formalism between these two aspects to improve the design of dexterous soft grippers.

A number of methods are proposed for dexterity evaluation or the ability to manipulate various objects skillfully. These methods can be classified into real dexterity and potential dexterity. Moreover, the evaluation of potential or real dexterity in a gripper is determined by what is makeable with its control system. The authors in the literature have not yet chosen a global reference method for this. Thus, dexterity assessment has been performed differently in each publication. In terms of a specific assessment of grippers, anthropomorphic hands typically measure potential dexterity with the Kapandji test, and in general, the Feix test is used as a measure of potential dexterity. Various manipulation

tasks like opening a bottle, writing with a pen, breaking an egg, rotating a rubric cube, pouring from a cup, and others, helped assess real dexterity.

Overall, this review points out the relationship between the degrees of freedom and the corresponding type of dexterity, potential or real. The survey proves that soft grippers which pass potential dexterity tests are capable of real dexterous manipulations.

5. Conclusions

We proposed a general exploitable approach for the characterization of dexterous soft grippers and their performance.

The use of active material properties to vary the stiffness of completely soft fingers could have the advantages of both soft fingers for better adaptability to the object's shape and the advantage of grasping stiffness (or structural rigidity) in the presence of external forces. Following this lead would be interesting to explore other hybridization strategies in further studies. The contributions of hybridization in dexterous manipulation and their modeling should also be investigated to seek the better precision and repetition of tasks. To increase grasping accuracy, tactile or external sensors can be used in future works, and the real-time and synchronous control of the soft fingers can also be addressed.

One other evolving technology, machine learning, should be exploited to overcome the current limitations of soft dexterous grippers. Using machine learning in soft robotics could improve control strategies, apprehend multi-material integration and nonlinearities, and allow for rapid computation to generate control inputs.

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