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Review

Artificial-Hand Technology—Current State of Knowledge in Designing and Forecasting Changes

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Received: 19 August 2019; Accepted: 26 September 2019; Published: 30 September 2019

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Abstract: The subject of human-hand versatility has been intensively investigated for many years. Emerging robotic constructions change continuously in order to mimic natural mechanisms as accurately as possible. Such an attitude is motivated by the demand for humanoid robots with sophisticated end effectors and highly biomimic prostheses. This paper provides wide analysis of more than 80 devices that have been created over the last 40 years. It compares both the mechanical structure and various actuators from conventional DC motors and servomechanisms, through pneumatic muscles, to soft actuators and artificial muscles. Described measured factors include angles, forces, torques, tensions, and tactiles. Furthermore, the appropriate statistics of kinematic configuration, as well as the type or number of drive units and sensory systems, show not only recent problems, but also trends that will be followed in the future.

Keywords: robotics; biomimetic; prosthesis; robotic hand; artificial hand; anthropomorphism

1. Introduction

Biomimetics, a present trend in many scientific fields, has been known and used by engineers for many years [1,2]. This term stands for imitating natural elements, techniques, and systems for the purpose of solving many human problems [3,4]. Natural solutions, improved by thousands of years of evolution, were the inspiration for many inventions, where the most known, considered by Leonardo da Vinci and built by the Wright brothers, was the first aeroplane, of which the wings' shape was based on that of birds [3]. There are many examples of such solutions: the Schmitt trigger, inspired by squids' neural impulse propagation, the Velcro mechanism, observed on woodland burs sticking onto dog fur, trains, form mimicking the kingfisher diving into water, or modern animal-move/shape robots [5–12]. The most important solution, from this article's perspective, is contained in ourselves.

The role of biomimicking the human hand, the most dextrous tool ever known, acquired special significance during the Second World War, when the number of amputees suddenly increased [13,14]. To recover their functionality, simple nonelectrical prostheses were applied that allowed to perform a pinch grasp. Their mechanical construction was based on a hook attached to the wrist and a single wire linked between it and the back. Flexion of the arm pulled the wire, thereby moving the hook [15–17]. Subsequently, electrical human-shaped robotic hands started to appear , but this was in 1967, when such hands became commercially available and it was not until 1977 that they began to have medical importance [18].

Since then, the ongoing growth of automation and space exploration induced a rise of new applications for artificial hands: teleoperations. Hazardous, such as radioactive, chemical, or biological, environments, require to follow strict safety procedures, and a human presence in those areas is best avoided. This also applies to extravehicular activity (EVA) [19–22]. To allow an operator to work with a mobile robotic hand, it should have a more humanlike range of moves, which means that both power and a precise grasp must be obtained. As proof, [23] showed that only 29 out of the 195 EVA tools could be used with a single hand. To that effect, we make distinction between a holding and an actuating hand. Dexterity improvement should go together with a natural shape and size for better visual feedback and inglove operations; as [24] rightly said, "a human will find it easier to control a robot hand with functions like their own hand".

The end of the 20th and 21st centuries brought big technological progress. This applied to new materials, processing abilities, designing techniques, and the miniaturization of existing devices and methods [25–27]. New tactile sensors not only reduced dimensions, but are also elastic, which makes them easier to place [28–30], similarly to DC motors where, instead of the old ones, high-power density devices are used. Furthermore, artificial muscles like shape memory alloys (SMAs), twisted and coiled polymers (TCP), dielectric elastomers (DEA), and others are gaining popularity [31–35]. Whole actuators lead to the possibility of installing more of them in the palm or forehand, therefore increasing the number of degrees of freedom (DOF) [36–38]. According to the material and fabrication techniques, 3D printing is indisputably the most important innovation, as it makes prototyping and replacing parts much faster and cheaper [39,40].

Nowadays, except for the well-known solutions described above, the importance of humanoid robots is increasing [20,41,42]. The upcoming exploration of Mars will need the help of robots with dextrous skills to build a base [43,44]. However, Earth is a place where such robots would be the most appropriable. Demographic analysis, carried by Japan, showed that, by the middle of the 21st century, about 30% of Japan's population will be over the age of 65. Simultaneously, a decreasing number of births will cause a huge demand for robots that can coexist with humans and take care of them [45–47].

That and other arguments show a promising future for artificial hands, but there is still a long way to go to design a device that could compete with a human hand.

The aim of this article is to review artificial hands developed by scientific research groups since the 1980s, as well as to discuss novel technology. The paper approaches the issue of mechanical construction through actuation and transmission methods, ending on applied sensory technology. Analysis of over 80 devices provides trends that robotic hands would follow in the near future.

In addition, it must be noted that the analyzed devices were searched in all available scientific databases with the phrases "artificial hand" and "robotic hand". Moreover, due to the large amount of data, the table with a complete comparison of all mentioned terms is included in an external repository [48].

2. Human-Hand Overview and Evaluation

2.1. Natural Principles

In order to better understand hand structure and purpose, and to introduce the nomenclature used in this paper, the main body systems are described below.

The human hand consists of five fingers: thumb, index, middle, ring and little, which are numbered from 1 to 5, respectively. Its skeletal system is composed of 27 bones, where eight are carpals and five metacarpals. Digits 2 to 5 have three bones each, called the phalanges: proximal, middle, and distal. The thumb differs from the other fingers and has only two bones, the proximal and the distal (Figure 1). Ligaments between the appropriate bones create joints that allow them to move in particular directions and ranges. Three main joint types can be distinguished: proximal interphalangeal (PIP), distal interphalangeal (DIP), and interphalangeal (IP) joints are simple hinge joints, which means that they can move in one axis. Another type is the condyloid, which forms metacarpophalangeal (MCP) joints and allows biaxial movement, i.e., flexion or extension, and adduction or abduction. The third and most important is the saddle joint of the thumb, the carpometacarpal (CMC). Due to specific construction, this joint provides triplane movement, that is, flexion or extension, abduction or adduction, and rotation. It should be noted that the CMC joint is defined as a joint with two degrees

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of freedom because there is no possibility to independently execute a third move. Nevertheless, as a result of these three actions, the human thumb can perform opposition, which makes it unique [49,50].

The contentious issue of hand kinematics is the opposition of the little finger. Levangie in [51] described the CMC joints of Fingers 2–5 as follows: the second and third may be considered as having 0 DOF, the fourth is the plane synovial joint with 1 DOF (flexion or extension), and the fifth is a 2 DOF saddle joint that permits flexion, extension, some abduction, adduction, and limited opposition. On the contrary, human-hand kinematics in [52,53] included CMC joints of the ring and the little finger as two biaxial joints. As settlement of this dispute is not in the aims of this article, the overall term of "little-finger opposition" is used in the following sections.

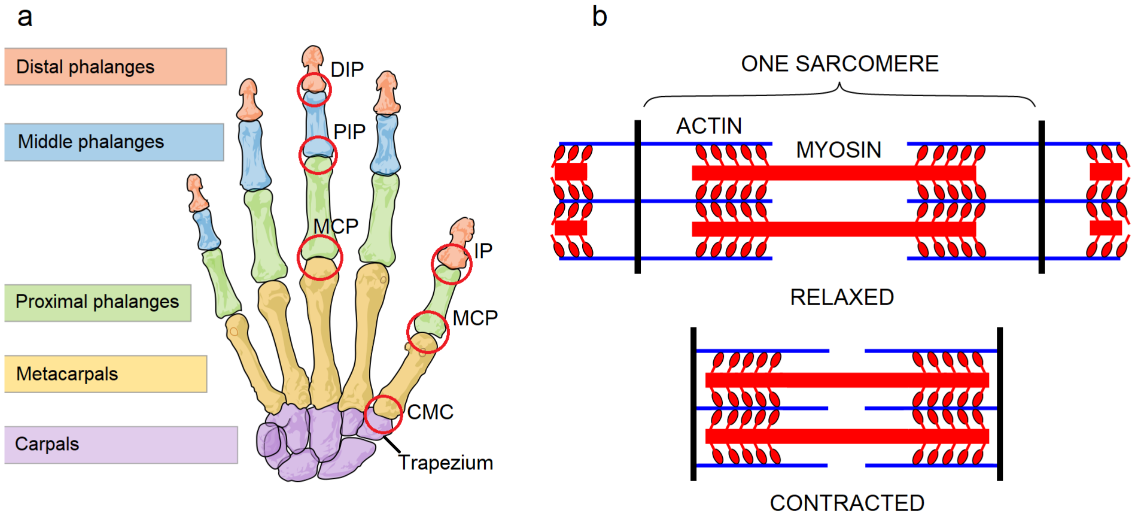

Figure 1. Human-hand principles: (**a**) skeletal system (based on figure by Mariana Ruiz Villarreal); (**b**) muscle-sliding-filament theory (based on figure from basicphysiology.com).

Muscles are natural one-way actuators, so they mostly work in opposing pairs. A basic unit of muscle fiber is a sarcomere. It consists of thin (actin) and thick (myosin) filaments. The mechanism of contracting is described by muscle-sliding-filament theory where, generally, thick filaments slide past thin ones. As a result, a muscle shortens and its volume simultaneously increases. More than 30 hand muscles could be classified by their location; those in the forearm respond to power grasps, and those in the hand to precise grasps and manipulation [54,55].

Motion transmission is carried by the tendon system. Elastic connective tissue, connected between muscles and bones, slides in sheaths that not only prevent it from rubbing, but also keep it in the right place close to the digits. There are simple, direct tendon connections as well as complex ones, i.e., the extensor mechanism, otherwise called the tendon network. The structure of the extensor mechanism combines forces from such muscles as interosseous, lumbrical, and extensor digitorum that, depending on the sequence, allow executing different finger moves [49,56].

The nervous system is the control unit of an organism that transmits signals to and from different parts of the body. As there is no need to explain the sensing-mechanism principles of upper limbs, the most significant are listed as follows: tension of muscle fiber, muscle-contraction velocity, and touch detection of the skin (pressure, slip, vibration, temperature, and pain). Furthermore, processing of these data happens in conjunction with vision, our dominant sense, and proprioceptors provide information about joint angle and body-part orientation [55,57–60].

There are many strategies for determining hand mobility, and the first works on it assumed such factors as parts of the hand used in grip, shape of the object, final position, and geometry [19,61]. However, in 1956, Napier divided tasks into prehensile (an object is seized or held) and nonprehensile (passive activity of hand like lifting or holding an object) actions [61]. He also considered that grasp stability is required for proper hand operations. As this could be achieved by holding an object

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between fingers and palm, or fingers and opposing thumb, grasps were classified as power or precise. The above solutions were used and published by Cutkosky as grasp taxonomy where the first level of the tree is divided into precise and power grasp, and then branches out into grasps that depend on object geometry [62]. This classification and many others were incorporated into the recent work of Feix et al., which provides many more details of grasp properties (Figure 2).

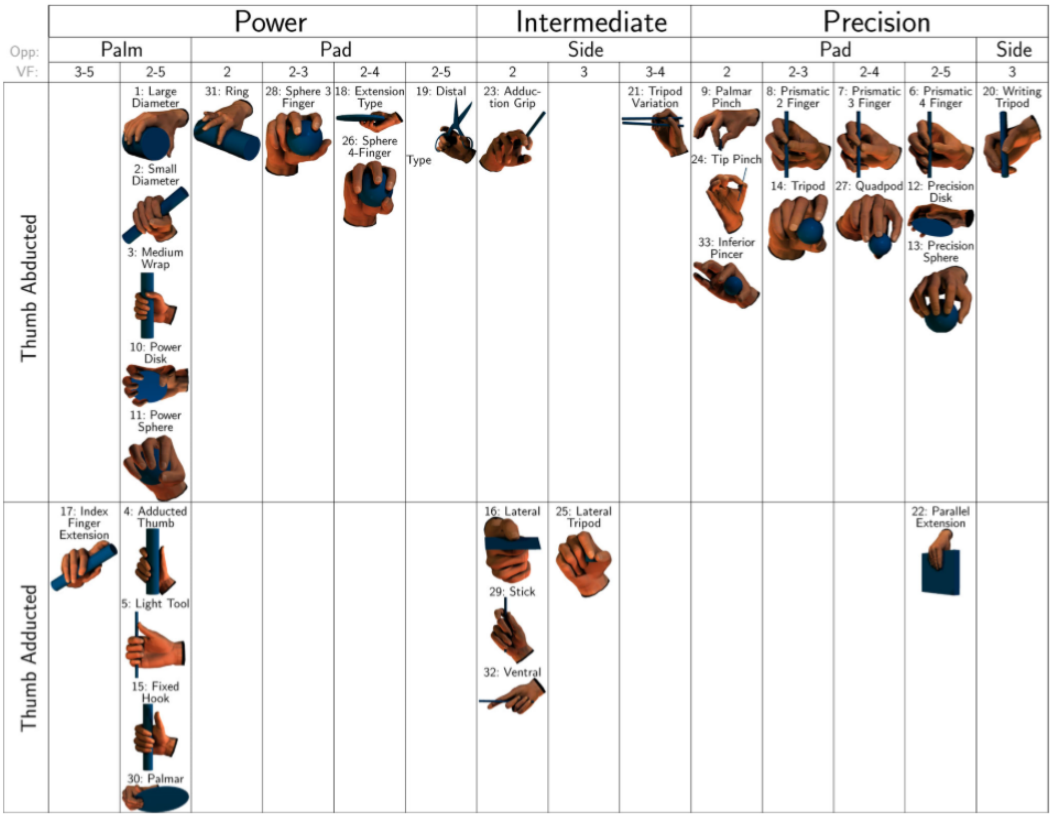

Figure 2. Feix grasp taxonomy. Reproduced with permission from [63], IEEE, 2019.

Taxonomy has a total number of 33 grasps that are split into the following aspects:

- power, intermediate, and precision grasp;
- type of thumb opposition: palm, pad, and side;
- thumb adduction or abduction; and
- virtual fingers, number of forces applied in different directions.

2.2. Artificial-Hand Examination

In order to compare a robotic hand with that of a human, comparison methods must be considered. Commonly used by most researchers is an investigation of how many grasps, from both Cutkosky and Feix taxonomy, the device is able to perform. More complex examination, in prosthetics compliance, is the Southampton Hand Assessment Procedure (SHAP) test [64], where the dynamics of the whole prosthesis system is tested. It consists of two tasks, where first an amputee has to manipulate six abstract objects. The second part includes 14 activities of daily living (ADL). If the user is unable to complete a task in 100 s, it is considered a failure. Another was introduced by Kapandji [65] to examine thumb-opposition abilities by simply touching various parts of the hand with the thumb tip.

In opposition to the methods mentioned above that allow a comparison of a robotic hand with a human hand, Biagiotti et al. [66] proposed an approach to contrast devices with defined indices. The anthropomorphic level takes into account three features, kinematics, contact surfaces, and size. It also defines the potential dexterity index of a given mechanical construction; hence, fingertip

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or whole-hand grasp and manipulation are rated. Moreover, the index of the sensory system was considered; thus, angle, tactility, force or tension, and additional sensors were indicated.

3. Construction

The precise mathematical approach of grasping an object is presented in [67], but a basic projecting principle is provided in [23]. This states that, to obtain a stable grip, at least three fingers are required, the thumb and two fingers opposable to it. Moreover, to perform in-hand manipulation, a fourth finger must be arranged so that three-point grasp is guaranteed while one of the fingers is being replaced.

As rigid digits cannot always provide stable grasp, solutions based on pincers [68,69] are not only discounted in this paper but they were also superceded over time by more complex devices.

3.1. Finger Configurations

Most artificial hands are human-based, which means that there are four palm fingers (index–little) and a thumb [38,70–73]. However, some research groups found solutions with three [74–81] or four [23,40,82–90] fingers applied (Figure 3). While the former group mainly contains optimized grasp algorithm testing platforms, the latter consists of more versatile devices. As proof of the above statement concerning the number of fingers, Lee et al. [90] and Mnyusiwalla et al. [89] present robotic hands that perform in-hand manipulation of a ruler, bulb, and can.

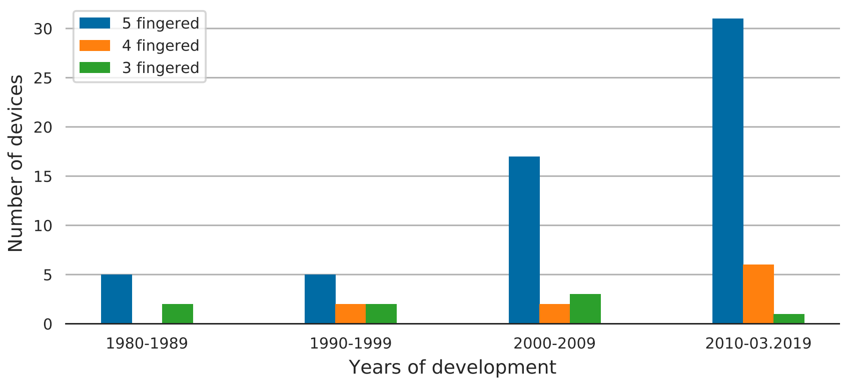

Figure 3. Timeline of number of fingers in robotic hands.

Figure 3 clearly shows no dependencies or a trend of an increasing number of constructions with fewer than five fingers, and the ratio of these mechanisms is dropping. The appearance of such devices could simply be explained by both construct simplification and restricted space [40,88].

3.2. Joint Types

Finger classification is one of the basic and superficial types of categorisation. For closer determination of prehension ability, joint analysis has to be conducted.

First of all, the nomenclature must be clear. The concept of degrees of freedom is commonly used in mechanical engineering and robotics to describe mechanism mobility [91]. This term states the number of independent input parameters required to explicitly determine the state of the whole system. For example, a kinematic chain with two revolute joints, each driven by single actuator, has 2 DOFs. The same system but coupled, so one actuator controls both links, is perceived as having 1 DOF. The necessity of this explanation comes from the arbitrary usage of "degrees of freedom". Authors exploit it to show mechanical construction (only the number and type of joints) as well as hand dexterity (including actuation and transmission) [92–94]. In compliance with the above definition, the first application is not correct in some cases and could lead to misunderstandings. In this regard, the term "degree of motion" (DOM) is introduced in this chapter to describe the mechanics of robotic hands with no interconnections. The concept "degree of freedom" is used in the context of the whole hand in the next chapter where actuating systems are considered. In addition, some research groups

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distinguish both aspects by using DOF and active DOF, where the latter means joints with independent actuation [89,95].

There are several kinds of joints that are applied to artificial hands and they are summarized in Table 1. Most frequently, a simple hinge is used for an axial motion like flexion and extension of PIP and DIP links [96–99]. The gimbal is a combination of two or three hinges that rotate around a geometric center point, and is often employed in MCP joints where abduction is preferred [92,100]. Another type, the pivot ball, has three degrees of motion, which is arguably a good solution for thumb CMC application; however, in MCP, one of the motions must be prevented from torsional activity. This joint was used in [101,102] as an MCP connection, but neither author mentioned the phenomenon of third axis rotation. Alternative designs are ellipsoidal or saddle joints that are inspired by the human skeletal system. Both [93,100,103] devices were based on biocorrect bone models, thereby replicating a natural-link strategy. Contrary to previously described constructions, these were not equipped with a mechanism that keeps parts of the structure together. Hence, an elastic ligament was provided to stabilize bones and constrain motions, as well as to hold synovial fluid that reduces friction between two articulated surfaces.

Table 1. Characteristics of main joint types.

Type	Motion Axis	Additional Instruments (Angle Sensor, Torsion Spring, etc.)	General Characterization
Hinge	1	YES	Simple, cheap, commonly used
Gimbal type	2–3	YES	Combined hinge, commonly used biaxial
Pivot ball and socket	3	NO	Good for thumb, high friction, torsional prevention required
Ellipsoidal	2	NO	Biomimic, rarely used, complicated geometry, needs ligaments to hold parts
Saddle	2	NO	Biomimic, rarely used, complicated geometry, needs ligaments to hold parts
Elastic	Multiaxial	YES	Cheap, unstable, actuators and transmission system exposed to damage

There is also a relatively new group of elastic devices that have pneumatic actuation. They are made of very stretchable silicone (EcoFlex) that, through inner chambers, can bend in a specified direction when pressurised air is applied. Deimel et al. in [104] presented a single-mold hand where even joints could not be identified as only sections of five fingers, and inner and outer palm were mentioned. In addition, they were controlled by four supplying channels. Despite that, the hand not only passed the Kapandji test, but was also able to perform 31 out of the 33 Feix grasps. On the other hand, Qi et al. [105] proved that properly projected fingers and multichannel actuators (described in the next section) lead to humanlike construction. This hand had 2 DOM in MCP and CMC joints, and 1 in PIP, DIP, and IP, so there was no difference from typical rigid devices.

Robotic hands where nothing except joints is made of flexible components like rubber or spring belong to elastic devices [106–108]. Such a structure is cheap and easy to apply, but it does not protect from side or torsional impact that may cause damage to the actuation and transmission system.

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3.3. Joint Configurations

The number of joints in a robotic hand varies depending on the chosen architecture. Commonly, fingers from index to little have 3 to 4 DOM each and are able to flex or extend, and abduct or adduct [24,45,109–114]. There is some research that introduced untypical link applications or reductions [106,115,116]. In [90], MCP joints of palm fingers, instead of a conventional yaw-pitch type, were designed as a roll-pitch. This modification helped with in-hand manipulation that was confirmed by appropriate tests, especially 16 Cutkosky grasps that showed that abduction could successfully be replaced. The Kitech hand is known under a new name, Allegro hand, and is commercially available as one of the better prostheses. Another metacarpophalangeal solution was presented in [39,117], where the first joints of Fingers 2–5 were constructed as one part having 1 DOM (flexion–extension). It had no trouble performing most SHAP points. Another example is the Robonaut hand [20,118] that also included the opposition of the little and ring fingers. For the same purpose, having better adhesion, [40] utilized three CMC joints (palm fingers) that each had a single degree of motion.

The feature primarily affecting whole-hand dexterity is the thumb. Its extraordinary mobility participates in the majority of grasps [62,63]. Three methods for the first finger are utilized:

- with opposing joint (most devices) [95,101,119–124],
- placed in opposition [21,38,89,125–127], and
- manually reconfigurable [70,106,107].

The first solution has at least 2 or 3 DOM in the CMC joint and 1 DOM in MCP and IP each. These constructions are highly biomimic since versatility of such a thumb allows them to perform most types of human movement. More advanced structures involve [128], where the first finger has 5 DOM and highly mimics human mobility. On the contrary, the latter is unable to accomplish precise and power circular grasps due to the parallel work of the first finger to the others. The last group is represented by typical prosthetic applications where the amputee decides how a task would be executed and manually sets a thumb location [112]. In [107], there were nine lockable positions in order to meet the demands of Kapandji, but commercial prostheses show that a small posture is sufficient [129,130].

In summary, we can conclude from all the analyzed devices that the optimal robotic hand should have 16 DOM: 1 in the DIP, PIP, and MCP joints of the index–little fingers, 1 in the MCP and IP of the thumb, and 2 DOM in the CMC joint. This configuration allows to perform most practical grasps except those where Fingers 2–5 abduction–adduction is required. The carpometacarpal can usually oppose and rotate or flex–extend, while the next two joints simply flex and extend to enclose the grasp with the palm fingers. Appliances with fewer than 16 degrees of motion lose dexterity. The most sophisticated group consist of devices with more than 19 DOM. Abduction and adduction are available as well as some additional DOM in the thumb or palm. The most humanlike robotic hand is the Shadow hand developed by the Shadow Robot company, with 23 DOM that almost ideally mimics natural construction [131].

In Figure 4, hands with five or four fingers were divided into the three groups described above and presented by time period. The most prosperous is the middle one, with 16–19 DOM, because of relatively good human abilities and not many complications, allowing to apply it in prostheses or to test algorithms and new actuators. The development of advanced ones is limited due to recent challenges in combining new technologies, i.e., actuating devices, proven in the next section and supported by appropriate tests. Consequently, legit solutions from the first two groups are more readily used.

This chapter mainly includes features directly affecting device dexterity. Notwithstanding, weight, size, materials and manufacturing methods should be considered and are well-discussed in [129,130,132,133] in the context of prosthetics.

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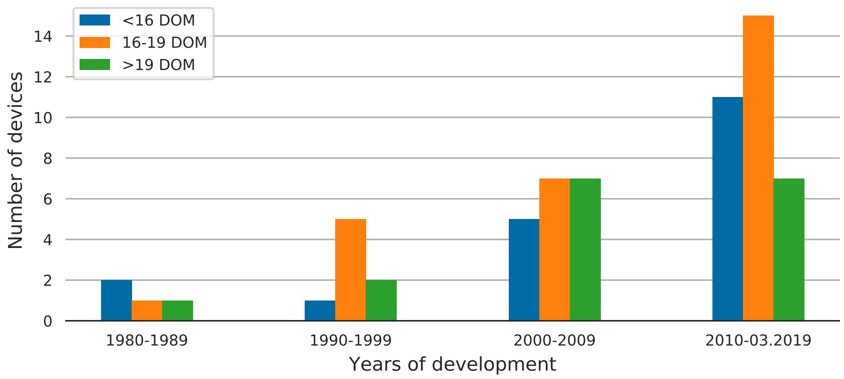

Figure 4. Timeline of configurations of degrees of motion in robotic hands.

4. Actuating System

4.1. Actuator Types

A type of actuating device has a major impact on artificial-hand dynamics. Varying-drive responses affect joint velocity, while power (with transmission efficiency) has influence on the force produced by the fingertips and the whole mechanism. It should be noted that these are not the only aspects that have to be considered during the design phase, since size, weight, and noise are generally restricted. There are a number of parameters that specify a chosen unit, so general categorization should be employed. Controzzi et al. [132] and Weir [134] described actuators typically divided into DC motors, pneumatic/hydraulic actuators, and a few new types, such as SMAs and EAPs. Instead of that, Del Cura et al. [135] briefly presented the existence of motors and active materials that leads to linear or rotational movement, where all could be categorized by experience into conventional and nonconventional.

This article combines all of the above, so no homogeneous classification is adopted. The first group consists of actuators based on rotary motion; devices like motors, electric actuators, servos are specified. Another fuses both pneumatics and hydraulics; broadly speaking, these use pressurised gas or a liquid medium. The last gathers active materials also called artificial muscles, a relatively new group of actuating units.

There are two main types of DC motors that are related to inner design. Brushed motors have rotating windings so a commutator and brushes are used to change polarization. Mechanical contact between them wears down both parts in time and shortens the device lifetime. It also generates noise that is not desirable in prosthetics. A better solution is a brushless motor that has stationary windings, making it contactless. Hence, it is not only noiseless, but also has simpler construction, higher efficiency, power density, and generated torques (see Table 2).

Regarding these parameters, both motor types require a reduction system to decrease speed and increase momentum for workable applications. Miniature gearmotors and standalone gearbox modules are used. The authors of [116] used a miniature Pololu with a 35:1 reduction that allowed to rotate joints with a speed of 20 deg/s. RCH1 Hand [45] with Maxon RE-maxl7 motors and separate gears (64:1) achieved 2750 deg/s in the DIP joint with a total grasping force of 30 N. These and other examples [40,75,77,79,94,136,137] showed that a free-standing motor, regardless if it is brushed or brushless, is not able to drive such mechanisms like a robotic hand.

At the expense of size, servos provide an inbuilt gear reduction mechanism with a potentiometer so that precise positioning is achievable. Furthermore, due to increased output torque reaching 7 Nm in [73], angular velocity was reduced, interestingly to the same average value of 270 deg/s [24,36,85,108,138]. This is similar to linear actuators, where instead of rotational, linear displacement is produced [39,81,106]. Solutions like [88,137] rotated the fingertip with 1396 and 450–800 deg/s, simultaneously delivering 30 (grasp) and 15 N (fingertip) force, respectively. A stepper motor is another type of actuator that provides position control, but as other motors,

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it requires a gearshift. Yang et al. [139] does not mention a gear ratio, but 5 V Escap motors used in their hand allowed to generate 10 N fingertip force, which does not differentiate it from the above solutions [24,39,86,99].

Table 2. Comparison of motor-based actuators.

Actuator	Model	Power Supply (V/A)	Torque/Force (Stall)	Power Density [W/kg]	Speed	Weight [g]	Cost [$]
Brushed DC motor	Maxon motor DCX10	12/0.01–0.16	0.905 (1.37) mNm	159	4530 rpm	6.3	104
Brushless DC motor	Maxon motor EC20	24/0.03–0.84	7.74 (19.9) mNm	227	5220 rpm	22	93
Ultrasonic motor	Shinsei USR30-B4	110/	50 (100) mNm	132	250 rpm	19	–
Servomotor	Hitec HS-475B	6/0.18–1.1	(539) mNm	–	55 rpm	40	28
Stepper motor	Escap P110-064-2.5	24/0.65–0.9	3–5.5 (7) mNm	157	<10,000 rpm	23	143
Linear actuator	Actuonix PQ12-P	12/0.2	8 (15) N	–	15 mm/s	15	65

Alternatively to the electromagnetism phenomenon, a reverse piezoelectric effect may be used to produce force and movement. Strictly in piezoelectric motors, an applied electric field causes the shape change of material that, for example, repeatedly pushes the rotor and makes it rotate. Such articulation provides high torque, but the construction is complicated and expensive; hence, robotic-hand applications have not been reported yet [129,130,132,135]. However, the same work principle is used in ultrasonic motors, where the transmission method is different. Its approach is to generate a propagation wave on a stationary elastic ring that, due to mechanical contact with the rotor, causes its rotation [135]. This type of motor is magnetically resistant, has high torque, and a fast response, but physical contact drastically shortens its lifetime. In [111], the disadvantage of a nonlinear torque characteristic was considered and, in order to prevent it from potential damage, motors were coupled with fingers by elastic wire so that uncontrolled impact could be softened. The authors declared that the velocity of MCP and the others joints was 486 and 900 deg/s, respectively, while a value of only 2 N of fingertip force during a force-control test was noted.

Noteworthy is the solution of Sonoda and Godler [140]. They proposed an application of a DC motor, but instead of conventional reduction system, a “Twist Drive” was used. Two tendons were linked to a motor shaft at one end and to a digit at the other with an offset between them. When the motor shaft rotated, the wires would twist, adequately shortening their length to that connection so that pulling occurred. In spite of nonlinear transmission characteristics, the authors proved that a simple P/Pi controller allowed stable hand movement as well as 10 N force per each finger.

Another group of actuators consist of pressurised-medium-driven devices such as actuators, muscles, and custom-made ones. Generally, they are specified as compliant, impact-proof, and of low precision, since the air (typically exploited gas) has a large compressibility coefficient. Furthermore, dynamics is strongly dependent on pressure used in the system.

First, a linear actuator is a rigid unit that could be both one- or two-way. It is not possible to miniaturize it because of the piston fitted inside, as well as square reliance between a cylinder diameter and generated force [135]. Moreover, additional space for equipment, i.e., valves, pressure regulators, and a gas reservoir, must be prepared. Owing to these limitations, actuators were used for test

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purposes where soft, humanlike moves were required [84,93,100], or in automatics like the Utah/M.I.T hand that allowed not only 31 N fingertip force, but also a 10 Hz open–close cycle. In order to tackle the precision problem, Kim et al. [115] proposed a two-mode actuator. The first cylinder is for big and fast displacements (468 deg/s) and, when an object is reached, the second is activated (250 ms delay) to execute small movements with a sufficient amount of power (29.1 N in fingertips). As the hand is supplied by hydrogen peroxide decomposition, a complex transmission system allows to lock joints on the desired positions in order to minimize air consumption. Although it was reduced to 23.5% compared to conventional actuators, the occupied space limited the number of actuators in a five-fingered 11 DOM hand to four.

A well-known one-way type of actuator is the McKibben muscle, a so-called pneumatic muscle. It is so named due to its build and working principle. It is made of an elastic tube covered with a braided mesh sleeve, where one end is plugged and another is the air inlet. When pressure increases, the tube expands, and the mesh architecture imposes longitudinal contraction [141]. It features elasticity, low weight, up to 150 Hz work frequency and large available forces (see Table 3), making it a prospective solution for robotics [110,142]. Despite the high characteristic nonlinearity and low precision of pneumatic actuators, the creators of the Shadow hand [131] limited its actuating speed to 0.5 Hz so that 0.6° joint-positioning accuracy was feasible.

Table 3. Comparison of conventional pneumatic actuators.

Actuator	Nominal Length [mm]	Displacement	Force [N]	Speed [Hz]	Life Time [Cycles]	Weight [g]	Cost [$]
McKibben muscle (Festo ⌀5)	30–1000	20%	140	<150	10^7	77	–
Linear actuator (Airpel cylinder M9)	68 + stroke	12.5–300 mm	47	–	>10^7	36–144	105

A relatively new group consists of soft pneumatic actuators. They also require a pressurised medium, but control is more difficult. Some applications use silicone molds that have an inner chamber system because of which all parts bend in a defined direction. Such a solution was applied in [104], where the hand was single-mold with four air channels. Similarly, in [105] three additional fluidic elastomer actuators (FEAs) were applied to MCP joints. As FEAs are silicone tubes with special windings, connecting three of them in a joint allows the precise control of movement by the appropriate activation order. Dexterity tests demonstrated that 1 bar was required to bend the MCP joint by 90°. Other solutions assumed pulling the tendon with expanding balloons [120], but even in [87], where 35 N wire tension was reached, authors did not mention its lifetime. Direct applications in joints are also used, like in [114] in which a tube covered by two materials with different elasticity moved the fingers, or the device presented in [71,127], where the advantage of fluid medium, that is, the highest achievable forces, occurred with 25 Nm joint torque.

The last actuator group is active materials, where changes in a crystal lattice are the movement source. The most popular are shape memory alloys (SMA) [102,143]. They are based on a phase transformation between two states, martensite and austenite. Generally, when an alloy is under load and its temperature is increased, the material recovers to its original shape [33,144,145]. The most important advantage of this material is its small weight and noiseless work, appreciated in prosthetics [125]. Unfortunately, the phase-temperature characteristic has big hysteresis that causes control problems and was actually reported by many researchers [37,98,146]. To solve this problem, many schemes were applied, including a conventional PID [80], C-segmentation with Peltier modules [37,98] and fuzzy algorithms [147]. Moreover, to manage nonlinear systems, a neural network

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was speculated [80,148]. Despite the employed complex control methods, the main problem of heat exchange occurs. Because of this, time response is poor, 1 Hz in [80,149] and less than 0.1 Hz in [147]. The typical strain varies between 2% and 3% (see Table 4), so long wires must be used [149]. To shorten actuator length, springs are a better solution [126,150]. For a better understanding, human-muscle parameters are included [151–154].

Table 4. Comparison of artificial and human muscles.

Actuator	Stress [MPa]	Strain [%]	Power Density [W/kg]	Efficiency [%]	Life Time [cycles]	Activation Type (Value)	Speed [Hz]	Cost [$/kg]
human [144,145,151–154]	0.1	20–40	>100	30	10^9	ATP (70–140 mM/min)	4–20	–
SMA [33,144,145,155,156]	100–400	2–3	1000	<10	10^5	heat (30–130 °C)	<3	1.4k–13.7k
DEA (VHB) [32,144,145,157,158]	<7	<380	400	60–90	10^6	electric field (100–412 MV/m)	10	170
TCP [31,145,159,160]	19	<49	27,100	<1.32	1.2×10^6	heat (50–250 °C)	<7.5	5

Another actuator powered by heat is the twisted and coiled polymer (TCP). Also called the fishing-line muscle since the same material is used. TCP muscles are fabricated by twisting fibers under a particular load and then coiling them together. Such a composite must then be annealed and trained to keep the form of the shape [117,160]. Parameters such as a high power-to-weight ratio, elasticity, and cheap and easy fabrication make them a prospective solution in robotic applications [145]. Saharan and Tadesse in [113] presented electrically powered muscles that actuated both a finger and a locking mechanism. More sophisticated control is realised by liquid flow. In [31,161], a device was presented with TCP muscles enclosed in a silicone tube (equipped with a spring for prestrain). Cold water, 21 °C, and hot, 60–99 °C, went through the silicone channel and cooled and heated the muscle. As high as 0.5 Hz contraction frequency was available, but the problem of hydraulic inertia was exhibited, as it took 1.5 s for water to flow from source to actuator. To prevent this phenomenon, the authors in [117] increased muscle length by a pulley system, and bigger and faster displacement was possible. They also investigated coil-number impact on dynamic properties. As a result, it was observed that a muscle with three more fiber contracts has higher force, while two coils are faster; contraction time of 1–1.15 s was achieved.

Finally, there are dielectric elastomers based on polymers with a high elasticity coefficient and powder electrodes on each side. Due to Maxwell stress, large deformation is generated, but it must be noted that 100–400 MV/m electric fields are used [144,158]. The most studied material is a 3 M Company product (VHB, also used in tapes) that allows a working frequency in the range of 5–20 Hz [157]. Instead of longitudinal expansion that causes considerable strain, even up to 380% [145], lateral utility was also considered [32]. So, this type was used in [162] where a multilayer, trapezoidal DEA actuator was placed directly onto the joint. With an average 2 kV supply, a maximal force of 3.3 N was reached as well as 8% strain.

To clarify, the above-described types of actuators, both classical and those from the group of artificial muscles, were described due to their direct use in artificial hands, which was the main requirement in all solutions compared in this article. Nevertheless, it should be noted that huge interest exists in the field of new actuation methods, e.g., carbon nanotubes, electroactive polymers, and stimuli-reponsive gels [144,145,163]. Moreover, hybrid solutions were also considered, for example, in [164], where the McKibben muscle was combined with SMA wire; actuators with two movement sources, e.g., in [34], of which the gripper is based on a DEA with a special architecture of active layers,

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so that electroadhesion occurred and stated the main gripping force of the device. These and others are currently implemented in grippers where bending movement is mostly used for actuation [35,165,166]. However, some of them are promising and can be used in artificial hands in the future, hence all research progress should be followed.

One group, not classified, deserves attention: springs and torsion springs. They must be mentioned as they are preferable passive back-drive actuators [72,140,161]. They are ordered to prestrech soft actuators for proper work [125] as well as to reduce oppositional-tendon tension [150] and eliminate backlash [20]. Furthermore, a known spring constant allows precise force and displacement measurement with an additional aperature [82].

In Figure 5 devices chosen over the years are presented. Trends show in a clear and explicit way that, most frequently then and now, applied drive units are motor-based ones. DC motors not only became easy accessible and cheap, but also extensive knowledge and experience in control methods are widely available.

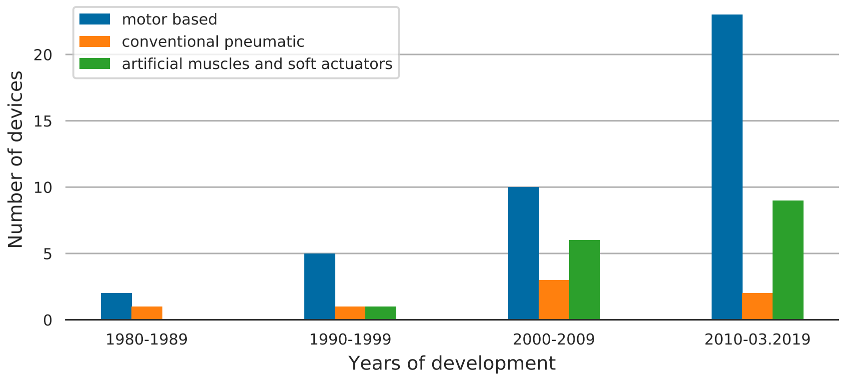

Figure 5. Application timeline of different types of actuators.

However, weight and dimensions do not always fulfil the requirements of prosthetic hands and other applications, not to mention pneumatic/hydraulic actuators. Consequently, unconventional solutions, like soft actuators and artificial muscles, have gained more attention, as they are lightweight, strong, and cheap. The increasing number of devices with such actuators proves that the next generation of robotic hands would abandon common drive units and replace them with more advanced ones that may exhibit human features.

4.2. Transmission Approach

There is no actuator that could at once be directly placed in a joint and deliver enough torque. Some robotic hands try to face that problem, but either motors installed in the digits, farthest from the proximal part, require bevel gears or custom-made pneumatic/fluidic occupied space above the joints [71,99,127,140]. The need for a sufficiently dynamic and humanlike appearance led to palm or external (forearm) location; thus, a transmission mechanism must be provided [167]. Furthermore, the number of actuators in the bulk of robotic hands is lower than the degrees of motion, so some of the joints are coupled in different ways, most frequently, DIP and PIP [78].

Stiff connections are preferred for drive units installed in the immediate vicinity of the finger base. Such solutions as four-bar linkage were applied in [88,122,136,139], which allowed precise and stable positioning with the use of servomotors and DC motors. In the Robonaut hand, an original solution used a flexshaft to transmit rotation from BLDC motors to the leadscrew in the palm, where it was converted and applied to four-bar linkage [20,118]. Another basic mechanism was included in [84] and in [39]. Both of them were equipped with linear actuators. For that reason, a slider rocker mechanism secured the motor shaft from vertical forces, especially in Rehand, which is a prosthesis, so it was exposed to daily leaving activities. The next example of rigid parts in transmission systems are various types of gears. In [86], Takeuchi et al. implemented a complex chain of shafts and bevel

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gears. A 2 DOF MCP joint moved thanks to more than eight gears. A DC motor placed in the proximal part responded with six gears and three shafts for simultaneous PIP and DIP joint rotation. Such an application requires precise and decent assembly and components, so that slipping or locking does not occur. A gear rack is the other kind, where not only is conversion from rotating to linear movement (and vice versa) possible [97,115], but gearbox features as well. Although all above constructions were able to execute two-way movement, a significant amount of space must be considered during the design phase. More importantly, none of them was backdrivable, so any impact to the active axis could damage both transmission system and actuator.

The biomimic method of transmission refers to fibrous connective tissue, the tendon. It is used more or less in all types of actuators. Since McKibben and artificial muscles are one-way actuators in cooperation with elastic filament, actuation must be considered so fingers can be controlled by pulling links. It works as described in SMA-actuated hands [98,146,149] and in the SBC hand [37], in which abduction–adduction was possible. In the Shadow hand [131] an impressive number of 40 tendons were grouped and redirected from the forearm, through the wrist, to a 24 DOM hand. It should be noted that pneumatic muscles used in this hand require prestretching; thus, all construction was metallic in order to counteract occurring forces and stresses. Moreover, the authors pointed out that the hand is controlled both in a joint-angle and joint-stiffness loop, which partially solves the impact problem.

Tendons are also applied in devices with conventional two-way actuators. In such applications, they are directly routed and attached to phalanges, and pulleys are also used. In Robonaut Hand 2 [168], another original actuation method was presented based on linear movement like previously [20,118], with tendons being immediately connected to joints. Most important in that research was the fact that the authors carried out tests of a tendon work environment. In this project, such factors as sliding material and lubricant were considered to elongate tendons' lifetime, which has not been included anywhere else yet. Directly attached ligaments were also used in [72,78,108], where extension was handled by compression or torsion springs. The Robioss hand, and the hand built by Yamano et al. used a tendon-wrapped round pulley to perform flexion and extension via a servomotor and ultrasonic motor, respectively [89,111]. Contrary to these, the DLR Hand [95] used elastic elements between motor and connection point. The ability to store impact energy by these elements protects the hand from potential damage, which was proven by an appropriate test: a cylinder bar hitting the hand with a speed of 3.8 m/s.

The most biomimetic tendon routing involves a complex extensor hood, also called a net of tendons. It allows to independently control the MCP joint from the other fingers and perform moves like flexion, extension, abduction, adduction, and even rotation. It is difficult to recreate this system since it not only has a complicated architecture, but tissue stiffness varies irregularly too. Until now, only few projects have been performed; the Wilkinson and Weghe research groups that used nylon/Kevlar rubber wires, or the Xu and Todorov team, whose hand has the highest humanlike tendon hood, laser-cut from an elastic sheath. [92,169,170].

4.3. Underactuation and Shape-Adaptive Motion

Considering robotic-hand parts always leads to the need for the reconciling of two objectives: number of actuators and control strategy. There are many schemes for reducing control complexity where precise kinematic calculations were presented [171–173], and robot trajectory was based on captured human movements [174]. One of the possible and already adopted methods is underactuation. Generally speaking, a hand is underactuated when it has a smaller number of actuators than the number of degrees of freedom. Since some of the joints are passively controlled, a shape-adaptive grip occurs, which was observed in human adhesion, too [134,175,176].

In [84,112,139], four-bar mechanism variations were used to distribute drive to distal phalanges. While their first had 16 DOF, actuated by a record one actuator through a complex gear system in the palm, the last was able to perform even some precision grasps. Contrary to this, both [81] and [106] used a single tendon attached to distal phalanges to control a 9- and 10-DOF hand, respectively, with three actuators. Moreover, Tavakoli and De Almeida showed that their device could perform

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the 10 most necessary grasps in daily activities. The same solution was applied in [40,126], where a special tendon-routing technique provided following rotation by distal digits when previous ones were blocked by an object. It was also used in the X hand, of which the tendon system was additionally equipped with springs and that passed the Kapandji test [119].

It should be noted that all passive pneumatic hands meet the requirements of shape adaptation because of uncontrolled finger flexion that is affected by enfolding an object in a finger chain or finger–palm grip [104,114].

4.4. Number of Actuators

Robotic hands mainly have a limited number of actuators due to different reasons. For example, prosthetic hands (at least for now, when EMG is used) do not have enough control signals from amputees so actuators could be reduced. On the other hand, some applications require a specific type of drive unit of which the size may also decrease the instaleld parts.

Nevertheless, the required number for proper control depends only on the kinematic model, since it was proven by Caratheodory that any kinematic chain with n degrees of freedom can be fully controlled by a minimal number of $n + 1$ independent tendons. Hence, underactuated hands with an actuator number that is lower than the number of DOF are perceived as unstable. Moreover, Steinitz showed that the same chain with more than $2n$ tendons is redundant; [67] and Morecki et al. [177] defined an n number as the minimum for bidirectional actuators coupled with a joint by an endless tendon loop. As $n + 1$ construction tends to exhibit buckling, as well as other instability problems [19], most devices use more than the $n + 1$ strategy. Such solutions have reduced the number of DOF and actuators, so they are not more complicated and rather practical. However, decreasing degrees of freedom in robotic hands takes us farther from the purpose of devices with human dexterity and versatility.

Although the literature proves that the largest possible number of DOF/actuators is desired [131], Figure 6 shows that the number of actuating devices installed in hands (four- and five-fingered) has not been increasing over the years. Furthermore, stabilization of solutions was observed, which is related to the conclusions from the previous sections. More specifically, the two biggest groups can be distinguished that have a mean value of 16 and 20 degrees of motion, and are marked in green and orange, respectively. Most of the first group, as described earlier, consists of prosthetic hands that have restricted space; hence, the average number of actuators is five. The same can be deducted from Belter et al. 2013 research, where commercial and research constructions are compared on the graph of number of joints–actuators [130]. Another group, concentrated on the 20 DOM point, constitutes more sophisticated devices with a number of joints closer to that of humans. Nonetheless, the number of actuators is slightly higher also due to its size, which leads to the problem of an apppropiate actuating unit.

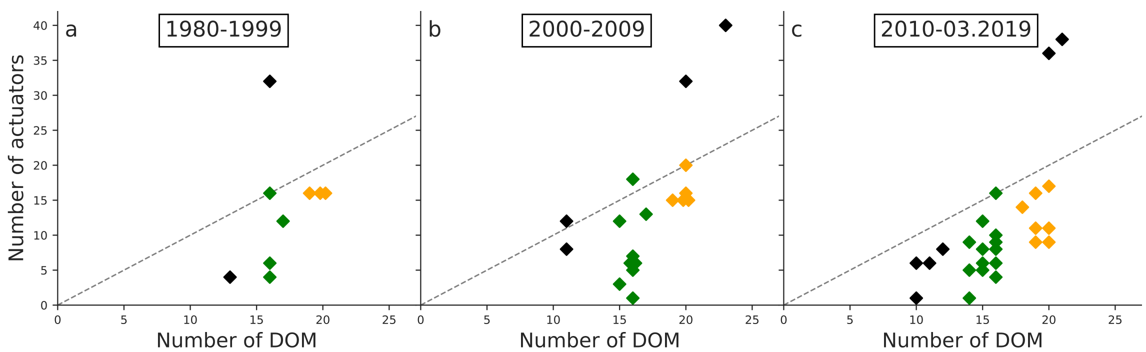

Figure 6. Number of degrees of motion to number of actuator ratio with two main groups of artificial hands highlighted: common, green; more advanced, orange. Statistics presented for three periods of time: (**a**) 1980–1999, (**b**) 2000–2009, (**c**) 2010–03.2019

Few advanced robotic hands can not be ommited. Solutions like SBC Hand driven by 32 SMA wires [37], multiply mentioned Shadow Hand with 23 DOM and 32 McKibben muscles [131] and DLR

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Hand with high biomimetic construction and 38 DC motors [95] prove how advanced human like performences are available and they will indisputably be icons in future, as Utah/MIT Hand [38] with 32 pneumatic actuators from 80′ is now.

5. Sensors

Humans without their senses could be compared to the first automatic machine that could execute some work but did not respond to any information from the environment. This led to evident problems, where the most important and dangerous were self-damage or injury to someone else. Since the purpose of artificial hands is to imitate humans' most advanced abilities, it must be considered with the appropriate senses–sensors.

A basic type of feedback is the angle position that may relate to both joint and actuator position. Since servomotor electronic systems provide angular information, and DC motors can easily be supplemented with encoders as well as pneumatic actuators with pressure gauges/sensors [89,110,136], more challenging is to apply an appropriate aperture in the finger joints. Instead of potentiometers [82,115], which introduce unwanted mechanical correlation and friction, contactless Hall-effect sensors with high resolution and good repeatability are a better solution [121,138]. The working principle is based on a diametrically magnetized magnet placed concentrically in a joint that is detected by a sensor. Contrary to commonly used circular magnets, ellipsoidal magnets are used in Robonaut Hand 2 for that characteristic to be more linear [168]. Strain gauges and bend sensors are rarely used due to problematic installation, nonlinear characteristics, and low resolution [80,108].

A robotic hand with a closed position loop is able to perform all of the possible gestures, limited only by joint range. This situation changes diametrically when external force is applied either from a manipulated object or finger collision. To prevent potential damage, force, torque, and tension data-collection methods are applied. The conventional technique assumes estimating torque by measuring the actuator circuit current, used in [73] and [90], which is well-known and developed, but a number of factors could disturb the mathematical model. One of them was included in the RoboRay Hand, so the control algorithm compensated for friction occurring in the entire construction [137]. In opposition to angular positioning, a force tasks implementation of strain gauges in various forms. For example, in [38], the tendon slid over a pulley that was placed on the strain gauge so that tension was checked with joint torques of up to 130 N; in Gifu Hand II, a six-axis force sensor was included in the fingertips, which was based on gauges [36] and many others [23,139]. Once more, Robonaut Hand 2 presented an original solution where it was observed that conduit (covering tendon) compressive force was equal to tendon tension within an error of 5%–10% [168]. Going forward, angular-position disparity with spring displacement [82,111] and differences in actuator-chamber pressure [93] were presented, but the most innovative method involved photoactive elements [115]. The authors in [178] constructed a miniature tension sensor consisting of a fork shape that had an LED diode and phototransistor on the gap sides. An elastic frame covered the whole part, while a screen attached to the inner side of frame interrupted the light beam. When the tendon pulled the elastic surface, the amount of detected light increased, hence the voltage changed. Extensive tests confirmed that sensors placed in fingertips can withstand forces up to 200 N with very linear characteristic and generally no histeresis.

The missing factor separating from inhand manipulation as well as accurate grasp parameters is tactile prehension of the human hand. The major challenge is to mimic human-skin mechanoreceptors responsible for interaction with the environment and providing sophisticated prehensile information. While natural mechanisms allow to detect such phenomena as vibration, touch, and pressure, the state of the art in robotics was found to be at a phase of introducing thin elastic sensors. Despite simple contact sensors [45,77,121] of which the function, except for the palm and side forces, could be replaced by solutions described above, there are more efficient: force-sensitive resistors. They are relatively flexible sheaths built from conductive polymer that changes resistance due to external force or pressure. Although their architecture only allows to achieve single-force measurement, they are frequently implemented on fingers and digits [72,89,127,138]. A more developed 3×3 array sensor appeared

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in [75], as well as a 4 × 4 and 0.1 mm thick tactile sensor delivered by Tekscan Inc. [100]. These can not compete with the Gifu Hand II, where the total number of 624 detecting points were applied for the whole construction [36]. Worth noting is Quantum Tunnelling Composite (QTC) technology, of which products are composites of metals and nonconductive polymers that, due to external force/pressure, change their resistance [60]. Sensors used in the Shadow hand provide 34 independent measuring points on each fingertip [131]. For better research and wide technology description, it is worth to check [179] that is fully dedicated to robotic-hand-sensor technology.

High potential referring to sophisticated tactile-sensing methods lies in rapidly expanding material technology that affects many science fields, i.e., robotics. To better illustrate this phenomenon, searches in Google Scholar with phrases like "tactile sensor" and "artificial skin" were classified by the appropriate time period in Figure 7.

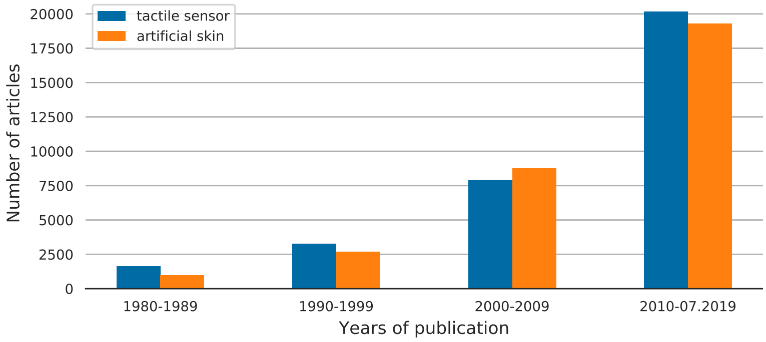

Figure 7. Timeline of interest in artificial tactile sensing.

This clearly shows that the number of publications and therefore available solutions is increasing. Consequently, if the state of art and the above trends are taken into account, it could be said that future devices will not only provide high-resolution measurements, surface recognition, and versatility, but they may also deliver information about potential damage (pain) and even temperature.

6. Conclusions

Artificial hands have come a long way. As a consequence of the broadening knowledge and technical capabilities, they have evolved into more complex and sophisticated purposes. Telemanipulation tasks not only started a dynamic growth of research for industry hands, but also impacted replacement passive prostheses with electric ones. The most important have been the last 40 years, when electronic parts became miniaturized, new, more efficient actuators were designed, high-resolution sensors and materials, and 3D printing technology becoming more common. All of them resulted in humanlike sizes and kinematic devices, of which the prehensile abilities allowed to execute both precise grasps from whole-hand taxonomy and some kind of inhand manipulation, reflecting human dexterity. Hence, current applications assume that humanoid robots able to replace humans at work and take care of them require the provision of versatile end effectors and prostheses replacing the functionality of amputated limbs.

Hand-construction analysis, i.e., finger and joint configuration, demonstrates that robotic hands with human shape are the most desired, which the biggest group of five-fingered and 16–19 DOM devices confirms. However, looking at joint types, complete and inseparable solutions like hinge and ball joints are preferred over biomimetic ellipsoidal and saddle ones, which not only have a complicated geometry but also require special connections—ligaments—to keep parts together. Since these joints have only been used in few appliances, they still require better exploration and may be used in future devices. Although the fact that pneumatic actuators are able to drive the hand with acceptable dynamics, motor-based ones are most frequently used due to the availability of miniature units as well as broadly developed control strategies. Provided statistics presented the undeniable domination of this type of drive unit and an increasing interest in unconventional actuators. While soft

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pneumatic actuators own typical problems, i.e., need for additional equipment and power source, artificial muscles are perceived as worthy successors because of human-muscle abilities like linear contraction, volume, and being lightweight. Regrettably, current solutions using SMA, TCP, and EAP actuators exhibited some problems with control, especially with regard to time response. Because of this, new smart materials have been strongly developed so that they will supersede conventional rotating devices in the near future. Currently, the focus should be on the implementation and testing of these new types of artificial muscles, which were partly mentioned in Section 4. Applying them in robotic-hand systems would speed up the verification of their dynamic properties and the suitability for this specific system.

With reference to sensory systems, the most challenging task is to replicate human skin with its sophisticated tactile sensing. Commonly used contact sensors or arrays changing resistance due to external forces allow to precisely detect a manipulating object or superficial inhand moving. Multidisciplinary research on this topic proved the importance of versatile skin purposes and would lead to robotic hands with natural abilities. According to this, development of ultrastretchable polymer sensors should be continued to supercede recently used macrosensors, which are either bulky or at risk of measurement errors (estimating methods).

In fact, it is difficult to distinguish one specific factor that would directly affect the entire structure because all of them are strongly correlated, but, based on the included analyses, the biggest impact on artificial hand development is from the active parts—actuators. Application of biomimetic muscles first of all leads to a reduction of construction volume, which makes the overall design more humanlike. More space in the outline of the hand allows for a larger number of and more advanced sensors. It should be noted that the muscles themselves would probably be able to obtain some kind of feedback. As described above, we should focus on the development of power units in order to increase the biomimicity of the entire device, but, at the same time, research on other aspects like sensory systems and control algorithms must be carried out. Such a strategy would result in cascading progress, so forthcoming generations could be designed in the patterns of living organisms; however, there is still a long way to go.

Author Contributions: Conceptualization, J.S. and G.R.; funding acquisition, G.R.; investigation, J.S.; project administration, G.R.; validation, J.S. and G.R.; visualization, J.S.; writing—original draft preparation, J.S.; writing—review and editing, G.R.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

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