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A Century of Robotic Hands

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grasping, manipulation, robotic hands, artificial hands, soft hands

Abstract

This article reports on the state of the art of artificial hands, discussing some of the field's most important trends and suggesting directions for future research. We review and group the most important application domains of robotic hands, extracting the set of requirements that ultimately led to the use of simplified actuation schemes and soft materials and structures—two themes that clearly emerge from our examination of developments over the past century. We provide a comprehensive analysis of novel technologies for the design of joints, transmissions, and actuators that enabled these trends. We conclude by discussing some important new perspectives generated by simpler and softer hands and their interaction with other aspects of hand design and robotics in general.

1. INTRODUCTION

Capturing the richness and complexity of the human hand has been an ambition of many fields of human knowledge, including medicine, literature, religion, philosophy, and the arts (1). Since at least the end of the sixteenth century (2), science and engineering have tried to match the sensory and motor functions of the human hand. Such wide interest comes from the important functions the hand performs, which include motor functions (grasping, holding, pushing, pulling, punching, manipulating, etc.) and sensory functions (both active and passive exploration of surface texture, moisture, and temperature, as well as feeling of vibration, pressure, force, etc.) and culminate in social functions (caressing, menacing, hand shaking, pointing, saluting, playing, and all kinds of gesturing, both voluntary and involuntary). Despite this fascination with hands, they still elude full comprehension. This is one of the reasons why artificial hands remain one of the hardest challenges in robotics (3, 4).

The design approach followed by many researchers has consisted of attempting to closely replicate the appearance and dexterity of human hands with sophisticated designs integrating many actuators and sensors; examples include the Utah/MIT Hand (5), Robonaut Hand (6), DLR (Deutsches Zentrum für Luft- und Raumfahrt) Hand II (7), Gifu Hand II (8), and Shadow Dexterous Hand (9). Although the state of the art is rich with advanced prototypes in both robotics (10–13) and prosthetics (14, 15), it can be fairly said that this approach has resulted in a limited number of real-world applications in industry robotics, service robotics, or prosthetics. To increase the relevance to such applications, several novel approaches and solutions have been proposed in recent years for the development of effective and reliable artificial hands. Indeed, while achieving perfect structural and functional anthropomorphism—i.e., resemblance to the human hand not only in appearance but also in movement and function—might be overly complex, some recent innovations in hand design aim at achieving robust, easily programmable, and economically viable robotic hands capable of performing a useful subset of the functions of human hands.

International competitions such as the first Amazon Picking Challenge (16, 17), the last DARPA Robotics Challenge (18), the 2016 Cybathlon (19), and the Robotic Grasping and Manipulation Competition (20), where most of the sophisticated grasping technologies have been challenged, showed that approaches aiming at simplified designs provide notable benefits. The winner of the first Amazon Picking Challenge was an end effector based on a suction system (16); none of the humanoid robots employed in the DARPA Robotics Challenge had a fully actuated anthropomorphic hand, and more than 15 teams (out of 25 participants) used an underactuated hand with three or four fingers; the winner of the Powered Arm Prosthesis Race at the 2016 Cybathlon used a body-powered hook (21); and an anthropomorphic but heavily underactuated hand was the winner of the Hand in Hand competition at the 2016 Robotic Grasping and Manipulation Competition (22).

The trend toward a principled simplification of hand design can be regarded as part of a larger movement. In the last few decades, many robotics research groups have focused on minimalist design approaches: While retaining many of the advantages of anthropomorphic design, a principled simplification in both design and control can sensibly reduce the system complexity in terms of number of actuators, sensors, and lines of code to program. Additionally, soft-robotics approaches have been useful, with several recent hand prototypes designed according to such principles and achieving very good results in terms of grasping versatility, robustness, and reliability—e.g., the Open Bionics Hand (23), Delft Cylinder Hand (24), Yale Multigrasp Hand (25), and RBO (Robotics and Biology Laboratory) Hand 2 (26).

This article reviews the state of the art of artificial hands over the past century, with a focus on two emerging trends: the replacement of rigid mechanical structures with soft materials and actuation, and the simplification of the hand design. To limit the scope of the survey, we analyze these aspects while admittedly neglecting other important ones, such as kinematics and sensorization. To a first approximation, at least, these other aspects are independent from those considered here and are covered by other surveys (27, 28). The purpose of this work is to present how the minimalist design approach and soft-robotics technologies have influenced the world of hand design, particularly in their effect on the physical structure of hand joints and links, the type and control of actuators, and the distribution and coordination of movement. This analysis is supported by a comprehensive database of artificial hands covering 106 years of engineering (see **Supplemental Table 1**). The temporal layout of this database is displayed at a glance in **Figure 1**.

Supplemental Material >

We start by discussing, in Section 2, the main application fields of robotic hands and their requirements. Section 3 explains the method used to analyze the state of the art of artificial hands. In Section 4, we present evidence of the two trends mentioned above, and discuss their manifestations and the correlation between technological solutions adopted in different application domains. Finally, in Section 5, we discuss the most interesting opportunities (in our opinion) and novel perspectives contributed by this design approach.

2. APPLICATIONS AND DESIGN REQUIREMENTS

Artificial hands have many potential application domains, each with different requirements. In this section, we analyze and organize the main fields of application, with the goals of (*a*) highlighting broad classes of application domains, which will be used for the analysis that follows in Section 3, and (*b*) establishing a structured vision of the design goals and required properties that these applications entail, providing information about the different technological enablers (discussed in Section 4).

2.1. Assistive Robotics

Assistive robots must be able to interact and cooperate in a safe way with the environment and humans during their activities of daily living. These robots require hands that can operate despite harsh conditions and incomplete information, and they have severe limits on encumbrance (meaning that the hands need to be small, light, and flexible). Moreover, their hands must ensure a high level of comfort, safety, and robustness. Examples of robotic hands designed or adapted to assist sick or elderly people or people with disabilities include the DLR/HIT (Harbin Institute of Technology) Hand II (103), Fluidic Hand (220), Human-Like Artificial Hand (87), and SCCA (Self-Contained Compliant Anthropomorphic) Hand (177). **Figure 2*a*** shows one of the most famous examples of the application of hands in this field: the DLR/HIT Hand II, used in combination with the DLR Lightweight Robot arm to assist a disabled person in a daily living task (221).

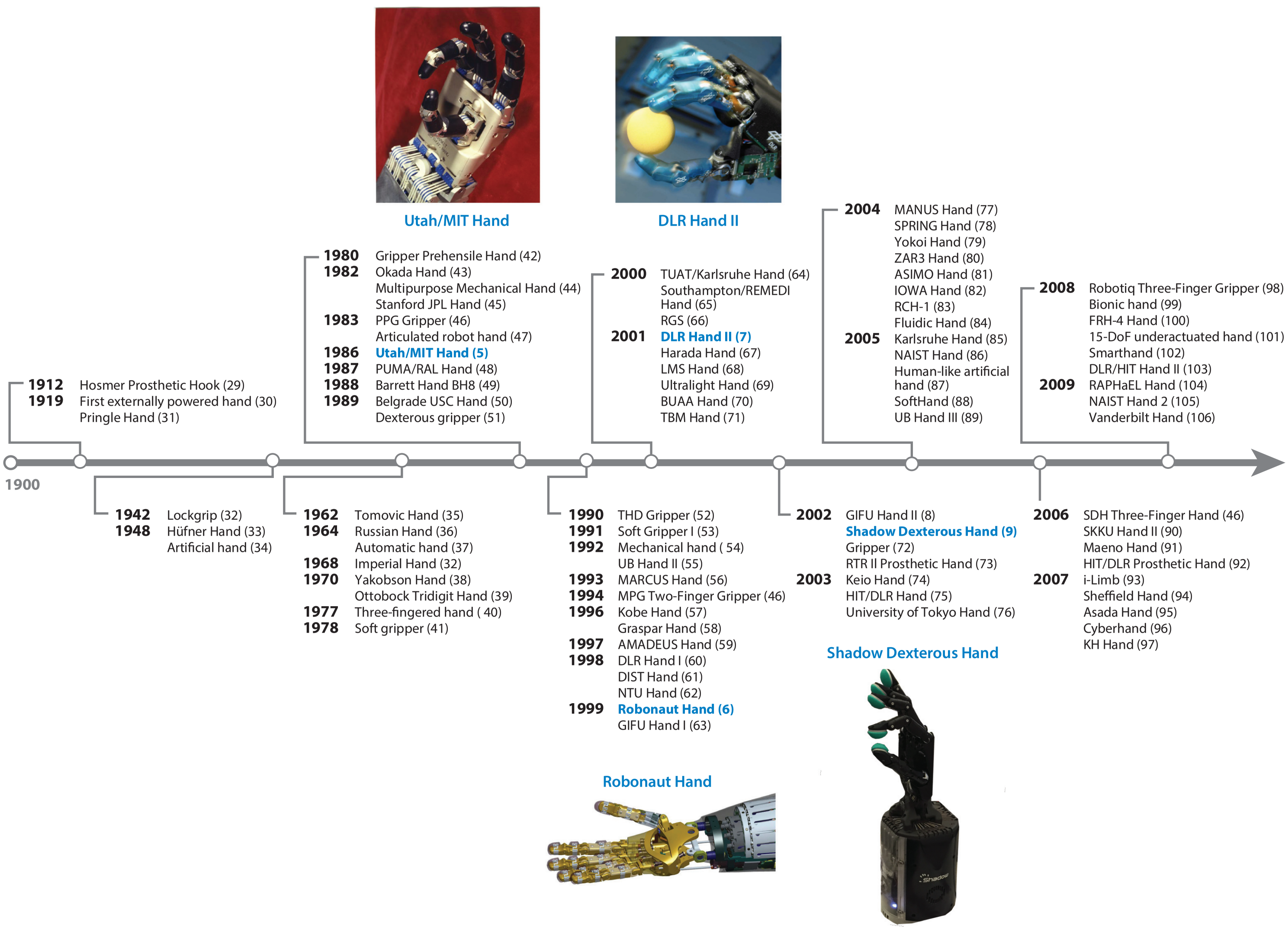
2.2. Prosthetics

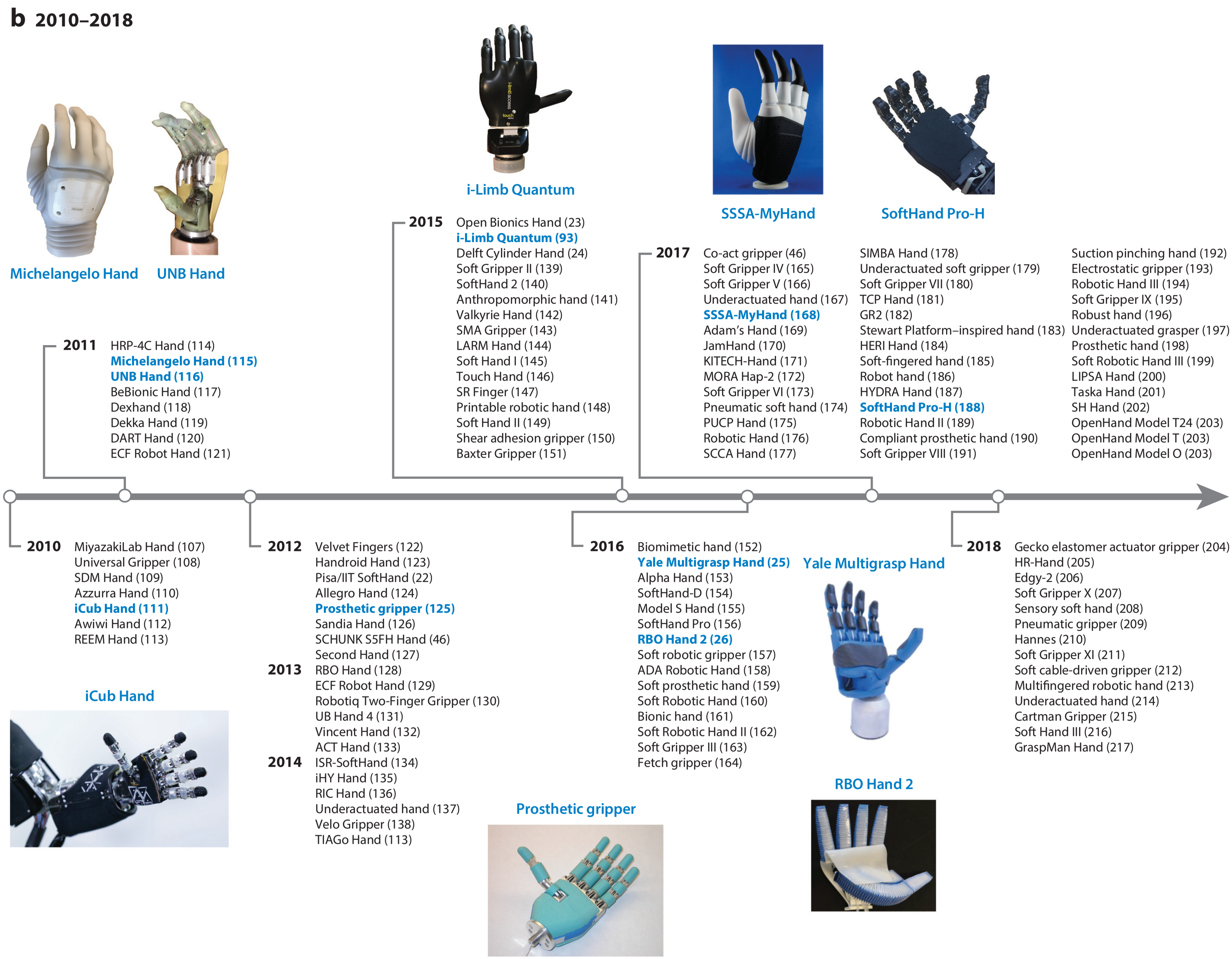
Prosthetics require reduced weight and encumbrance, simple controls to accommodate the limited number of inputs available for amputees, high interaction capabilities with humans and the

Figure 1 (*Figure appears on next page*)

A time line of all the hands considered for the analysis presented in this review, covering 106 years of engineering (1912–2018, with hands up through 2010 listed in panel *a* and hands after 2010 listed in panel *b*). Image of the Utah/MIT Hand courtesy of the Computer History Museum; image of the Robonaut Hand courtesy of NASA (**https://robonaut.jsc.nasa.gov/R2**); image of the DLR Hand II adapted from Reference 218 with permission; image of the iCub Hand courtesy of the Istituto Italiano di Tecnologia; image of the prosthetic gripper courtesy of the Laboratoire de Robotique at Université Laval; image of the Yale Multigrasp Hand adapted from Reference 219 with permission; image of the SSSA-MyHand courtesy of Prensilia S.r.l. (**http://www.prensilia.com**). Abbreviation: DoF, degree of freedom.

a 1900–2009


Utah/MIT Hand
DLR Hand II
1900
1912 Hosmer Prosthetic Hook (29)
1919 First externally powered hand (30)
Pringle Hand (31)
1942 Lockgrip (32)
1948 Hüfner Hand (33)
Artificial hand (34)
1962 Tomovic Hand (35)
1964 Russian Hand (36)
Automatic hand (37)
1968 Imperial Hand (32)
1970 Yakobson Hand (38)
Ottobock Tridigit Hand (39)
1977 Three-fingered hand (40)
1978 Soft gripper (41)
1980 Gripper Prehensile Hand (42)
1982 Okada Hand (43)
Multipurpose Mechanical Hand (44)
Stanford JPL Hand (45)
1983 PPG Gripper (46)
Articulated robot hand (47)
1986 Utah/MIT Hand (5)
1987 PUMA/RAL Hand (48)
1988 Barrett Hand BH8 (49)
1989 Belgrade USC Hand (50)
Dexterous gripper (51)
1990 THD Gripper (52)
1991 Soft Gripper I (53)
1992 Mechanical hand (54)
UB Hand II (55)
1993 MARCUS Hand (56)
1994 MPG Two-Finger Gripper (46)
1996 Kobe Hand (57)
Graspar Hand (58)
1997 AMADEUS Hand (59)
1998 DLR Hand I (60)
DIST Hand (61)
NTU Hand (62)
1999 Robonaut Hand (6)
GIFU Hand I (63)
2000 TUAT/Karlsruhe Hand (64)
Southampton/REMEDI Hand (65)
RGS (66)
2001 DLR Hand II (7)
Harada Hand (67)
LMS Hand (68)
Ultralight Hand (69)
BUAA Hand (70)
TBM Hand (71)
2002 GIFU Hand II (8)
Shadow Dexterous Hand (9)
Gripper (72)
RTR II Prosthetic Hand (73)
2003 Keio Hand (74)
HIT/DLR Hand (75)
University of Tokyo Hand (76)
2004 MANUS Hand (77)
SPRING Hand (78)
Yokoi Hand (79)
ZAR3 Hand (80)
ASIMO Hand (81)
IOWA Hand (82)
RCH-1 (83)
Fluidic Hand (84)
2005 Karlsruhe Hand (85)
NAIST Hand (86)
Human-like artificial hand (87)
SoftHand (88)
UB Hand III (89)
2006 SDH Three-Finger Hand (46)
SKKU Hand II (90)
Maeno Hand (91)
HIT/DLR Prosthetic Hand (92)
2007 i-Limb (93)
Sheffield Hand (94)
Asada Hand (95)
Cyberhand (96)
KH Hand (97)
2008 Robotiq Three-Finger Gripper (98)
Bionic hand (99)
FRH-4 Hand (100)
15-DoF underactuated hand (101)
Smarthand (102)
DLR/HIT Hand II (103)
2009 RAPHaEL Hand (104)
NAIST Hand 2 (105)
Vanderbilt Hand (106)
Robonaut Hand
Shadow Dexterous Hand


b 2010–2018
Michelangelo Hand
UNB Hand
i-Limb Quantum
SSSA-MyHand
SoftHand Pro-H
2010
MiyazakiLab Hand (107)
Universal Gripper (108)
SDM Hand (109)
Azzurra Hand (110)
iCub Hand (111)
Awiwi Hand (112)
REEM Hand (113)
2011
HRP-4C Hand (114)
Michelangelo Hand (115)
UNB Hand (116)
BeBionic Hand (117)
Dexhand (118)
Dekka Hand (119)
DART Hand (120)
ECF Robot Hand (121)
2012
Velvet Fingers (122)
Handroid Hand (123)
Pisa/IIT SoftHand (22)
Allegro Hand (124)
Prosthetic gripper (125)
Sandia Hand (126)
SCHUNK S5FH Hand (46)
Second Hand (127)
2013
RBO Hand (128)
ECF Robot Hand (129)
Robotiq Two-Finger Gripper (130)
UB Hand 4 (131)
Vincent Hand (132)
ACT Hand (133)
2014
ISR-SoftHand (134)
iHY Hand (135)
RIC Hand (136)
Underactuated hand (137)
Velo Gripper (138)
TIAGo Hand (113)
2015
Open Bionics Hand (23)
i-Limb Quantum (93)
Delft Cylinder Hand (24)
Soft Gripper II (139)
SoftHand 2 (140)
Anthropomorphic hand (141)
Valkyrie Hand (142)
SMA Gripper (143)
LARM Hand (144)
Soft Hand I (145)
Touch Hand (146)
SR Finger (147)
Printable robotic hand (148)
Soft Hand II (149)
Shear adhesion gripper (150)
Baxter Gripper (151)
2016
Biomimetic hand (152)
Yale Multigrasp Hand (25)
Alpha Hand (153)
SoftHand-D (154)
Model S Hand (155)
SoftHand Pro (156)
RBO Hand 2 (26)
Soft robotic gripper (157)
ADA Robotic Hand (158)
Soft prosthetic hand (159)
Soft Robotic Hand (160)
Bionic hand (161)
Soft Robotic Hand II (162)
Soft Gripper III (163)
Fetch gripper (164)
2017
Co-act gripper (46)
Soft Gripper IV (165)
Soft Gripper V (166)
Underactuated hand (167)
SSSA-MyHand (168)
Adam's Hand (169)
JamHand (170)
KITECH-Hand (171)
MORA Hap-2 (172)
Soft Gripper VI (173)
Pneumatic soft hand (174)
PUCP Hand (175)
Robotic Hand (176)
SCCA Hand (177)
SIMBA Hand (178)
Underactuated soft gripper (179)
Soft Gripper VII (180)
TCP Hand (181)
GR2 (182)
Stewart Platform–inspired hand (183)
HERI Hand (184)
Soft-fingered hand (185)
Robot hand (186)
HYDRA Hand (187)
SoftHand Pro-H (188)
Robotic Hand II (189)
Compliant prosthetic hand (190)
Soft Gripper VIII (191)
Suction pinching hand (192)
Electrostatic gripper (193)
Robotic Hand III (194)
Soft Gripper IX (195)
Robust hand (196)
Underactuated grasper (197)
Prosthetic hand (198)
Soft Robotic Hand III (199)
LIPSA Hand (200)
Taska Hand (201)
SH Hand (202)
OpenHand Model T24 (203)
OpenHand Model T (203)
OpenHand Model O (203)
2018
Gecko elastomer actuator gripper (204)
HR-Hand (205)
Edgy-2 (206)
Soft Gripper X (207)
Sensory soft hand (208)
Pneumatic gripper (209)
Hannes (210)
Soft Gripper XI (211)
Soft cable-driven gripper (212)
Multifingered robotic hand (213)
Underactuated hand (214)
Cartman Gripper (215)
Soft Hand III (216)
GraspMan Hand (217)
iCub Hand
Prosthetic gripper
Yale Multigrasp Hand
RBO Hand 2

environment, and features that enable devices to operate in harsh and unstructured conditions. Hand prostheses are artificial devices designed to replace missing limbs. The state of the art includes many different solutions, such as the Ottobock Michelangelo Hand (115), the i-Limb Quantum (93), the Open Bionics Hand (23), the Yale Multigrasp Hand (25), and the SoftHand Pro (188). **Figure 2*b*** shows an example of a prosthetic hand: a BeBionic hand (117) used by an amputee.

2.3. Supervised Manipulation

The robotic device must be able to perform manipulation tasks while assisted remotely by a human supervisor who provides high-level decisional and planning commands. Limited perception and environmental constraints make this application challenging. Indeed, the human operator usually suggests the trajectory to be executed by the robot. Hands designed for this application have requirements in terms of robustness, efficiency, and simplicity in control. This application is typical of industrial environments. Examples of robotic hands designed or used to operate in this field are the iHY (iRobot-Harvard-Yale) Hand (135, 223) and the electrostatic gripper presented by Schaler et al. (193). **Figure 2*c*** shows an example: an operator using a tablet to program and supervise the action of a robotic manipulator and its end effector.

Figure 2

Examples of artificial hands employed in different application domains: (*a*) assistive robotics (the DLR/HIT Hand II and DLR Lightweight Robot arm assisting a disabled person in a daily living task), (*b*) prosthetics (the BeBionic hand used by an amputee), (*c*) supervised manipulation (a robotic manipulator controlled by a tablet app), (*d*) teleoperation (the NASA Robonaut controlled by a teleoperator; **https://robonaut.jsc.nasa.gov/R2**), (*e*) teleinteraction (a teleoperated robot interacting with a person), (*f*) social robotics (a REEM robot helping a person in a mall), (*g*) entertainment (a NAO robot playing with a child), (*h*) service robotics (the DLR Justin robot equipped with the DLR Hand II), (*i*) autonomous manipulation (the RBO Hand, used here to handle food), and (*j*) logistics (the Velvet Fingers end effector manipulating a box). Panel *a* adapted from Reference 221 with permission; panels *b*, *c*, *e*, and *g* adapted from Shutterstock; panel *h* adapted from Reference 222 with permission; panel *i* courtesy of OCADO Technology.

2.4. Teleoperation

Teleoperation is the direct operation of a robotic system from a remote position. The main difference between teleoperation and supervised manipulation is that the human operator commands the robot at a much lower level, often with an almost one-to-one correspondence between user actions and robot motions, with an interface that aims at transparency. One of the main uses of teleoperation is to minimize the need for humans to be physically present in dangerous situations (e.g., in irradiated environments or at sites of chemical spills) or after catastrophic events (e.g., earthquakes). Other relevant applications are related to underwater robotics (e.g., the retrieval of archaeological artifacts from the ocean) (137). These technologies must be designed to operate in unknown and sometimes harsh scenarios and guarantee a safe interaction with the environment (e.g., in order to grasp fragile or heavy objects). Such systems usually have strict requirements in terms of robustness, control simplicity, and adaptivity. Examples of robotic hands designed to operate in this field are the KH (Kinetic Humanoid) Hand (97), the RAPHaEL (Robotic Air Powered Hand with Elastic Ligaments) Hand (104), the Handroid Hand (123), and the SCHUNK S5FH Hand (224). **Figure 2*d*** shows an example: teleoperation of the NASA Robonaut (225) to accomplish a bimanual task.

2.5. Teleinteraction

Teleinteraction, which derives from teleoperation, aims at communication over distance using audio, video, and interaction through a robotic system. These technologies are envisioned mainly to cooperate with people, especially in daily living scenarios. Hands designed for such applications need high specifications in terms of interaction capabilities with humans and the environment, comfort, and pleasantness. The main design requirements are related to natural motion behaviors, safety, robustness, and control simplicity. Examples of robotic hands designed or used in this field of application are the mechanical hand presented by Jau (54) and the hand used by the robot ASIMO (81). **Figure 2*e*** shows an example: a teleoperated robot interacting with a person.

2.6. Social Robotics

Social robots are systems able to communicate with humans. This type of robot is designed to have a human-like (or human-acceptable) appearance and is usually equipped with a screen to facilitate communication and interaction. Hands designed for these robots usually need a high level of human–robot interaction capabilities and pleasantness, and they have strict requirements in terms of safety and design. Examples of robotic hands designed to operate in this field are the Alpha Hand (153) and the RBO Hand 2 (226). **Figure 2*f*** shows an example: the REEM humanoid robot (113) helping a person in a mall.

2.7. Entertainment

The aim of entertainment applications is to have a robot for recreation (e.g., toys), for domestic use, or for animatronics in amusement parks or museums. These robots often try to emulate a human, animal, or cartoon character, not only in their appearance but also in their behavior. Such robots usually do not need hands capable of complex interactions with people, and they work in conditions that are under supervised control. Moreover, their hands are often designed with a rigorous design formalism and are characterized by natural movements. Examples of robotic hands designed to operate in this field of application are the hand of the iCub robot (111) and the one used for the robot HRP-4C (114). **Figure 2*g*** shows an example: a NAO robot playing with a child.

2.8. Service Robotics

Service robots are created to assist humans in performing several kinds of tasks and are often intended to operate in a semiautonomous or fully autonomous way. They are designed to work in scenarios such as domestic environments and require high reliability and good interaction with humans and the environment. Their design requirements relate mainly to robustness, adaptivity, simplicity of control, and natural motion. Examples of robotic hands designed to operate in this field of application are the Ultralight Hand (227) and the MiyazakiLab Hand (107). **Figure 2*h*** shows an example: the DLR Justin robot (228), equipped with the DLR Hand II, grasping a broom and cleaning the floor.

2.9. Autonomous Manipulation

Robots designed for autonomous manipulation are usually intended to be used in structured environments, although such robots have recently been used in unstructured environments. The former approach is typical of pick-and-place industrial scenarios. Versatile but robust grippers (with two or three fingers) are usually preferred. Historically, grippers (e.g., 43, 48, 52) adopted in this context have been designed for minimum interaction with people, use in well-structured environments, and use in environments where information about the object and the status of the robot are always well known. Robustness, adaptivity, and design formalisms are among the main requirements. Some recent trends are changing this approach to autonomous manipulation, looking for new end effectors that can interact with the environment (and, to some extent, with people) to show intrinsic adaptivity, and that can deal with uncertainties due to limitations in the robot sensorization and perception. Requirements such as robustness and safety are still mandatory in this context. Examples of possible fields of use include harvesting and bin picking from boxes containing disorganized objects of different shapes. Examples of robotic hands designed to operate in this field of application were described by Brown et al. (108), Johnson et al. (229), and Borst et al. (230). **Figure 2*i*** shows an example: the RBO Hand, used here to perform autonomous food-handling tasks.

2.10. Logistics

Systems adopted in logistics are intended for fast and productive handling of goods in industrial chains. Two main approaches can be found in the state of the art of end effectors for logistics: the use of fixed, ad hoc end effectors, explicitly designed for a certain product and a specific supply chain, and the use of general-purpose systems, able to handle several kinds of goods and characterized by intrinsic versatility. The former approach has been characterized by a high level of reliability and an intrinsic robustness, together with the need for perfect knowledge of the environmental conditions and a rigorous design. The latter approach is looking for systems that can interact with the environment and work in unstructured conditions while still maintaining a high level of robustness and efficiency. Examples of robotic hands designed to operate in this field of application are Fetch and Freight (164) and various SCHUNK hands (46). **Figure 2*j*** shows an example: the Velvet Fingers end effector (122) manipulating a box.

2.11. Summary

The analysis and observations above suggest some useful considerations that can be used in the following sections. First, the different application domains can be divided into three broad categories: prosthetics and rehabilitation (assistive robotics and prosthetics), industrial (supervised manipulation, autonomous manipulation, and logistics), and human–robot interaction (teleoperation, teleinteraction, social robotics, entertainment, and service robotics). Moreover, depending on the application domain, it is possible to isolate and highlight some design goals and, consequently, the related design requirements. The robustness and adaptivity of the end effector are among the main features required to accomplish most of the goals of the application considered. This is particularly true if we consider tasks that include robot–environment interaction or lack of environmental information. In this case, robust systems allow a margin of error, while adaptability helps to simplify the control required. Furthermore, high efficiency, combined with robustness and adaptability, can limit the encumbrance. Prosthetics and rehabilitation applications require a particular focus on the safety and naturalness of the motion of the device in order to improve human–robot interaction, comfort, and pleasantness. Finally, another important aspect is simplicity of control, which also facilitates operation in harsh conditions for applications such as teleoperation and autonomous manipulation.

Figure 3 summarizes the results of the application domain analysis, showing possible application domains, design goals that must be respected to operate in the specific field of application, and design requirements needed to realize the desired goals.

3. A 1912–2018 DATABASE OF ROBOT HANDS

Supplemental Table 1 provides a database of the main artificial hands developed from 1912 to 2018. This table, which includes 199 references (mainly from scientific articles), has been compiled

Supplemental Material >

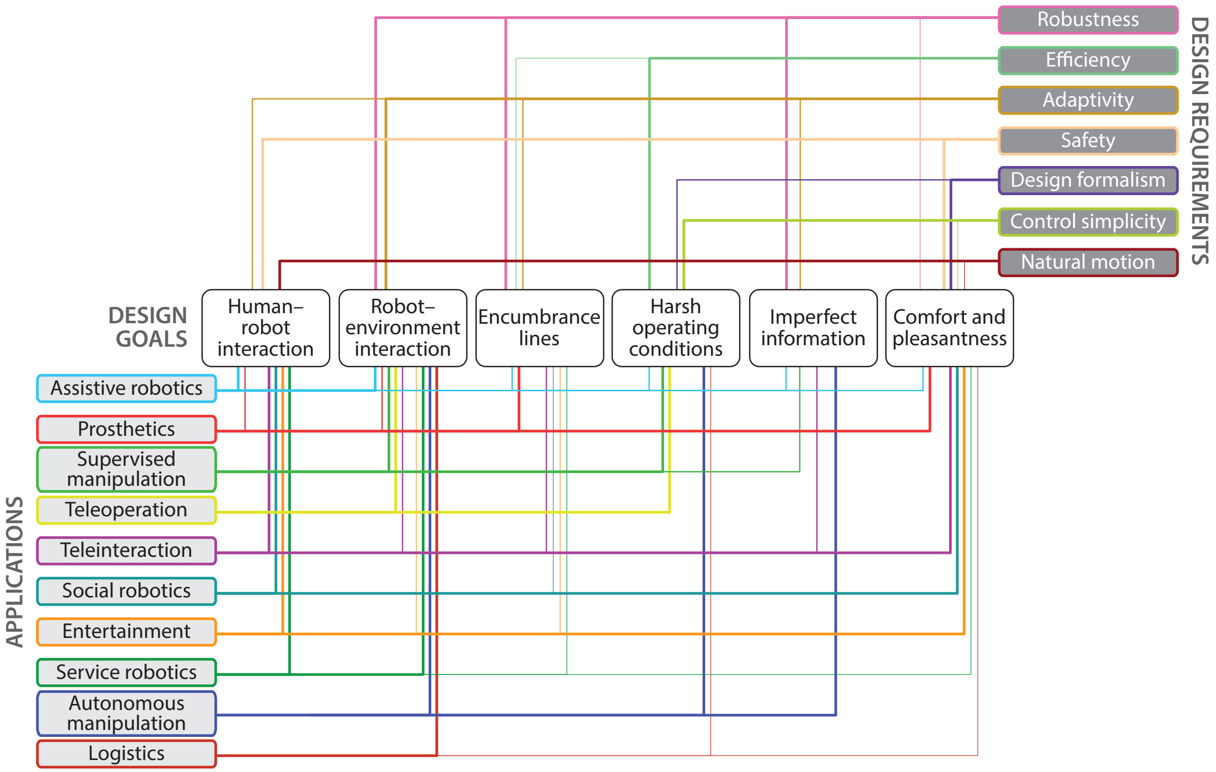


Figure 3

Map of possible correlations between applications (*bottom left*), design goals (*center*), and design requirements (*top right*). Connections are represented by colored lines; thicker lines imply stronger connections.

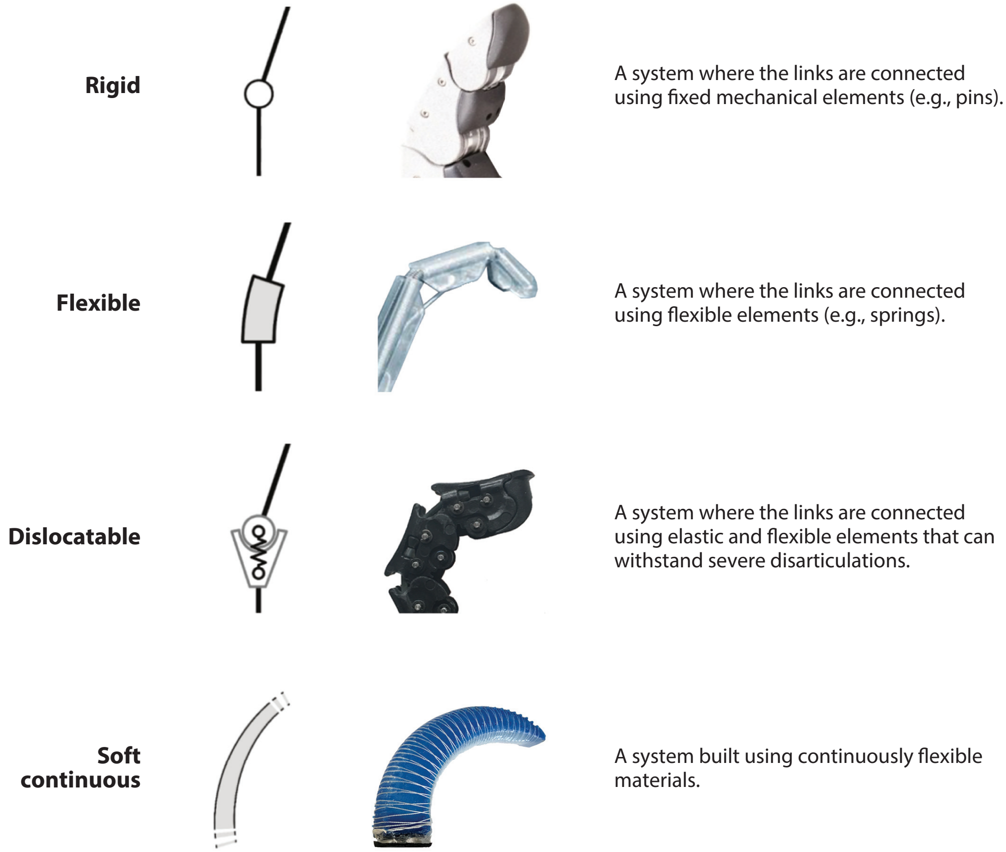


Figure 4

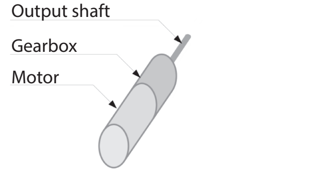
Different types of hand joints: rigid, flexible, dislocatable, and soft continuous. Images of the rigid, flexible, and soft continuous systems courtesy of DLR, the University of Bologna, and the Robotics and Biology Laboratory at Technische Universität Berlin, respectively.

based on the criteria explained below. The table reports the following information for each device: year of publication, device name, and reference; number of joints and their type; number of degrees of freedom (DoFs) and degrees of actuation (DoAs); transmission architecture; number of motors and type of actuation; and application field(s) among the three broad areas indicated in Section 2 (prosthetics and rehabilitation, industrial, and human–robot interaction).

3.1. Compilation Criteria

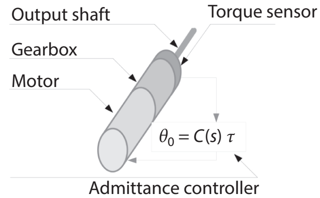
We used the compiled information to analyze trends and isolate the technological enablers that are driving the development of the next generation of artificial hands, with particular attention to joint design, transmission architecture, and actuation systems. To include all the different design arrangements and solutions proposed to date, we considered four types of joints: rigid, flexible, dislocatable, and soft continuous (see **Figure 4**). We also considered the most common actuation principles in the literature (**Figure 5**) and different transmission architectures (**Figure 6**).

Rigid actuator



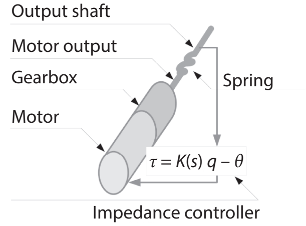
A device with negligible compliance that can reach and hold a specific position if external forces are exerted on its output. These actuators, which derive directly from industrial servomotors, are preferred when high accuracy is required.

Actuator with active impedance/ admittance control



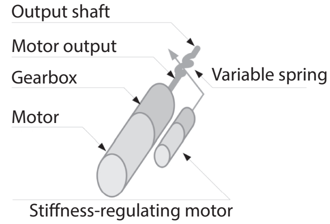
Similar to a rigid actuator but featuring an appreciable amount of compliance on its output, which comes from very fine tuning of control gains and/or the integration of an output torque (or force) sensor. This actuator can actively regulate the compliance (and damping) of the system and display more flexible interaction behavior, but its performance is constrained by the bandwidth of the control system, and its robustness is constrained by the torque limits of the output sensor (when present).

Series elastic actuator



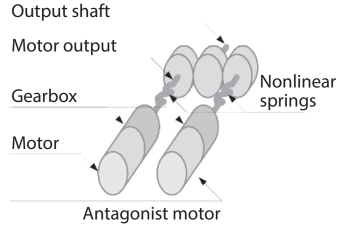
An actuator where the output shaft is driven through a spring. The system presents a fixed physical elasticity provided by the spring, which, being intrinsic, is not limited in bandwidth and is more robust than a torque sensor.

Explicit stiffness variation actuator



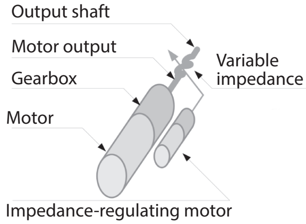
An evolution of the series elastic actuator that includes a physical elastic element on its output that can adjust its stiffness thanks to a second (usually smaller) actuation unit and a suitable mechanism. Because the implemented variable stiffness is physical, it has no bandwidth limitations, and the position and stiffness are regulated independently.

Agonist–antagonist variable-stiffness actuator



A system with an output behavior similar to that of the explicit stiffness variation actuator. It combines two similar (usually equal) prime movers, each connected to the output shaft through a nonlinear elastic transmission. It can control both the position and the physical stiffness of its output shaft by applying synchronous or opposite motions of the two prime movers. Stiffness and position are not controlled independently, and the stiffness behavior is usually nonlinear.

Variable-impedance actuator



A further evolution of the actuators described above in which both the stiffness and the damping of the actuator output impedance can be changed, and both are implemented by the physical action of one or more elastic and damping elements. The equilibrium position depends on external forces and the mechanical properties of the actuator. Implementations, as well as advantages and disadvantages of the system, may vary significantly depending on the physical principles used to implement the variable stiffness and damping.

Figure 5

Different actuation principles: rigid actuator, actuator with active impedance/admittance control, series elastic actuator, explicit stiffness variation actuator, agonist–antagonist variable-stiffness actuator, and variable-impedance actuator.

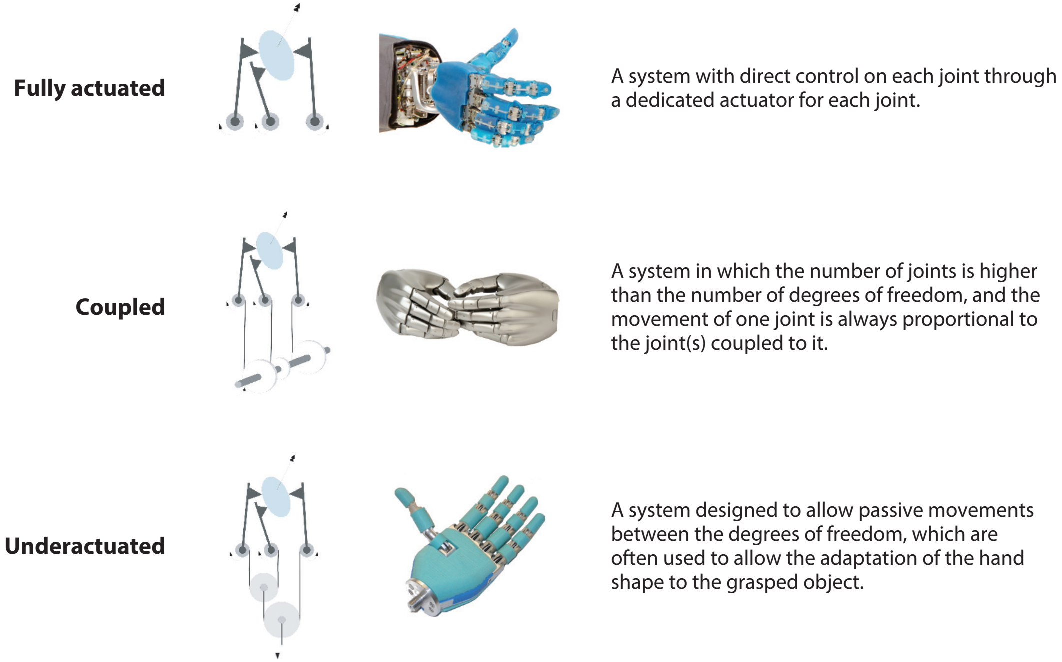


Figure 6

Different types of transmission architectures: fully actuated (e.g., 7), coupled (e.g., 103), and underactuated (e.g., 125). Images of the fully actuated and coupled systems courtesy of DLR; image of the underactuated system courtesy of the Laboratoire de Robotique at Université Laval.

4. EMERGING TRENDS

Supplemental Material >

From **Supplemental Table 1**, one can obtain the distribution over the years of hands with rigid joints versus those with soft joints, hands with rigid actuation versus those with soft actuation, and hands with independent control of fingers versus those with a different approach to the simplification of the motion architecture of fingers (for a detailed description, see Section 4.2). **Figure 7** shows this comparison in terms of the cumulative number of hands of each type, and **Figure 8** does so in terms of the percentages of each type.

As shown in **Figure 8**, there is distinct growth after the year 2000 in the use of soft actuation systems and simplified architectures (e.g., underactuated hands). Moreover, **Figures 7*c*** and **8*c*** highlight an increasing interest in the use of hands with synchronized motion principles.

Figure 9 shows the cumulative number and percentages of hands for the three classes of applications. Although prosthetics and rehabilitation is the largest application field over the entire period, there was an increased interest in the development of hands for industrial applications starting at the end of the 1970s and a growing interest in hands designed for human–robot interaction starting at the end of the 1990s. Notably, hands have been much more evenly distributed across the three domains in the past few years than they have been in the past.

The number of hands developed and published has increased considerably in the last decade, with an explosion of new prototypes in the last three years in particular. In our opinion, this interesting phenomenon stems from two main factors: an increasing interest in open-source hardware and the increasing dissemination of rapid prototyping technologies, which enables the easy and economical fabrication of mechanical components with complex geometries. The first factor is

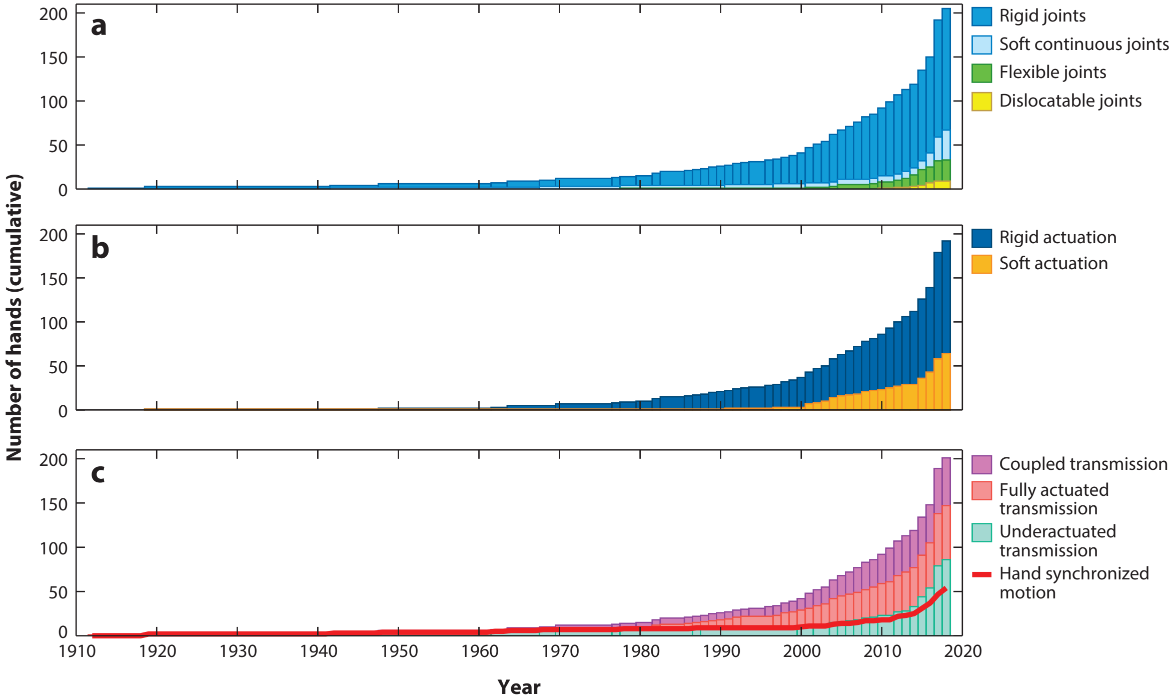


Figure 7

Cumulative distributions of hands from 1912 to 2018 based on (*a*) the joint type (rigid, soft continuous, flexible, or dislocatable), (*b*) the actuation type (rigid or soft), and (*c*) the transmission architecture type (coupled, fully actuated, or underactuated). In panel *c*, the red line shows the cumulative number of hands that embed hand synchronized motion.

supported by the growing number of open-source initiatives—such as the Open Hand Project (203), the Natural Machine Motion Initiative (231), the Soft Hands platform (232), the open-source e-NABLE community (233), and the OpenBionics Initiative (234)—that aim to foster and disseminate designs and approaches. Moreover, many of the proposed new solutions are based on open-source licenses for both software and mechanics. Examples include the standard Baxter Gripper (151), which derives from the Yale OpenHand Project's Model T42 (203); the Hannes prosthetic hand (210); and the hand of the robot TIAGo from Pal Robotics (113), the last two of which adopt technologies from the Pisa/IIT (Istituto Italiano di Tecnologia) SoftHand (22) under the Natural Machine Motion Initiative's OpenHardware licensing scheme. Open-source hardware and rapid prototyping are enabling researchers to easily reproduce different proposed technologies and then build new prototypes and test new ideas.

4.1. Soft-Robotics Technologies and Hands

As shown by **Figure 7**, many research groups have been investigating the development of artificial hands that take inspiration from biological structures—moving from rigid, machine-like designs to solutions where softness is embedded in the mechanics of both the articulations and the actuation systems. This section discusses these two aspects in more detail.

4.1.1. Softness in joint design. Traditionally, most hand devices have used rigid joints, but novel solutions such as flexible or soft joints are becoming increasingly popular. As described by

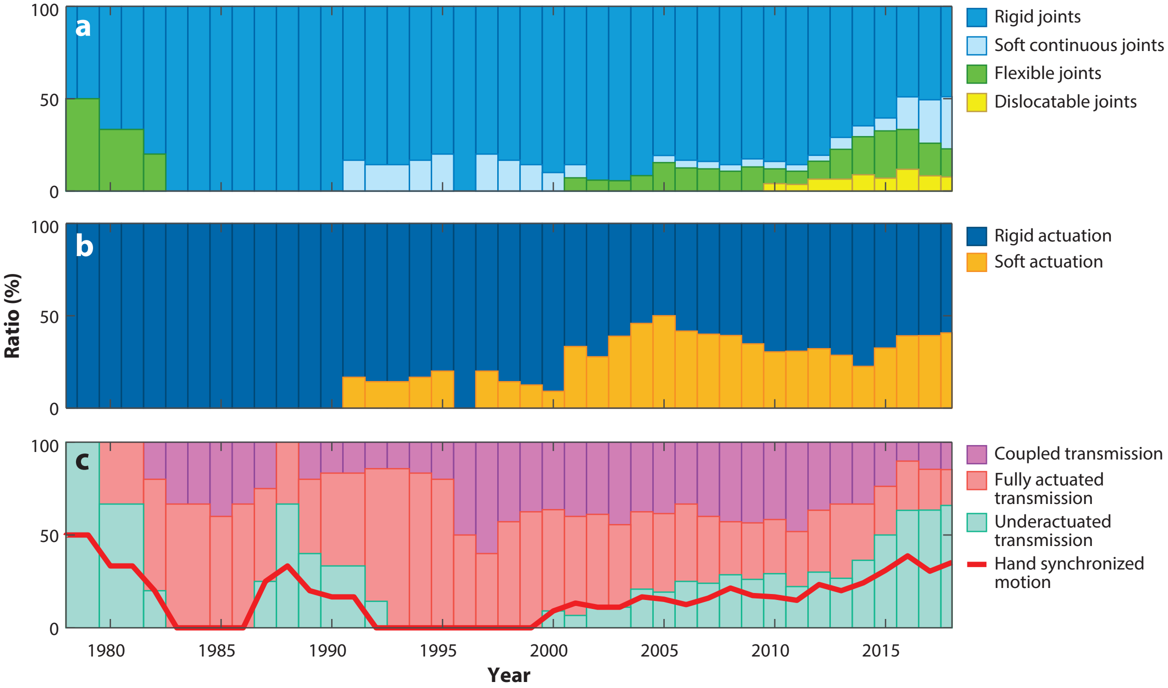


Figure 8

Relative distributions of hands from 1978 to 2018 based on (*a*) the joint type (rigid, soft continuous, flexible, or dislocatable), (*b*) the actuation type (rigid or soft), and (*c*) the transmission architecture type (coupled, fully actuated, or underactuated). In panel *c*, the red line shows the percentage of hands that embed hand synchronized motion.

Shintake et al. (235) and Hughes et al. (236), the implementations of soft joints range from articulated structures, where the flexibility results from the use of elastic elements, to fully compliant systems that are continuously deformable into myriad possible shapes. Softness is typically created by using different material fabrication techniques, from casting and molding to 3-D printing. In general, soft articulated solutions take more direct inspiration from the human musculoskeletal system and produce systems where the compliance is concentrated in the joints, as in the Model S Hand (155), Alpha Hand (153), Delft Cylinder Hand (24), Handroid Hand (123), Bionic Hand (99), FRH-4 Hand (100), Keio Hand (74), and UB (University of Bologna) Hand III (89).

Soft continuous systems—such as the RBO Hand 2 (26), ECF (Electro-Conjugate Fluid) Robot Hand (129), MiyazakiLab Hand (107), Universal Gripper (108), SDM (Shape Deposition Manufacturing) Hand (109), Karlsruhe Hand (85), and Ultralight Hand (69)—take inspiration from invertebrates, and their whole structure is built using continuously flexible materials. Successful examples like the RBO Hand 2 (26), Soft Gripper (165), Open Bionics Hand (23), Delft Cylinder Hand (24), and Yale Multigrasp Hand (25) highlight the use of soft robotic hands in a wide range of applications.

Soft robotic hands exploit the flexibility of joints to adapt the shape of the figures to the object (or environment) when grasping, substantially simplifying the control strategies (as in, e.g., 125, 135). Soft robotic hands are particularly suitable for use in unstructured environments, where conventional rigid hands require complex control algorithms just to approach an object, and for avoiding collisions with the environment (as in, e.g., 112). Interactions with objects and environmental constraints are used to functionally change the shape of the hand (as in, e.g., 22, 26, 135).

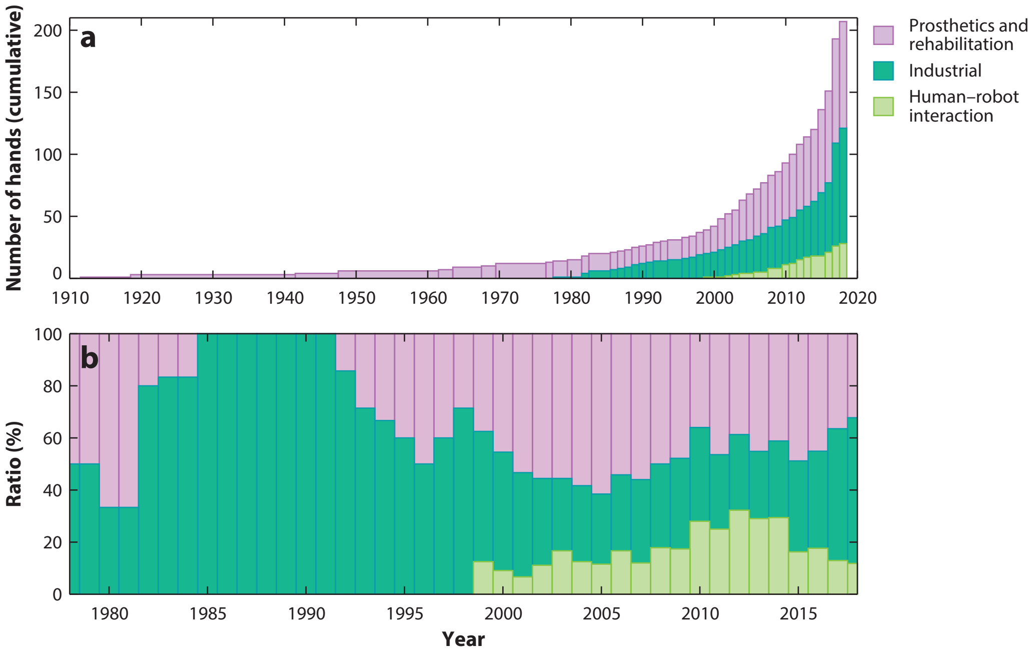


Figure 9

(*a*) Cumulative distributions of artificial hands from 1912 to 2018 and (*b*) relative distributions of artificial hands from 1978 to 2018 for the three broad application classes: prosthetics and rehabilitation, industrial, and human–robot interaction.

The compliance of the joints considerably increases the robustness of the robotic hand, which can support strong impacts with the environment or heavy disarticulation. These characteristics guarantee safe human–robot interaction, extending the use of soft robotic hands to various areas, including medical applications.

The growing research interest and technological advancement in soft robotics will lead to a significant increase in the use of soft robots in service robotics, industrial settings, and health care in the next few years. Such a trend is already evident in **Figure 10**, which shows correlations among the three application domains and the different types of joints.

Human–robot interaction applications, for example, tend to avoid using rigid joints, probably because of the unnatural and unsafe behavior of rigid joint technologies. Designs for human–robot interaction applications tend to prefer dislocatable joints, designs for industrial applications tend to prefer flexible and soft continuous joints, and designs for prosthetics and rehabilitation applications tend to prefer flexible and dislocatable joints.

4.1.2. Softness in actuation principles. Rigid actuation has been the most used approach for finger movement for many years, but as shown in **Figures 7** and **8**, alternative compliant solutions are becoming increasingly popular. Indeed, recent applications, such as human–robot interaction, have introduced novel and challenging design goals where the use of compliant actuators can provide significant advantages over traditional actuation.

As presented in **Figure 5**, the compliance in the actuation mechanisms can be introduced through stiffness or impedance modulation or by using soft and flexible materials. The latter are particularly suitable for soft continuous robotic hands, such as shape-memory alloy actuators and pneumatic actuators, which modulate stiffness by controlling the pressure of compressed air.

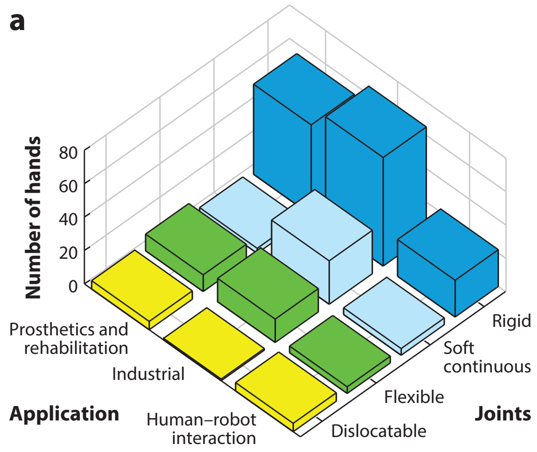


Figure 10

Correlations among the three broad classes of application (prosthetics and rehabilitation, industrial, and human–robot interaction) and the four types of soft joints (rigid, soft continuous, flexible, and dislocatable) for (*a*) 1912–2018 and (*b*) 2009–2018.

Figure 11 shows the correlations among the three application domains and the two types of actuation. Especially in the last decade, the number of soft actuators employed in the design of artificial hands has noticeably increased, with the highest rate of use in industrial and human–robot interaction applications.

4.2. Architecture Simplification

Figure 7 highlights the ongoing interest of the research community in solutions that simplify the motion architecture of artificial hands. Several approaches have been adopted, the most relevant of which (fully actuated, coupled, and underactuated) were described in **Figure 6**. Note that the

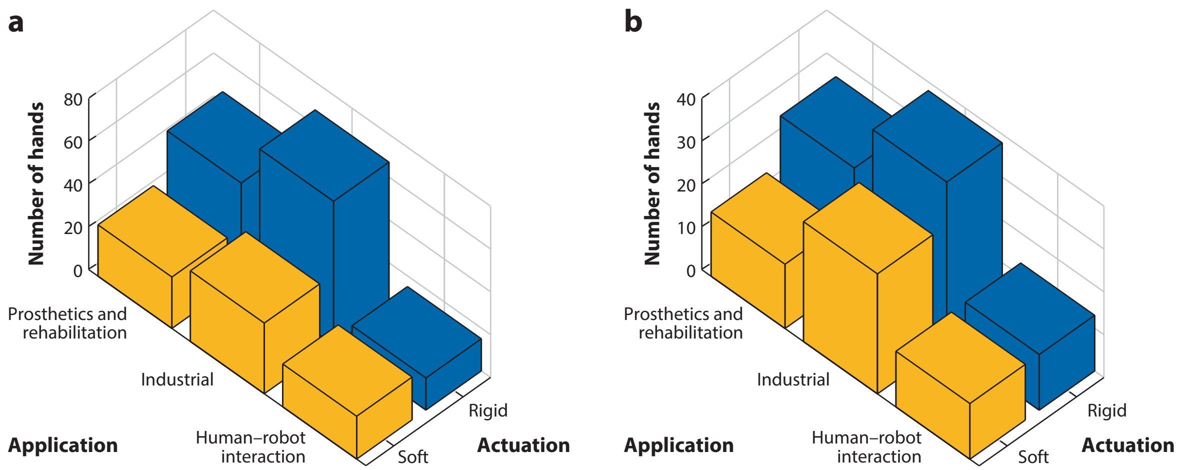


Figure 11

Correlations among the three broad classes of application (prosthetics and rehabilitation, industrial, and human–robot interaction) and the two types of actuation (rigid and soft) for (*a*) 1912–2018 and (*b*) 2009–2018.

adoption of one of these motion architectures is not directly related to the adoption of a specific kind of joint (rigid or soft) or actuation principle (rigid or soft). Some prototypes have also combined all three transmission architectures in a single device.

The first and, for many years, most common approach to hand motion was full actuation, where the number of DoFs is equal to the number of joints; the DLR Hand II is a significant example of this architecture. A different approach to simplification is the coupled architecture. These hands use one actuator to control each DoF, and if one of the joints reaches a contact, all the joints coupled to it will stop. Fully actuated and coupled architectures have been predominant in the last decade, but underactuation has now emerged as a novel way to simplify designs. Underactuated systems allow passive movements between DoFs, which are determined by the equilibrium of the contact forces with passive elements such as springs or, less often, clutches or brakes (see 237, 238). Because they use fewer motors, they save space, weight, and cost, which has led to the development of a large number of underactuated hands and adaptive grippers (for a complete review, see 239).

One particularly investigated aspect of robotic and prosthetic underactuated hands is adaptivity. Hands and grippers [such as those proposed by Laliberté et al. (72) and Dollar & Howe (109), respectively] are characterized by many DoFs but just one DoA. The use of a coupled or underactuated motion architecture can be related to some of the DoFs of the hand, e.g., fingers or pairs of fingers. Some special approaches in the design of the motion architecture extend the idea behind coupled and underactuated actuation to all of a hand's joints. This approach is trivial in hands with a reduced number of DoFs and DoAs (e.g., prosthetic grippers) but nontrivial in anthropomorphic hands with many DoFs. Only in the last two decades has a novel approach to the simplification and coordination of finger movements emerged. This approach, which we refer to as hand synchronized motion (as opposed to synchronized motion only within each finger), takes inspiration from biology and neuroscience and proposes a systematic method for designing artificial hands with a simplified architecture. Neuroscience studies suggest that the brain uses the hand as an organized and ordered ensemble. Particular patterns of muscular activities can form a so-called base set, analogous to the concept of basis in the theory of vector spaces (240): a minimal number of linearly independent elements that, under specific operations, generate all members of a given set, in this case, the set of all movements. Such a base set is referred to as the space of postural synergies or the eigengrasp space (241, 242). Different approaches in robotics have recently tried to take advantage of the idea of synergies, aiming to reproduce the same coordinated and ordered ensemble of human hand motion (95, 141). The word synergies is strictly related to the neuroscientific context and can generate confusion if used improperly in an engineering context. For that reason, we prefer the term hand synchronized motion, which is purely descriptive and does not necessarily imply a connection with any neuroscientific context.

The results shown in **Figure 12** highlight how, in the last decade, hands with underactuated transmissions dominate in all applications, even if there are still a good number of solutions with coupled transmission in prosthetics and rehabilitation and with independent transmission in industrial applications. Almost all solutions that implement hand synchronized motion rely on underactuated transmissions.

5. FURTHER PERSPECTIVES

The previous sections have highlighted some new trends and technological solutions in artificial hands. The primary aim of this review was to analyze these trends and highlight the main methods and approaches proposed over the years, and a complete analysis of the consequences that such new designs can have in the use, planning, and control of novel and future hands is beyond the

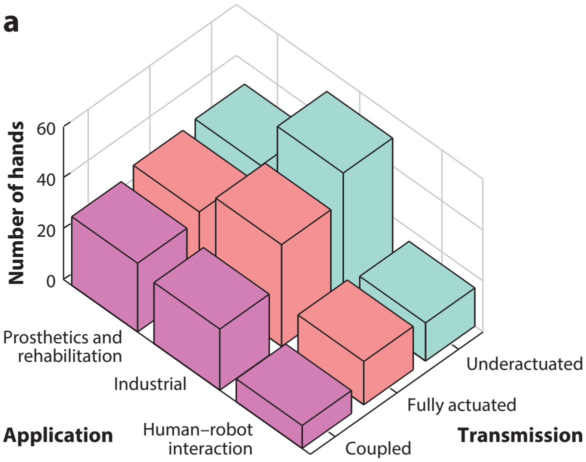


Figure 12

Correlations among the three broad classes of application (prosthetics and rehabilitation, industrial, and human–robot interaction) and the three types of transmission architectures (coupled, fully actuated, or underactuated) for (*a*) 1912–2018 and (*b*) 2009–2018.

scope of the article. However, we would like to discuss a few important consequences that these emerging trends are having, or could have, in the field of artificial hands.

5.1. Planning

In our opinion, softness and adaptivity enable artificial hands to carry out real interactions with objects, the environment, and people. As discussed by Bonilla et al. (243), such new capabilities shift the conventional paradigm of grasp planning, moving it away from a timid approach, in which the fingers must interact only with the object when performing a grasp, without perturbing the equilibrium of the object, the environment, or the hand itself. This approach to manipulation, which is a consequence of the rigidity of the contacts and the fragility of the hand, has been recently challenged by the introduction of adaptable, underactuated, and/or soft hands. Devices such as the underactuated Robotiq Three-Finger Gripper (98), RBO Hand and RBO Hand 2 (26, 128), iHY Hand (135), and Pisa/IIT SoftHand (22) are designed to be much simpler and much more robust with respect to the entire interaction process. This approach allows these hands to be used in more daring interactions with the objects in an environment—using their full surface for enveloping grasps and exploiting objects and environmental constraints to functionally shape the hand, going beyond its nominal kinematic limits by exploiting structural softness (as discussed in, e.g., 244).

Figure 13 illustrates the differences between the rigid and soft approaches to manipulation. In the classical paradigm (**Figure 13*a***), the planner searches for suitable points on the object that generate a nominal grasp of good quality and for trajectories that can bring the fingertips there while avoiding contact with the environment. In the corresponding example shown in **Figure 13*b***, in order to grasp the cup while avoiding the wall on the left, the planner must find a path in a narrow passage. Soft manipulation (**Figure 13*c***) subverts this scheme. In the example shown in **Figure 13*d***, hand–object, object–environment, and hand–environment contacts are not avoided; rather, they are sought after and exploited to shape the hand itself around the object. The set of all possible physical interactions among the hand, the object, and the environment, which define the hand–object functional interaction, is sometimes referred to as the set of enabling constraints.

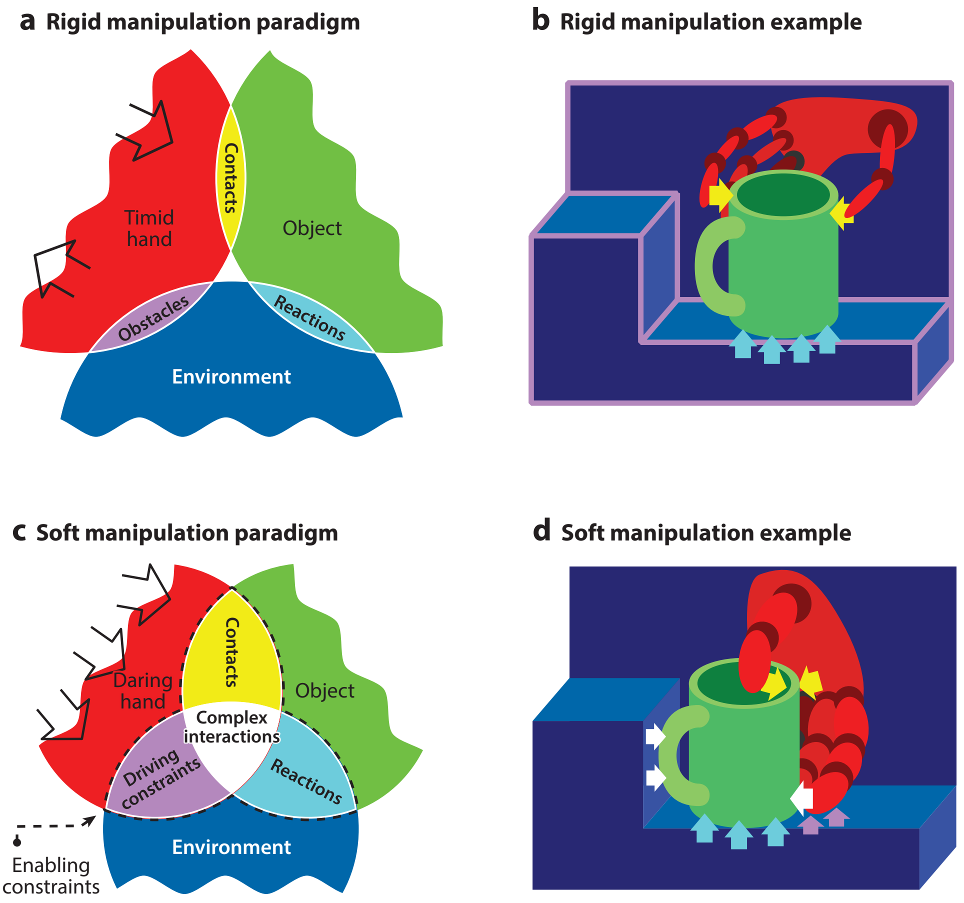


Figure 13

Paradigm shift in manipulation, from (*a*,*b*) rigid manipulation to (*c*,*d*) soft manipulation. Primary colors identify the scenario's main actors: red for the robotic hand, blue for the environment, and green for the target object. Secondary colors codify simple interactions between the actors: yellow for hand–object, cyan for object–environment, and purple for environment–hand. Complex interactions that involve all three actors simultaneously are shown in white. Figure adapted from Reference 243 with permission.

The analysis of such possibilities constitutes a new challenge for existing grasping algorithms. Adaptation to entirely or partially unknown scenes remains difficult, and only a few approaches have been investigated so far.

5.2. Sensorization

For many years, one of the main challenges in the development of artificial hands related to adding different kinds of sensors, such as joint torque measurement and finger posture reconstruction. The novel approaches proposed in the last three decades require fewer sensors and, at least in some fields, reduce the need for precision and accuracy in the sensorization. A new set of minimalist sensor systems (as in 245–247) can minimize the amount of sensorization and help to further simplify hand designs.

5.3. Robustness

One of the most evident benefits of the new design trends toward simplified soft hands is the unprecedented level of robustness. Such robustness will bring new attention to some aspects that will require consideration: the need for a new set of benchmarks and evaluation criteria that can guide the development of new hands and the need to maintain focus on systems that can benefit from this new capability. For instance, because artificial hands can now be used in the real world, the designs must be reliable and effective, and parameters like material life and fatigue need to be assessed quantitatively. A set of physical tests was presented by Falco et al. (248), and examples of proposed solutions or achievement were described by Grebenstein et al. (249) for the DLR Hand and by Zisimatos et al. (250) for the Open Bionics Hand.

5.4. Tactile Exploration

Besides vision-based methods, hand compliance offers the real possibility of using tactile exploration for 3-D reconstruction of unknown environments and objects. Tactile sensing can solve some severe limitations of computer vision, such as sensitivity to illumination and limited perspective. As an example, a combined procedure based on dynamic potential fields that aims to reconstruct 3-D object models, which are then used for grasp planning and execution, was presented by Bierbaum et al. (251) and subsequently extended by Herzog et al. (252).

5.5. Costs

Reduced complexity and the possibility of using new fabrication technologies are opening the way to reduced costs for the production of artificial hands. Moreover, the design of robust and compliant joints comes with an interesting side effect: the possibility of using materials with lower mechanical strength and precision. The softness of the joints and actuation enables the use of rubber and plastic materials, allowing for fabrication processes that can reduce costs for commercial devices (e.g., by using injection molding) and for advancement in research (e.g., by using rapid prototyping techniques).

6. CONCLUSION

The main objective of this article was to analyze the state of the art of artificial hands as well as new trends that are emerging in the field. We reviewed and grouped the most important application domains of robotic hands, extracting the set of requirements that ultimately led to the development of soft-robotics solutions and the simplification of actuation arrangements. We also provided a comprehensive analysis of the novel enabling technologies for the design of joints, transmissions, and actuators that enabled these two novel trends. We limited our discussion to these aspects while neglecting others (such as finger kinematics and sensors), aiming to emphasize the effect of these two new approaches over other design parameters that, at least in our opinion, have had a minor impact. We concluded with an in-depth discussion of the advantages of soft and simple hand designs and by reporting the most important new perspectives generated by those designs and their interaction with other aspects of hand design and robotics in general.

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Errata

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