Finger Mechanisms for Robotic Hands

M. Ceccarelli

Abstract The problem of grasping with robots is solved by using suitable finger mechanisms that are inspired from structures in nature. A variety of solutions have been experienced and are used in a variety of designs all around the world. This paper discusses a survey of possibilities by addressing attention to characteristics and problems in the design and operation of those finger mechanisms. The author's experience with LARM hand is reported to show practical results in attaching the problem of improving efficient solutions with better finger mechanisms.

Keywords Artificial hands · Finger anatomy · Finger mechanisms · Kinematic design

1 Introduction

Manipulation of objects with fingered robotic hands is an aspect which can be used in many applications, [6], also in industry and service contexts and it attracts still great interest as indicated in [1, 4, 16].

Since a recent past, in order to develop anthropomorphic finger mechanisms researchers have used two different approaches: complex mechanisms in order to perform manipulation tasks with high dexterity, or design of mechanisms with a reduced number of degrees of freedoms (DOFs) and actuators with less performances but a fairly simplified device operation.

Using underactuated mechanisms it is possible to achieve an adaptive grasp that mimics the human grasping action for which it is possible to consider two kinds of structures, namely using flexibility of links or designing underactuated mechanisms as pointed out in [8]. A mechanism is defined underactuated when its number of

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actuators is smaller than the number of degrees of freedom of the mechanism. It is possible to identify two types of underactuated finger mechanisms, depending on whatever a tendon or a link transmission is used. Example of tendon finger mechanisms is presented in [2], and a pulley-cable solution is described in [3].

When large grasping forces are required, underactuated linkage mechanisms are usually preferred, like in [2] where a 1-DOF mechanism with suitable four-bar linkages and flexible elements is used to move all phalanxes of fingers, in [17] where an underactuated linkage with force control is studied or in [19] where a 5 fingered underactuated prosthetic hand is reported.

Since the end of 1990s at LARM in Cassino design and research activities have been carried out in order to design a low-cost easy-operation robotic hand with anthropomorphic fingers, denominated LARM Hand [5].

In this paper the design of a new underactuated finger mechanism has been proposed for LARM Hand, as focused on requirements referring to 1-DOF, anthropomorphic grasp, and mechanism's compact size.

2 Fingers in Nature

Fingers in nature are related to hands and feet when considering a grasp in a broad sense as a task by which interaction is with an object to be manipulated or with the ground to be in contact with, respectively.

Such a variety of task configurations has generated a variety of finger anatomy but with solutions that still show a common structure. The anatomy of fingers in hands both in humans and primates is illustrated in the example in Fig. 1, [11]. The anatomy is characterized by a bone structure with a serial kinematic configuration and a muscle complex system by which each bone is moved through two or more counteracting muscular tendons. The main terminology of human anatomy is reported in Fig. 1 and it is usually used also for artificial hands.

In Fig. 2, examples of finger configurations are reported as referring to horses and cats with a structure that still shows sequential bones and parallel architecture muscle system. The similarity with human anatomy is recalled by the similar terminology of the parts in those other fingers.

Summarizing, the anatomy of fingers in nature shows the following design characteristics:

- A serial bone-link structure whose main purpose is rigidity and load capability
- An actuation muscle system aiming to rotate each bone-link independently but with coordinated movements with other finger links

The operation of fingers in nature is devoted to grasp and interaction with objects by exerting proper force during a proper motion for pure mechanical purposes.

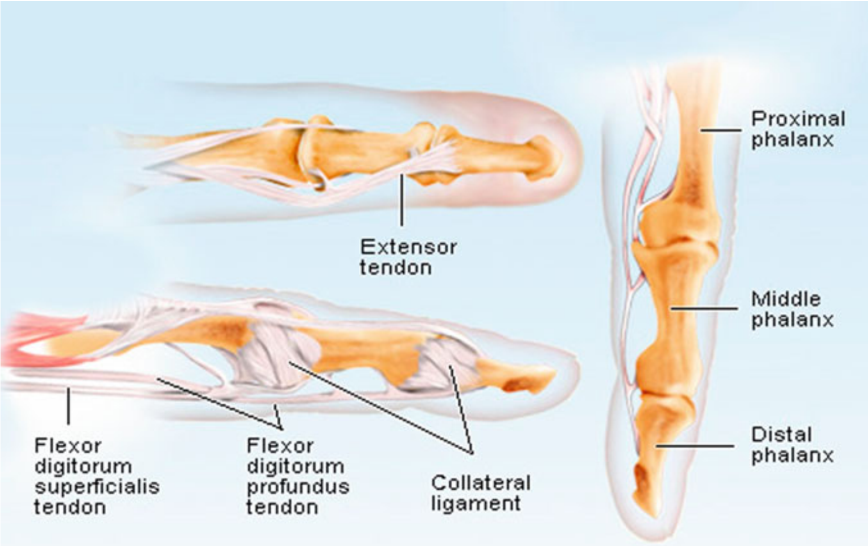

Fig. 1 Anatomy of human fingers, [11]

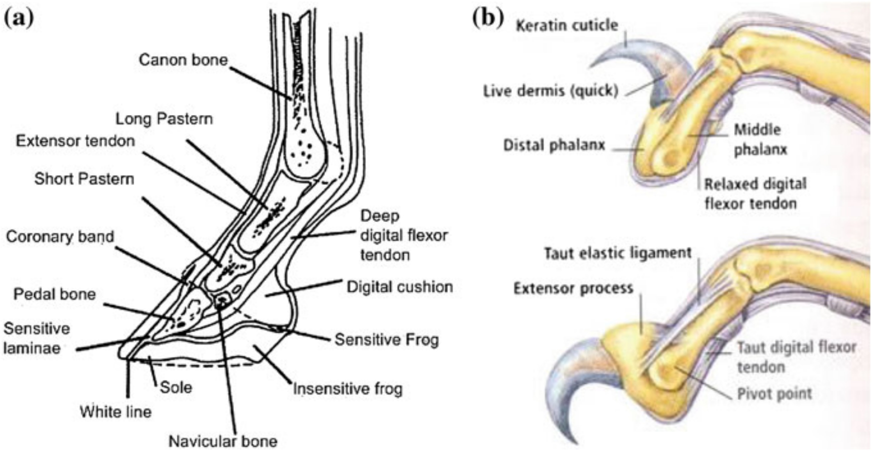

Fig. 2 Anatomy structures in: **a** horse fingers, [9]; **b** cat fingers, [12]

3 Requirements for Artificial Fingers

Artificial fingers are conceived to replicate the design and operation of fingers in nature for performing grasping actions at the most. Artificial fingers are developed for automatic machinery, and recently mainly for robotic systems, [6]. Some applications are also directed to prosthesis implementations. In this paper attention is focused on artificial fingers for robots.

Requirements can be outlined by looking both to the mimicking design purposes and operation peculiarities. However, 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

In general, the size of grasping devices for robots is designed as function of prescribed grasps with a given set of objects. In particular, for humanoid robots artificial hands are usually of hum-like size but different smaller or larger solutions can be required in other robotic systems and manipulators.

The above-mentioned aspects can be considered with proper numerical ranges of requirements after a careful analysis of peculiarities and aims in design procedures for the adopted finger solution structure. A general procedure can be outlined as in the block diagram of Fig. 3 where the core procedure application of mechanism design procedures with specific algorithms taking into account the grasping purposes and features.

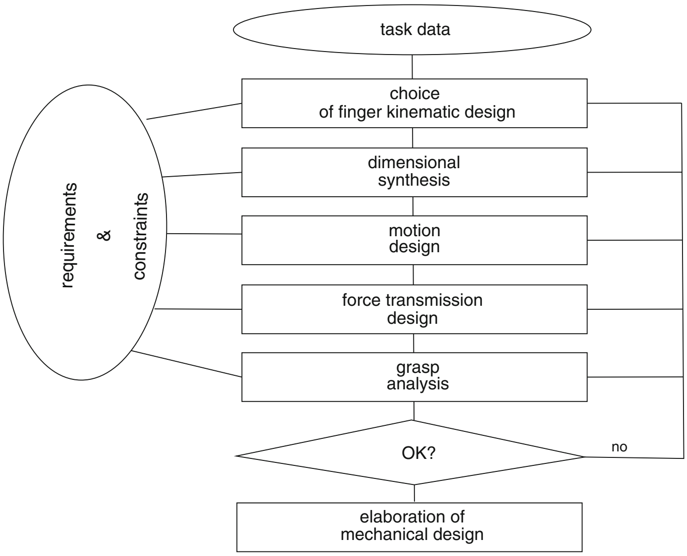

Fig. 3 A flowchart for design procedure of finger mechanisms

4 Mechanisms for Fingers

Artificial fingers are conceived as inspired by natural solutions so that in general they show structures with phalanx bodies with serial chain configuration. Figure 4 summarizes such an inspiration by looking also at the phalanx actuation with motion joint angles θi (i = 1, …, 3) and joint torque τi (i = 1, …, 3) with serial design, Fig. 4a or parallel architectures, Fig. 4b. Indeed a variety of actuating mechanisms are used to obtain actuation solutions with phalanx bodies that are even part of them.

Examples of the most used mechanisms for finger design are reported in Figs. 5, 6, 7 as referring to design finger structures which are based on linkages, tendons, or direct drives, respectively.

In Fig. 5 an artificial human hand is shown with the fingers that are designed with linkages as a product that is available in the market even at very low cost and fairly easy robot implementation, [15]. Phalanxes are links of the linkage and the finger mechanism shows a kinematic chain that can have 1 or more DOFs. In general linkages are used in finger structures to obtain 1 DOF finger mechanism whose actuator can be active on the first joint like in the example in Fig. 5.

Figure 6 shows a general scheme of tendon driven finger design where each phalanx body is actuated by two antagonist cables whose pulling gives motion and force to the phalanxes, [14]. This solution is clearly inspired from the human anatomy and it is the most common used structure in robotic hand for humanoid

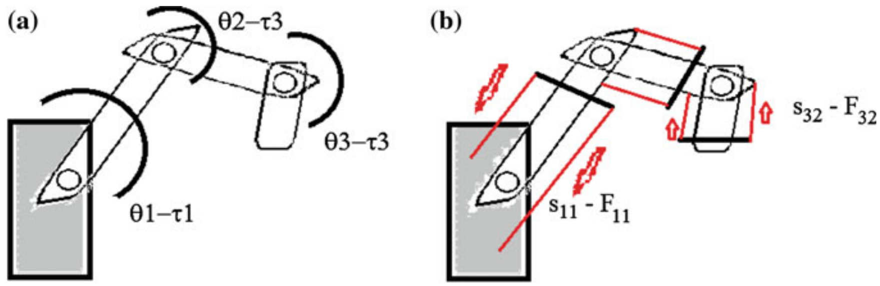

Fig. 4 Kinematic main structures for finger mechanisms: **a** serial chain as inspired by bone structure; **b** parallel architecture as inspired by muscle actuators

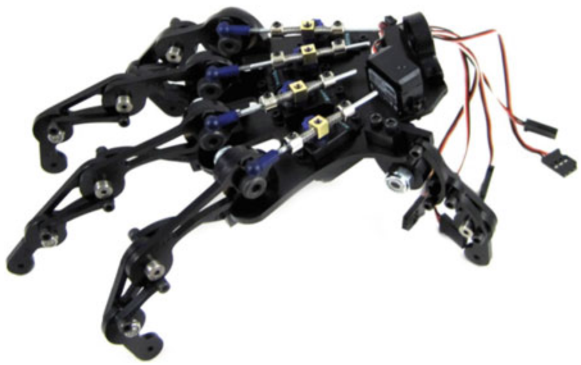

Fig. 5 Finger linkage mechanisms with rigid links in an artificial hand, [15]

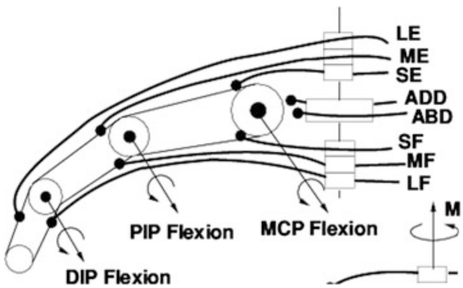

Fig. 6 A scheme of finger mechanism with tendon/cable actuation of the phalanxes, [14]

robots. Complexity refers to the multiple actuators that are needed to act in coordination for the antagonism operations.

Figure 7 shows examples in which the phalanx body is the main issue to obtain grasping adaptability to object characteristics. In Fig. 7a, [13], deformable material

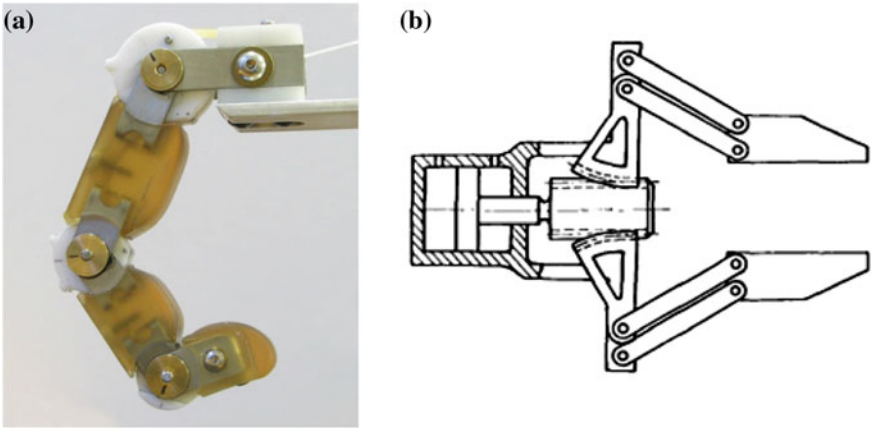

Fig. 7 Examples of finger mechanisms with phalanx bodies: **a** as deformable body, [13]; **b** as rigid link, [10]

is used as active cover of phalanx bodies where as in Fig. 7b, [10], rigid link fingertip is used in a gripper for grasping rigid bodies with possibility to shape its geometry to facilitate multiple contacts with grasped objects.

5 LARM Solutions and New Designs

A last version of LARM Hand is reported in Fig. 8a, with three 1-DOF fingers, a palm, and a standard flange for connection with robots [5]. The size of this prototype is 1.2 times larger than an average human hand as summarized in Table 1 [7]. The actuation system consists of three DC motors with a reduction gear train on each axis. The 1-DOF human-like finger mechanism for LARM Hand is designed according to the scheme in Fig. 8b. Each finger is composed of two cross two

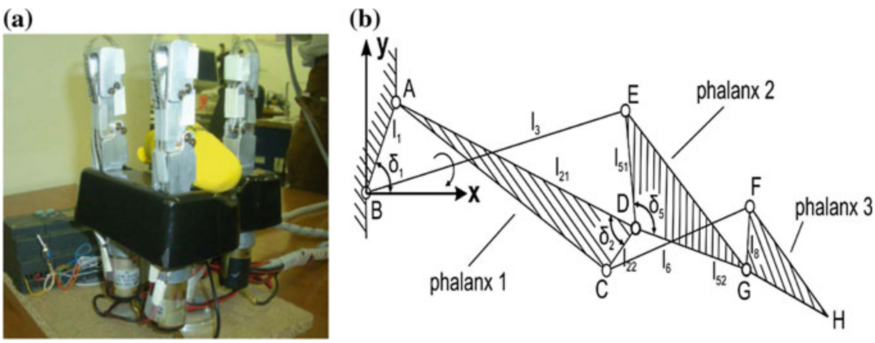

Fig. 8 LARM Hand IV: **a** prototype built in 2007; **b** finger mechanism's scheme [5]

Table 1 Structural parameters of the LARM Hand IV in Fig. 8

(mm)								(deg)		
l_1	l_{21}	l_{22}	l_3	l_{51}	l_{52}	l_6	l_8	δ_1	δ_2	δ_5
8.8	24.1	3.9	28.5	6	19.9	25	6.9	83.5	51	129

four-bar linkages. Phalanx 1 is the input bar of the first four-bar linkage and is also the base frame of the second four-bar linkage. Phalanx 2 is the input bar of the second four-bar linkage and it is also the coupler of the first four-bar linkage. Phalanx 3 is the coupler of the second four-linkage. The linkage design is characterized by a limited grasping adaptability that is determined by the linkage proportions for the finger configurations. In order to improve the capability of grasping objects with different sizes and shapes, solutions with underactuated mechanisms have been considered in previous works, [17, 18, 20].

Underactuation with spring elements as passive joints can be considered as convenient solution for artificial finger designs, [2]. Thus, at LARM attempts have been worked out to define suitable solutions with slight modifications of the original LARM finger design with the aim to improve the grasping adaptability to object shapes but by preserving the original features of 1 DOF actuation and linkage configurations within the finger body.

In particular, Fig. 9 shows a solution with torsional springs in order to obtain underactuated behavior of the four-bar linkages, [18]. Figure 10 refers to a first design for underactuating the LARM finger mechanism by using a linear spring within the body of phalanx 2, [17].

In order to design a new 1-DOF underactuated finger for LARM Hand, new kinematic solutions have been developed by using considerations in [8]. In [20] in order to obtain a new underactuated finger mechanism for LARM Hand a mechanism search has been worked out to identify several possible solutions.

The selected solution for a new finger mechanism is shown in Fig. 11. It is composed by 8 links and 9 revolute joints. Phalanxes are respectively links 2, 6 and 8. This mechanism has a limited manufacturing complexity because of the reduced number of bodies and linkage structure. Because of underactuation this mechanism is able to grasp objects with different shapes remaining within the finger body during its movement.

The mechanism operation can be described according to characteristic configurations for specific contacts by using suitable virtual equivalent mechanisms that have been used in [17, 18] to characterize the underactuated behavior of a finger

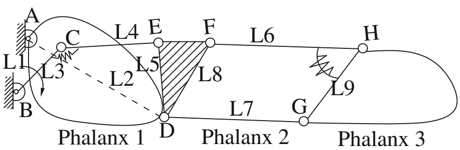

Fig. 9 Underactuated LARM finger mechanism with torsional springs, [18]

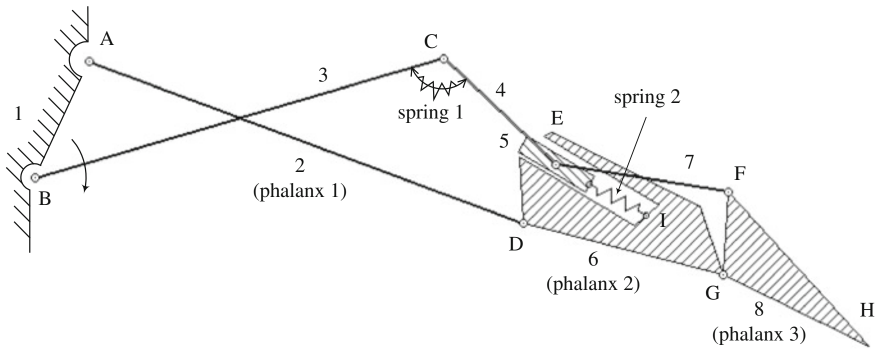

Fig. 10 Underactuated LARM finger mechanism with a linear spring, [17]

mechanism. Namely, equivalent mechanisms can be identified for the cases: no phalanxes in contact; only phalanx 1 in contact with an object; phalanxes 1 and 2 in contact. Referring to the first situation, a phalanx is free when there is no contact force and a torque acts on it. Generally a phalanx is free before it will touch an object. In this case, links that are connected by spring can be considered as a single virtual link. Here links 3 and 4 can be considered as acting as one virtual link 9 as shown by dashed line segment BD in Fig. 11b. Link 6 and 7 can be considered as another virtual link 10 through segment FI. Therefore, the proposed finger mechanism can be simplified as the equivalent mechanism of Fig. 11b, which recall the original linkage in LARM Hand, shown in Fig. 8b. In the second situation, phalanx 1 is stopped while phalanxes 2 and 3 are free. In this case, link 2 and joints E and F are fixed and they act as a virtual base as shown in Fig. 11b. Spring 1 will start to be deformed because of motor push. But spring 2 will be not activated because phalanxes 2 and 3 are free. Links 6 and 7 can still be considered as one single virtual link 10. Thus, the finger mechanism can be simplified as the equivalent mechanism in Fig. 11b. When phalanx 2 is stopped because in contact with object, link 6 and joints E, F and G are fixed and phalanxes 1 and 2 act as a virtual base. Thus, also spring 2 will start to be deformed.

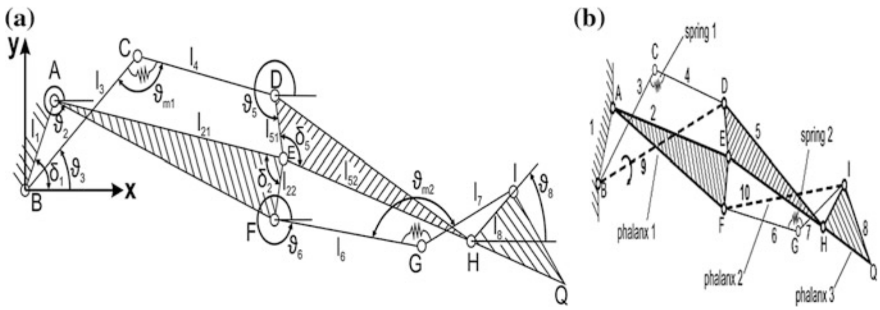

Fig. 11 A new underactuated solution for LARM Hand fingers: **a** a scheme with structural parameters; **b** an equivalent mechanisms during functioning

The experience of LARM finger designs with underactuated linkages has been developed satisfactorily by considering requirements in a procedure like in Fig. 3 and by preserving the peculiarities of the original LARM design. Nevertheless, although underactuated linkages with springs shows feasible operations, practical mechanical design with convenient handsome features is still a problem and further design research is under development.

6 Conclusions

In this paper finger design has been approached by looking at the mechanism design for finger structures that can be also the driving systems as inspired from anatomy of fingers in nature. The role of the finger mechanism is outlined by discussing requirements and peculiarities for the grasping tasks and by referring to the common general topologies that are used in artificial robot hands. In particular the experiences with LARM Hand are reported to outline future developments with solutions that can be based on underactuated linkages.

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