A Novel Design Method of Anthropomorphic Prosthetic Hands for Reproducing Human Hand Grasping

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***Abstract*—Because hand is often used for grasping, developing a design of prosthetic hands, particularly light and compact underactuated anthropomorphic transradial prostheses for reproducing human hand complex grasping is crucial for upper-limb amputees. Obviously, the less the number of actuators is, the worse the anthropomorphic motion capability of the prosthetic hands will be. This paper aims to design a transmission mechanism with few motors actuating fingers which could serve the relatively accurate grasp movement of a human hand and has the potential to be embedded in a palm including the motors. We start with establishing an index for evaluating the anthropomorphic motion capability of a prosthetic hand. Based on the optimization of this index, we determine the number of actuators in fingers and the transmission relationship between the actuators and the metacarpophalangeal(MCP) joints. Then, a new design method to mechanically implement the transmission relationship based on a novel decomposition of transmission matrix is proposed in this paper. Utilizing this method, we obtained the final mechanical structure of a new prosthetic hand.**

I. Introduction

Hand is used for grasping at the most time in everyday life[1]. For upper-limb amputees, regenerating a hand which not only has the same grasping functions with a real human hand but also reproduces the anthropomorphic grasping movements has been looked forwarded for a long time. But for researchers, to design this kind of prosthetic hands, especially underactuated transradial prostheses, is a big challenge. Previous research pays more attention to functions of a prosthetic hand, usually ignores the hand posture or motion accuracy generated by human. From the view of grasp functions, the thumb is to opposite the fingers and plays an important role in grasping stability. From the statistical investigation of nature human hand movement [2], the thumb is the most independent of the digits. This means that the mechanisms of the thumb and the fingers of the anthropomorphic prosthetic hand could be designed separately. The thumb is designed with two actuators embedded in a palm—one for abduction/adduction, the other for flexion/extension—to generate the human thumb motion and the final grasp stability in this paper. The limitation of the rest palm space requires embedding as few actuators as possible to drive the fingers. However, the design of fingers which can perform the accurate hand posture and motion with both actuators and transmission mechanism embedded in the rest of strict palm space is really challenging.

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As we have designed a kind of compliant underactuated fingers with the inter-finger joints linear coupled before contacting objects [3], the metacarpophalangeal(MCP) joints could be considered as the actuating joints, and this paper focus on the design method of the transmission mechanism connecting the actuators with the MCP joints, especially the MCP joints of fingers for reproducing the human MCP joints movements which reflects the characteristic of the human fingers' movement during grasping.

A common design method is to group the fingers with each group actuated by one motor through a transmission mechanism based on the independence among fingers [4-10]. This kind of prosthetic hand has the ability to achieve several typical grasp functions with a light, compact palm structure close to human. The main disadvantage of this method is ignoring the truly human hand motion during grasping and restriction to limited grasp types.

Another interesting design method [11-14] called hardware synergy or adaptive synergy is based on the term synergy from the biomechanical concept. It means that a minimal number of linearly independent elements under specific operations can generate all members of the given set [14], namely, the motion set of different grasp types. Actually, previous research has discovered the existence of posture synergy in several common grasp postures [15]. And the similar phenomenon of synergy also exists in continual motion patterns. So this method makes it possible for a prosthetic hand to reproduce the human hand motion during grasping, involving a mechanical implementation of few input and multiply output transmission matrix. However, as the complex relationship between the actuators and the joints, the mechanical implementation is difficult, and often causes bulky in the mechanical structure so that it is hardly suitable for the strict palm space of a self-contained prosthetic hand.

In this paper, we start with extracting human hand grasping data, presenting a method for selecting the best number of actuators to reproduce the human hand grasping, especially the motion of the fingers. A new design method of mechanically implementing a double input and multiply output transmission matrix is proposed: firstly decompose the transmission matrix into two matrices; secondly design the geometrical constraints based on the characters of the decomposed matrices; finally generate mechanisms from the geometrical constraints and connect them. Utilizing this method, the final mechanical structure including two actuators could be designed and have the potential to be embedded in a prosthetic palm leaving space for the motors of the thumb.

II. The Determination of the Actuator Numbers in Fingers

Before developing the design of an underactuated transradial prosthesis for reproducing human hand grasping, we must answer the following questions: how many actuators for the fingers at least can realize accurate human hand grasping? To reproduce the accurate human grasping, what is the transmission relationship between the actuators and the metacarpophalangeal(MCP) joints ?

In this section, we firstly collect the human hand grasping data, then establish an index for evaluating the anthropomorphic motion capability of an underactuated prosthetic hand, finally obtain the number of actuators and the transmission relationship between the actuators and the metacarpophalangeal (MCP) joints.

A. Acquisition of human hand grasping data

We choose 33 grasp types based on the grasp taxonomy proposed by Feix [16] and record one grasp sequence in a grasp type with the grasped object as small as possible for the grasp pattern so that the grasp motion is obvious. A commercial hand motion recording system CyberGlove was used to sample the movement data of n MCP joints every 0.02 s during each grasp and finally we gain T observations from 33 different sequences in total. Each grasp started from the same initial posture with fingers fully extended to the final stable grasp.

B. Index for evaluating the anthropomorphic motion capability of a prosthetic hand

Let n denotes the number of MCP joints, s the number of actuators and T the number of observations from the motion sequence. The constraint $s \le n < T$ must be satisfied. Then we define the matrix $\mathbf{Q} \in \Re^{n \times T}$ representing the set of human hand motion acquired before and the matrix $\tilde{\mathbf{Q}} \in \Re^{n \times T}$ represents the set of underactuated prosthetic hand motion when performing the same grasp pattern as a human hand.

The matrix $\boldsymbol{\sigma} \in \Re^{s \times T}$ represents the driving signal of the actuators. The matrix $\mathbf{S} \in \Re^{n \times s}$ is a transmission matrix which represents the relationship between the actuators and MCP joints, and relates the matrix $\tilde{\mathbf{Q}}$ and $\boldsymbol{\sigma}$:

$$\tilde{\mathbf{Q}} = \mathbf{S}\boldsymbol{\sigma} \tag{1}$$

Assuming the matrix $\mathbf{S}$ is column full rank and $\boldsymbol{\sigma}$ is row full rank, we can reach the following conclusion based on the properties of the rank:

$$Rank(\tilde{\mathbf{Q}}) = Rank(\boldsymbol{\sigma}) = s \tag{2}$$

As the motion of metacarpophalangeal joints reflects the characteristic of the fingers' movement, the following index was defined as a means for evaluating anthropomorphic motion capability of a prosthetic hand:

$$Err = \left\|\mathbf{Q} - \tilde{\mathbf{Q}}\right\|_F^2 \Big/ \left\|\mathbf{Q}\right\|_F^2 = \sum_{i=1}^{n}\sum_{j=1}^{T}\left|q_{ij} - \tilde{q}_{ij}\right|^2 \Big/ \sum_{i=1}^{n}\sum_{j=1}^{T}\left|q_{ij}\right|^2 \tag{3}$$

where Err represents the relative error of the joint movement between human and prosthetic hand. The smaller Err is, the better the anthropomorphic motion capability of the prosthetic hand will be. Naturally, it is necessary to explore a way to maximize the anthropomorphic motion capability of the prosthetic hand with a given number of actuators.

It is actually an index optimization problem. Equation (2) indicates that the rank of matrix $\tilde{\mathbf{Q}}$ equals to the number of actuators s. The matrix $\mathbf{Q}$ can be rewritten as follows by singular value decomposition:

$$\mathbf{Q} = [\mathbf{u}_1 \mathbf{u}_2 \cdots \mathbf{u}_r]\operatorname{diag}\{\lambda_1, \lambda_2, \cdots, \lambda_r\}[\mathbf{v}_1 \mathbf{v}_2 \cdots \mathbf{v}_r]^T \tag{4}$$

where $\mathbf{u}_i \in \Re^{n \times 1}, i = 1, 2, \cdots, r$, $\lambda_1 \ge \lambda_2 \ge \cdots \ge \lambda_r$ is the singular values of matrix $\mathbf{Q}$, $\mathbf{v}_j \in \Re^{T \times 1}, j = 1, 2, \cdots, r$, $s \le r \le n < T$.

According to (2), the rank of matrix $\tilde{\mathbf{Q}}$ is equal to the number of actuators s. when the matrix $\tilde{\mathbf{Q}}$ satisfies the following relationship:

$$\tilde{\mathbf{Q}} = \sum_{i=1}^{s} \lambda_i \mathbf{u}_i \mathbf{v}_i^T \tag{5}$$

We can conclude that the index Err reaches the minimum which could be defined as the minimum relative error $Errmin$:

$$Errmin = 1 - \sum_{i=1}^{s} \lambda_i^2 \Big/ \sum_{j=1}^{n} \lambda_j^2 \tag{6}$$

This conclusion has been proved by Eckart and Young[17] in the early time. It means that if a prosthetic hand with s actuators driving 4 fingers serves all the movements that generated by the matrix $\tilde{\mathbf{Q}}$, the anthropomorphic motion capability of the prosthetic hand will reach maximization with the given number of actuators. $Errmin$ quantitatively evaluates the anthropomorphic motion capability between fingers of a prosthetic hand with s actuators.

C. Determining the number of actuators

As we pay attention to the design of transmission mechanism between fingers in this paper, that is, $n = 4$ in (4). Based on the conclusion before, utilizing the collected data of actual human MCP joints, we can obtain the minimum relative error $Errmin$ under s actuators, and essentially s is the rank of matrix $\tilde{\mathbf{Q}}$, as Fig.1. The acquisition of $Errmin$ in Fig.1 is just from mathematical model shown before. And we want to show the best anthropomorphic motion capability between fingers of a prosthetic hand under s actuators in theory. Note that if

$s=0$, it means that there is no actuator driving the fingers, and matrix $\tilde{\mathbf{Q}}$ can be considered as a null matrix. So $Errmin$ equals to 1 under $s=0$. Moreover, we intuitively show the motion sequence acquired from actual human hand and generated by s actuators under the situation of (6) in Fig.2 simultaneously. Actually, the motion sequence generated by s actuators is from the matrix $\tilde{\mathbf{Q}}$.

In Fig.1, the blue imaginary line shows a trend of rapidly decrease. When $s \geq 2$, $Errmin$ is quite small and tends stable. Fig.2 intuitively shows that there are still many movements that could not be reproduced by choosing one actuator with $s=1$, However, the actual motion sequence could be exactly followed by the generated motion sequence with $s=2$. It means that two number actuators may be a choice for the four fingers of a prosthetic hand to mimic the movement of a human hand, and on this basis, adding the number of actuators will not significantly improve the anthropomorphic motion capability between 4 fingers of a prosthetic hand.

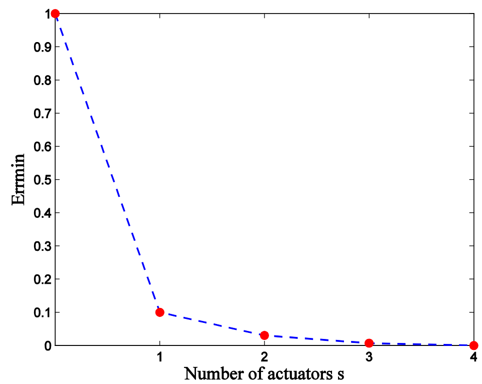


Figure 1. The relationship between relative error $Errmin$ and the number of actuators s. $Errmin$ is acquired from the mathematic model shown in section II -B, and s is the rank of matrix $\tilde{\mathbf{Q}}$. The red points present the values of $Errmin$ under s actuators. The blue imaginary line shows the trend.

Combining (1) and (4) with $s=2$, we can set up the following relationship to realize the best anthropomorphic motion capability of the prosthetic hand, and the matrices $\mathbf{S}$ and $\boldsymbol{\sigma}$ are obtained from the data of actual human hands:

$$\mathbf{S}=k[\lambda_1\mathbf{u}_1\ \lambda_2\mathbf{u}_2],\quad \boldsymbol{\sigma}=\frac{1}{k}[\mathbf{v}_1\,\mathbf{v}_2]^T \tag{7}$$

where k is a scaling factor that making matrix $\mathbf{S}$ and $\boldsymbol{\sigma}$ practically meaningful.

III. Mechanical Implementation of Transmission Matrix

Based on the analysis before, we can conclude that a prosthetic hand with 2 actuators driving 4 fingers could correctly reproduce the actual motion generated by human MCP joints motion in theory, but in practical, mechanically implementing the transmission matrix $\mathbf{S}$ with both actuators and mechanism embedded in the palm is still challenging. Actually, it's a problem of designing a double-input and four-output transmission mechanism.

Many researchers [11-14] have tried different ways to solve this problem. Many mechanisms are designed and provide significant reference to the design of artificial hands. But there is no mechanism designed for transradial prostheses which demand stricter palm space and weight. From the mathematical perspective of mechanical implementation, they choose the way of mechanically implementation of every column of the transmission matrix, and adding them up. This method of mechanical implementation usually leads to mechanical complexity and hardly applied to the design of prosthetic hands especially transradial prostheses. In this section, we propose a novel method of mechanical implementation different from the previous ways in the mathematical views and well applied in the design of the transradial prostheses.

A. Decomposition of transmission matrix

As we have obtained the number of actuators $s=2$, the transmission matrix $\mathbf{S}$ could be decomposed as:

$$\mathbf{S}=\begin{bmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \\ s_{31} & s_{32} \\ s_{41} & s_{42} \end{bmatrix}=\begin{bmatrix} s_{11}+s_{12} & & & \\ & s_{21}+s_{22} & & \\ & & s_{31}+s_{32} & \\ & & & s_{41}+s_{42} \end{bmatrix}\begin{bmatrix} \frac{s_{11}}{s_{11}+s_{12}} & \frac{s_{12}}{s_{11}+s_{12}} \\ \frac{s_{21}}{s_{21}+s_{22}} & \frac{s_{22}}{s_{21}+s_{22}} \\ \frac{s_{31}}{s_{31}+s_{32}} & \frac{s_{32}}{s_{31}+s_{32}} \\ \frac{s_{41}}{s_{41}+s_{42}} & \frac{s_{41}}{s_{41}+s_{42}} \end{bmatrix} \tag{8}$$

Let

$$\mathbf{D}=\begin{bmatrix} s_{11}+s_{12} & & & \\ & s_{21}+s_{22} & & \\ & & s_{31}+s_{32} & \\ & & & s_{41}+s_{42} \end{bmatrix},\mathbf{S}^{'}=\begin{bmatrix} \frac{s_{11}}{s_{11}+s_{12}} & \frac{s_{12}}{s_{11}+s_{12}} \\ \frac{s_{21}}{s_{21}+s_{22}} & \frac{s_{22}}{s_{21}+s_{22}} \\ \frac{s_{31}}{s_{31}+s_{32}} & \frac{s_{32}}{s_{31}+s_{32}} \\ \frac{s_{41}}{s_{41}+s_{42}} & \frac{s_{41}}{s_{41}+s_{42}} \end{bmatrix} \tag{9}$$

where $\mathbf{D}\in\Re^{4\times4}$ is a diagonal matrix and the matrix $\mathbf{S}^{'}\in\Re^{4\times2}$ have the following property:

$$\forall i \quad s^{'}_{i1}+s^{'}_{i2}=1 \tag{10}$$

where $s^{'}_{i1}, s^{'}_{i2}\in\mathbf{S}^{'}$.

Substituting (8) and (9) in (1), we can obtain:

$$\tilde{\mathbf{Q}}=\mathbf{DL} \tag{11}$$

$$\mathbf{L}=\mathbf{S}^{'}\boldsymbol{\sigma} \tag{12}$$

where $\mathbf{L}\in\Re^{4\times T}$ is a connection matrix.

B. Mechanical Implementation of Transmission Matrix $\mathbf{S}^{'}$

Equation (12) can be rewritten as follows:

$$\mathbf{l}_i=s^{'}_{i1}\boldsymbol{\sigma}_1+s^{'}_{i2}\boldsymbol{\sigma}_2 \tag{13}$$

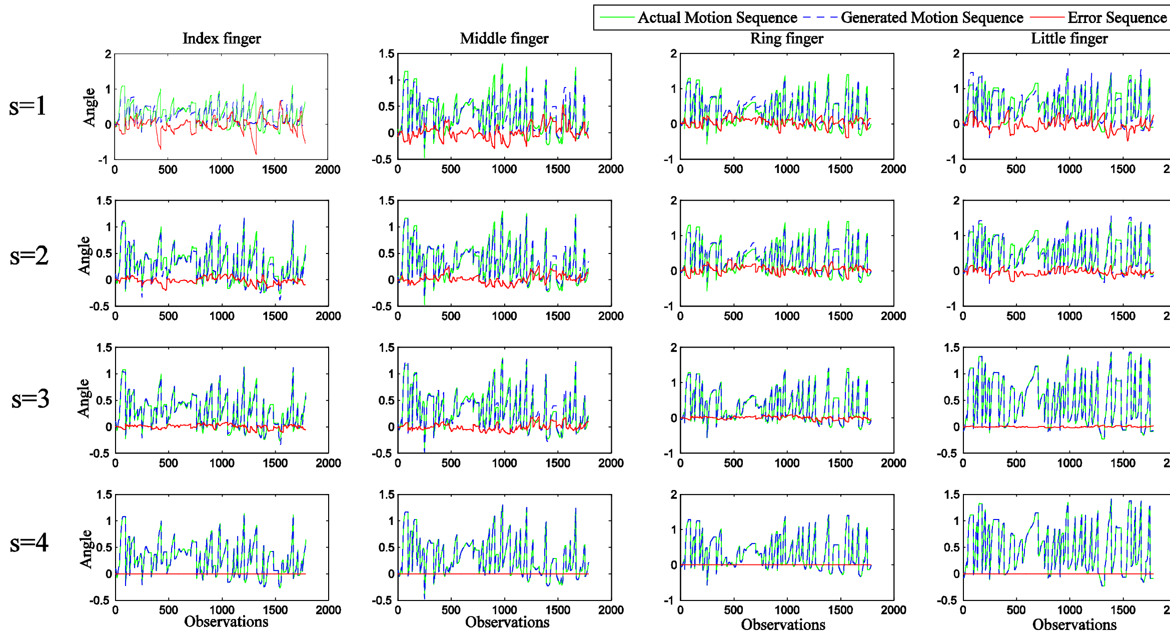


Figure 2. Comparasion of the real fingers motion sequence and generated anthropomorphic motion sequence under s actuators. The generated anthropomorphic motion sequence is obtained from matrix $\tilde{\mathbf{Q}}$ and the error sequence is obtained from matrix $\mathbf{Q}-\tilde{\mathbf{Q}}$.

where $\boldsymbol{\sigma}_j \in \Re^{1\times T}, j=1,2$.

Design of a transmission mechanism is to exert geometrical constraints in transmission part in essence. So what kind of constraints exerted in transmission part could reproduce the kinematic relationship shown in (13)? To answer this question, we give a proposition to present the appropriate constraints in the following part.

As shown in Fig.3, we firstly define the points A and B as 'input points' that represent double inputs, points $C_i(\mathrm{i}=1,2,3,4)$ as 'output points' which represent four outputs. At any instant t, the coordinates of the points are $A(x_A, y_A(\mathrm{t})), B(x_B, y_B(\mathrm{t})), C_i(x_C^i, y_C^i(\mathrm{t}))$ separately.

Proposition. *If points A, B, and $C_i(\mathrm{i}=1,2,\cdots,n)$ satisfy the following conditions:*

1. *Points A, B, $C_i(\mathrm{i}=1,2,\cdots,n)$ move on leading lines $x=x_A, x=x_B, x=x_C^i$, and $x_A \neq x_B$;*
2. *Points A, B, $C_i(\mathrm{i}=1,2,\cdots,n)$ keeps in line all alone during motion.*

Then we can obtain the relationship between input points and output points:

$$y_C^i(t) = \left(1-\frac{x_C^i - x_A}{x_B - x_A}\right) y_A(t) + \frac{x_C^i - x_A}{x_B - x_A} y_B(t) \tag{14}$$

Considering (13) and (14), let

$$s_{i2}^{'} = \frac{x_C^i - x_A}{x_B - x_A} \tag{15}$$

We conclude that the kinematic relationships presented in (13) and (14) are equivalent. It means that the transmission mechanism with the geometrical constraints described in proposition can mechanically implement the matrix $\mathbf{S}^{'}$. The design of transmission mechanism utilizes the combination of sliders and guiders to guarantee the geometrical constraints, as Fig.3.

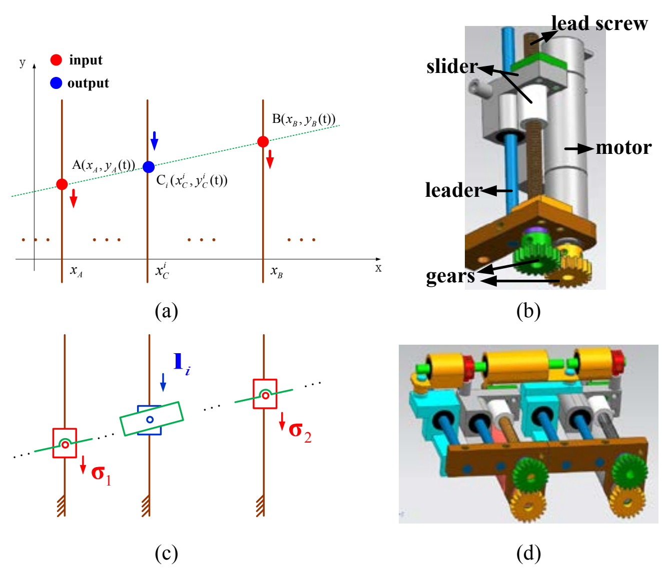


Figure 3. Mechanical implementation of matrix $\mathbf{S}^{'}$. (a) shows the geometrical constraints that could implement matrix $\mathbf{S}^{'}$. (c) is a schematic diagram of mechanism that implements the constraints in (a). (b) presents the motor driving part. (d) is the final mechanical structure that implements matrix $\mathbf{S}^{'}$. Note that the leading lines expressed in this paper are not the exact fixed guiders in (d), but the moving lines of the input and output points.

According to (15), we can obtain the relationship between the practical locations of the leading lines and the values of

s'_{i2} which we have gained before. Assuming the locations of the leading lines $x = x_A, x = x_B$ are fixed and $x_A < x_B$, the line $x = x_C^i$ is decided by s'_{i2}. When $s'_{i2} < 0$, the line $x = x_C^i$ is located on the left side of line $x = x_A$; When $s'_{i2} = 0$, the line $x = x_C^i$ overlaps the line $x = x_A$; When $0 < s'_{i2} < 1$, the line $x = x_C^i$ is located in the middle of line $x = x_A$ and line $x = x_B$; When $s'_{i2} = 1$, the line $x = x_C^i$ overlaps the line $x = x_B$; When $s'_{i2} > 1$, the line $x = x_C^i$ is located on the right side of line $x = x_B$. The relationship is intuitively shown in Fig.4.

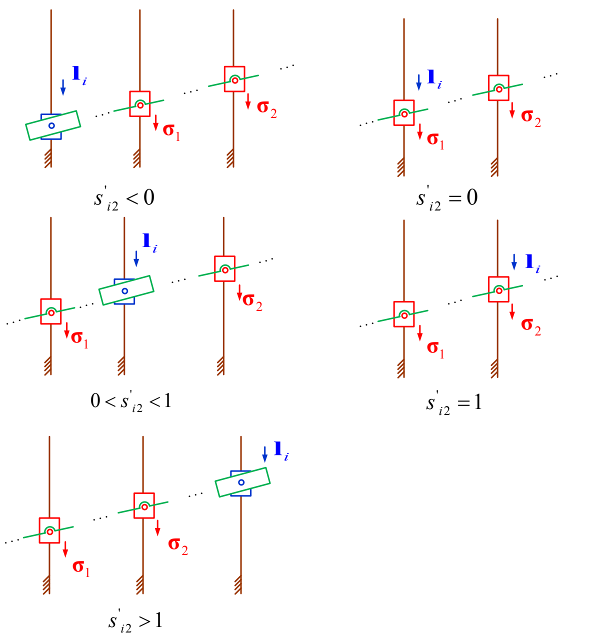


Figure 4. The relationship between the practical location of the *i*-th output leading line (with blue slider) and s'_{i2}. Note that when s'_{i2} obtain 0 or 1, the *i*-th output fixed guider(with blue slider) overlaps one of the input leading lines (with red slider). This always leads to simplification in the design of the mechanical structure, and means a lot to the design of a self-contained prosthetic hand.

C. *Mechanical Implementation of Transmission Matrix* **D**

As the transmission matrix **D** is a diagonal matrix, it makes inputs and outputs forming one-to-one match. We utilize the mechanism shown in Fig.5 to realize one-to-one match.

According to the mechanism, the transmission relation could be decided by the radios of pulleys in proportional part and stiffness of both extension and torsion springs. The role of extension springs is to add compliance among fingers, and torsion springs serve the function of back driving the fingers.

Taking the mechanism in Fig.5 (a) as an example, we can model the relationship between $\mathbf{l}_i$ and $\tilde{\mathbf{q}}_i$:

$$\tilde{\mathbf{q}}_i = \frac{r_i R_i k_i}{a_i (k_{0i} + r_i^2 k_i)} \mathbf{l}_i \tag{16}$$

where a_i represents the linear relationship between the displacement at the output of proportional part and rotation angle of the *i*-th MCP joint. The other parameters are shown in Fig.5 (a).

If $s_{i1} + s_{i2} > 0$, let

$$\frac{r_i R_i k_i}{a_i (k_{0i} + r_i^2 k_i)} = s_{i1} + s_{i2} \tag{17}$$

Thus the mechanism shown in Fig.5(a) could implement the *i*-th diagonal element of diagonal matrix **D**. If $s_{i1} + s_{i2} < 0$, the mechanism shown in Fig.5(b) which add a reverse wheel could implement the element. Furthermore, if $r_i^2 k_i >> k_{0i}$, we could simplify (17) and consider both the condition $s_{i1} + s_{i2} < 0$ and $s_{i1} + s_{i2} > 0$:

$$R_i / (a_i r_i) = |s_{i1} + s_{i2}| \tag{18}$$

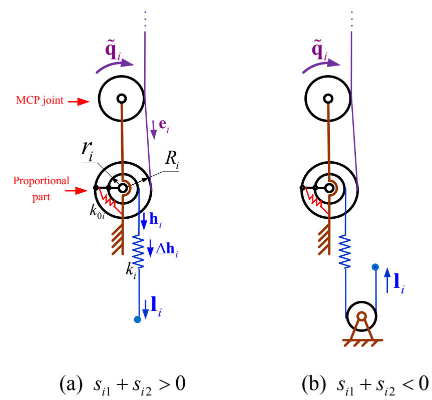


Figure 5. Mechanical implementation of the *i*-th diagonal element of diagonal matrix **D**. If the element $s_{i1} + s_{i2} > 0$, choose the mechanical design as (a). If the element $s_{i1} + s_{i2} < 0$, choose the mechanical design as (b).

D. *Mechanical Implementation of Transmission Matrix* **S**

From the perspective of mathematical form, the matrix **S** can be seen as product of matrices **D** and $\mathbf{S}'$. The mechanical implementation of matrix **S** is connecting the mechanisms that implement matrices **D** and $\mathbf{S}'$. We obtain the final drive mechanism that implements matrix **S**, as Fig.6.

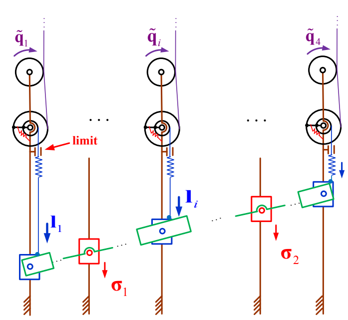


Figure 6. Mechanical implementation of matrix **S**. The limit shown in the picture is to ensure the input diplacement of the propotianal part equaling to the output diplacement of the double-pull mechanism.

E. Modification of Transmission Matrix $\mathbf{S}$

In Fig.4, we find that if $s_{i2}^{'}$ obtains 0 or 1, the lines $x = x_A$ or $x = x_B$ will overlap $x = x_C^i$, and the number of leading lines and fixed guiders will be reduced. This always leads to simplification in the design of the mechanical structure, and means a lot to the design of a prosthetic hand. Moreover, we hope to place linear bearings in each moving pair to improve the mechanical property, including placing linear bearings between any adjacent leading lines.

Note that (7) are not the only solutions to the transmission matrix $\mathbf{S}$ and driving signal matrix $\boldsymbol{\sigma}$. If we simultaneously modify the matrices $\mathbf{S}$ and $\boldsymbol{\sigma}$ as follows:

$$\mathbf{S}^* = \mathbf{ST}, \quad \boldsymbol{\sigma}^* = \mathbf{T}^{-1}\boldsymbol{\sigma} \tag{19}$$

where $\mathbf{T} \in \Re^{2\times 2}$ is a nonsingular matrix.

Thus the product of matrices $\mathbf{S}^*$ and $\boldsymbol{\sigma}^*$ is still equal to the product of matrices $\mathbf{S}$ and $\boldsymbol{\sigma}$. The relative error Err can still reach $Errmin$. It means that the solutions of these two groups both serve the best anthropomorphic motion capability of a prosthetic hand with two actuators driving four fingers.

As matrix $\mathbf{T}$ contains four independent variables, we can define $\mathbf{T}$ as:

$$\mathbf{T} = \begin{bmatrix} f_1 \cos\varphi_1 & f_2 \cos\varphi_2 \\ -f_1 \sin\varphi_1 & -f_2 \sin\varphi_2 \end{bmatrix} \tag{20}$$

To obtain matrix $\mathbf{S}^*$, an optimization method is mentioned to make the mechanical structure as compact as possible and can be embedded in the palm. The optimization goal is minimizing the width of the double-pull mechanism shown in Fig.5, and the distance between the leading lines at each end could represent the width of the mechanism. The following constraints must be satisfied. Firstly, the lines $x = x_A$ and $x = x_B$ must overlap two of $x = x_C^i (i = 1,2,3,4)$, so that the number of fixed guiders will be reduced from six to four and the mechanical structure will be simplified. Secondly, the distance between any adjacent leading lines must be larger than one constant to place a linear bearing. Thirdly, as the strict limitation of palm space, both the stroke of the sliders moving on the guiders and the ratios in proportional part must be constrained within limit. Finally, matrix $\mathbf{T}$ must be full rank. After integrating the constraints and optimization goal above, we get the final set as follows:

$$\begin{aligned}
&\min : \max_{\substack{m,w \\ m\neq w}} \left\{ \frac{\max\limits_{\substack{i,j \\ i\neq j}} \left| f_2 x_{i2}/(f_1 x_{i1} + f_2 x_{i2}) - f_2 x_{j2}/(f_1 x_{j1} + f_2 x_{j2}) \right|}{\min\limits_{\substack{i,j \\ i\neq j}} \left| f_2 x_{i2}/(f_1 x_{i1} + f_2 x_{i2}) - f_2 x_{j2}/(f_1 x_{j1} + f_2 x_{j2}) \right|} \right\} \\
&\text{subject to:} \\
&\varphi_1 = \arctan(s_{w1}/s_{w2}), \quad w = 1 \vee 2 \vee 3 \vee 4 \\
&\varphi_2 = \arctan(s_{m1}/s_{m2}), \quad m = 1 \vee 2 \vee 3 \vee 4; m \neq w \\
&P_0 \le \left|1/(f_1 x_{i1} + f_2 x_{i2})\right| \tilde{q}_i^{range} \le P_{\max}, \quad i = 1,2,3,4 \\
&\gamma^0 \le a_i \left| f_1 x_{i1} + f_2 x_{i2} \right| \le 1/\gamma^0, \quad i = 1,2,3,4 \\
&f_1 f_2 \sin(\varphi_2 - \varphi_1) \neq 0
\end{aligned} \tag{21}$$

where $s_{ik}^* = s_{i1}t_{1k} + s_{i2}t_{2k}$, $i = 1,2,3,4; k = 1,2$. P_0 and $P_{\max}$ are the limit values of the stroke. $\tilde{q}_i^{range}$ is the *i*-th MCP joint range of motion. γ^0 is the limit value of the ratios in proportional part to ensure all pulleys can be manufactured.

There are four variables in the optimization. φ_1, φ_2 are discrete variables with finite values and f_1, f_2 are continuous variables. The enumeration method is used here to search the transmission matrix $\mathbf{S}^*$ and ensure the final mechanical structure parameters.

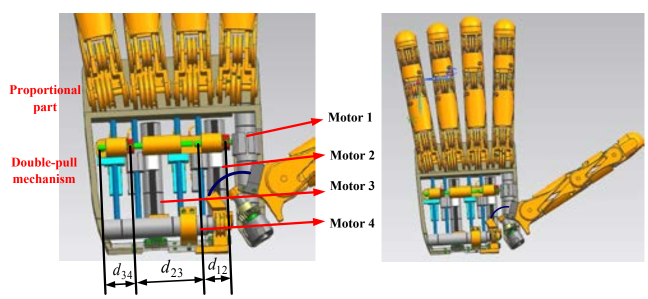
IV. Results and Discussion

Utilizing the method mentioned above, we get the final structure parameters listed in table 1. The subscript 1, 2, 3, 4 in table 1 corresponds to index finger, middle finger, ring finger, and little finger. The width of transmission mechanism connecting the motors and the fingers can reach 60.7 mm at least and have the potential to be embedded in the palm leaving space for the motors actuating thumb.

Fig.7 shows the final design of the self-contained prosthetic hand with four motors. Motor 1 and motor 4 actuate the thumb for abduction/adduction and flexion/extension. Motor 2 and motor 3 jointly driving the fingers through the mechanism proposed in this paper to reproduce human grasping movements.

TABLE I. THE FINAL MECHANICAL STRUCTURE PARAMETERS

Parameters	values	Parameters	values
R_1	7.8 mm	r_1	4.0 mm
R_2	7.5 mm	r_2	4.4 mm
R_3	7.5 mm	r_3	7.0 mm
R_4	6.6 mm	r_4	7.5 mm
d_{12}	14.0 mm	d_{23}	32.7 mm
d_{34}	14.0 mm	d_{14}	60.7 mm



(a) The final structure of the palm (b) Structure of the hand

Figure 7. Final design of the self-contained prosthetic hand with four motors. Motor 2 and motor 3 jointly drive four fingers through the transmission mechanism proposed in this paper to reproduce human grasping. Motor 1 actuates the thumb for abduction/adduction, and motor 4 serves the function of flexion/extension for the thumb.

Fig.8 shows the experiments of the proposed prosthetic hand performing several typical grasping tasks which commonly appeared in everyday life including power grasp, tripod, palmer pinch and lateral pinch. We can see that both the grasping movements and the final postures are humanlike,

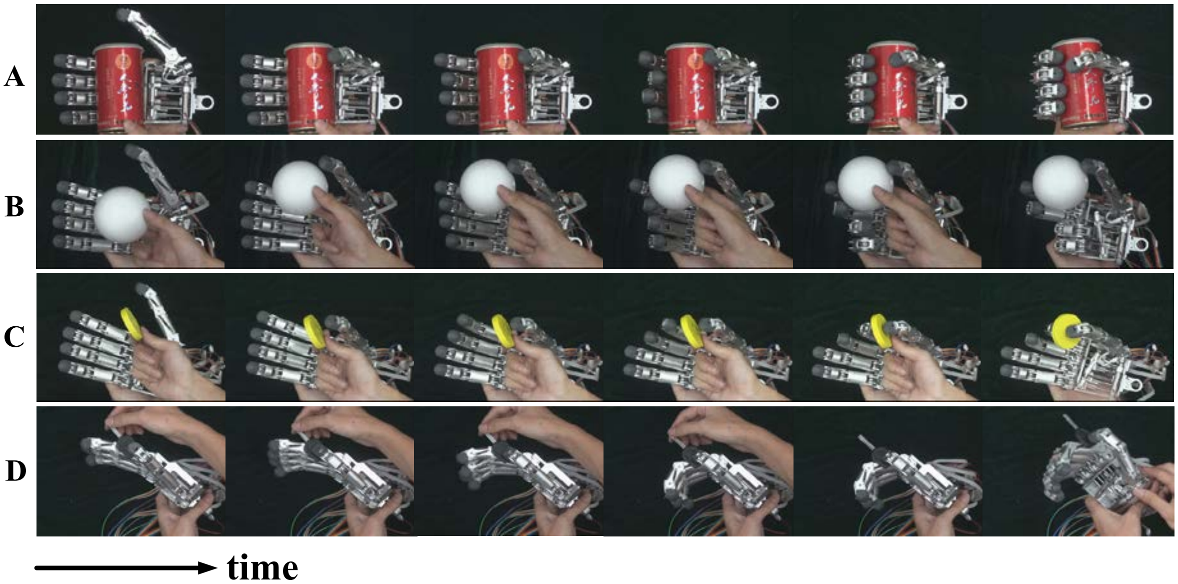


Figure 8. The proposed prosthetic hand performs several typical grasping tasks including power grasp(**A**), tripod(**B**), palmer pinch(**C**) and lateral pinch(**D**).

and during each task the grasp is stable.

For upper-limb amputees, reproducing a hand which totally serves the same physical appearance, functions and movements as a real human hand is a strong craving. Previous research pays more attention to functions but ignores the anthropomorphic movements. However the humanlike movements are still very important for a prosthetic hand, as it plays the role of replacing a real human hand in every ways. Compared with other prosthetic hands, the proposed prosthetic hand in this paper not only realizes the common grasping functions, but also serves higher anthropomorphic grasping motion and posture accuracy.

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