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# Creative mechanism design for a prosthetic hand

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**Abstract:** In this paper, an auxiliary methodology called the creative mechanism design is introduced into the innovation of gripping devices for prosthetic hands. This methodology is a systematic approach based on modification of existing devices for the generation of all possible topological structures of mechanisms and mechanical devices. An existing gripping device (Teh Lin ATG-5F prosthetic hand) constructed by a planar six-bar linkage with one degree of freedom is dealt with by using this methodology. Through the processes of generalization, number synthesis, specialization and particularization for the existing design, five new mechanisms are created in this study to apply to anthropomorphic prosthetic hands. The results show that the methodology for creative mechanism design is a powerful tool for creating new categories of mechanisms to avoid existing designs that have patent protection and can help designers in the conceptual phase. Also, this methodology is validated as a useful way to improve prosthetic hands for amputees.

**Keywords:** prosthetic hand, gripping device, amputee, creative mechanism design, planar linkage, topological structure

## NOTATION

$a, \dots, g$	revolute joint in a mechanism
$F_i$	fingerlike member
$F_l$	floating link
$F_r$	frame link
$In$	input link
$J_R$	generalized revolute joint
$m_{ii}$	diagonal element of the topology matrix
$m_{ik}$	non-diagonal element of the topology matrix
$M_T$	topology matrix
$Th$	thumblike member

## 1 INTRODUCTION

Numerous people worldwide have suffered from amputations due to accidents. Amputees require appropriate prostheses to assist their daily lives. Prosthetic hands are one category of upper limb prostheses that can partially substitute for functions of human hands. To stimulate more functions of prosthetic hands, related research

and development have involved several fields, including medicine, bionics, biomechanics, robotics, electrobiology, biomechanism design, rehabilitation and so on. The biomechanism design for prosthetic hands is usually an important and complex task, especially when the mechanisms attempt to simulate dextrous fingers with multiple joints actuated. In contrast to the design of dextrous digit mechanisms, the more practical and easily manipulated design in the marketplace for amputees may be gripping devices, which are mainly constructed by mechanisms with one degree of freedom [1–11].

A gripping device for a prosthetic hand usually consists of a thumblike member and at least one fingerlike member to grip an object, which are primarily driven by several types of mechanical element, such as worm and worm gears [1], cables or tendons [2–5] and linkages [6–11]. For these, planar four-bar linkages [6–10] and six-bar linkages [11] are frequently adopted, which are lighter than gears and have more accurate motion transmissibility and rigidity than cables and tendons. For realistic imitation of human finger motions when the prosthetic hand is gripping, the thumblike and fingerlike members are further designated as multiple joints [2–5, 12–15] or can be driven individually [12, 15, 16]. Guo *et al.* [13] applied a six-bar linkage with one degree of freedom to form an anthropomorphic three-jointed finger mechanism with dimensional optimization. Dechev *et al.* [14] used a four-bar linkage and a six-bar linkage,

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both with one degree of freedom, to form the thumb and finger mechanisms respectively to construct an experimental child-sized prosthesis called the TBM hand. Moreover, to ensure that the gripping devices can adaptively and firmly hold the object within the hand and be non-backdrivable, several mechanical and electric devices are employed to lock the gripping devices after the object is gripped. Mechanisms such as gear trains [1], detent means and electromagnets [6], friction planetary drives and backlocks [7], non-backdrivable ultrasonic motors [8] and brakes [10] are applied to lock the gripping devices.

As seen in the survey of current patents and research concerning prosthetic hands, the practical designs for prostheses to replace the hand and the forearm of an amputee must satisfy as many functional requirements as possible:

1. A fundamental gripping device, consisting of at least a thumblike member and a fingerlike member to perform the gripping, grasping and holding actions of a human hand, must be provided. An important design concept of the gripping device is the use of a linkage mechanism with one degree of freedom to perform the relative motion between the thumblike member and the fingerlike member [6–11].
2. The digitlike members must be dextrous and have multiple applications; that is, the prosthetic hands should have at least two gripping forms to allow wider usage. Several developed dextrous prosthetic hands and their corresponding drive means are able to achieve this objective [12, 15, 16]. Nevertheless, these designs might be difficult to use as a human auxiliary prosthesis nowadays owing to the complications of the manipulative process and the arrangement of the command interface, which may contribute to the higher production cost. In particular, when the prosthetic hand is designated as a multi-degree-of-freedom mechanism, amputees may encounter difficulties in manipulating the actuators by their EMG signals.
3. When the gripping device touches an object and then holds it in the palm, the thumblike and fingerlike members must be locked at the instantaneous configuration to prevent the object from dropping to the ground by gravity. Several patents have involved mechanical and electric devices characterized by numerous assemblies to lock the gripping configuration [1, 6–8, 10].

The purpose of the present paper is to demonstrate a systematically innovative procedure for the fundamental gripping devices for prosthetic hands by using an auxiliary methodology called the creative mechanism design [17–21]. The methodology for creative mechanism design, mainly proposed by Yan [20, 21], is a systematic approach based on modification of existing devices for

the generation of all possible topological structures of mechanisms and mechanical devices. It is helpful to designers in the conceptual phase. An existing design that has patent protection can be avoidable by using the creative mechanism design. In the following sections, several new fundamental gripping devices are generated from an existing patent [11] (ROC Patent 323509) by using the methodology for creative mechanism design step by step. The design results in this paper should support the concept that the systematically innovative procedure is practical for improvements in human prostheses.

## 2 DESIGN METHODOLOGY

The flow chart of the design methodology for creative mechanism design is shown in Fig. 1 [21], where the design steps are demonstrated as follows:

- Step 1.* Identify available existing designs to determine the specifications and topological characteristics that designers or users would prefer.
- Step 2.* Arbitrarily select an existing design and transform the original mechanism to its generalized kinematic chain with only links and revolute joints.
- Step 3.* Employ the number synthesis algorithm to derive an atlas of generalized kinematic chains that have the same numbers of links and joints as that obtained in the second step.
- Step 4.* Assign types of links and joints to each generalized kinematic chain to meet arbitrary design requirements and constraints, to obtain the feasible specialized kinematic chains.
- Step 5.* Particularize each feasible specialized kinematic chain into its corresponding schematic format of mechanism.
- Step 6.* Identify existing designs from the atlas of feasible mechanisms, to remove the original mechanism and obtain new designs.

The six steps of the methodology shown in Fig. 1 for the gripping device are illustrated in the following sections in detail.

## 3 EXISTING MECHANISM

A majority of practical designs for prosthetic hands and gripping devices involve a planar four-bar linkage to perform the relative motion between the thumblike member and the fingerlike member [6–10]. The generation of the relative motion between the two members is regarded as a function generation problem in the field of kinematic synthesis of linkage mechanisms [22, 23]. Since the four-bar linkage is limited in its design parameters,

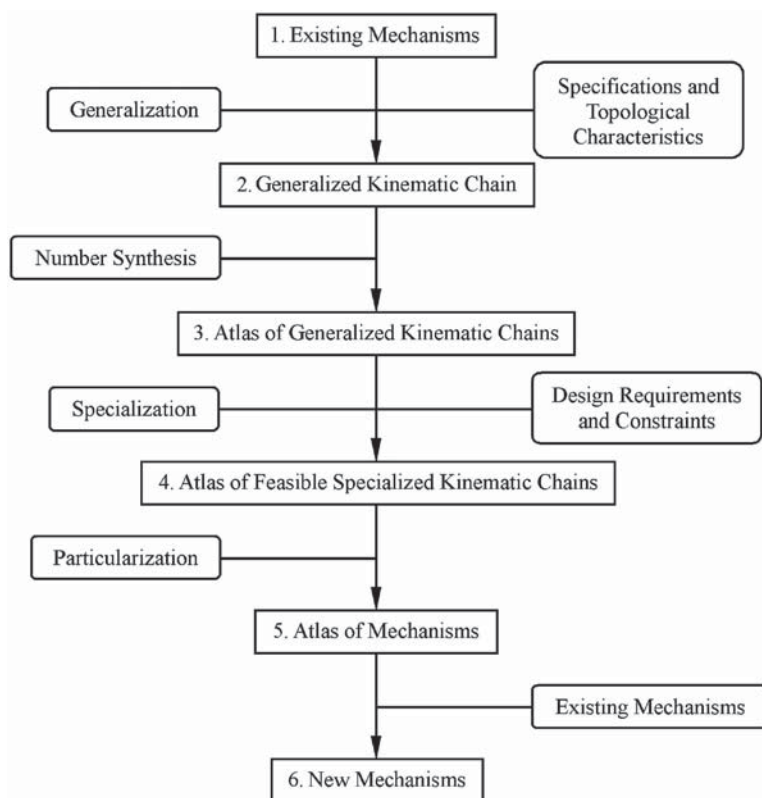


Fig. 1 Flow chart of the design methodology for creative mechanism design

the number of Chebyshev precision points [22] is also limited. An alternative selection is to adopt a planar six-bar linkage for prosthetic hands to increase the number of Chebyshev precision points, such as the Teh Lin ATG-5F prosthetic hand shown in Fig. 2a. The Teh Lin ATG-5F prosthetic hand is a realized product of the conceptual design in an existing patent [11] (ROC Patent 323509). A sketch of its mechanism and exploded assemblies are shown in Figs 2b and c respectively.

By analysing Fig. 3, the kinematic diagram of the existing design (Fig. 2), the characteristics of the Teh Lin ATG-5F prosthetic hand can be summarized as follows:

1. It is a planar mechanism with one degree of freedom.
2. It consists of six members and seven joints.
3. It has seven revolute joints (joints *a* to *g*;  $J_R$ ).
4. It has one frame link (member 1; Fr).
5. It has one frame-pivoted link as the input link actuated by a motor (member 2; In).
6. It has one frame-pivoted link as the thumblike member (member 3; Th).
7. It has one frame-pivoted link as the fingerlike member (member 4; Fi).
8. It has two floating links (members 5 and 6; Fl).

The topological structure of this six-bar prosthetic hand can be represented by its topology matrix,  $M_T$  [20, 21],

that is

$$M_T = \begin{bmatrix} Fr & J_R & J_R & J_R & 0 & 0 \\ a & In & 0 & 0 & J_R & 0 \\ b & 0 & Th & 0 & J_R & J_R \\ c & 0 & 0 & Fi & 0 & J_R \\ 0 & d & e & 0 & Fl & 0 \\ 0 & 0 & f & g & 0 & Fl \end{bmatrix} \quad (1)$$

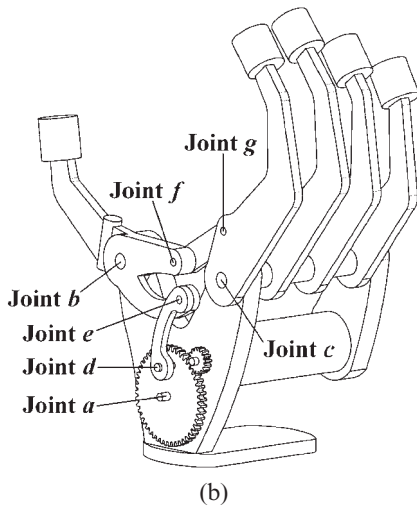
The  $M_T$  of the mechanism with six links is a  $6 \times 6$  matrix. The diagonal element  $m_{ii}$  represents the type of link *i*. If link *i* is adjacent to link *k*, non-diagonal element  $m_{ik}$  on the upper right represents the joint incident to links *i* and *k*, and that on the lower left represents the name of the joint. If link *i* is not adjacent to link *k*, then  $m_{ik}$  is zero.

#### 4 GENERALIZED KINEMATIC CHAIN

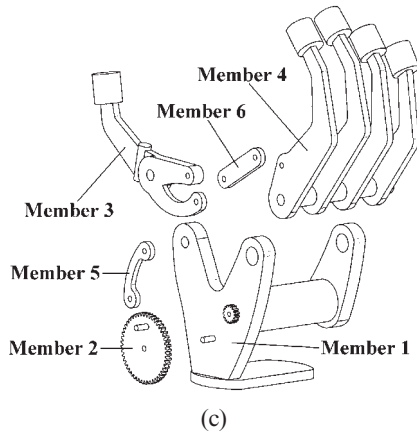
The existing six-bar prosthetic hand is selected as the original design, which is then transformed into its corresponding generalized kinematic chain. The principles of generalization are based on the following conditions [21]:



(a)



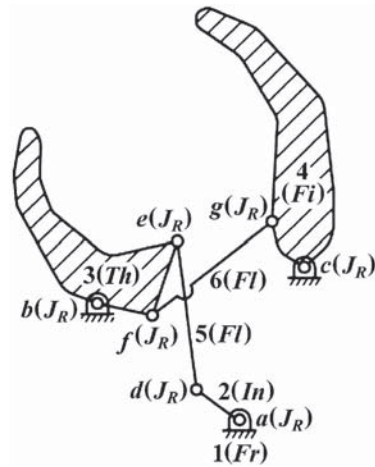
(b)



(c)

**Fig. 2** (a) Teh Lin ATG-5F prosthetic hand (courtesy of Teh Lin Prosthetic and Orthopaedic Incorporated), (b) sketch of the mechanism of the prosthetic hand shown in (a), and (c) exploded assemblies of the mechanism shown in (b)

1. All joints between members of a mechanism are transformed into revolute joints.
2. All members of a mechanism are transformed into generalized links, such as a binary link, ternary link, quaternary link and so on.



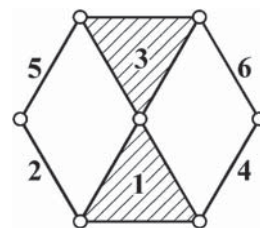
**Fig. 3** Generalization of the existing mechanism

3. The topological incidence and adjacency among members and joints of a mechanism and its corresponding generalized kinematic chain should be the same.
4. The number of degrees of freedom for a mechanism and its corresponding generalized kinematic chain should be the same.

Through this process, the generalization of the original mechanism shown in Fig. 3 is carried out as follows:

1. The frame link (member 1) is generalized into a ternary link (link 1).
2. The input link (member 2) is generalized into a binary link (link 2).
3. The thumblike member (member 3) is generalized into a ternary link (link 3).
4. The fingerlike member (member 4) is generalized into a binary link (link 4).
5. The floating links (members 5 and 6) are generalized into binary links (links 5 and 6).
6. The frame link is released.

Hence, the original mechanism is transformed into a generalized kinematic chain with six links and seven revolute joints, as shown in Fig. 4, which is the well-known Watt chain.



**Fig. 4** Generalized kinematic chain

## 5 ATLAS OF GENERALIZED KINEMATIC CHAINS

The purpose of this step is to synthesize all possible kinematic chains that have the same numbers of degrees of freedom, links and joints as the generalized kinematic chain shown in Fig. 4. The number synthesis algorithm [24] can be employed in this step to derive an atlas of generalized kinematic chains. Since the generalized six-link chain is the Watt chain, it is well known that the other six-link chain to satisfy the goal of this step is the so-called Stephenson chain [25]. The Watt and Stephenson chains are all possible categories of six-link chains with one degree of freedom. Thus, the atlas of generalized kinematic chains with six links and seven joints is shown in Fig. 5.

## 6 ATLAS OF FEASIBLE SPECIALIZED KINEMATIC CHAINS

This step must be the key to the whole methodology for creative mechanism design. The arbitrary design requirements and constraints determined on the basis of the topological structure of the existing mechanisms or the designer's judgement are taken into account in the atlas of generalized kinematic chains to obtain the non-isomorphic feasible specialized kinematic chains. Specific types of links and joints in the atlas of generalized kinematic chains are assigned to satisfy the arbitrary design requirements and constraints.

For prosthetic hands, the design requirements and constraints are as follows:

1. There must be a frame link.
2. There must be an input link adjacent to the frame link, which would be actuated by a motor fixed on the frame link.
3. There must be a thumblike member adjacent to the frame link.
4. There must be a fingerlike member adjacent to the frame link.
5. The frame link, the input link, the thumblike member and the fingerlike member must be distinct members.

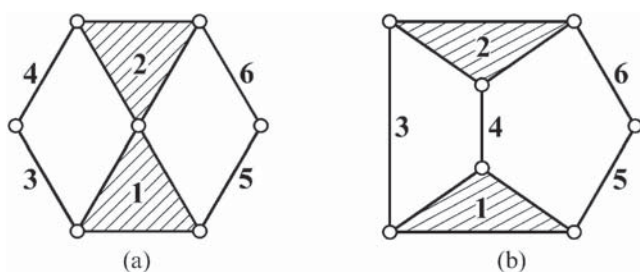


Fig. 5 Atlas of generalized kinematic chains with six links and seven joints

Accordingly, the results of assigning frame link, input link, thumblike member and fingerlike member to the two kinematic chains shown in Fig. 5 are listed step by step.

### 6.1 Frame link (Fr)

For the kinematic chain shown in Fig. 5a, the assignment of the frame link generates two non-isomorphic results shown in Figs 6a and b. For the kinematic chain shown in Fig. 5b, the assignment of the frame link generates three non-isomorphic results shown in Figs 6c to e. Figure 6 shows the five inversions of the six-bar chain with one degree of freedom.

### 6.2 Input link (In)

For the kinematic chain shown in Fig. 6a, the assignment of the input link generates two non-isomorphic results shown in Figs 7a and b. For the kinematic chain shown in Fig. 6b, the assignment of the input link also generates two non-isomorphic results shown in Figs 7c and d, since both the binary and ternary links adjacent to the frame link can be selected reasonably. For the kinematic chain shown in Fig. 6c, the assignment of the input link generates two non-isomorphic results shown in Figs 7e and f. For the kinematic chain shown in Fig. 6d, only one of the ternary links adjacent to the frame link can be assigned as the input link (see Fig. 7g). For the kinematic chain shown in Fig. 6e, the assignment of the input link generates two non-isomorphic results shown in Figs 7h and i, since both the binary and ternary links adjacent to the frame link can be selected reasonably.

### 6.3 Thumblike member (Th)

For the kinematic chain shown in Fig. 7a, the assignment of the thumblike member generates two non-isomorphic results shown in Figs 8a and b. For the kinematic chain shown in Fig. 7b, the assignment of the thumblike member generates only one non-isomorphic result shown in Fig. 8c. For the kinematic chains shown in Figs 7c and d, only one link adjacent to the frame link can be assigned as the thumblike member in each chain, the results of which are shown in Figs 8d and e respectively. For the kinematic chain shown in Fig. 7e, the assignment of the thumblike member generates two non-isomorphic results shown in Figs 8f and g. For the kinematic chain shown in Fig. 7f, only one of the binary links adjacent to the frame link can be assigned as the thumblike member (see Fig. 8h). For the kinematic chain shown in Fig. 7g, only the ternary link adjacent to the frame link can be assigned as the thumblike member (see Fig. 8i). For the kinematic chains shown in Figs 7h and i, only

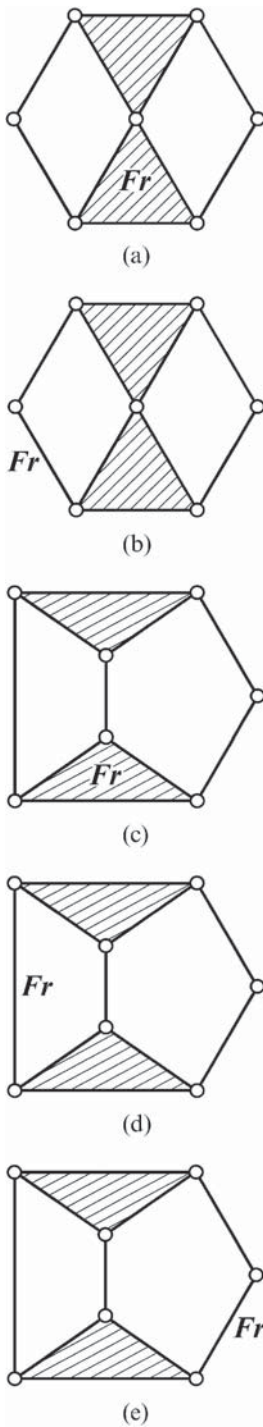


Fig. 6 Specialized kinematic chains with a frame link

one link adjacent to the frame link can be assigned as the thumblike member in each chain, the results of which are shown in Figs 8j and k respectively.

6.4 Fingerlike member (Fi)

The last step in specialization for the prosthetic hands is to assign the fingerlike member for the kinematic chains shown in Fig. 8. Since the fingerlike member must

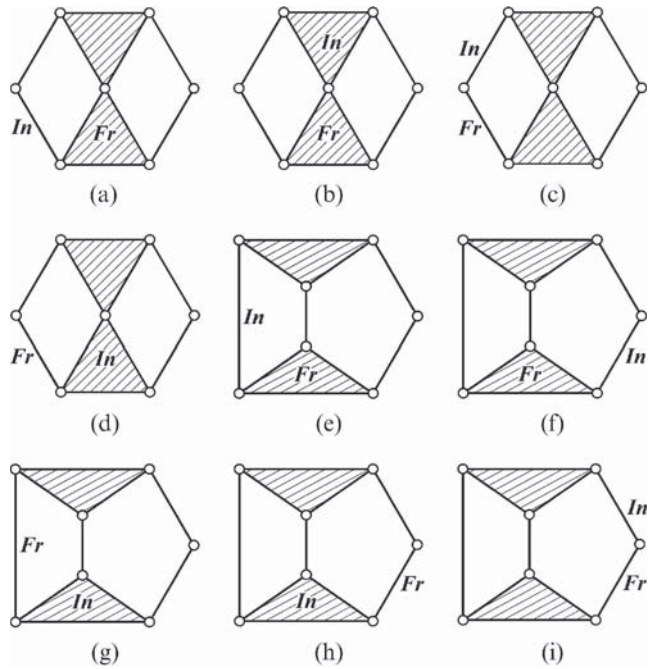


Fig. 7 Specialized kinematic chains with a frame link and input link

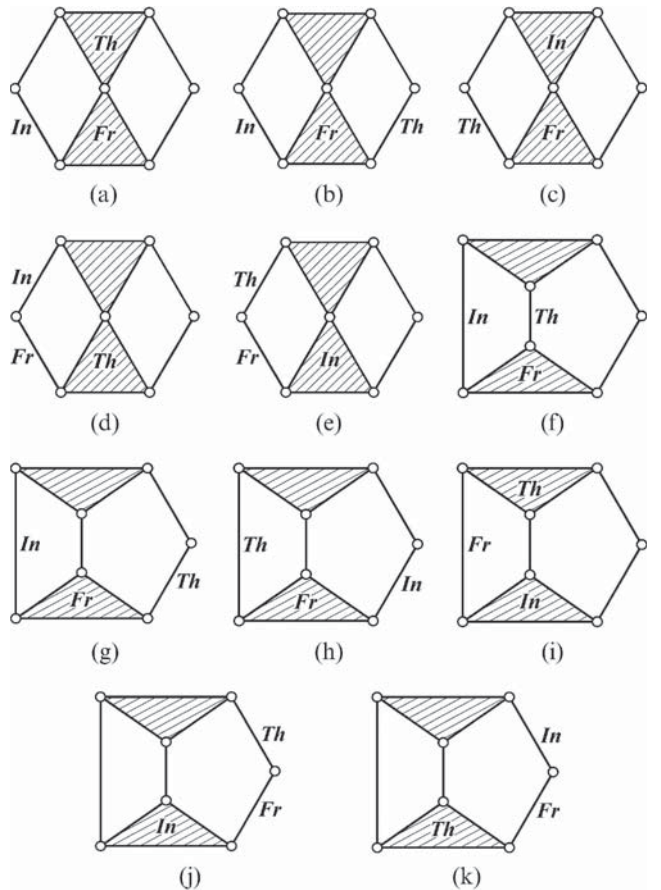


Fig. 8 Specialized kinematic chains with a frame link, an input link and a thumblike member

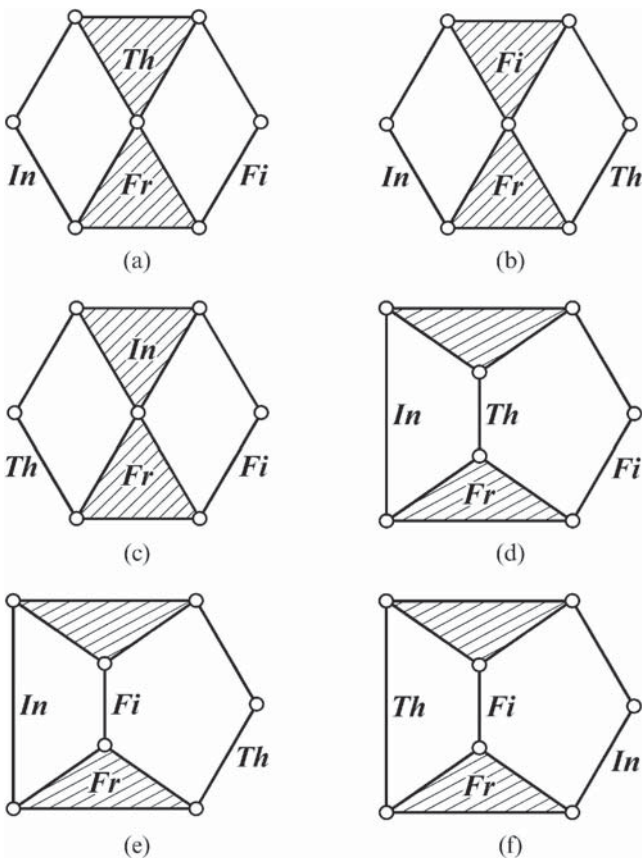
be adjacent to the frame link, the kinematic chains without any unassigned link adjacent to the frame link shown in Fig. 8 can be removed. Hence, the kinematic chains shown in Figs 8d, e, i, j and k are eliminated. For the residual kinematic chains shown in Figs 8a, b, c, f, g and h, the assignment of the fingerlike member generates six non-isomorphic results shown in Figs 9a to f respectively, which are the feasible specialized kinematic chains confirmed to the design requirements and constraints.

**7 ATLAS OF MECHANISMS**

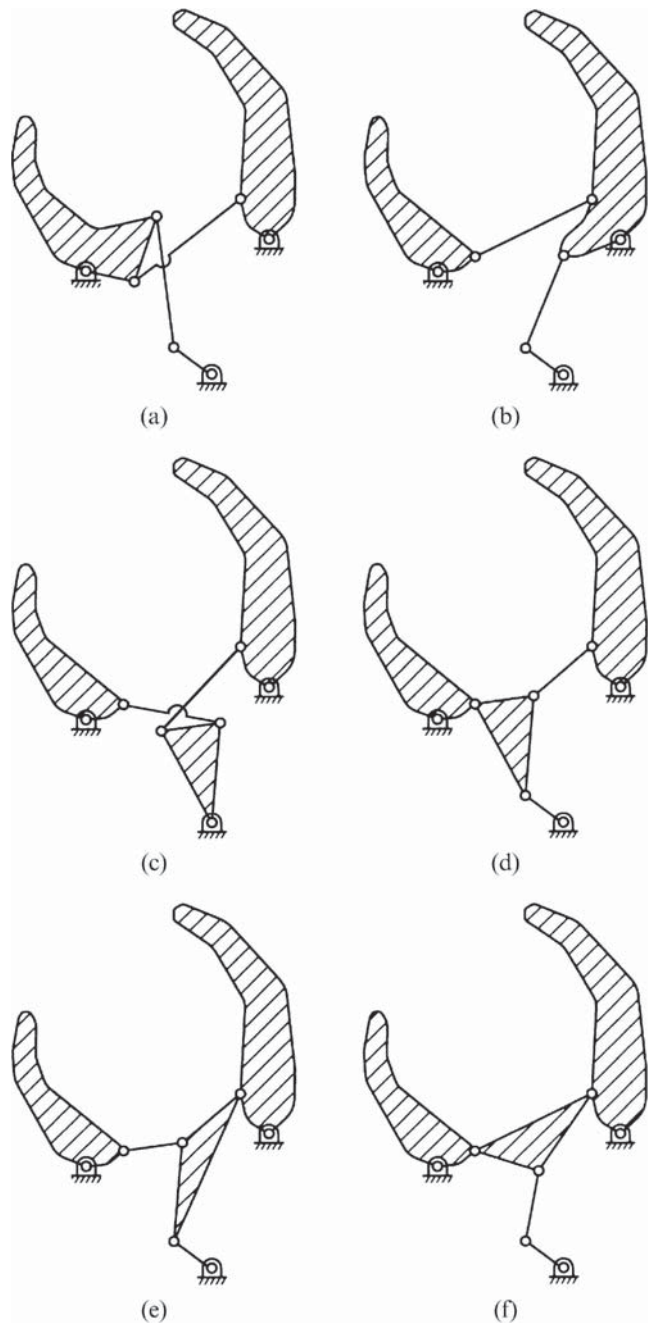
In this step, each feasible specialized kinematic chain is particularized into its corresponding mechanism in a skeleton drawing. A reverse process of generalization is performed by employing the generalizing rules backwards [20, 21]. For the six feasible specialized kinematic chains shown in Figs 9a to f, their corresponding mechanisms are shown in Figs 10a to f respectively.

**8 NEW MECHANISMS**

The final step of the design methodology is to identify the new mechanisms from the atlas of mechanisms by removing the original designs. The residual mechanisms



**Fig. 9** Atlas of feasible specialized kinematic chains

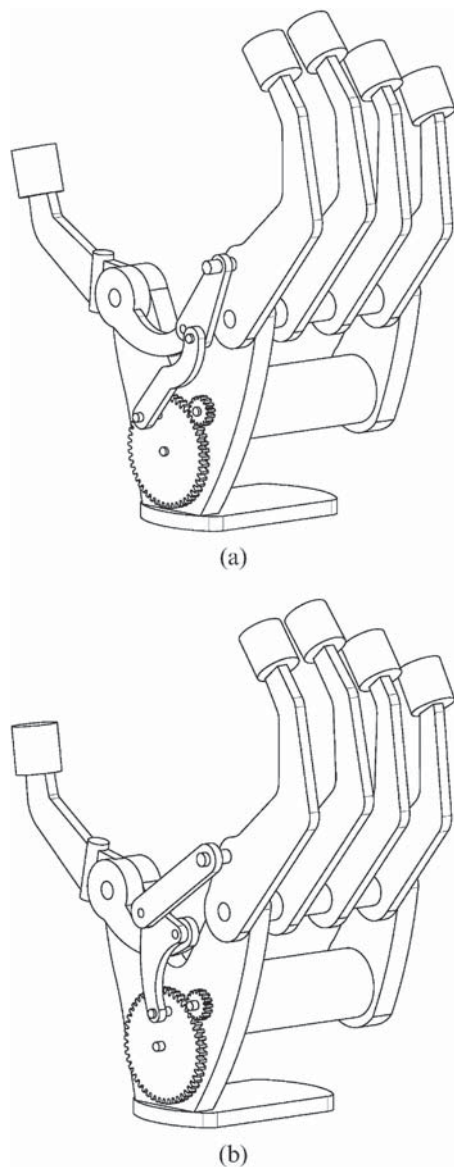


**Fig. 10** Atlas of mechanisms

can be claimed for patents or applied to the embodiment phase.

For the six mechanisms shown in Fig. 10, that in Fig. 10a is the Teh Lin ATG-5F prosthetic hand, i.e. the original design. Therefore, five new categories of six-bar prosthetic hands for amputees are obtained, as shown in Figs 10b to f. The mechanisms shown in Figs 10d and f have been submitted and claimed for parts of conceptual designs for Chinese patent applications by the authors [26, 27], and sketches of the corresponding embodiment gripping devices are shown in Fig. 11.





**Fig. 11** (a) Sketch of the embodiment gripping device shown in Fig. 10d, and (b) sketch of the embodiment gripping device shown in Fig. 10f

## 9 CONCLUSIONS

A systematic design methodology called the creative mechanism design has been introduced to generate new concepts of fundamental gripping devices for prosthetic hands. Through the processes of generalization, number synthesis, specialization and particularization for an existing design (the Teh Lin ATG-5F prosthetic hand), five new mechanisms have been created in this study to apply to anthropomorphic gripping devices. The most important step in this methodology is the fourth step, which is to determine the arbitrary design requirements and constraints by designers to obtain the feasible specialized kinematic chains. Different design require-

ments and constraints for an existing design may contribute to entirely different design results. Two of the five created mechanisms have been submitted and claimed for parts of conceptual designs for patents by the authors. This methodology can help designers as an effective tool to create new categories of mechanisms to avoid existing designs that have patent protection. Also, this methodology is validated as a useful way to improve prosthetic hands for amputees.

Performance analysis and dimensional optimization of the five created mechanisms will be the subjects of subsequent studies. In addition, improvement and innovation for the dextrous finger mechanisms and locking devices mentioned in the introduction will be topics of further investigation.

## ACKNOWLEDGEMENT

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