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Review

Robotic hand: A review on linkage-driven finger mechanisms of prosthetic hands and evaluation of the performance criteria

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ABSTRACT

Mechanical design of an artificial finger is the key factor in determining the performance of a prosthetic hand. To achieve a simple, dexterous and functional bionic hand, researchers have argued that two main requirements should be incorporated in developing an artificial finger: (i) an anthropomorphic structure and (ii) the capability of grasping objects in a stable and secure way. This paper first considers the existing body of literature on the various performance criteria used for prosthetic fingers. These criteria are classified into a) *grasp* and b) *physical* characteristics. To this end, various perspectives of existing papers on prosthetic finger's features such as shape-adaptivity, natural motion, stability, force isotropy, workspace, and weight are considered. Furthermore, existing linkage-driven fingers of hand prostheses are reviewed. For this purpose, relevant articles published between 2000 and 2019 were searched, and a total of 28 linkage-driven mechanisms from about 280 papers were selected and assessed based on the performance criteria. Finally, according to the intended use of a prosthetic hand, this paper suggests some key considerations needed for developing an anthropomorphic artificial finger.

1. Introduction

The hand is one of the most functional limbs of the human body which is able to perform a variety of daily tasks. In different communities, many lose this essential limb due to numerous reasons such as congenital causes, diabetes, and unpredictable accidents. Owing to amputees' appeal for replacing a tool with their lost hand, development of the hand prosthesis technology is a major incentive for researchers. Cordella et al. conducted a comprehensive survey of almost 1000 subjects [1]. Based on that research, in the viewpoint of amputees, a suitable prosthetic hand has different features such as resemblance with the human hand anatomy, low weight, low cost and high functionality (capability of performing handy grasp patterns, particularly power and precision grasp [2]). To accomplish the mentioned goals in a prosthetic hand, various designs and models have been proposed so far. In some cases, they have been commercialized.

Belter and Dollar [3] have compared the general features of 5 commercial and 11 research hands such as type and the number of motors, the number of degrees of freedom (DOFs), coupling methods among phalanges, the range of motion of the finger's joints, and the amount of forces applied in different grasp patterns. In addition to investigating the human grasp patterns and various driving systems, Controzzi et al. [4] have compared the specifications of several prosthetic hands

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in terms of anthropomorphic characteristics, the actuators and sensors, the kinematic of the hands, and the materials used in the prostheses. Melo et al. [5] have assessed the technical characteristics of 27 robotic hands regarding the number of fingers, the number of DOFs, actuator system, and sensing process. They have also introduced the grasp patterns and the control strategies in hand prostheses. Riet et al. [6] have evaluated 4 commercial and 4 research hands concerning the actuators, cost, weight and contact sensors. Furthermore, they have investigated the grasp categories, the grip strength in power and lateral grasp, and the passive load of hook grasp in the considered hands. In [7], Belter et al. have presented a detailed analysis of mechanical specifications of 7 commercial and 13 research hands. They have studied the type and number of motors, the number of joints, the number of DOFs, the grasping forces, the fingers' range of motion, weight, the fingers' flexion and extension movements, the size of the hands and the achievable grasps of the proposed hands. Kulkarni et al. [8] have discussed different aspects of prosthetic hands including mechanical specifications, control systems and EMG signals. They have also presented the details of mechanical characteristics of 5 commercial and 8 research hands. The former provides a detailed comparison between body-powered and myoelectric-powered prosthetic hands. In [9] the design methods and theoretical analysis of under-actuated finger mechanisms have been reviewed alongside presenting several prototypes of under-actuated fingers; i.e. less motors than the DOFs [10]. Nazma and Mohd have studied different aspects of tendon-driven prosthetic hands [11]. Kate et al. have conducted an extensive research on 3D-printed upper limb prostheses [12].

Up to now, different methods to drive the prosthetic fingers such as a combination of links, tendons [13,14], gears [15–18], cam [19], and combined driving systems [20] have been employed. However, overviewing the relevant papers clears that in most of the prosthetic hands, the phalanges of the fingers are coupled by linkage or tendon. Many have compared these two types of coupling between phalanges [10,21–25]. Tendon-driven mechanisms have light and simple structure. In addition, under-actuation achievement is considerably straightforward. On the contrary, the linkage ones have the capability of exerting high forces, less frictional impact, accurate operation, and more durability.

In none of the published papers, the detailed characteristics of artificial fingers, the indispensable components of a prosthetic hand, have been reviewed. In this paper, 28 distinct finger mechanisms subject to the criteria defined as follow are reviewed. Due to the beneficial structure of linkage-driven prosthetic fingers, particularly for commercial purposes, we have only considered them. The goal of this paper is to guide developers of prosthetic hands and make them familiar with the general features and performance criteria of a finger mechanism. Besides, by reviewing the linkage-driven finger mechanisms, creating new ideas for a better finger mechanism would convert into a straightforward task.

The rest of this paper is organized as follows: Section 2 outlines how we selected the relevant papers from a comprehensive search. In Section 3, the evaluated criteria of artificial fingers are completely discussed. Section 4 presents the mechanical features of the selected 28 linkage-driven finger mechanisms based on the criteria of the previous section. In Section 5, the general trends of the considered mechanisms are discussed. Some conclusive recommendations are mentioned in the last part of the paper.

2. Search method

This research was conducted during 3 years, from August 2016 to July 2019, while the authors were developing FUM hand prosthesis. The literature search was limited by English-language journal and conference papers being published between 2000 and 2019. To this end, beside a manual review, the electronic databases, including Google, Google Scholar, Science direct, IEEExplore and Scopus were systematically searched. The keywords used for this research were "upper limb prostheses", "robotic hand", "linkage-driven prosthetic finger", "anthropometric finger mechanism", "under-actuated finger", "shape-adaptive mechanism", and "performance criteria of prosthetic hands". Following a careful investigation of all the titles and abstracts of the articles, many relevant papers were selected. Those intended to the hand assistive mechanisms such as exoskeletons were not involved in this research. Finally, 28 linkage-driven finger mechanisms of prosthetic hands were selected.

3. Performance criteria of artificial fingers

To evaluate the fingers of hand prostheses, different aspects of the finger mechanisms associated with their performance should be clarified. In light of the points highlighted in the relevant literature, some important criteria for the description of a finger structure have been obtained. Based on these criteria, we evaluate the performance of the finger mechanisms of prosthetic hands. In the following, we will completely define and discuss the importance of eleven significant criteria categorized into grasp and physical aspects.

3.1. Grasp characteristics

3.1.1. Natural motion

In several prosthetic hands, the finger mechanisms are developed based on an anthropomorphic feature that is the natural motion of the human hand [10,26]. This motion can be defined as pre-shaping of the fingers before contacting with an object, a linear relationship before the motion of the phalanges, and the range of motion of the joints of the fingers [27] . In this paper, the natural motion is considered as the preshaping of the phalanges by a linear relationship before reaching an

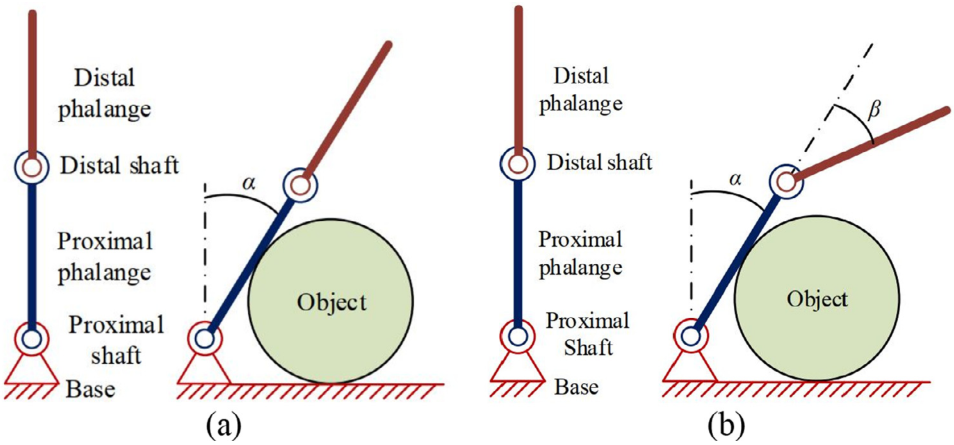

Fig. 1. Comparison of non-preshaping (a) and preshaping (b) [29].

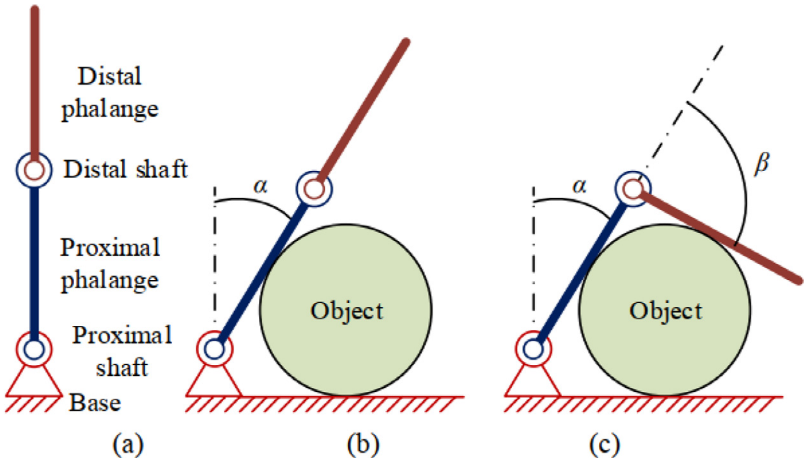

Fig. 2. Shape-adaptive grsaping mode of a two-phalange finger [29]. (a) first stage (b) initial contact (c) entire grasp.

object. In fact, prior to the contact, a non-preshaping finger mechanism resembles motion of a one-phalange finger, shown in Fig. 1(a). By contrast, there is a constant relative angle between the phalanges in an anthropomorphic finger (Fig. 1(b)). The lack of natural motion may cause failure in grasp. To illustrate, if an object slides on one phalange, the motion of the further phalanges, executed natural motion, would prevent grasp collapse [28].

3.1.2. Shape-adaptivity

Shape-adaptive mechanisms have been noticeably used in many of the research prosthetic hands. The stability of some grasp patterns like power grasp can be improved by this characteristic. This feature is categorized into two different aspects including shape-adaptive hands and shape-adaptive finger mechanisms. In the first type, by reducing the number of actuators, two or more fingers of an artificial hand are driven by only one actuator. In fact, once one finger touches an object, the movements of the other fingers continue to the end of the grasp process [30]. In the second type, which is considered in the present study, shape-adaptivity is defined as the phalanges' individual movements. In accordance with Fig. 2, following with the first phalange's touch with the target object (Fig. 2(b)), the second phalange, which is equipped with the shape-adaptive joint, rotates to wrap the object (Fig. 2(c)). If there is a shape- adaptive joint between the second and third phalange, this process continues until the third phalange touches the object. In order to create a shape-adaptive joint, a passive element such as a spring is commonly used. Shape-adaptive mechanisms are also classified into direct and indirect types. In the direct type, movements of all phalanges are supplied by the motor at which the first joint is installed. However, only the first phalange is actively driven in the indirect ones. In this case, other phalanges are flexed by the movement of an element, a mechanical sensor, which is located in the contact surface of each phalange (except distal phalange) with the environment. The following articles investigate the shape-adaptive characteristic [16,27,29,31–33].

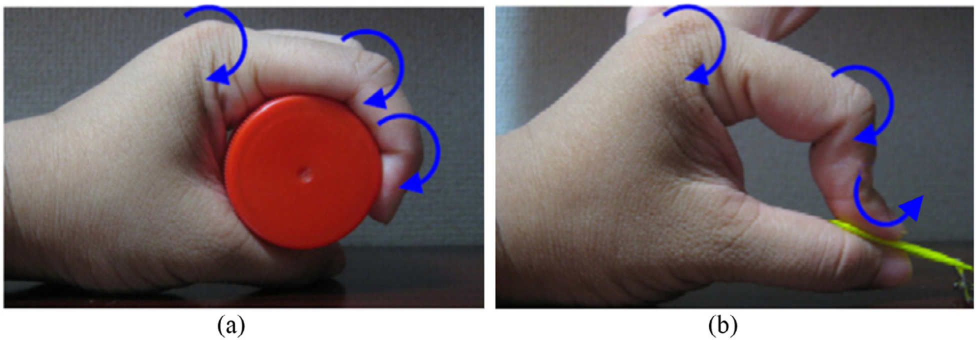

Fig. 3. Comparison of conventional motoin (a) and pinching motion (b) of the human finger [34].

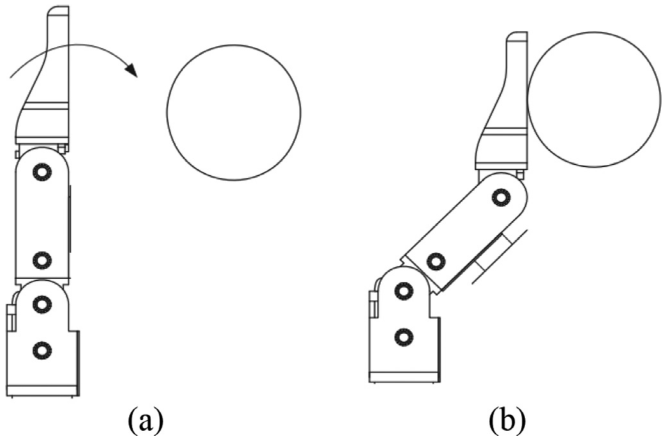

Fig. 4. Parallel grasp process of PISA finger. (a) Initial stage (b) last stage [34].

3.1.3. Pinching motion

One of the most important grasp patterns is pinch grasp. This grasp is the coordination of the index finger and thumb to hold an object. During this operation, the distal phalanx remains straight or rotates in counterclockwise direction, while in the conventional motion of the fingers, all phalanges rotate in clockwise direction (Fig. 3). In other words, considering the initial straight stage of the phalanges, the distal phalange only perform a translation motion (Fig. 4).

The prevalence of pinching motion is not as much as natural and shape-adaptive motions, but it particularly seems beneficial in grasping thin objects such as a card or a key. There are linkage-driven [34], tendon-driven [35] and gear-based [16] finger mechanisms performing pinching process in their operation. This characteristic is also called parallel grasp process. It is worth mentioning that during pinching, only the distal phalanges of the index finger and thumb touch the objects.

3.1.4. Stability

The main duty of a prosthetic hand is to grasp and manipulate different objects in a stable and secure way so as to lessen the possibility of slippage and failure in grip. In 36,37] various strategies for slip prevention and force control have been employed to obtain a firm grasp. Given that the principle in grasping process is that all the involved fingers are individually stable, in the present study, a grasp is stable if and only if each finger is in the static equilibrium [38,39]. In other words, according to the free-body diagram, the contact forces should be either positive or zero in a stable grasp. Negative forces may only appear in shape-adaptive mechanisms which have more than one DOF and equipped with elastic elements such as a spring [40–42]. For example, as shown in Fig. 5, Birglen et.al [40] analytically computed values of the contact forces for a three-phalange under-actuated finger, precisely displaying the stability of the whole contact configuration zone as well. Where the value of the phalanges forces are negative, a grasp will fail. The volume of the stable loci was measured approximately 14%. One issue which occurs as a result of the negative forces is the ejection phenomenon (Fig. 6). Prevention of this phenomenon is highly difficult in under-actuated mechanisms. However, by considering mechanical constraints, the occurrence of this issue can somehow be avoided [38]. In actuated mechanisms, as the finger motion is entirely controlled by the drivers, the incidence of negative forces and the resulted ejection phenomenon are not possible.

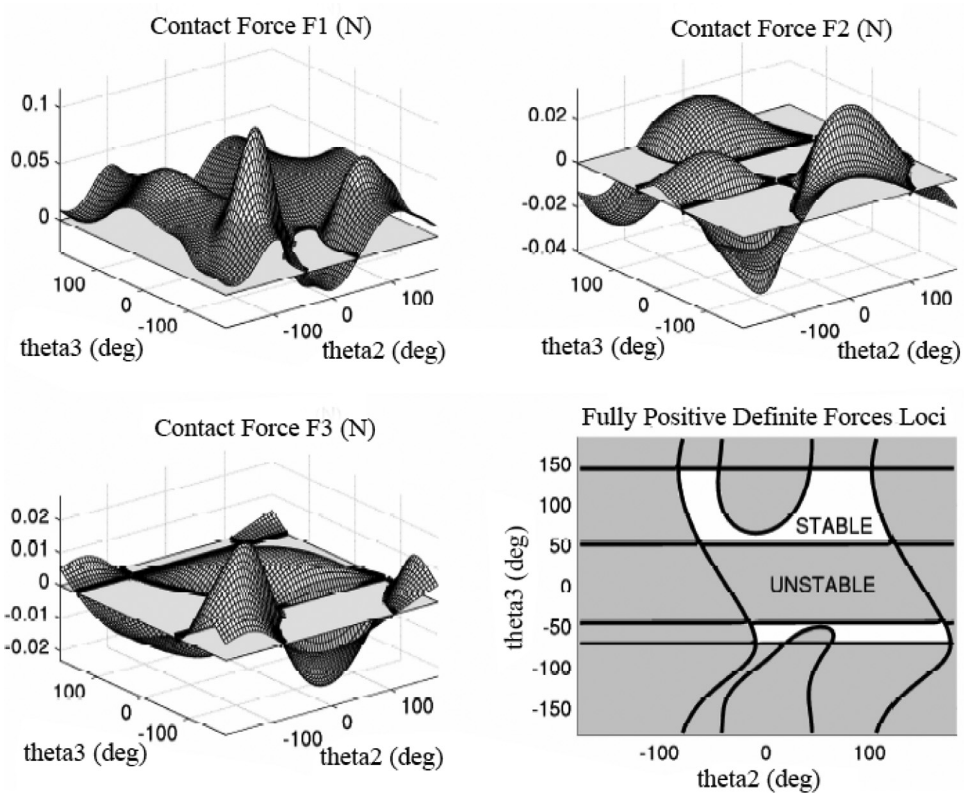

Fig. 5. An example of a three-phalange finger contact forces and the stability loci [40].

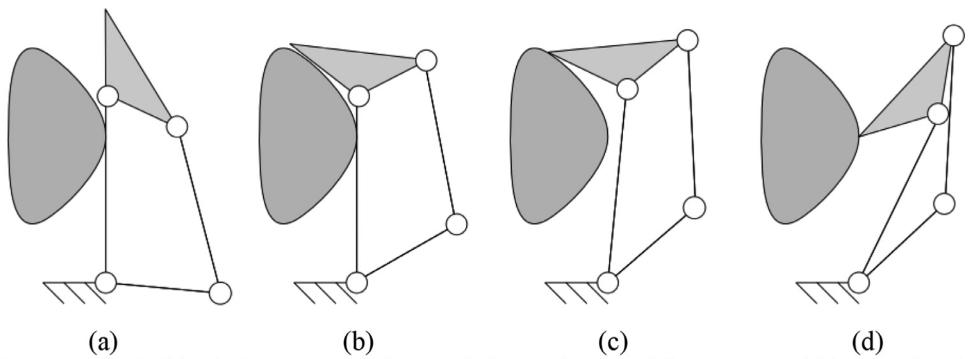

Fig. 6. An example of the ejection phenomenon in a two-phalange under-actuated finger [38]. (a) Initial contact (b) entire contact (c) loss of first phalange's contact (d) ejection phenomenon.

3.1.5. Force isotropy

To achieve a uniform force distribution in a finger, the value of the contact forces of the phalanges should approach each other. Such fingers are called force isotropic fingers, making the grasp softer and prevent damage to fragile objects. A Force isotropic finger has precise control of grasping pressure and a tighter grasp. This definition is merely meaningful in shape-adaptive fingers where an entire grasp occurs. Doria et al. and Larouche et al. introduced two performance indexes to evaluate this criterion [43,44].The first attempt to analyze this feature is to drive the equations of contact forces, like the procedure of computing the stability loci of a mechanism. This is usually done by employing virtual work or potential energy methods [38,39]. By equalizing the terms of the contact force matrix, the force isotropic conditions can be obtained. There are just certain configurations in a finger under which it is force isotropic. For instance, Krut [45] presented a cam-tendon mechanism which exerts identical forces to the object in any configuration of the phalanges by only the middle of its phalanges. Liang et al. plotted the contact forces of a two-phalange finger, named COSA-E, with regards to various parameters [32]. Fig. 7 shows the changes in the contact forces with the changes in the contact locations in COSA-E finger. As can be seen, the larger the h_2 is, the more similar are the forces.

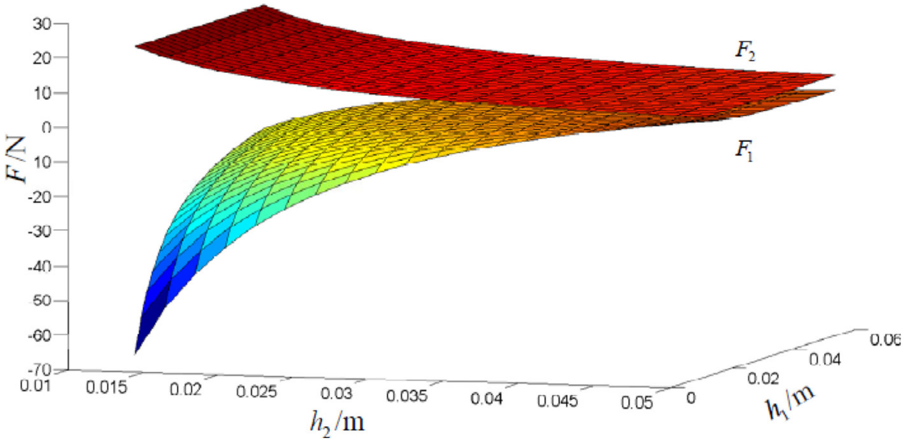

Fig. 7. Contact forces of the COSA-E finger [32]. h1 is the distance between contact location on the first phalange with the first joint and h2 is that of second phalange.

To sum it up, the reader is recommended that refer to [38] in which the subject of force isotropy for linkage-driven, tendon-driven, and soft grippers are completely discussed. Based on the mentioned reference, aside from the influence of the geometrical parameters of the system and the finger configuration, the stiffness of the implemented springs has a tremendous effect in force isotropic conditions.

3.1.6. Workspace

The workspace of fingers significantly affects the performance, accuracy, and stability of a prosthetic hand. The numerous degrees of freedom of human hand bring a complicated workspace and capability to grasp various objects. Modeling the human finger workspace is highly complex. By extending the overlap of the finger's workspace, the number of achievable grasps would increase bringing about high functionality of the artificial hand [46]. The workspace of a finger mechanism depends on the number and length of the phalanges and their range of motion. It is computed based on the kinematic equations parallel to considering the mechanical constraints. In most artificial hands, all fingers except thumb have planar motion. The pointed effect of the thumb on the performance of a bionic hand motivates researchers to design an artificial thumb with at least two DOFs. For instance, in bebionic hand [7], the thumb not only executes flexion and extension motions, but it also has the abduction and adduction movements. Having only two different modes in the abduction and adduction direction, the workspace of the mentioned prosthesis includes two planes. By contrast, the abduction and adduction motion of the i-Limb hand [7], a well-known commercial artificial hand, is driven actively leading to a three-dimensional workspace. In [47–51] the workspace of the fingers of various prostheses were analyzed. As an example, Fig. 8 shows the workspace of Allegro hand in four views [46].

3.1.7. Stiffness

Based on Hook's law, stiffness (the inverse of compliance [52]) is defined as the relationship between a general force and the provoked movements. In the bionic hand area, it can be divided into grasp stiffness and mechanism stiffness. In grasp stiffness, the movements of the grasped objects are analyzed respect to the changes in the external exerted wrenches [53], while the stiffness of the mechanism is attributed to the relationship between driving torques or forces exerted by the actuators and the phalanges movements [54]. Dong et al. presented a method in which they determine the grasp stability through computing the grasp stiffness matrix [55]. On the other hand, by analyzing the amount of the stiffness of the finger and the actuator torque and position, many pieces of information such as the contact locations and any unusual movement of the finger like ejection phenomenon can be obtained. Different kinds of mechanisms have a particular behavior with regards to the stiffness. In under-actuated mechanisms, the finger stiffness has a non-linear behavior, with increasing after the first and the second contact with the target (Fig. 9). By contrast, that of one-DOF fingers seems to have a linear behavior. Theoretical-wise, it can be deduced that the finger's stiffness goes to infinity when its rotation ceases after it is in contact with an object [56].

Due to high functionality of springs in the prosthetic's structure, opting an appropriate one with adequate stiffness is an underlying problem. High-stiff springs consume a noticeable amount of battery charge, whereas compliant ones would make the finger less robust. Generally, the springs are used for three distinctive purposes. One is to return the finger to its original position which is more privilege in tendon-driven mechanisms. The second functionality is when used as a shock absorber. Demonstratively, when an external wrench is applied to the finger, through implementing a spring and a slut, the impact is resisted which results in reducing the risk of breakage and damage to the user [7]. The third usage is to make possible the shape-adaptive motion.

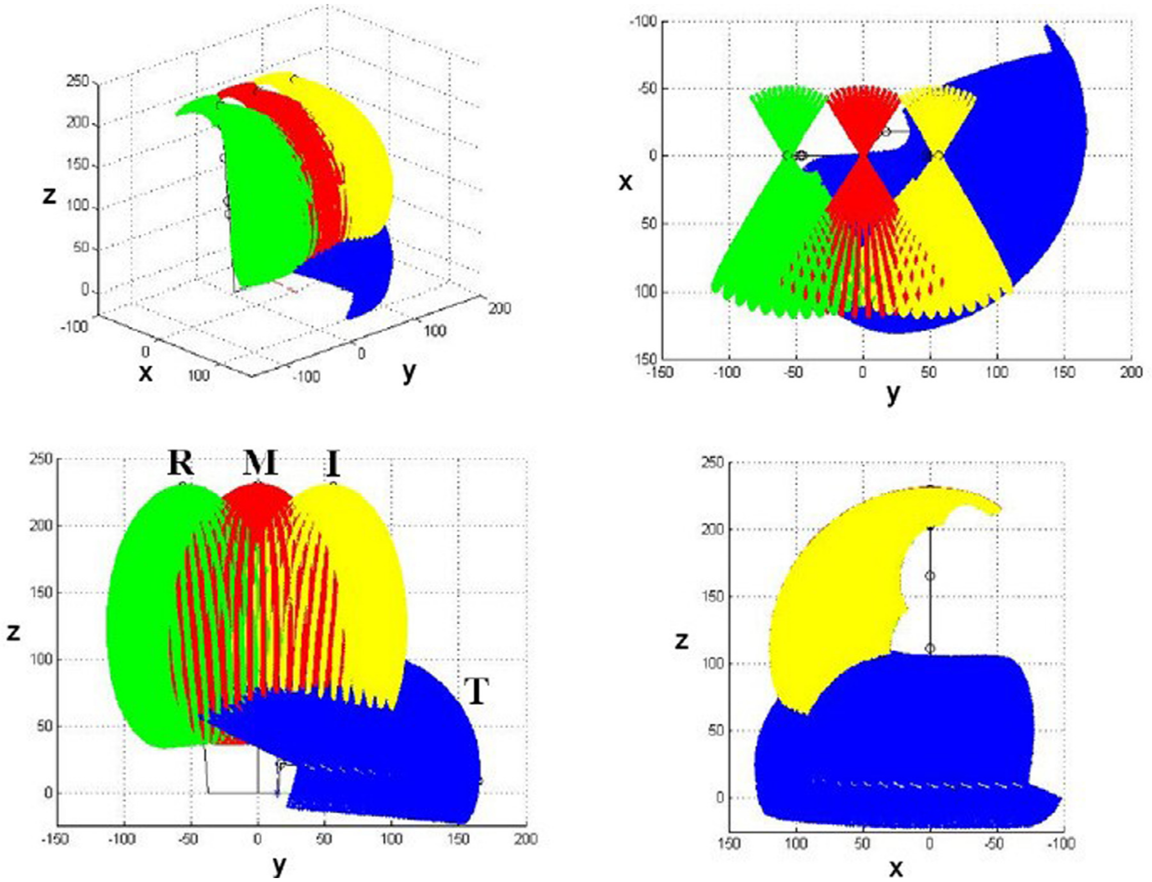

Fig. 8. The workspace of Allegro hand's fingers [46]. The axes are in mm. R: Ring finger M: Middle finger I: Index finger T: Thumb.

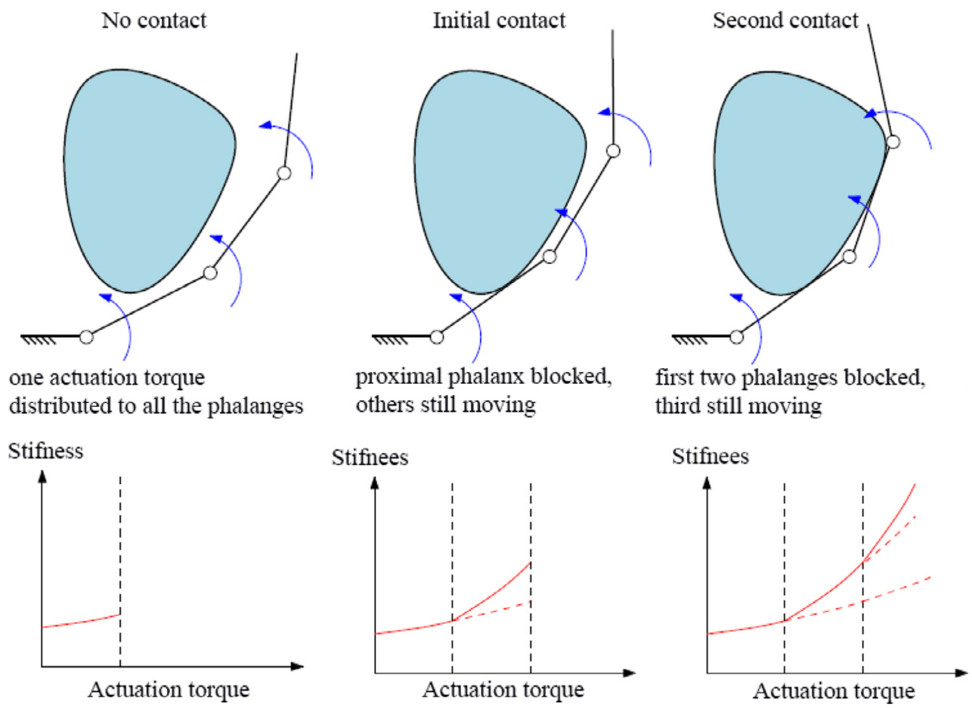

Fig. 9. Presentation of the Non-linear stiffness of an under-actuated finger [56] .

3.2. Physical characteristics

3.2.1. Weight

The weight of the human hand comprises approximately 0.5 and 0.6% of the whole body weight for men and women respectively [57]. Therefore, it can be deduced that the weight of the hand of a mature person is about 400 g. Attainment to a prosthetic hand weighing close to the human hand is a real challenge. Regarding the statistical reports and surveys which have been published in [1,58], being light should be considered as the priority in designing a bionic hand. Many abandon using their prosthesis due to physical pains resulted from high weight of that. Generally, the weight of commercial hands is approximately 500 g. In contrast, the majority of research hands weigh more than 1 kg because of using more complicated structures [7]. It can be said that a considerable portion of the weight of a prosthetic hand is owned by the fingers. The Number of phalanges, type of mechanism, geometric dimension and the material used in the structure directly affect a finger's weight. Illustratively, the more compact the structure is, the less weight the finger. Besides, shape-adaptive mechanisms are heavier than non-shape-adaptive ones owing to comprising more parts. Apart from the weight of a prosthesis, mass distribution significantly influences user comfort. The manufacturer of bebionic hand claims that positioning the motors in the palm makes the hand to be felt lighter and more comfortable. Nevertheless, the motors of i-limb hand have been located inside the fingers. Obviously, if the center of mass of the prosthesis is located close to the user's forearm, the produced wrenches will reduce which provides more comfort.

3.2.2. Number of phalanges

Designers of prosthetic hands have expressed different opinions about the number of phalanges. A three-phalange prosthetic finger not only has the similarity with the human hand but also leads to improve grasping performance [24]. However, this feature may cause increasing complexity of structure and weighing the prosthesis. Given that the simplicity in designing an artificial hand is a priority, most commercial artificial fingers have been developed by one or two phalanges.

3.2.3. Compactness

The compactness of a finger is defined as the ratio between the width and length of a finger [44]. It is ideal to develop a finger as compact as the human finger. Having an anthropomorphic and compact finger, the user can simply wear a glove and easily perform donning and doffing processes. In order to produce a prosthetic hand, which meets cosmetic factors, it should not have any protruding features.

3.2.4. Manufacturing process

Several methods can be used to manufacture the mechanical parts of a prosthetic hand. One typical technique is to machine light metals such as aluminum. The machining cost and time of a bionic hand would be high owing to tiny parts and complicated designs. Another method is injection molding. Whereas this method is not appropriate for individualizing a prosthesis so as to initial cost and long developing time attributed to manufacturing a new mold, it is noticeably time- and cost-efficient in mass production. Furthermore, 3D-print technology has been developing in recent years. This method is extensively used by "open bionic" as a commercial company and also widely in prototypes of research hands. Aside from providing the possibility of producing sophisticated designs, this technology makes the hand lighter and cheaper [12]. Nevertheless, the main disadvantages of 3D-printed hands are their low strength and inability of exerting high forces. This low strength increases the risk of part breakage in donning and doffing process of silicone gloves.

In [59] a hybrid technique claimed as the most cost-efficient and customizable method for producing a bionic hand is offered. An impact-resistant compliant four-bar linkage with a complete explanation of the fabrication process was also presented by Choi et al. [60]. Both two mentioned methods are a combination of 3D-print technology and injection molding.

4. Finger mechanism discussion

This section investigates 28 linkage-driven prosthetic fingers presented in relevant articles between 2000 and 2019. Detailed specifications of the mechanisms including type and number of DOFs; the number of phalanges, joints, and links; shape-adaptivity, natural motion, compactness and actual dimension are completely discussed. Regarding the literature, artificial fingers have one to four DOFs. Owing to the weight and space limitations in designing a finger, increasing the number of DOFs is challenging. Furthermore, According to the human hand, the number of phalanges of an artificial finger is not considered more than three. Considering the mentioned limitations in an artificial hand, individual motors for driving each of the phalanges is not reasonable, and then most of the mechanisms are actuated by only one motor. This leads researchers to design either under-actuated mechanisms or one-DOF fingers. Majority of the following mechanisms are comprised of four-bar linkages. This is categorized into coupled four-bar linkage and under-actuated four-bar linkage. Coupled four-bar linkage refers to the mechanisms that provide preshaping motion similar to the human hand prior to touching an object. Under-actuated ones are used for making the finger shape-adaptive. In addition, planar and spatial five-bar mechanisms and various combination of bars and ternary links have been used. The prevalence of natural motion and shape-adaptivity in finger mechanisms, incorporated in 19 and 22 mechanisms of the total 28 papers respectively, emphasizes the importance of these criteria in designing an artificial finger. There is a direct relationship between the number of DOFs and shape-adaptive criterion in a finger mechanism. One-DOF mechanisms, which have either one, two or three phalanges, are not shape-adaptive,

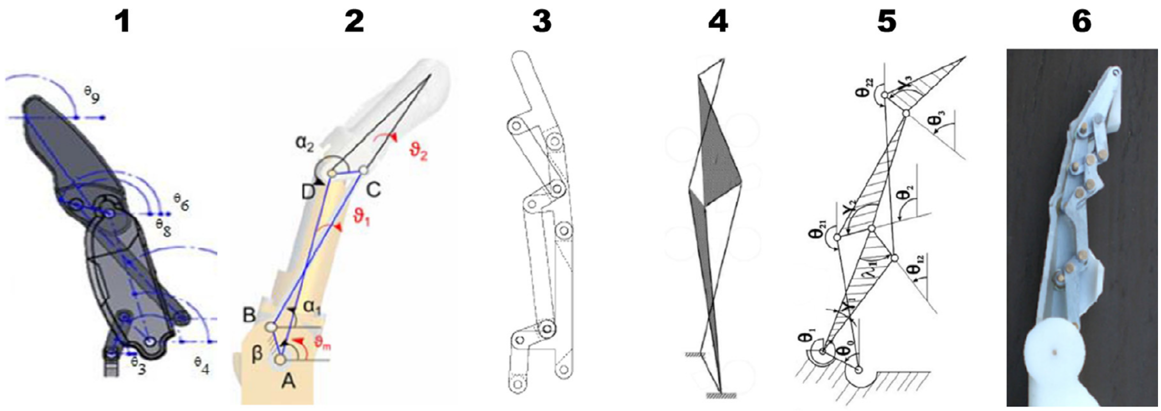

Fig. 10. One-DOF prosthetic fingers. (1) The prosthetic finger developed by Leal-Naranjo et al. [62]. (2) The S-finger developed by Imbinto et al. [61] (3) TBM finger developed by Dechev et al. [30]. (4) The prosthetic finger developed by Omarkulov et al. [24]. (5) The LARM finger developed by Rodrıguez et al. [63]. (6) The prosthetic finger developed by Jang et al. [64].

Table 1
Overview of one-DOF prosthetic fingers and their features.

Fig 7	Mechanism type	Number of phalanges-links-joints	Natural motion	Shape-adaptive	Compactness	Actual dimension (mm)
1 [62]	One C-FBL	2-3-5	Yes	No	H	58
2 [61]	One C-FBL	2-3-4	Yes	No	H	83
3 [30]	Two C-FBL	3-6-9	Yes	No	L	66
4 [24]	Two C-FBL	3-5-7	Yes	No	H	95
5 [63]	Two C-FBL	3-5-7	Yes	No	H	89.1
6 [64]	Stackable FBL	3-20-28	Yes	No	L	–

FBL: Four-bar linkage; C-FBL: Coupled four-bar linkage; H: comprising fewer than 2 links per phalange; L: comprising more than 3 links per phalange.

Table 2
Overview of two-DOF prosthetic fingers and their features.

Shape adaptivity								
Fig 9	Mechanism type	Number of phalanges-links-joints	Natural motion	Shape-adaptive	Type	Element	Compactness	Actual dimension (mm)
1 [66]	Two C-FBL	3-5-9	Yes	Yes*	Direct	Whiffle tree	H	–
2 [67]	One U-FBL	2-4-4	No	Yes	Direct	One linear spring	L	99
3 [68]	Block-linkage-slot transmission	2-4-4	No	Yes	Indirect	One linear spring	L	52
4 [42]	One U-FBL, One C-FBL	2-6-5	Yes	Yes	Direct	One torsional spring	L	70
5 [69]	One U-FBL	2-4-5	No	Yes	Direct	One linear spring	L	–
6 [23]	One U-FBL, One C-FBL	2-4-5	Yes	Yes	Direct	One torsional spring	H	–
7 [70]	One coupled-adaptive multi-bar linkage, One C-FBL	3-8-9	Yes	Yes*	Direct	One linear spring	L	96
8 [71]	One multi-bar linkage, One C-FBL	3-6-8	Yes*	Yes*	Direct	Weak springs or rubber bands	L	–
9 [72]	One U-FBL, One C-FBL	3-6-7	Yes*	Yes*	Direct	One torsional spring	L	95.4

FBL: Four-bar linkage; C-FBL: Coupled four-bar linkage; U-FBL: Under-actuated four-bar linkage; *: between two phalanges; H: comprising fewer than 2 links per phalange; L: comprising more than 3 links per phalange.

as shown in Fig. 10. Two-DOF Fingers comprise either two or three phalanges with only one shape-adaptive joint, illustrated in Fig. 11. Three-DOF fingers (Fig. 12) include three phalanges and two shape-adaptive joints. There is also a spatial four-DOF mechanism (Fig. 12(4)) executing the abduction and adduction motions for the finger. Furthermore, based on the compactness definition, considering a compact mechanism with fewer than 2 links per phalanges, 8 and 20 mechanisms have high and low compactness respectively. As Tables. 1–3 indicate, the inversing relationship can be inferred between compactness and shape-adaptive criteria. In fact, we should sacrifice the compactness characteristic to have an artificial finger with more similar movements to the human finger. In this paper, we classify the collected 28 mechanisms into three parts: one-DOF actuated mechanisms, two-DOF under-actuated mechanisms, and under-actuated mechanisms with more than three DOFs.

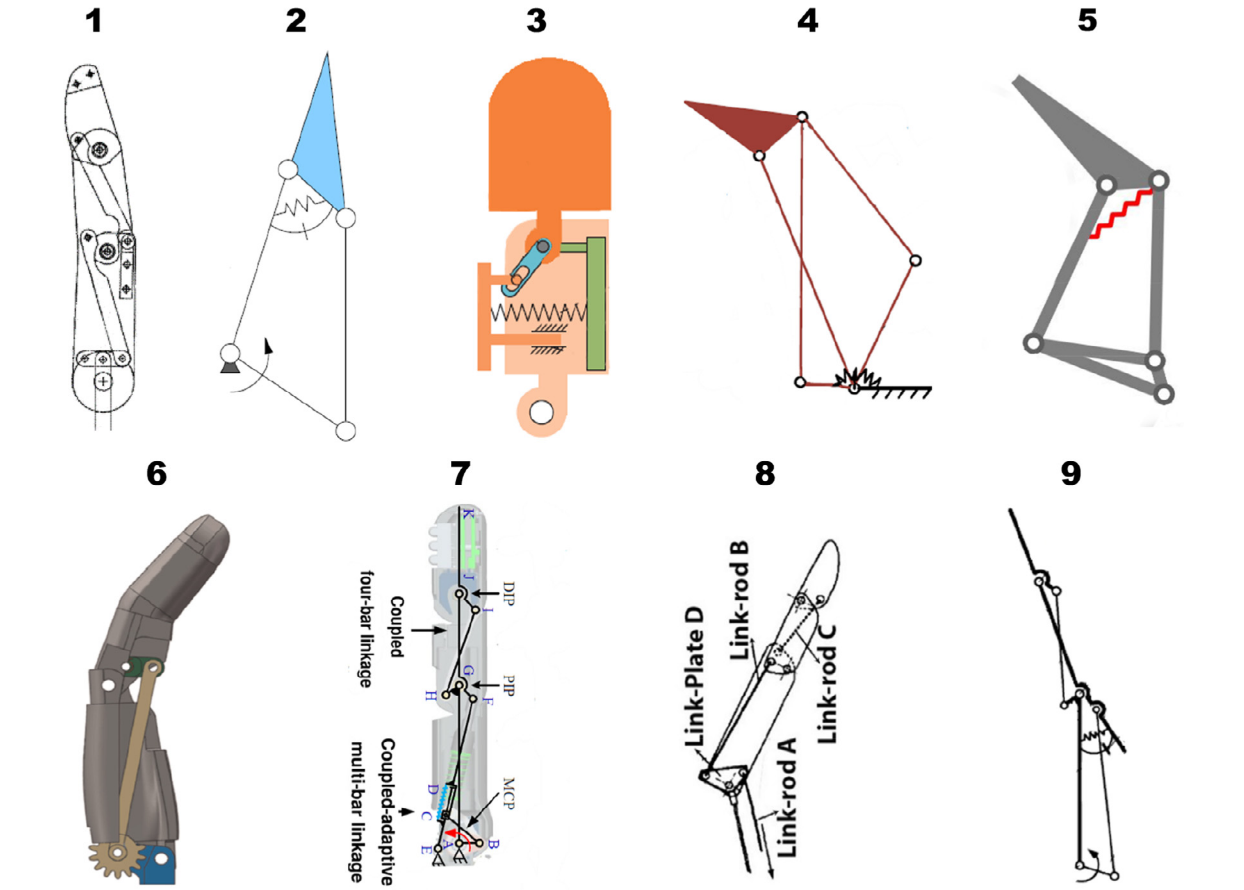

Fig. 11. Two-DOF prosthetic fingers. (1) The Southampton finger developed by Kyberd et al. [66]. (2) The SARAH finger developed by Laliberte et al. [67]. (3) The LISA finger developed by Jin et al. [68]. (4) The COSA finger developed by Zhang et al. [42]. (5) The prosthetic finger developed by Stavenuiter et al. [69]. (6) The UA finger developed by Li et al. [23]. (7) The prosthetic finger developed by Cheng et al. [70]. (8) The TUAT/Karlsruhe finger developed by Fukaya et al. [71]. (9) The prosthetic finger developed by Yang et al. [72].

4.1. One-DOF actuated mechanisms

A summary of one-DOF artificial fingers are presented in Fig. 10 and Table 1. It can be seen that the coupled four-bar linkage is widely used in one-DOF mechanisms. In all the prostheses of this section, the finger motion will stop immediately if one phalange touches an object. The finger mechanisms shown in Fig. 10(1) and (2) comprise two phalanges with one four-bar linkage [61,62], while others (Fig. 10(3)–(5)) are constituted by three phalanges with a four-bar linkage [24,30,63]. In addition, Fig. 10(6) shows a finger with three phalanges wherein the stackable double four-bar linkage has been embedded [64]. The importance of simplicity, robustness, and compactness in commercial hands prompt the designers to implement one-DOF fingers in their hands. For example, the two-phalange mechanisms (Fig. 10(1) and (2)) are used in bebionic and Vincent hands successively. We also used the mechanism shown in Fig. 10(2) in FUM Bionic Hand [65]. Meanwhile, Ottobock Company, as one of the most reputable manufacturers of prostheses, made a finger with only one phalange with names Sensor hand and Michelangelo hand. Although the former two prostheses cannot perform most of the human grasp patterns, many prefer to buy them due to the ease of operation.

4.2. Two-DOF mechanisms with one under-actuated joint

Currently available two-DOF finger mechanisms are presented in Fig. 11 and Table 2. In the Southampton finger (Fig. 11(1)), the shape-adaptive property is provided for the second phalange of the finger using a whiffle-tree mechanism. Furthermore, implementing two coupled four-bar linkage creates natural motion for the entire finger [66]. The SARAH finger, shown in Fig. 11(2), has a spring by which the second phalange rotates after the first phalange touch. Prior to the contact with an object, the spring prohibits the relative movement between the phalanges [67]. In the LISA mechanism (Fig. 11(3)), by connecting a linear spring to a plate which is compressed once an object contacts with the plate, the second phalange rotates. This mechanism, like the mechanism of Fig. 11(2), does not have the relative motion between phalanges before

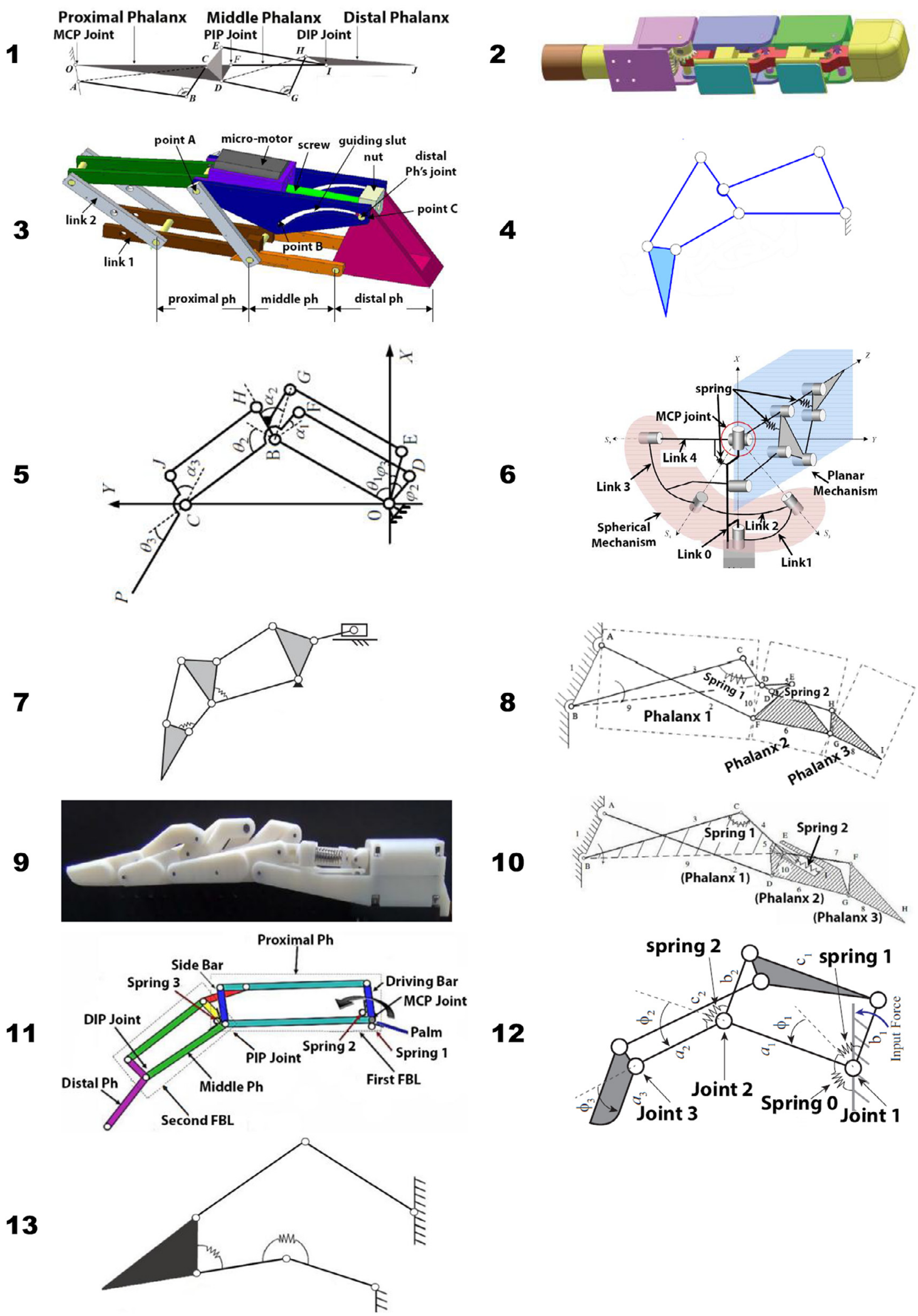

Fig. 12. Prosthetic fingers with three and more DOFs. (1) The prosthetic finger developed by Yoon et al. [10]. (2) The LISA finger developed by Jin et al. [68]. (3) The prosthetic finger developed by Azlan et al. [34]. (4) The SARAH finger developed by Laliberte et al. [67]. (5) The prosthetic finger developed by Mu et al. [73]. (6) The prosthetic finger developed by Tae-Uk et al. [74]. (7) The Ca.U.M.Ha. finger developed by Rea [75]. (8) The prosthetic finger developed by Li et al. [76]. (9) The prosthetic finger developed by Yoon et al. [27]. (10) The prosthetic finger developed by LiCheng et al. [77]. (11) The prosthetic finger developed by Gopura et al. [78]. (12) The prosthetic finger developed by Hirano et al. [28]. (13) The prosthetic finger developed by Khakpour and Birglen [79].

Table 3
Overview of the prosthetic fingers with three and more DOFs and their features.

Shape adaptivity									
Fig 10	Mechanism type	NUM of DOF	NUM of phalanges-links-joints	Natural motion	shape-adaptive	Type	Element	Compactness	Actual dimension (mm)
1 [10]	Two five-bar mechanisms, One C-FBL	3	3-9-10	Yes	Yes	Direct	Two torsional springs	L	93.81
2 [68]	block-linkage-slot transmission	3	3-7-7	No	Yes	Indirect	Two linear springs	L	–
3 [34]	Two U-FBL equipped with a guiding slut	3	3-15-9	Yes	Yes	Direct	Two torsional springs	L	120
4 [67]	Two U-FBL	3	3-7-7	No	Yes	Direct	Two torsional springs	L	140
5 [73]	parallelogram linkage	3	3-10-9	Yes	Yes	Direct	Actuated mechanism	L	82.3
6 [74]	One spherical five-bar mechanism, Two U-FBL	4	3-11-12	No	Yes	Direct	Three torsional springs	L	130
7 [75]	Two U-FBL, slider crank mechanism	3	3-7-8	No	Yes	Direct	Two torsional springs	L	91
8 [76]	Two U-FBL	3	3-8-9	Yes	Yes	Direct	Two linear springs	L	94
9 [27]	Stackable FBL, slider crank	3	3-20-28	Yes	Yes	Direct	Two linear springs	L	110
10 [77]	Two slider-crank FBL	3	3-6-7	Yes	Yes	Direct	One torsional spring, One linear spring	L	132.1
11 [78]	Two U-FBL	3	3-9-9	Yes	Yes	Direct	Three torsional springs	L	95
12 [28]	Two U-FBL	3	3-7-7	No	Yes	Direct	Three torsional springs	L	90
13 [79]	Linkage transmission	3	3-5-6	No	Yes	Direct	Two torsional springs	H	190

FBL: Four-bar linkage; C-FBL: Coupled four-bar linkage; U-FBL: Under-actuated four-bar linkage; L: comprising more than 3 links per phalange.

the contact with an object [68]. The COSA mechanism (Fig. 11(4)) has two more links than the mechanism of Fig. 11(2) that provides the natural motion for the finger [42]. Fig. 10(5) shows a two-phalange mechanism, developed by Stavenuiter et al., similar to Fig. 11(2), with one more ternary link. This difference originates from the underactuated grasper, presented by Stavenuiter et al., with a differential mechanism to change the level of shape-adaptivity [69]. By adding a link to the mechanism of Fig. 10(4), the UA finger (Fig. 11(6)) has the capability of performing the shape-adaptive motion [23]. A key point in this mechanism is that the driving torque should be inserted to the coupler link (the brown link in Fig. 11(6)), while in the mechanism of Fig. 10(4) the torque can be applied to either the coupler link or the proximal phalange. In Fig. 11(7), a three-phalange artificial finger is shown. Through a series combination of a coupled under-actuated multi-bar linkage and a coupled four-bar linkage, the shape-adaptive motion for the second phalange and the natural motion for all the phalanges are provided [70]. The TUAT/Karlsruhe finger (Fig. 11(8)) has the shape-adaptive motion between two first phalanges and the natural motion between two last phalanges. To illustrate, there is no relative motion between the phalanges before any contact with an object. After the first phalange contact, due to being shape-adaptive, the second phalange rotates relative to the first one. Along with the motion of the second phalange, the implemented coupled four-bar linkage makes the distal phalange to rotate [71]. In Fig. 11(9), a series combination of the fingers shown in Figs. 11(2) and 10(4) generate a three-phalange two-DOF prosthesis [72]. Its moving process resembles the finger in Fig. 11(8).

4.3. Three and more DOFs mechanisms

Technical properties of three- and four-DOF mechanisms, shown in Fig. 12, are demonstrated in Table 3. Except for the only actuated 3-DOF finger (Fig. 12(5)), developed by Mu et al., which has three motors with a complicated layout and a parallel combination of three links [73], other mechanisms are under-actuated. The mechanisms of Fig. 12(2), (3), (4), (6), (7),

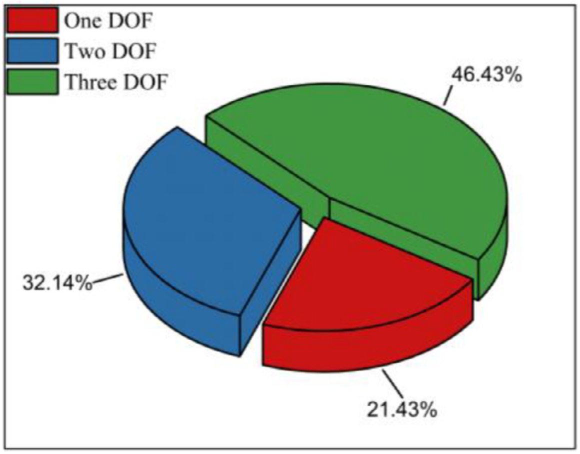

Fig. 13. Distribution of the number of DOFs in the finger mechanisms.

(11),(13) do not have pre-shaping motion meaning that the finger's phalanges remain straight relative to each other before contact with objects, just like Fig. 1. The fingers in Fig. 12(2) and (4) are the three-phalange models of LISA (Fig. 11(3)), an indirect self-adaptive mechanism, and SARAH (Fig. 11(2)), developed by Jin et al. [68] and Laliberte et al. [67] successively. The prostheses in Fig. 12(3), (6), (7) are quite similar to SARAH three-phalange finger (Fig. 12(4)) with some differences. That is shown in Fig. 12(3), developed by Azlan et al., has an extra linear actuator with a micro-motor embedded inside the middle phalange which brings about a shift in distal phalange operation from grasping to pinching. Azlan et al. mentioned that during pinching operation the rotation of the last phalange is in opposite directi-on with the other two phalanges, providing a more suitable configuration of the finger for pinch grasping tasks [34]. Fig. 12(6) depicts a four-DOF mechanism which has a special five-bar linkage enabling it to perform abduction and adduction motions beside a planar mechanism like SARAH finger for flexion and extension [74]. The only difference between Ca.U.M.Ha finger (Fig. 12(7)), developed by Rea et al., and SARAH finger is that it is driven by a crank slider [75]. Fig. 12(11) shows a three-phalange shape-adaptive mechanism without preshaping motion, developed by Gopura et al. [78]. Its resemblance with SARAH finger is also striking. Fig. 12(13) depicts the last three-DOF mechanism without preshaping, analyzed by Khakpour and Birglen [79]. The concept design of this mechanism was first demonstrated in Birglen research [80], providing type synthesis of shape-adaptive finger mechanisms.

As opposed to the preceding 7 mechanisms, others have preshaping alongside being shape-adaptive. Yoon et al. developed a three-phalange artificial finger (Fig. 12(1)) with two five-bar and one coupled four-bar linkage being capable of performing all anthropomorphic movements including natural and shape-adaptive motions [10]. The motion characteristics of the fingers developed by Li et al. (Fig. 12(8)) and Licheng et al. (Fig. 12(10)) are similar to the mechanism presented in Fig. 12(1). Apart from a slight difference in the second phalange of the two mentioned mechanisms, a torsion spring in Fig. 12(8) and a linear spring with a slider in Fig. 12(10), their structure is noticeably similar to each other [76,77]. Fig. 12(9) shows a structurally complicated finger, like Fig. 10(6), comprised three mechanism layers with two linear springs to create natural and shape-adaptive motions for the three phalanges [27]. The last mechanism (Fig. 12(12)) developed by Hirano et al., which is somehow similar to SARAH mechanism, has a particular characteristic. It has the natural motion in the presence of spring 0 and in the spring absence it lacks preshaping motion [28].

5. Discussion

Based on the data demonstrated in Tables 1–3, this section provides information about the general trends of linkage-driven finger mechanisms. Since only one 4-DOF mechanism was revealed in our review of preceding research, in the following figures, the authors labeled the associated fingers in Table 3 as three-DOF mechanisms. It is noteworthy that except the mechanism in Fig. 12(5), others are under-actuated or have one DOF. Most of the obtained linkage-driven mechanisms were developed for research purposes. By this way, the goal is to generate a stronger resemblance *to* the characteristics of human hand in prostheses. This, in turn, might sacrifice some issues such as robustness, weight and simple manufacturing process. Fig. 13 shows that near half of the mechanisms have three DOFs. It means that researchers are inclined to consider three phalanges with individual movements in finger mechanisms. Two-DOF and one-DOF mechanisms include about one third and one fourth of the total number of mechanisms respectively.

In terms of the actual dimension, as Fig. 14 shows, the fingers' lengths usually range from 50 to 140 mm, although more than 80 mm lengths seems to be irregular for fingers of a prosthetic hand. It is clear that, the more the number of DOFs (and consequently more phalanges), the more the actual dimension of the fingers.

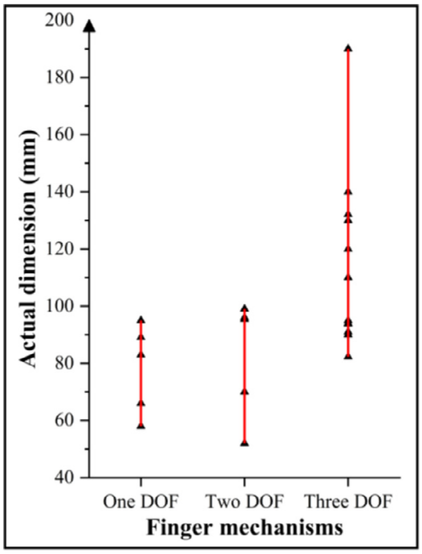

Fig. 14. Actual dimension of the finger mechanisms based on the number of DOFs.

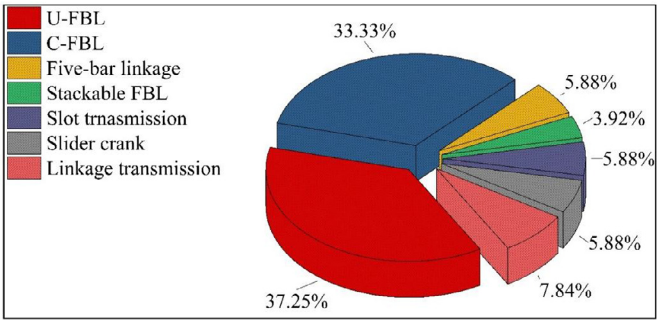

Fig. 15. Distribution of the type of mechanisms in the linkage-driven fingers. U-FBL: Underactuated four-bar linkage, C-FBL: Coupled four-bar linkage.

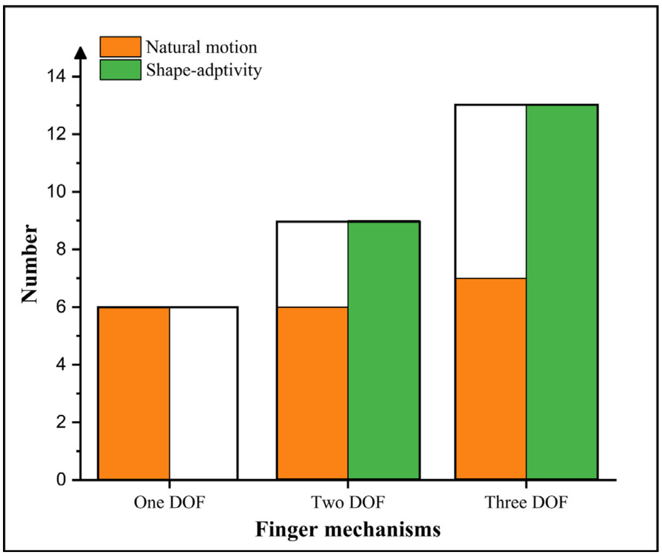

Fig. 16. The number of implemented natural motion and shape-adaptivity in linkage-driven finger mechanisms.

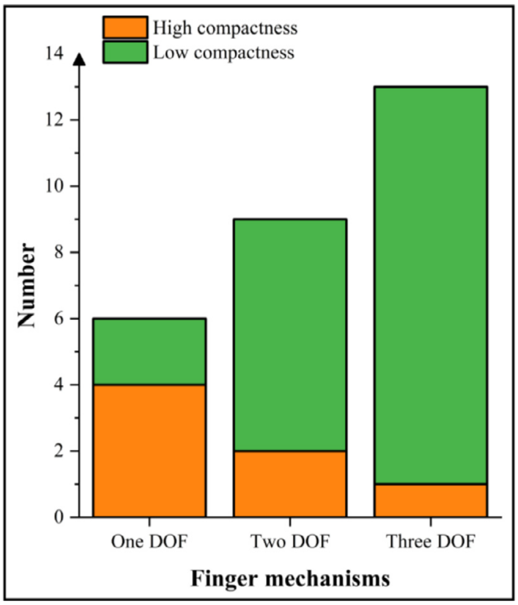

Fig. 17. A comparison of finger mechanisms based on compactness.

Fig. 15 provides information about the type of mechanisms implemented in the studied fingers. As can be seen, the coupled and under-actuated four-bar linkages are widely used in this area, comprising about 33% and 37% of the entire distribution in the pie chart. Other type of mechanisms have been used almost with the same proportion (5%). Coupled and under-actuated four-bar linkages have a noticeable effect on generating natural motion and shape-adaptivity, respectively. As shown in Fig. 16, all the one-DOF fingers have natural motion, which seems to be necessary to compensate the weak grasping performance of one-DOF fingers, particularly in power grasp pattern. Increasing the DOFs of mechanisms, i.e. making the finger shape-adaptive, results in eliminating the natural motion due to complexity growth. However, there are considerable number of fingers with both natural and shape-adaptive characteristics. Such mechanisms are not an appropriate choice for a commercial hand prosthesis. Fig. 17 demonstrates that how increasing the number of DOFs reduces the compactness of the fingers.

6. Conclusion

This paper investigated the mechanical aspects of artificial fingers, being the most important components of bionic hands. After a comprehensive discussion about the performance criteria (which were classified into grasp and physical characteristics), existing linkage-driven artificial fingers were reviewed extensively. It was discovered that implementing a specific feature in a prosthesis structure is a trade-off between anthropomorphism, complexity, dexterity, and user comfort. The usefulness of incorporating a specific characteristic in the mechanism of an artificial finger largely depends on the intended application of the hand. For example, being shape-adaptive would be beneficial in power grasp patterns, while in precision patterns, fully-actuated mechanisms seem to be more successful. In particular, considering the ease of operation and reducing the possibility of ejection phenomenon, it seems that manufacturers of commercial hands prioritize simplicity and robustness in their design.

As a result of the extensive study conducted by the authors, and three years hands on experience in developing the FUM Bionic Hand, the following suggestions and considerations are prescribed:

1.. Defining a particular task for a prosthesis can be advantageous. A prosthesis for daily life tasks is preferred to be simple and robust.
2. In order to carry out precision grasp patterns, single-DOF fingers have preference.
3. In power grasp patterns, shape-adaptive mechanisms perform a more stable grip.
4. Incorporating appropriate mechanical constraints reduces the occurrence of ejection phenomenon in shape-adaptive mechanisms and the subsequent failure in grasp.
5. The more the number of located springs in a mechanism, the more the consumption of battery. Therefore, the designer should opt for fewer springs with low stiffness, albeit to the point of not to undermining the functionality.
6. Developing materials with high strength to density ratio such as carbon fibers have considerable advantages in prostheses area. The limitations of manufacturing a hand by composite materials should be considered in design process.

Declaration of Competing Interest

None.

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