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# Mechanisms for Robotic Grasping and Manipulation

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## Keywords

robotic hands, manipulation, intrinsic dexterity, extrinsic dexterity, grasp quality, anthropomorphic grippers, compliant grippers, soft grippers, underactuation, physical interactions

## Abstract

This article reviews the literature on the design of robotic mechanical grippers, with a focus on the mechanical aspects, which are believed to be the main bottleneck for effective designs. Our discussion includes gripper architectures and means of actuation, anthropomorphism and grasp planning, and robotic manipulation, emphasizing the complementary concepts of intrinsic and extrinsic dexterity. We also consider interactions of robotic grippers with the environment and with the objects to be grasped and argue that the proper handling of such interactions is key to the development of grasping and manipulation tools and scenarios. Finally, we briefly present examples of recent designs to support the discussion.

## 1. INTRODUCTION

Since the beginning of robotics, the interaction of robotic manipulators with their environment has been the subject of numerous investigations. One of the earliest and most obvious uses of robots consists in picking up objects and placing them at a predefined destination. Therefore, grasping has been and continues to be one of the primary tasks assigned to robots. The design of a robotic gripper can be as simple as an electromagnet mounted on a crane to pick up metallic objects, or as complex as advanced articulated hands (e.g., 1) or in-hand prostheses (2) with multiple degrees of freedom (DOFs). Complex designs include many mobile parts and can manipulate objects, interact with the physical environment, and in some cases give feedback to the robot or user (3).

Although a plethora of grippers can be found in the literature, ranging from simple to very complex, research initiatives in this area continue to abound. One of the reasons for this continued research is that, so far, no single gripper is capable of performing every possible grasping or manipulation task; even when considering only grasping tasks and leaving aside manipulation, none of the solutions proposed thus far can claim to be able to grasp any part in any scenario that lies within human capabilities. As a consequence, many specialized grippers dedicated to very specific tasks are used in industry. Some of these tailored solutions are even developed by the users themselves.

A significant hindrance in the design of general-purpose grippers is that it requires expertise across multiple fields, including mechanical engineering, electrical engineering, software engineering, computer science, and in some cases biomechanics. Further increasing the difficulty is that the design requirements and the design approaches themselves are not well defined. For example, should a designer try to categorize the potential tasks using a taxonomy (4, 5) and plan the features of a gripper based on the performance of such tasks, or should the design be completely task independent and focus on allowing fingers to move freely with several DOFs to adapt to any unforeseen task? Should the contact situations with the environment be considered from the outset? Does the successful performance of certain difficult tasks guarantee the ability to perform simpler general-purpose tasks? This problem is illustrated in **Figure 1*a***, where it is not clear whether the task defines the gripper or the gripper defines the task. The same dilemma arises when addressing the sensing needs at the mechanical level, as illustrated in **Figure 1*b***. For example, should a sensor be mounted on a finger to detect a contact with the environment, or should the structure of the gripper be designed to produce smooth, compliant contacts without explicitly needing to detect such contacts?

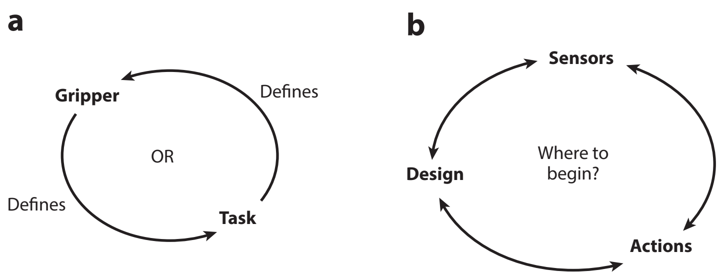


**Figure 1**

(*a*) One of the chicken-and-egg problems of robotics: Does the task define the gripper, or does the gripper define the task? (*b*) How should sensors factor into mechanical design? For example, should a sensor on a gripper be able to detect contact with the environment, or should the gripper be designed so that it can make contact without requiring sensors?

This article reviews the state of the art in mechanisms for robotic grasping and manipulation; more specifically, it addresses these from the point of view of gripper design and the mechanics of grasping. We briefly discuss sensing issues, but only in the context of their direct relevance to the mechanics of grippers. Piazza et al. (6) presented a comprehensive review of robotic and prosthetic hands, and the scope of the present article is different in that it focuses on the grasping action itself. Instead of attempting to categorize the different aspects of gripper design with respect to the engineering disciplines involved, the article is organized according to concepts. In Sections 2–4, we review the mechanical principles used in gripper design and highlight their impact on the features of the grippers, with a focus on relevance to recent research. This discussion includes an overview of the different structures used to build fingers and hands (Section 2), the means of actuation and transmission and the mechanisms that produce certain behaviors in order to adapt to the shape of objects (Section 3), and a brief overview of the use of sensing in mechanical grippers (Section 4).

We then address the morphology and kinetostatics of grippers. Naturally, robotic grippers are often compared with the human hand, which may be considered the holy grail of dexterous manipulation. Section 5 describes anthropomorphic grippers and their features, and Section 6 reviews grasping behavior based on statics and how this approach can be used to obtain efficient algorithms.

Robotic manipulation with grippers is reviewed in Sections 7– 9. This multidisciplinary field of research considers the manipulation of objects using either the mechanical features of the gripper itself (intrinsic dexterity) or the interaction with the environment by taking advantage of features and phenomena that are exterior to the gripper (extrinsic dexterity). Considering the interaction of grippers with the environment—and not only with the objects to be grasped—is a relatively recent trend that has opened the way to novel gripper concepts capable of performing tasks that were otherwise not possible (7–10).

Finally, Section 10 discusses the reasons behind the prevalence of some robotic solutions and the hurdles to robotic implementation; this section covers insights into the trade-offs of performance versus complexity versus robot awareness and describes implementation issues and recent trends. Section 11 concludes the article.

## 2. GRIPPER ARCHITECTURES

By nature, grasping involves a mechanical interaction between a gripper and an object to be grasped. The basic principles of mechanics are therefore at the core of this interaction. These principles can be exploited and the solutions implemented in a variety of ways, yielding several families of grippers (11), and here we describe different types and components of robotic grippers based on their mechanical features. These features are used not only in robotic grippers but also in other robotic mechanical systems, and therefore, they can be explained without the need to present the complete mechanical system in which they are used. Although the classification used here is somewhat arbitrary, it constitutes an attempt to provide an overview of existing grasping approaches.

### 2.1. Linkage-Based Finger Mechanisms

Much like robot manipulators, finger mechanisms can be based on linkages composed of rigid bodies connected by kinematic pairs (joints) and can be classified as serial or parallel mechanisms. In serial mechanisms, each link is attached to at most two other links, and a single open kinematic chain is defined from the base to the fingertip (**Figure 2*a***). As such, the number of DOFs of a finger mechanism based on a serial linkage is usually equal to the number of phalanges. Serial architectures are popular in prosthetic hands because of the reduced number of parts needed,

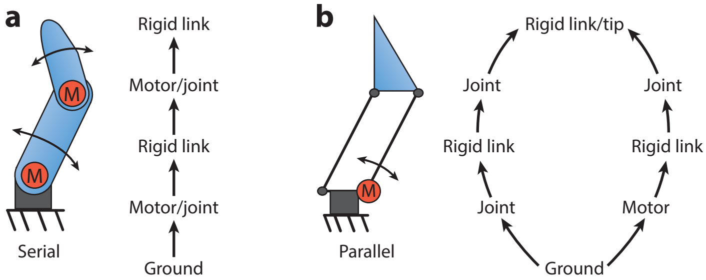


**Figure 2**

Examples of (*a*) a serial mechanism and (*b*) a parallel mechanism used in the design of a finger mechanism for robotic grippers. Abbreviation: M, motor.

which in turn yields lighter, more compact architectures (12). Parallel architectures of finger mechanisms, by contrast, are more popular in industrial settings (13) (**Figure 2*b***). This type of architecture uses more complex kinematic chains, in which a given link may be connected to more than two other links. The DOFs of such fingers may differ from the number of phalanges because of the kinematic constraints introduced by the complex linkage.

## 2.2. Underactuated Grippers

In both serial and parallel architectures, the number of degrees of actuation (DOAs) of a finger, which corresponds to the number of actuators, may differ from the number of DOFs of that finger. Indeed, in fully actuated fingers, in which the number of DOAs is equal to the number of DOFs, the configuration of all components of the finger is uniquely determined by the actuator coordinates. By contrast, in underactuated fingers, in which the number of DOAs is smaller than the number of DOFs, the configuration of the finger at a given time depends not only on the actuation state but also on the interaction of the finger with the environment or the object to be grasped. Underactuated fingers have been the subject of numerous investigations over the past several decades, mainly because of their ability to naturally adapt to the shapes of objects and because of the reduced number of actuators that they require (14).

Linkage-based fingers and tendon-driven fingers are often underactuated in order to reduce the number of actuators and allow the gripper to naturally adapt to the shape of the grasped object under the effect of the interaction forces (14, 15). This property is sometimes referred to as mechanical intelligence (16). Underactuated grippers behave similarly to soft grippers (discussed in Section 2.4), the distinction being that underactuated grippers have a finite number of DOFs, while soft grippers behave as continuous media undergoing continuous deformation.

In underactuated fingers, even if the actuators are locked, the fingers can still move under the action of external forces. The desired grasping behavior is therefore established at the design stage based on kinetostatic analyses and the use of elastic components (e.g., springs) and mechanical limits. A typical grasping sequence of a simple underactuated finger is illustrated schematically in **Figure 3**. As can be seen in the figure, the contact of an object with some of the phalanges drives the motion of the finger, thereby producing a natural grasping behavior. Many underactuated grippers have been proposed in the literature (e.g., 14, 15, 17–23). Underactuation is obtained using a variety of means, including linkages, gearing, and pneumatics, among others. Underactuated grippers are believed to represent an effective compromise among flexibility, simplicity, and performance in many situations.

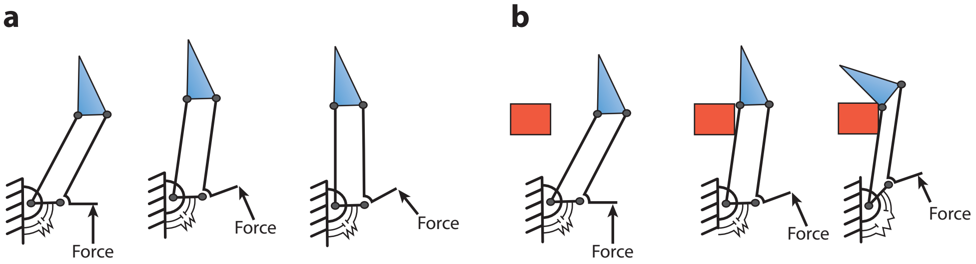


**Figure 3**

(*a*) Finger closing sequence with no object. (*b*) Underactuation closing sequence activated by contact with an object.

## 2.3. Compliant Grippers

Compliant mechanisms are mechanisms in which relative motion is produced by the elastic deformation of components instead of by conventional joints (24). The main advantages of compliant mechanisms are the elimination of the clearance and backlash, which are inevitable in conventional mechanical joints. This approach can be used advantageously in the design of grippers to reduce the number of moving parts, produce compact designs, and shorten the fabrication-to-application cycle (25–28). With the rise and accessibility of additive manufacturing (3D printing), the use of compliant mechanisms in grippers is becoming attractive since, for instance, a finger or a planar gripper can be printed and be ready to use immediately. Nevertheless, there are drawbacks to the use of compliant mechanisms in grippers, such as the force needed to deform the articulations and the increased complexity of the kinetostatic analysis of the interaction between the gripper and the environment. Also, the motion produced by compliant mechanisms is more difficult to model than that of articulated mechanisms, since most designs require using complex finite element analysis.

Another class of compliant mechanisms, origami-inspired structures, has been proposed in order to create arrangements that are flexible only in specified directions. Lee et al. (29) presented an example of a gripper based on this type of design.

## 2.4. Soft Grippers

The types of grippers discussed so far are built using rigid components (possibly articulated with compliant joints), which provides relatively predictable and controllable mechanisms. However, such grippers may not be appropriate for tasks in which the object to be grasped or the environment in which the gripper is used is delicate and requires soft handling. An example of such an application is fruit harvesting. A more appropriate approach in such cases consists in using so-called soft grippers. Soft grippers are made of soft, compliant material and are designed to distribute the grasping contact loads over surfaces that are large enough to reduce the local contact stresses. One of the main features of soft grippers is their low stiffness. Hence, in addition to limiting the grasping stresses, soft grippers' low stiffness and ability to absorb impact energy help protect against impact forces in the event of a collision between the gripper and its environment. Soft grippers may be seen as one instantiation of the more general concept of soft robotics (30).

Many soft gripper designs have been proposed (e.g., 17, 22, 31). Several of them use air as a means of powering the gripping action. For example, Wang et al. (32) used a pneumatic system to drive the closing motion of the fingers, and the compliant nature of these fingers enables them to adapt to object shapes. Moreover, since air can also be used for vacuum purposes, the fingertips can be equipped with suction cups that use vacuums to help them more securely grasp objects if necessary. This approach is an example of the exploitation of a single power source for multiple grasping actions. Other works have taken a similar approach, using a centralized source of power to drive not only the fingers but also the palm of the gripper in a soft pneumatic manner (31). The palm mechanism adds to the complexity of the design but increases closing speed and grasping force and allows a greater variety of grasp types.

### 2.5. Grippers with Active Surfaces

Some grippers use active surfaces to move the contact points along the phalanges of fingers after an initial contact is established. This tangential motion of the contacts is produced by active belts or tracks (33–35). This feature enables the gripper to reposition objects directly and continuously. In some of the proposed designs, the belt surfaces cover extensive portions of the fingers, which yields the ability to manipulate flexible fabric lying on hard surfaces (33). Active surfaces have also been used to switch the contact mechanism from locked to unlocked, allowing the influence of the friction force on the grasp to be activated or deactivated (36).

Jamming grippers are a class of active-surface grippers that act in a more soft or deformable fashion. Their principle can be described as follows. Consider gripper fingers that approach an object from the top and make contact with some points on the object to perform a pinch grasp. Before the object is lifted, the grasping forces are coplanar and horizontal. However, a vertical force directed upward is needed to lift the object. This force is typically the static friction force resulting from the contacts with the object. Jamming grippers can take advantage of the friction force by first applying forces at the contact points located around the object through soft, deformable mechanisms or membranes. Once a sufficient pressure is achieved, the jamming mechanism is activated. This mostly locks parts of the mechanism in place or deforms contact membranes in order to maximize the area of the surface in contact with the object. The gripper is then lifted, and since some relative movement occurs at the contact points, friction forces appear to counter this movement, and a lifting force is generated. The universal jamming gripper (37) takes advantage of the friction coefficient in this manner by using granular material inside a soft membrane activated by pneumatic actuation. Nishida et al. (38) later presented a variation of this design that uses magnetorheological fluids instead of air to activate the membrane. Similarly, arrays of pins have been proposed to create walls around an object, and as the pins are twisted, a jamming of the object occurs (39).

Another type of active surface consists in using electrostatic forces to grasp objects (40–42). This approach is used mainly for objects that are otherwise difficult to grasp, such as pieces of fabric. However, it cannot be used for objects that are sensitive to static electricity, such as electronic components.

## 3. ACTUATION AND TRANSMISSION

The preceding section presented different mechanisms used in the design of grippers. These mechanisms each have kinetostatic properties that influence the transmission of the power from the actuators to the fingers. In addition to these characteristics, it is necessary to consider the properties of the actuators themselves as well as the transmission from the actuators to the fingers. The types of actuators most commonly found in grippers are electrical, hydraulic, or pneumatic (43). Electrical actuators are generally preferred because they are convenient and easy to integrate into robotic grippers. Nevertheless, because grippers are mounted at the end effector of a robot (or included in a prosthesis), their mass should be minimized in order to avoid taxing the payload capability of the robot (or the human user). Hence, small motors with large reduction gear ratios are typically used in order to reduce the mass of the gripper while allowing reasonable grasping forces. However, this design approach has the disadvantage of reducing the speed at which the fingers can move and react. Very fast (44) or very strong (45) robotic grippers can be obtained but require compromises.

Since the actuation is often connected to a single port of entry of a finger mechanism, many research results on actuation and transmission mechanisms can be used in the design of robotic grippers. As an alternative to more conventional transmissions, clutches based on magnetorheological fluids have been proposed to transfer power from a single power source in a robot to multiple actuators. This approach has been applied to a robotic hand powered by the same source as the robot (46).

In an ideal mechanical system, a continuously variable transmission allows the adaptation of the reduction ratio to the task to be performed, e.g., moving fingers in free space quickly or applying large loads for a grasping action (47). However, such a complex transmission is difficult to include in a gripper because of the need for compactness and the limited power available. Instead, alternative solutions have appeared that use modes of transmission in order to adapt the behavior according to the context. An example of this approach is the use of cables that can rapidly pull the finger during free motion and are then twisted when contact occurs, thereby applying much larger forces on the finger for the grasping action itself (48, 49).

### 3.1. Tendon- and Cable-Driven Grippers

As an alternative to linkage-based transmissions, cables or tendons can be used to physically connect actuators to robot or finger links or phalanges. The use of tendons or cables to drive a finger mechanism usually leads to very compact designs, which is an advantage for prosthetics in particular, since compact fingers are desirable for aesthetic reasons. As shown by Mason & Salisbury (50) and Lee & Tsai (51), tendons need to be maintained in tension, which can be accomplished using systems of pulleys with additional actuators or passive elastic return mechanisms (52). Tendon-driven grippers can be fully actuated or underactuated. Cable-driven fingers that do not use articulated phalanges can also be built, using, for example, the concept of tensegrity (53). Such an approach has the potential to yield very light and compliant fingers, although the design of stable and effective tensegrity mechanisms remains a challenge, especially in the context of grasping, where interactions with the environment must be considered.

### 3.2. Remote Actuation

Whether they are used as hand prostheses or with industrial manipulators, size and mass constraints are prevalent in the design of robotic grippers. In the case of prostheses, it is evident that the size should be similar to that of the human hand. In industrial applications, the requirements are imposed by the tasks (e.g., bin picking or assembly tasks may require a small hand that can reach occluded and constrained zones) or by the payload to be handled (which may call for a light design). One issue influencing all of these aspects is therefore the placement of the actuators, which are typically some of the heaviest components of a gripper.

A design approach that leads to light and compact hands consists in relocating the actuators away from the hand and transmitting the actuator motion via cables or other transmissions, as in the Utah-MIT hand (54). As shown in **Figure 4*a***, if multiple actuators are used, moving them to the forearm results in a smaller hand design while requiring a complex transmission to link the actuators to the gripper. In more recent designs, the actuators are located in the forearm and wrist, as seen in **Figure 4*b*** (55), although this still leads to a large number of actuation modules in grippers with a large number of DOAs.

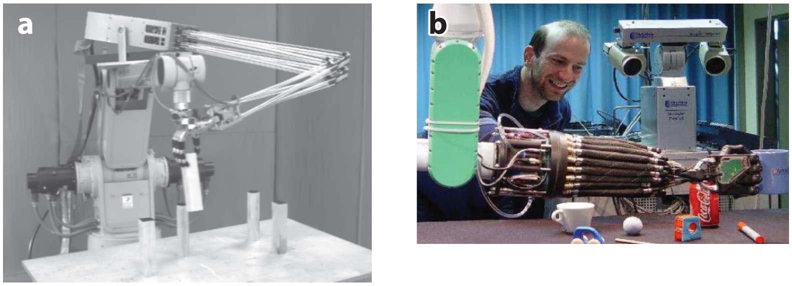


**Figure 4**

(*a*) The Utah-MIT hand, which has the actuation moved to the forearm. (*b*) The Shadow Dexterous Hand, which has a built-in forearm and wrist. Panel *a* adapted from Reference 54 with permission from World Scientific Publishing; permission conveyed through Copyright Clearance Center, Inc. Panel *b* adapted from Reference 55 with permission from IEEE; copyright 2007 by IEEE.

Parallel robots are especially appropriate for actuating grippers remotely (56, 57). To this end, extra DOFs can be added in the design of the mechanical architecture, and hence all of the actuators of a robot (including the gripper actuators) can be mounted on the base (56). This can limit the effective workspace of the manipulator, but such problems can be alleviated by the extra DOFs, as shown by the designs presented in **Figure 5** (58, 59).

## 4. SENSING

Sensing in manipulation and grasping is a broad topic (for a recent review, see 60), and this article does not claim to cover it. Robotic grasping may use a wide variety of sensing modalities, ranging from the use of joint encoders to devices that capture more external measurements, such as camera-like sensors that are used to monitor the robot, the gripper, and the workspace. Some researchers have even used radars to infer the position of a gripper in order to monitor its relations with the environment (61). In the manipulation of fragile objects, forces can also be measured directly on a human expert and then used as a prediction model for the robot to follow (62).

In robotic grippers, contact forces are sometimes measured directly at the fingers, hence the use of tactile sensors (see, e.g., 63–67). Such sensors are used in cases where the accurate manipulation of an object is required and the inference of the contact forces through the motor torques is not precise enough.

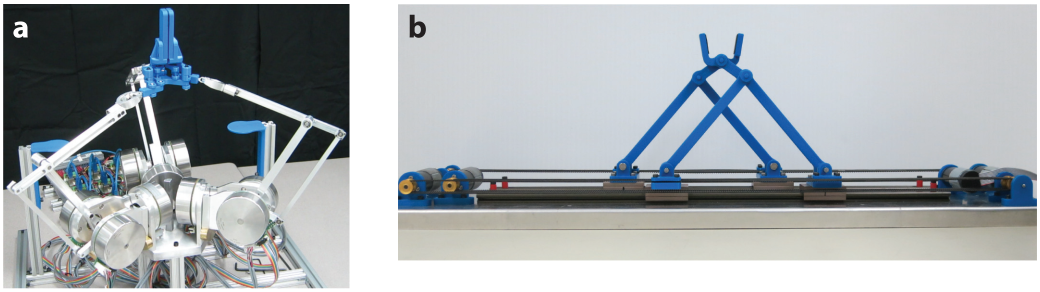


**Figure 5**

(*a*) A (6+3)-DOF redundant robot with all of the motors mounted at the base; the gripper is operated by the base actuators. (*b*) A (3+1)-DOF redundant robot with all of the motors mounted at the base; the gripper is again operated by the base actuators, and the end effector has unlimited rotatability. Abbreviation: DOF, degree of freedom.

Nevertheless, as pointed out by Yamaguchi & Atkeson (60), tactile sensing is not commonly used in robotic grippers, especially in industry. There can be several reasons for this situation, including the added complexity, the difficulty of interpreting tactile sensing information, the lack of robustness of the sensors, and the trend toward simple, rugged grippers. Also, even if tactile sensors are used, proper grasp planning requires an insightful knowledge of the mechanics of the grasping tasks.

## 5. ANTHROPOMORPHIC GRIPPERS

The resemblance of a robotic hand to the human hand, based on its kinematics, its contact surfaces, and its size, can be used to assess its level of anthropomorphism (68). In fact, the three main characteristics on which anthropomorphism is evaluated are (*a*) the presence of morphological features such as an opposing thumb, a palm, fingers, and phalanges; (*b*) the movement produced when grasping and its similarity to the behavior of the human hand; and (*c*) the size of the hand compared with that of the human hand (43). This combined metric takes into account the finger movements, the interaction with an object, and the size and weight of the hand. In other words, according to this metric, anthropomorphism goes beyond simple shape and size comparisons. Given the mechanisms involved in the human hand (69), it is not surprising that designs that achieve comparable size and weight to a human hand also make use of tools such as underactuation, cable-driven transmissions, and remote actuation (70).

## 6. GRASP PLANNING

The planning of grasps is also an important issue. For a given gripper and a given object, the success or failure of a grasp is highly dependent on the approach taken to seize the object. From a purely geometric perspective, one possible approach is to use caging, i.e., finding a gripper configuration that will guarantee that the object cannot escape (71). We should point out that caging is different from grasping per se, since caging does not necessarily imply that the object is rigidly constrained by the gripper.

Grasp planning usually involves more than the shape of the object and the finger trajectories. The kinematics of the object and the gripper and their interaction must be considered (72). In this context, grasp planning is a complex problem even if the geometry of the object and the gripper are known beforehand. Grasp quality indices have been proposed to characterize the quality or effectiveness of different possible grasps (72, 73). Grasp quality indices can be used as cost functions for design, planning, or benchmarking purposes. Grasp analyses usually focus on statics, but as algorithms become more effective and manipulator performance increases, solutions taking advantage of the dynamics of robots may appear. Hence, the dynamic effects acting on an object, and consequently their effects on grasps, can be taken into account (74). Grasp planning is intimately connected to the benchmarking of grippers (75) and to their design. Even studying how to design grippers that are optimal at failing to grasp has provided insight into new designs and grasp protocols (19). As grasp indices and algorithms for grasp and manipulation planning have been proposed, studies have emerged that compare these algorithms (76, 77). In recent years, methods have also been proposed that use expert examples to obtain better grasp planning algorithms (78, 79). Efforts have also been devoted to finding alternatives to deep learning in order to investigate methods tailored to applications such as grasping (80).

One issue in evaluating grasp properties is that the gripper capabilities have a strong influence on the possible grasps, and this is not always considered when grasps are proposed. To alleviate this limitation, researchers have proposed algorithms that take gripper and object properties as input parameters (81). This approach addresses the need for algorithms that can be used following gripper upgrades, i.e., upon the implementation of mechanical improvements in the gripper.

## 7. ROBOTIC MANIPULATION

To perform complex tasks, grippers may need to be able to perform in-hand object manipulation, i.e., producing motions of the object relative to the gripper in a controlled fashion. In-hand manipulation remains challenging (82), especially in situations where the objects are not known a priori. One possible technique is the walking finger approach, in which fingers are successively repositioned on the surface of the object to move it (83). This type of manipulation, while intuitive, is complex to implement in a robust and precise way because of the overwhelming number of factors involved. For this reason, some research initiatives focus on the use of deep learning to achieve manipulation (84). Manipulation in a cluttered environment, in which objects must be picked up from piles and access to the predetermined optimal contact points is not always feasible, is also an ongoing topic of research (85). More top-to-bottom studies have focused on taking into account the motion planning of the robot and the grasp planning together to maximize global performance (86). In-hand manipulation can relieve the reliance on the robot arm for fine repositioning tasks and may also lead to more precise placement due to the scale of the hand relative to the arm. If certain aspects of the environment are uncertain, it can also be safer to use the actuators of the hand to carry out precise low-force adjustments rather than using the whole robot arm (35). Manipulation algorithms can take advantage of both the gripper and the robot and its environment. Therefore, a distinction must be made between the manipulation capabilities that arise from the features of the gripper itself and those that arise from the robot or the environment: The former provide intrinsic dexterity, while the latter yield extrinsic dexterity.

### 7.1. Intrinsic Dexterity

Intrinsic manipulation refers to the manipulation of objects using only the features of the gripper. As mentioned above, such an approach typically relies on the walking finger approach. However, alternative solutions exist, such as the use of rollers mounted on the fingers (35). In this approach, the manipulation problem can be viewed as having points navigating the surface of an object in a kinematic way. Nevertheless, challenges arise from discontinuities in the surface of the objects and the conditioning of the Jacobian of the manipulation task. Even when using active surfaces for manipulation purposes, architecture and kinematics play a significant role in dexterous tasks (35). Similarly to robot arms, different architectures yield different manipulation capabilities, and a universal design that would cover all possible situations is not yet available.

### 7.2. Extrinsic Dexterity

Extrinsic dexterity refers to the use of resources that are not intrinsic to the gripper and hence complements intrinsic dexterity (9). Such resources may include the dynamic capabilities of the robot, gravity, friction, contact surfaces in the environment, and the inertia of the objects. Recent work (9) has taken advantage of these external features to create a cage around an object or to exploit the dynamic capabilities of the robot and the object inertia to reposition the object within the hand. Extrinsic dexterity also applies to the grasping of objects in difficult environments; for instance, the surface on which an object is lying can be used to devise maneuvers that allow a gripper to pick up the object, as in the case of flat objects resting on a flat surface (7, 8, 33, 87). Another example of the application of extrinsic dexterity for grasping is a dexterous finger roller mechanism that takes advantage of the surface to pick up pieces of fabric (33). In some cases, extrinsic manipulation (88) can be used to move objects using friction and a stick in a precise and predictable manner, leveraging the model of the process.

## 8. INTERACTIONS WITH THE ENVIRONMENT

Robotic grippers are used in a wide variety of applications involving very different physical environments. Even though some robotic grippers and hands are capable of advanced motion (e.g., in-hand manipulation), they are not necessarily adequate for interactions with different types of environments. The stiffness of the environment is an important characteristic to be considered in the development of interaction capabilities. In industrial applications, environments are often very stiff. For example, the assembly of stiff components with tight tolerances is a challenge (89). Even though a precise robot arm is used together with a very precise gripper, it may be difficult to guarantee a successful operation. Jamming and collisions may occur, which could damage the parts or the gripper. One possible option to alleviate this problem is to modulate the joint stiffness of the robot (90, 91). Other options include the use of force/torque limiters, which disengage following a collision to prevent large forces from being generated (92, 93). Soft grippers are particularly appropriate for interacting with stiff environments because of their inherent low stiffness. However, this low stiffness also has drawbacks, as discussed in Section 2.4. Yet another recent approach to interact with a stiff environment is directional compliance. Based on this concept, a gripper can be designed to be flexible if forces are applied in certain specific directions while being stiff in other directions. Combined with a proper motion and grasp planning, this approach yields smooth, safe, and manageable contacts with the environment while allowing the performance of difficult grasping tasks (7, 8).

In field applications (e.g., in agriculture), environments are often more complex but also more compliant. For example, picking strawberries requires that the grasping action be performed with limited contact forces so as not to damage the fruit. However, the pulling motion may require significant forces, and hence an extensive study of the task must be completed beforehand (94). In another approach, instead of trying to reproduce the expert motion, the design of the gripper can be specialized for the task at hand, and hence many of the unknowns can be controlled at the design phase. This approach leads to highly specialized designs that excel at the targeted task, which are simpler to use because of the reduced set of possible movements (95). Finally, yet another option is to tailor the system to the task such that the interaction with the environment is minimal—for example, by using caging around the fruit and cutting the stem, enabling the gripper to leave with the object in hand without further manipulation (96).

We should also point out that the analysis of the results of the Amazon Picking Challenge shows that the success rate in bin picking is maximized by avoiding interaction with the environment as much as possible (by reducing the footprint of grippers) and using suction as much as possible (97). Although this observation may discourage researchers from pursuing further work on the design of advanced grippers, it should be kept in mind that current and future applications of robotic grippers extend far beyond bin picking. Moreover, many applications require interacting with the environment and controlling the pose of an object or tool with respect to the gripper, thereby justifying more complex and advanced grippers.

## 9. INTERACTIONS WITH HUMANS

Physical human–robot interaction is currently a popular research topic due to its great potential in many applications, ranging from manufacturing to personal robotics. Among other physical modalities, humans and robots can interact through grippers in a variety of ways. Examples of such interactions include operating a robot and gripper remotely using wearable devices (98) and using exoskeletons (99, 100). In a remote or direct control setting, information such as forces, positions, and stiffness can be rendered to the user via feedback through a haptic device (see, e.g., 101).

One useful task that can be performed by a robot is a so-called handover task, in which a robot holding an object is required to hand it over to a human coworker (102–104). By its nature, the handover task involves a robotic gripper. This task can be streamlined because the task is known and controlled until the object is grasped by the human being. The main challenge is then the detection of the user's actions in order to trigger the opening of the gripper and the timely release of the object. Performing this task the other way around, however, is much harder, because humans do not hold objects in a perfectly still manner and because the safety of the user must be assured in the process.

Interactions between humans and robots through grippers are not limited to handovers. In some cases, it is the very interaction of a human with a robot that is studied. With the aim of designing robots that can mimic as much as possible some aspects of the interaction between humans, some studies have been focusing on the human handshake (105). In this context, highly specialized robotic grippers have been developed to produce a handshake that is convincingly human (106–108). Several aspects, such as hand size, finger pressure, palm pressure, and skin stiffness, must be taken into account for this type of application (109). A Turing test for the robotic handshake is also the subject of recent research (110).

## 10. IMPLEMENTATION CHALLENGES AND RECENT TRENDS

Despite all of the advances reported in the preceding sections, the ability of robots to grasp general objects in unstructured environments remains far from that of humans (111). In fact, most robots used in the field have very little interaction with the environment, for several reasons. Consider first the most encountered types of grasping solutions implemented in the field: the vacuum gripper and the parallel pinch gripper (**Figure 6**). The main reason that these solutions are so commonly used is the simplicity of their implementation. More precisely, when using such devices, one property that greatly simplifies the grasping procedure is its decoupled nature: The robotic arm moves the gripper to a given location, and the gripper is then activated, but these two actions never occur concurrently. In a typical grasping procedure, the gripper is positioned close to the target object, the arm is stopped, the grasping mechanism is activated, and finally the manipulator moves away with the object in hand to a selected position. It is then evident that the manipulator and the gripper are never active at the same time—i.e., their actions are completely decoupled and do not require coordination, reducing the complexity of the task planning

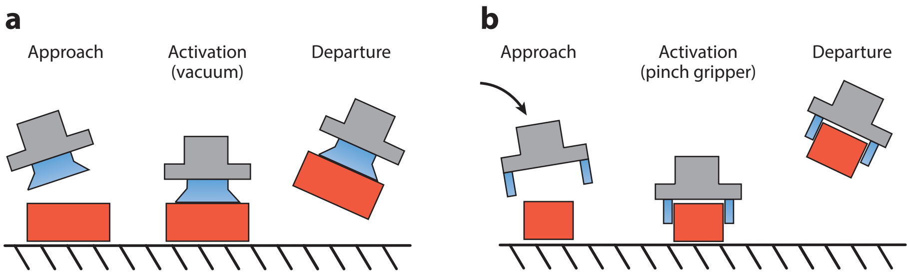


**Figure 6**

(*a*) Picking up an object with a suction cup. (*b*) Picking up an object with a parallel pinch gripper.

and control involved. This approach is especially appropriate with commercially available robot arms and grippers. Indeed, interfacing and coordinating the motion of a gripper and a robot arm that often come from different suppliers may require expertise beyond the capabilities of the user. With a decoupled approach, the robot and the gripper can function in parallel based on simple trigger signals that acknowledge the end of a task. The rise in popularity of collaborative robots has only further increased this type of object grasping implementation by enabling users to teach trajectories using direct physical interaction (through impedance or admittance control schemes), consequently reducing the need for expert task planning.

Another reason for limiting the physical interactions between a robot and its environment is that such interactions greatly increase the risk of catastrophic (and costly) failures. For instance, precise robotic arms handling costly—and possibly heavy—components in a stiff environment are rarely involved in complex interactions because, in such a setting, malfunctions could have dramatic consequences, including damaging the robot or gripper or compromising human safety. Therefore, alternative solutions are sought to reduce the risks associated with physical interaction and facilitate the implementation of more advanced scenarios. As pointed out by Bonilla et al. (111), much of the danger of interacting with the environment can be alleviated by the use of soft, compliant, or underactuated grippers, which therefore represents a promising avenue for further research.

To understand how soft, compliant, or underactuated grippers can improve real-world manipulation, it is necessary to consider the fundamentals of the problem. The first consideration in robotic grasping is the need to initiate contacts in a safe manner. Because of their accuracy requirements, robot arms are usually stiff. In order to apply a force or touch some component of the environment, the arm must approach the target and make contact; however, given the stiffness of the robot, establishing this contact is a delicate operation that may require force/torque sensing at a very high rate. This problem is amplified by the inertia of the robot—i.e., large actuation forces or torques can be required to impart large decelerations to the robot upon contact detection. Reducing the speed of the robot helps to lessen these effects to a certain extent but at the cost of deteriorating the performance. Nevertheless, once contact is established, the interaction forces can be controlled using force/torque sensing. The abrupt nature of the initial contact is clearly the problematic phase.

It is interesting to observe how humans use their hands in order to address the problem of the interaction with the environment. While current autonomous systems are unable to replicate human behavior, some prosthetic hands can achieve performance comparable to that of the human hand (see, e.g., 112). Two conclusions can be drawn from this observation: (*a*) The human capability to perceive and model the environment cannot yet be replicated by machines, and (*b*) using the flexibility and dexterity of advanced grippers in combination with the compliance of human muscles makes it possible to handle contacts safely and effectively. Therefore, it becomes apparent that combining a flexible or soft arm with a stiff gripper or combining a stiff arm with a flexible gripper could help to enable complex interactions.

Several of the phenomena involved in manipulating an object resting on a hard surface are presented in **Figure 7*a***. An example of how humans account for these interactions is the action of resting the hand on a surface while writing. In this scenario, the interaction is taking place between the surface and the finger or tool tip, and the stiffness is that of the (soft) hand. Similarly, many soft gripper designs could be used with conventional robot arms, or, conversely, a rigid gripper could be used with a soft arm. Nevertheless, compromises must be made between the complexity of the grippers required to implement such an approach and the benefits that they provide.

Investigating the initiation of contacts with the environment highlights all of the compromises that appear in the design of grippers, including rigid versus soft, fully actuated versus

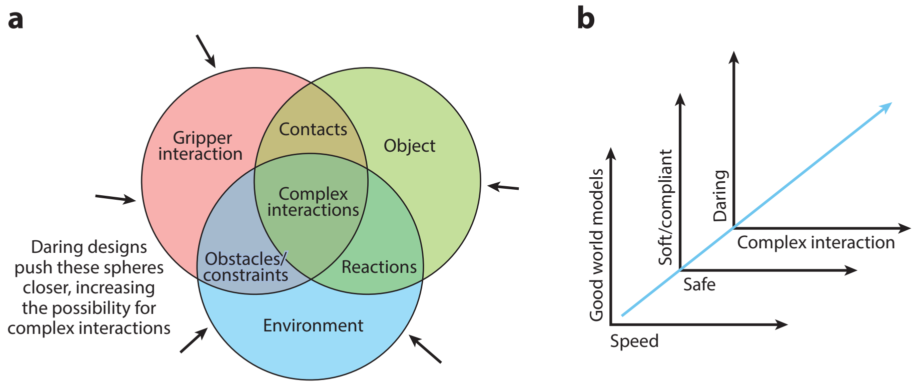


**Figure 7**

(*a*) The different aspects of the interactions among the gripper, the object, and the environment during manipulation. (*b*) The relationship between different performance requirements and gripper features to achieve interaction. The characteristics listed on the vertical axis are roughly proportional to the conditions of operation listed on the horizontal axis.

underactuated, speed versus safety, and controlled environment versus sensory perception. These compromises are represented schematically in **Figure 7*b***.

Two brief examples can illustrate the compromises and the use of design approaches to address the initiation of contacts for grasping. In the first example, from Babin et al. (8), a compliant finger is retrofitted on an existing gripper to provide the ability to grasp flat objects resting on a hard surface. This approach is based on the analysis of the statics of the scooping action used to pick up the object, which is illustrated schematically in **Figure 8*a***. The application of a force on the object with the opposing finger induces a friction force between the object and the finger that allows the compliant thumb to slide under the edge of the object and perform the scooping action without the object slipping away. This is illustrated in **Figure 8*b***, which shows the scooping of a book. The sequence begins with a rapid approach, where the compliant thumb first makes contact with the object. The approach velocity is then reduced until the fingers make contact with the object,

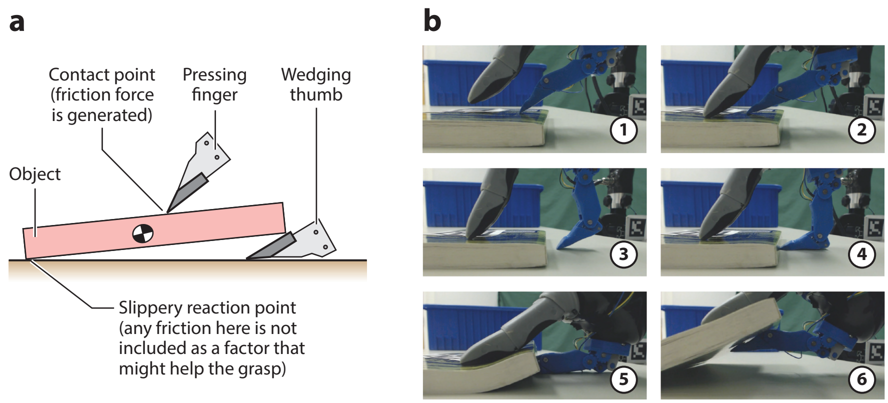


**Figure 8**

(*a*) Schematic representation of the scooping of an object, where a finger applies pressure on the object and a thumb is inserted from the side in a wedging motion. (*b*) The scooping motion performed by a robot manipulator retrofitted with a compliant thumb.

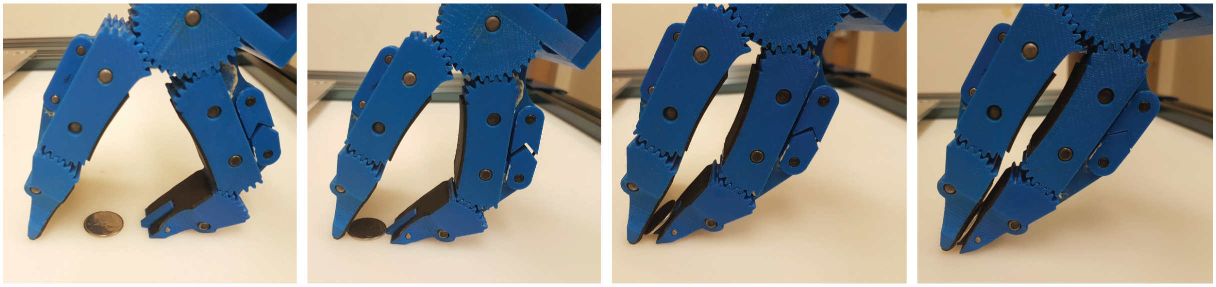

**Figure 9**

Scooping manipulation sequence performed by a gripper while the robotic arm is kept locked in place.

and meanwhile the compliant thumb is further bent. Once contact is achieved, constant pressure is applied by the fingers while the thumb pulls back. Once the edge of the object is cleared, the thumb pushes forward toward the object until it slides under the object, and the grasping is completed. The fact that the thumb is spring loaded and constrained by the surface on which the object rests enables it to stay in contact with the surface without precise positioning of the gripper.

In the second example, from Babin & Gosselin (7), a gripper is designed to scoop flat and thin objects on hard surfaces. The gripper includes a passive thumb that compensates for the positioning errors of the robot arm and epicyclic gear trains that provide large ranges of finger joint motions. One of the grasping modes that can be implemented with this gripper is referred to as idle scooping. In this mode, the grasping action is performed solely by the gripper, without requiring any motion of the robot, and therefore not requiring coordination. This is illustrated by the grasping sequence shown in **Figure 9**. A decoupled action of the robot and gripper is therefore possible, which is a considerable advantage, as mentioned above. In fact, the gripper presented by Babin & Gosselin (7) can be thought of as a means of producing a decoupled grasping action with an advanced gripper, whereas current decoupled systems are usually based on very simple grippers with limited capabilities. Indeed, the robot can approach the object, lock itself in place without interacting with the environment, have the fingers initiate the contact with the surface, and then, similarly to the procedure presented in **Figure 8**, have the thumb perform a scooping motion that ensures continuous tip contact with the surface. The difference is that, in this case, the gripper is designed to perform scooping motions that do not require position adjustments from the robot.

The above examples highlight recent trends and the advantages of considering the mechanics of the physical interaction at the design stage in order to obtain effective grippers. They also highlight the importance of introducing compliance in order to handle the initiation of contacts with the environment, which is a critical phase of the grasping action.

## 11. CONCLUSION

Although several other aspects are involved in gripper design, mechanical considerations still represent the main bottleneck—and the most promising research direction—in the development of novel concepts for effective grippers. As described above, robotic grippers can be built using parallel, serial, or hybrid architectures; can be based on several types of actuation principles; can feature rigid or flexible members; and can potentially include sensors. They are usually designed according to the tasks to be performed, although the design process may need to take several constraints into account, such as shape in the case of prosthetics. The primary difficulty in the effective use of robotic grippers is establishing contacts with the object to be grasped and with the environment, and this problem, which is related to the concept of extrinsic dexterity, lies at the core of the design challenge. This observation and several recent examples suggest that the decoupling of the motion and grasping actions in a robotic task has the potential to yield effective, safe, and attractive designs.

## DISCLOSURE STATEMENT

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