Mechanisms and Sensors for Robotic Fingers

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***Abstract*—: In the past years robotics has matured from being mostly used in the industry and made a break into our daily lives. Similarly, the research focus for grasping and manipulation has evolved from manipulators and grippers to dexterous anthropomorphic hands, capable of performing different tasks in unstructured environment. The fingers of these hands play a crucial role in their success and performance. Designing these fingers opens researchers to many considerations to choose the best suitable specifications for the fingers, some of which will be discussed in this paper.**

I. Introduction

The idea of copying the human hand is so old and may be contemporary of the first automata in the 18th century, e.g., La Musicienne of the inventor Jacquet-Droz [15]. This automate was able to play a wide variety of organ partitions with two five-finger hands actuated with steel cables connected to a programming cam shaft.
The human hand has been an inspiration for robotic hand designers for decades. The first robotic hand, as it is commonly referred to, was perhaps the end-effector of the Handyman, a robot developed by Ralph Mosher for General Electric in 1960. Around 1969, the first research projects on robotic hands with three fingers including a "thumb" in opposition —hence an anthropomorphic design— began in the United States and in Japan.
For a prosthetic hand the focus is much more on aesthetics, weight and broad range of functionality, while the supply of power is limited, so self-locking mechanisms are preferred. Today's prosthetic hands have integrated drive technologies and weigh less than 500 g; The average human hand is around 0.58% of the total body weight (approximately 400g).
Because of the dexterity of the human hand, many recent humanoid robots research projects addressed in their designs the anthropomorphism of the robotic hand. Many research laboratories around the world have developed prototypes of such hands as early as in the mid 1980's when the foundations of these studies were laid (Mason and Salisbury 1985), by taking the human hand as a model for the robotic manipulation, in terms of performance and versatility.
The dexterity of robots has always been clearly more limited than that of a well-trained human being.
In fact we can find anthropomorphic end-effectors with very poor dexterity level, even if they are called hands, they perform very rough grasping procedures. Similarly, we can find smart end-effectors, capable of sophisticated manipulation procedures, but without any level of anthropomorphism.
Anthropomorphism is not necessary for achieving dexterity, and nor sufficient. But still it is desirable goal in the design of robotic end-effectors in operating in an environment where tasks may be executed by a robot or by a man, or in tele-operation of the end-effector by a man, or when it is required that the robot has human-like aspects and behavior. Considering that the human hand is capable of prehension (grasping objects of different size and shape) and apprehension (understanding through active touch), then it is both an output and input device. It can apply forces and provide information about the state of the interaction with the object. These characteristics are desirable in advanced robot hands.

II. Robotic Fingers

Fingers of the hand are organs of manipulation and sensation. They move in the following ways: flexion, extension, abduction and adduction.
The anatomy of fingers in nature shows us the following design characteristics:

- A serial bone-link structure mainly for rigidity and load capability.
- An actuation muscle system aiming to rotate each bone-link independently but with coordinate movements with other finger links.

Human hands have a highly articulated thumb. Amputation of the thumb is cited to cause 40% loss of hand function and around 20% disability of the whole person. The main motions of the thumb are flexion, extension, abduction/adduction and opposition. The thumb facilitates the grasping tasks by means of these motions.
Designing fingers to accomplish assigned tasks is a complex procedure.
In general common requirements can be identified mainly

in the aspects for:

1) Motion properties in:
   - Grasping configurations
   - Smooth approaching motion
   - Adaptable motion configuration to object shapes
   - Reconfigurable grasping configurations
   - Workspace ranges
   - Limited motion impacts again objects to be grasped
2) Force capability in:
   - Stable grasping configurations
   - Efficient transmission of input power to grasping forces
   - Distribution of grasping forces among several contacts with grasped object
   - Positions of application points of the grasping forces
   - Adjustable grasping forces
3) Mechanical design in:
   - Stiff or compliant structure at grasp
   - Phalanx shape for adaptability to object shape
   - Room for sensors
   - Compact design versus human-like solutions
   - Lightweight solution with smart or traditional materials
   - Low-friction joints
   - Location of power source

Some of the key issues considered by developers or researchers when choosing the fingers specifications are:

- Number of Fingers
- Shape of the fingertips
- Compliant joints
- Built-in or remote actuation
- Transmission systems
- Sensors
- Materials and manufacturing

III. Number of Fingers

Number of fingers in anthropomorphic robotic hands can differ, but increased number of fingers provide a larger grasping surface and increases conformity to shapes.
A comparison chart for robotic hands researched and developed between the years of 1979 to 2016 is presented in the Table II
By reviewing dexterous robotic hands developed between 1983 to 2016 [1] it was visible that the five finger configuration is superior over the three or four finger setups (Fig.1). It was assumed that this trend is due to the fact that the robots are moving to more dynamic and human populated scenarios, where unlike the industrial grippers the new applications don't measure the effectiveness only in terms of repetition and high precision. Many studies used hands with different finger configurations for different applications with positive results. One does not overcome the other, though their purposes and applications might be different.
Due to their more available postures, the five finger hands can provide more flexibility and grasping postures compared to the traditional grippers, but it is also more complex.
The correct hand is dependent upon the tasks to be done and the environment in which such activities take place.

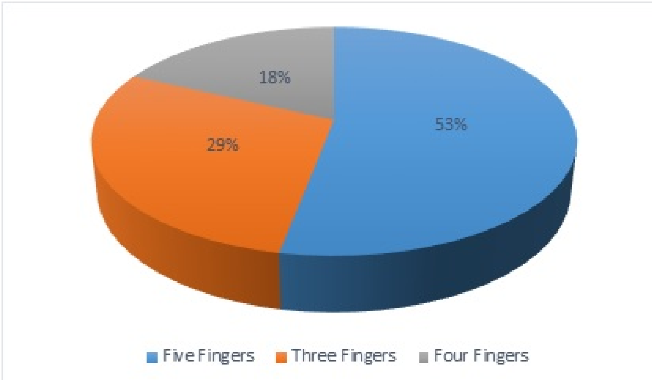

Fig. 1: Distribution of Finger Configurations

IV. Shape of the fingertips

Some hands have fingers with a flat fingertip, where only the flat surface is designed to interact with the object, such as the SDM hand (Fig.2) and the Barrett hand (Fig.3).
A different approach is to shape the finger surfaces in an

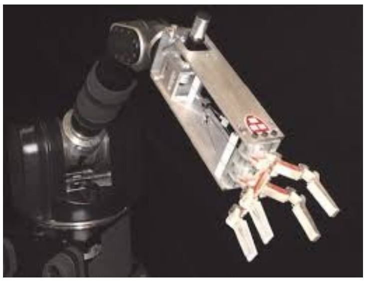
Fig. 2: SDM Hand


Fig. 3: Barrett Hand

anthropomorphic fashion, where the fingertip is round and allows for more flexible manipulation, such as the Robonaut Hand (Fig.4), and the Shadow Dextrous Hand (Fig.5).

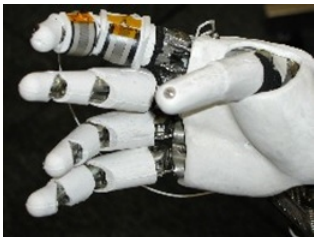

Fig. 4: Robonaut Hand

Fig. 5: Shadow Dextrous Hand

Finally, some hands have fingers with more generic round surfaces in cylindrical and spherical shapes such as the CyberHand (Fig.6).

Using flat finger pads can often increase the stability of grasps compared to a rounded geometry, but it may also prevent the fingers from being used effectively at a wide range of angles.

Fig. 6: CyberHand

However, there is little information on how the finger should be shaped in order to facilitate manipulation. There is a lack of studies on what finger surfaces are actually used during manipulation. This is likely due to the difficulty of effectively instrumenting the contact surfaces of the finger pads.

V. Traditional and Compliant Joints

The number of joints per finger in anthropomorphic robotic hands is extremely important since it provides the hand with conformance to shapes and acts as a contact surface for gripping and support structure for grasps.

There are two types of joint designs that have been widely used in robotic hands [2]. The first type uses standard mechanical components such as hinges, linkages, or gears and belts. Many important features have been achieved in this kind, including high degrees of modularity, built-in actuators, but it involves considerable systems-level complexity and implementation costs.

An alternative approach to traditional joints is the compliant joints. These types reduce overall complexity of the robotic hand's mechanisms and hands are able to withstand large impacts without damage. In addition, the advent of new materials and new technologies (e.g. Rapid Prototyping) largely encourages the development of this concept (Fig.7) (Fig.8) (Fig.9).

But it has also some disadvantages. The Range-of-Motion is limited. The Axis Drif; most compliant joints undergo imprecise motion as the center of rotation does not remain fixed with respect to the links it connects. And such joints can suffer Stress Concentration.

Fig. 7: The finger is obtained in a single teflon piece

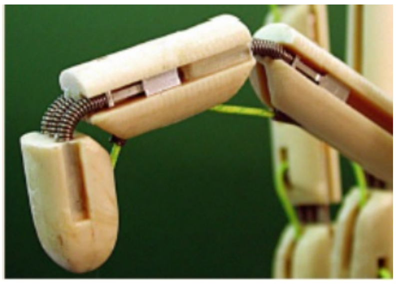

Fig. 8: Joint compliance is achieved with metallic springs

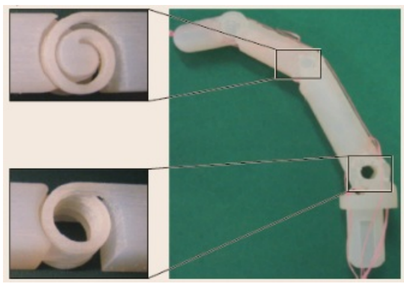

Fig. 9: Rapid prototyping allows for different compliant mechanisms as joints

VI. Built-in Actuation

In order to actuate the joints of a robotic finger, two basic approaches for the placement of the actuators are used [3]:

- Placing the motors as close as possible to each joint, directly in the fingers and sometimes integrating them within the joint itself (Fig.10).
- Placing the motors into the palm or in the forearm; in this case motion is transmitted to each joint by means of (complex) kinematic chains. (Fig.12)

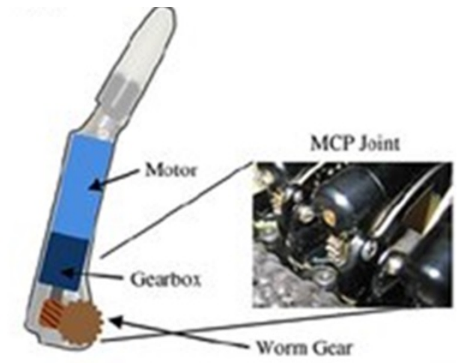

Fig. 10: Vincent finger motor (Vincent Systems) is housed in proximal phalange and rotates worm against fixed worm gear to flex finger.

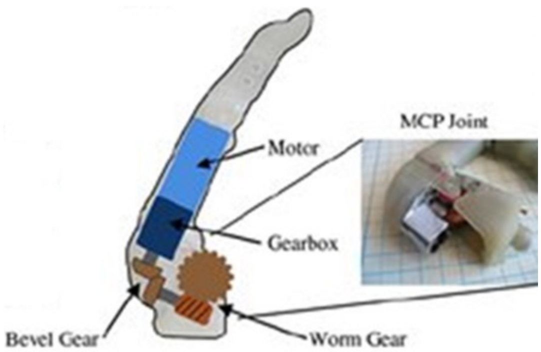

Fig. 11: iLimb finger (Touch Bionics) is actuated in same manner as Vincent finger but uses set of bevel gears between motor and worm drive. MCP = metacarpal phalange.

This built-in actuation simplifies the mechanical configuration of the joint, reducing the transmission chain complexity. It also has the advantage that the motion of the joint is kinematically independent with respect to other joints. However, the motors occupy a large room inside the finger structure, making it harder to host other elements, like sensors or compliant skin layers.

VII. Transmission

Remote actuation is an alternative solution to in-site actuation. In remote actuation, the joint is driven by actuators placed outside the links connected by the joint itself. This kind of systems can be classified according to the type of adopted transmission elements:

Fig. 12: Drive mechanism of Michelangelo hand (Otto Bock). Center drive element controls flexion of all four fingers and thumb. Second motor (which actuates against bronze worm gear) independently controls abduction/adduction of thumb.

- **Flexible Link Transmission**
  - Pulley-routed flexible elements (tendons, chains, belts)
  - Sheath-routed flexible elements (mainly tendon-like elements)

  This kind allows the actuators to be located remotely from the joints. Consequently reducing the dimensions and weight of the fingers. But the disadvantage of the flexible cables or flat bend transmission is that they can only be used to pull. In order to achieve the active two-way control a pair is required and this increases the complexity.

- **Rigid Link Transmission**
  - Parallel and nonparallel axes gear trains, like bevel gears, worm gears, and so on.

This kind gives the best stiffness properties to the transmission. Additionally such transmissions require less maintenance than the flexible kind and they allow bidirectional control of the joint. The disadvantage here is that using rigid transmission systems increases the weight, complexity and sometimes dimensions of the hand.
Considering the transmission types used in robotic hands developed since 1983 (Fig.13) we find out that the preferred transmission type is tendons. They allow to simplify the design and to take the actuators off of the hand. However the disadvantage is that they introduce errors. The second most used type is gears, they have more accuracy but also more friction. The direct transmission type is the less used type because of the difficulty in its design.
A brief comparison [4] based on different parameters, between the main transmission mechanisms that can be employed in artificial hands, is shown in (Fig.14).

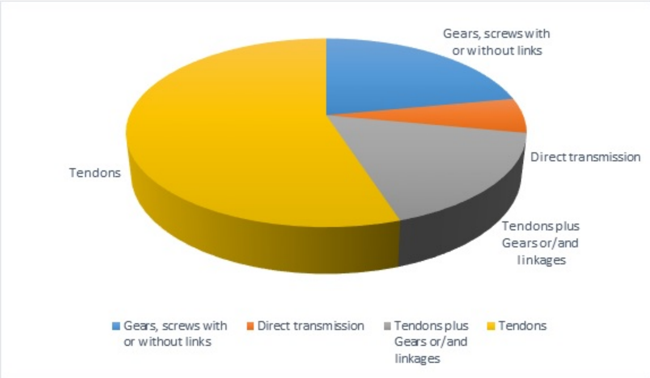

Fig. 13: Transmissions Types

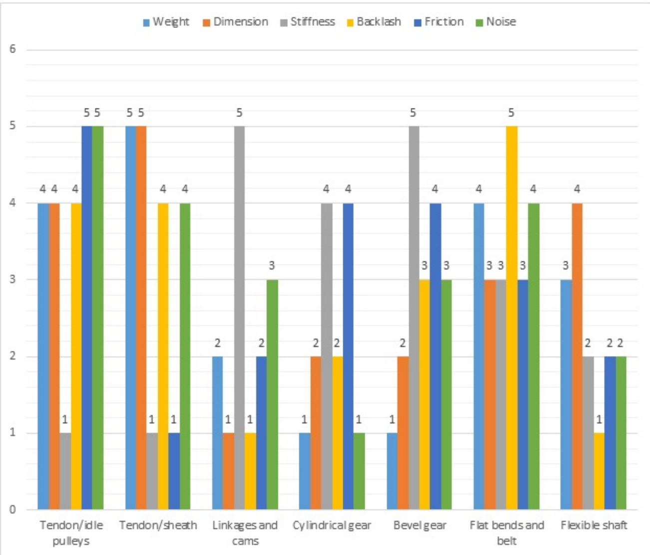

Fig. 14: Comparison between the main transmission mechanisms

VIII. Sensors

In robotics sensors can be classified in two main categories: Proprioceptive and Exteroceptive sensors.
The first type of sensors measures physical information related to the state of the device itself (e.g., position, velocity, and so on), while the second one is devoted to the measurement of data related to the interaction with objects/environment (e.g., applied forces/torques, friction, shape, and so on).
Tactile sensing is an essential element of autonomous dexterous robot hand manipulation. It provides information about forces of interaction and surface properties at points of contact between the robot fingers and the objects.
In general, the types of information that may be obtained from a tactile sensor are:

- **Contact:** This is the most simple information given by the sensor, concerning the presence or absence of a contact.
- **Force:** Each sensing element provides an information related to the amount of locally applied force, which can be used in several manners for successive elaborations.
- **Simple geometrical information**, i. e., position of the contact area, geometrical shape of the contact itself (planar, circular, and so on).
- **Main geometrical features** of the object: By proper elaborations of the data of the taxels, it is possible to deduce the type of object in contact with the sensor, for example a sphere, a cylinder and so on (data relative to the 3-D (three-dimensional) shape).
- **Mechanical properties**, such as friction coefficient, roughness, and so on. Also thermal properties of the object may be measured by a tactile sensor.
- **Slip condition**, i. e., the relative movement between the object and the sensor.

As proposed by [5] the minimum functional requirements for a robotic tactile sensing system mimicking human manipulation is summarized as:

- Detect the contact and release of an object.
- Detect lift and replacement of an object.
- Detect shape and force distribution of a contact region for object recognition.
- Detect contact force magnitude and direction for maintaining a stable grasp during manipulation.
- Detect both dynamic and static contact forces.
- Track variation of contact points during manipulation.
- Detect difference between predicted and actual grip forces necessary for manipulation.
- Detect force and magnitude of contact forces due to the motion of the hand during manipulation.
- Detect tangential forces due to the weight and shape of the object to prevent slip.
- Detect tangential forces arising from variations in object parameters (e.g. surface friction, elasticity, etc.) to prevent slip.

Most common tactil sensor configurations are:

- Resistive sensors
- Piezoelectric sensors
- Capacitative sensors
- Magnetic transduction sensors
- Photoelectric, or optical, tactile sensors

Main tactile sensors are presented in the Table I [6].

IX. Materials and Manufacturing

The design and fabrication of a prototype using traditional machinery techniques is a rather long and expensive process, and often the employment of rapid prototyping techniques provides several advantages. One of the main advantages is represented by the chance to develop parts with complex geometry that could not be manufactured using traditional techniques.
Won et al. [7] developed a five-finger anthropomorphic

TABLE I: Summary of tactile sensing technologies

Transduction Method	Advantages	itages
Capacitive	Can be flexible, wide dynamic	s, noise, limited resolution
Inductive	High sensitivity, repeatability	construction, electronics in v
Resistive: deformable contact area	Flexible, thin	s
Resistive: conductive fabric	Flexible, robust, simple	resolve more than one cont
Resistive: quantum tunneling composite	Sensitive, wide dynamic range	s, gas absorption
Resistive: strain gauge	Sensitive, wide dynamic range	pensive
Resistive: piezoresistive conductive polymer	Thin, low cost, simple	s, stiff
Resistive: piezo-MEMS	Small, multi-element	mber of wires in workspace
Resistive/Capacitive: liquid channels embedded in elastomer	Small, flexible, multidimensior	mber of wires in workspace
Polymer-MEMs (multi-modal)	Measures 6-DOF force, heat-fl	mber of wires in workspace,
Piezoelectric	Detects dynamics for slip and	cts dynamic events, thermal
Optical: video processing	Very high resolution, sensitive	tionally intensive, sensitive to
Optical: resistive	Flexible, low hysteresis	Complex fabrication
Magneto-elastic	Very sensitive, low hysteresis	Sensitive to external magnetic fields
Magneto-resistive	Robust, sensitive, low hysteresis	Noisy
Ultrasound	Can resolve static and dynami	ige, complex electronics

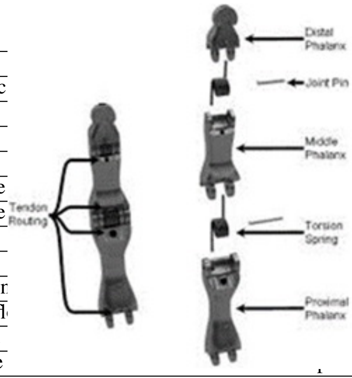

Fig. 16: High-strength, nickel-coated thermoplastic

hand by using a Selective Laser Sintering technique (SLS) (Fig.15), which allows joints to be manufactured in one-step without requiring assembly. The main drawback of SLS is the lack of mechanical proprieties (such as stiffness and strength), moreover it fails when dimension tolerances are narrowed.

Dalley et al. [8] developed a transradial anthropomorphic

Fig. 15: Selective Laser Sintering (SLS)

hand, in which the parts were physically realized in high-strength, nickel-coated thermoplastic using an additive directly incorporated during the manufacturing process (Fig.16); this method combines the flexibility of the rapid technique with the strength/stiffness of the metallic material. The main drawbacks of this method are the low fatigue resistance, and poor surface finish and geometrical tolerance that often requires re-machining by traditional methods.

Dollar and Howe [9] showed how a further integration of sensors, electronics and actuation could be obtained using polymer-based Shape Deposition Manufacturing (SDM) (Fig.17). Another advantage of the SDM technique is the possibility of simultaneously creating rigid links and compliant joints of the fingers, providing the hand with passive mechanical compliance useful for grasping in unstructured environments.

The use of compliant materials in manufacturing of joints allows a number of components to be avoided (such as pulleys, axis, torsion springs, and so on) and the ability to

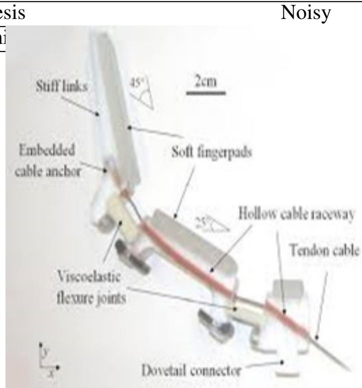

Fig. 17: Polymer-based Shape Deposition Manufacturing (SDM)

embed the extension system, disguised as releasing springs, in the structure thus resulting in a reduction in joint size. Examples of artificial hands exploiting compliant joints based on these principles were developed at the University of Bologna, Stanford, Genoa, Scuola Superiore Sant'Anna, and University of Iowa.

X. Conclusion and Future Trends

In this paper robotic fingers were discussed, their design considerations in choosing the suitable configuration, mechanism and sensors was discussed by considering several projects from past decades to the present. The growing use of the hands in human used environments and the emphasis on sensor development and new materials in the past years, hints that sensors and the use of soft and compliant materials will be the major research approaches in robotic fingers [10].

Another future trend is the development of artificial skins for the fingers with denser spatial resolution and a multitude of sensor modalities, as recent advances in biofabriction techniques could integrate engineered muscle tissues with artificial devices, leading to biohybrid robotics [11] [12].

Also as more and more sensors are being employed in smart-phones, which has a big market, will drive down the costs of these sensors and encourage their use in the artificial hand.

It is also believed that there is a need for standardization as it is seen of great importance not only for commercial purposes but also for classification of the newly developed devices [1].

TABLE II: Hand comparison chart from 1979 to 2016.

Name	Sensors	Fingers	Transmission	Research Institute	Year	DOF	DOA	Actuators	Weight [Kg]	Load [Kg]	Load [N]
Okada Hand	Potentiometers	3	Tendons		1979	11		DC Motors			
Stanford/JPL Hand	Tactile Sensors, Tension tendons sensors	3	Tendons	Stanford University	1983	9	9	Electrical (DC)	1.1		110.8
Utah/MIT	Hall effect sensors, Tendon tension sensors, tactile distributed sensors	4	Tendons	Utah University	1985	16	16	Pneumatic Cylinders	9	9	
Belgrade/USC Hand	Potentiometers as positions sensors, Force resistors	5		Belgrade University	1988	15	4	Electrical Motors		2.26	
BarrettHand	Optical Encoders, Tactile sensors	3	Tendons, worm gears	Barret Technology Inc.	1988	8	4	Electrical Brushless motors	1.2	6	
DLR Hand I	28 Sensors on each finger, hall sensors, optical position sensor, torque sensor, force sensor, tactile sensors and stereo camera	4	Tendons	DLR-German Aerospace Center	1997	16	12	Electrical			
Dist Hand	Rotation sensors in each joint	5	Tendons	Genova University	1998	16	16	Electrical	1		1.96
Robonaut Hand	42 sensors plus tactile sensors	5	Tendons	NASA Johnson Space Center	1999	19	14	Electrical Brushless Motors		9	
Gifu Hand	Magnetic encoder in the motors shaft and tactile distributed sensor	5	Gears , Links	Gifu University	1999	20	16	DC Micromotors	1.4	1.83	
Robotiq 3 Finger Gripper	current sensor, position sensor, grip sensor	3	gears and links	Laval University	1999	10	4	DC Motors	2.3	10	
Blackfingers	Position and force sensors directly on the actuator	5	Tendons	Politecnico de Milano	2000	22	36	Mckibben Actuators			
Tuat/Karlsruhe Hand		5	Tendons	Tokyo and Karlsruhe Universities	2000	24	1	Electrical	0.49		
Ultralight Hand		5	NONE	Research Center of Karlsruhe	2000	18	13	Flexible Fluidic actuators	0.2	1.22	
Variable Force Hand		5	Tendons	Hokkaido University	2000	10	5				
DLR Hand II	Torque sensors in each joint	4	Tendons	DLR-German Aerospace Center	2001	17	13	Electrical	2.2	3.059	
RTR Hand I	Hall effect sensors, strain gages as force sensors	3	Screws	Centro INAIL RTR, Scuola Superiore Santa Anna	2001	9	3	DC Micromotors			
Dexterous Robot		4	Tendons	Maryland University	2001	12					
Shadow EDC Hand	Hall effect sensors, Tactile sensors	5	Tendons	Robot Shadow Company Ltd.	2002	23	23	Pneumatic muscles	4		
Thinh Hand	Bend Sensors, Camera for visual control of the thumb pronation angle	4	Tendons	Florida University	2002	14	6	Electrical			

(continued)

Table II *(Continued)*.

Name	Sensors	Fingers	Transmission	Research Institute	Year	DOF	DOA	Actuators	Weight [Kg]	Load [Kg]	Load [N]
High Speed Multifingered Hand	Strain gages, Camera for image processing	3	Miniharmonic drive, bevel gears	Tokyo and Hiroshima Universities	2003	10	10	Electrical	0.8	2.85	
SMA Hand	Planed to have Position Sensors, Force Sensors and Touch Sensors	4	Shape Memory Alloy Wires	State University of New Jersey	2004	14		Electrical	1.3	3.6	
ARMAR Hand	Angle sensors, Force Sensors and Pressure Sensors	5	Flexible Fluidic Actuators	University of Karlsruhe	2005	8–18	8–16	Micro Gear Pump	0.49	11.21	
UB Hand III v1	Strain=gauge based sensors, position sensors, tendon force sensors	5	Elastic Hinges with Tendons	University of Bologna	2005	20	16	DC Brushed Motors			
RL1 Hand	Tendon Tension through mathematical approximation	3	Tendons	Universidad Carlos III de Madrid	2006	8	1	DC Motors	0.25	2	
AAA Hand	External optotrank (Infrared optical device)	3	Tendons	Scuola Superiore Santa Anna	2007	10	4	DC Motors	0.25	3.56	
FRH-4 Hand	Position Sensors, Tactile Sensors	5	Flexible Fluidic Actuators	Research Center Karlsruhe	2008	11	12	Gear Pump	0.216	11.21	
IH2 Azzurra	Tendon Force Sensors, 2 Axis fingertip force sensor	5	Tendons	Prensilia	2008	11	5	Electric Motors	0.6	10.2	
UB Hand III v2	Optical angular sensors, Optical Tensor Sensors, Strain gauge tension sensors	5	Tendons	Bologna University	2009	20		Mckibben Artificial Muscles			
TH-3R Hand		5	Gears, Racks	Tsinghua University	2009	15	4	Motors			
Columbia Hand	Position Sensors, Tactile Sensors	3	Tendons	Columbia University	2011	9	2	Motors			
The Handroid		5	Tendons	ITK Company	2011	16	5	DC Motors	0.725		
KYTECH Hand	Position Sensor	4	Gears	Korea Institute of Industrial Technology	2012	16	16	DC Motors	0.9	1.5	
The PISA/IIT Soft Hand		5	Tendons, Rolling cylinders	University of Pisa	2012	18	1	Electric Motor			
TDM Hand	No sensors, force approximation using Ozawa and Moriya technique	3	Tendons	Ritsumeikan University	2013	12	12	DC Motors		5.1	
iHY Robot Hand	Pressure sensors, Optic sensors	3	Tendons	Yale and Harvard University	2014	9	5	DC Motors		22	
Soft Robotic Hand	Resistive Bend sensors	3	Pneumatic tubing	Massachusetts Institute of Technology	2015			Pneumatic piston			
HALS		5	Tendon	Yokohama National U	2016	9	5	DC Motor	1.2	3.059	
RBO Hand 2		5	Pneuflex	Berlin University of Technology	2016	5	7	Pneumatic	0.178	0.5	
UW's Hand	Joint and Tactile Sensors	5	Tendons	University of Washington	2016		10	Servo Motors	0.942		

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References

[1] D. R. Ramírez Rebollo, P. Ponce, and A. Molina, "From 3 fingers to 5 fingers dexterous hands," *Advanced Robotics*, vol. 31, no. 19-20, pp. 1051–1070, 2017.

[2] B. Siciliano and O. Khatib, *Springer handbook of robotics*. Springer, 2016.

[3] J. T. Belter, J. L. Segil, A. M. Dollar, and R. F. Weir, "Mechanical design and performance specifications of anthropomorphic prosthetic hands: a review," *Journal of Rehabilitation Research & Development*, vol. 50, no. 5, pp. 599–618, 2013.

[4] R. Balasubramanian and V. J. Santos, *The human hand as an inspiration for robot hand development*. Springer, 2014, vol. 95.

[5] H. Yousef, M. Boukallel, and K. Althoefer, "Tactile sensing for dexterous in-hand manipulation in robotics—a review," *Sensors and Actuators A: physical*, vol. 167, no. 2, pp. 171–187, 2011.

[6] N. Wettels, J. A. Fishel, and G. E. Loeb, "Multimodal tactile sensor," in *The Human Hand as an Inspiration for Robot Hand Development*. Springer, 2014, pp. 405–429.

[7] J. Won, K. J. DeLaurentis, and C. Mavroidis, "Fabrication of a robotic hand using rapid prototyping," in *Proceedings of the 2000 ASME Mechanisms and Robotics Conference*. Citeseer, 2000, pp. 10–13.

[8] S. A. Dalley, T. E. Wiste, T. J. Withrow, and M. Goldfarb, "Design of a multifunctional anthropomorphic prosthetic hand with extrinsic actuation," *IEEE/ASME transactions on mechatronics*, vol. 14, no. 6, pp. 699–706, 2009.

[9] A. M. Dollar and R. D. Howe, "The highly adaptive sdm hand: Design and performance evaluation," *The international journal of robotics research*, vol. 29, no. 5, pp. 585–597, 2010.

[10] A. J. Spiers, B. Calli, and A. M. Dollar, "Variable-friction finger surfaces to enable within-hand manipulation via gripping and sliding," *IEEE Robotics and Automation Letters*, vol. 3, no. 4, pp. 4116–4123, 2018.

[11] A. W. Feinberg, "Biological soft robotics," *Annual review of biomedical engineering*, vol. 17, pp. 243–265, 2015.

[12] Y. Morimoto, H. Onoe, and S. Takeuchi, "Biohybrid robot powered by an antagonistic pair of skeletal muscle tissues," *Science Robotics*, vol. 3, no. 18, p. eaat4440, 2018.

[13] M. Ceccarelli, "Notes for a history of grasping devices," in *Grasping in Robotics*. Springer, 2013, pp. 3–16.

[14] G. Carbone, "Stiffness analysis for grasping tasks," in *Grasping in Robotics*. Springer, 2013, pp. 17–55.

[15] L. Birglen, T. Laliberté, and C. M. Gosselin, *Underactuated robotic hands*. Springer, 2007, vol. 40.

[16] M. T. Mason, *Mechanics of robotic manipulation*. MIT press, 2001.

[17] T. Iberall and C. L. MacKenzie, "Opposition space and human prehension," in *Dextrous robot hands*. Springer, 1990, pp. 32–54.

[18] L. Biagiotti, F. Lotti, C. Melchiorri, and G. Vassura, "How far is the human hand," *A review on anthropomorphic robotic end-effectors*, 2004.

[19] A. V. Sureshbabu, G. Metta, and A. Parmiggiani, "A systematic approach to evaluating and benchmarking robotic hands-the ffp index," 2018.

[20] J. Huber, N. Fleck, and M. Ashby, "The selection of mechanical actuators based on performance indices," in *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, vol. 453, no. 1965. The Royal Society, 1997, pp. 2185–2205.

[21] K. Andrianesis and A. Tzes, "Design of an anthropomorphic prosthetic hand driven by shape memory alloy actuators," in *Biomedical Robotics and Biomechatronics, 2008. BioRob 2008. 2nd IEEE RAS & EMBS International Conference on*. IEEE, 2008, pp. 517–522.

[22] C. S. Loh, H. Yokoi, and T. Arai, "New shape memory alloy actuator: design and application in the prosthetic hand," in *Engineering in Medicine and Biology Society, 2005. IEEE-EMBS 2005. 27th Annual International Conference of the*. IEEE, 2006, pp. 6900–6903.

[23] M. Ceccarelli, "Finger mechanisms for robotic hands," in *Recent Advances in Mechanism Design for Robotics*. Springer, 2015, pp. 3–13.

[24] W. T. Townsend, "Barretthand grasper: Programmably flexible part handling and assembly," *Humanoid Robotics: A Reference*, pp. 1–17, 2018.

[25] J. Banks, "Design and control of an anthropomorphic robotic finger with multi-point tactile sensation," 2001.

[26] A. Saudabayev and H. A. Varol, "Sensors for robotic hands: A survey of state of the art," *IEEE Access*, vol. 3, pp. 1765–1782, 2015.

[27] E. N. Gama Melo, O. F. Aviles Sanchez, and D. Amaya Hurtado, "Anthropomorphic robotic hands: a review," *Ingeniería y Desarrollo*, vol. 32, no. 2, pp. 279–313, 2014.

[28] H. Bos and M. Wassink, "Evolution of robotic hand," *University of Twente*, 2010.

[29] D. Alba, M. Armada, and R. Ponticelli, "An introductory revision to humanoid robot hands," in *Climbing and walking robots*. Springer, 2005, pp. 701–712.