# Kinematics and Workspace Analysis of an Exoskeleton for Thumb and Index Finger Rehabilitation

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***Abstract*—For the human hand rehabilitation, the palmar opposition is an important function to evaluate the recovery of hand motor capabilities. This paper proposes an exoskeleton-type hand rehabilitation assistive device which is able to be applied to index finger as well as thumb. The kinematics and workspace of index fingertip and thumb-tip are analyzed. The 'opposition space' is defined as the intersection of the workspace of thumb-tip and the index fingertip. A metric, what we call 'opposition degree', which is defined as the ratio of volume of opposition space to that of the index fingertip workspace, is proposed to present the available degree of opposition. As an example, the opposition degree of a human hand model is determined. This metric can also used to rate the ergonomic performance of the hand rehabilitation assistive device. This method can be applied to other fingers as well. The opposition simulation experiment is conducted to verify the kinematics of the proposed exoskeleton.**

## I. Introduction

THE human hand is a miraculous instrument that serves us extremely well in a multitude of ways. We successfully use our hands to identify objects and to extract a wealth of information about them, such as their surface texture, compliance, weight, shape, size, orientation, and thermal properties [1]. However, accident and diseases, stoke for instance, can lead to loss of sensation and motor functions of hand. In order to recover the lost functions, hand rehabilitative trainings are needed [2].

The hand motor capability can be quantified with some parameters, such as range of motion (ROM), speed of motion, and finger strength [3]. However, as one of the most important functions, the quantification of palmar opposition is still an open issue. Li-Chieh Kuo and his colleagues proposed the term of functional workspace and used area ratios of the functional workspace with respect to the two-dimensional maximal workspace of the other fingers to describe the motor capability [4]. However, the fingertip workspace is actually three-dimensional.

On the other hand, for the hand rehabilitation assistive device, it is necessary to provide some ergonomic criterion to instruct the design or evaluate the performance. We think the palmar opposition should be included. To the authors' knowledge, we haven't seen the published research which discusses the opposition function for the existing devices [5], [6],[7].

This paper proposes an exoskeleton-type hand rehabilitation assistive device which is able to be applied to index finger as well as to thumb. The physical prototype of index module has been developed while that of the thumb is under manufacturing. The kinematics and workspaces of index fingertip and thumb-tip are analyzed. We define the 'opposition space' to describe the intersection of the index fingertip workspace and thumb-tip workspace. We further propose a metric, what we call 'opposition degree', which is the ratio of volume of opposition workspace to that of the index fingertip workspace, to present the available degree of opposition. The metric can also used to rate the ergonomic performance of the hand rehabilitation assistive device. The opposition simulation experiment is conducted to verify the kinematics of the proposed exoskeleton.

The rest parts of this paper are organized as follows. The design of hand exoskeleton is proposed in Section II. The kinematics and workspace analysis are presented in Section III. Simulation experiment is implemented in Section IV. Finally, we conclude our research and discuss future work in Section V.

## II. Design of the Hand Exoskeleton

### A. *Kinematic Model of Index Finger and Thumb*

Compliance with the human hand anatomy is the premise for the designed exoskeleton able to be worn on the human hand. As shown in Fig.1, the anatomical structure of index finger is composed of three phalanges – distal, middle and proximal phalanges, which are connected in sequence by distal interphalangeal (DIP) joint, proximal interphalangeal (PIP) joint and metacarpaophalangeal (MCP) joint to metacarpal. While the anatomical structure of thumb is also composed of three phalanges which are connected in sequence by interphalangeal (IP) joint, metacarpaophalangeal (MCP) joint and carpometacarpal (CMC) joint. The joint structures are complicated and difficult to completely copy in mechanical design. So the finger's kinematic structure should be reasonably simplified.

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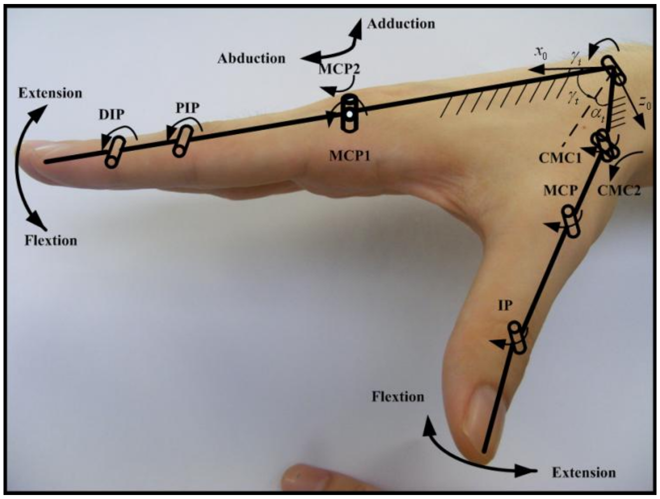



Fig. 1 Kinematics of the index finger and thumb

As shown in Fig. 1, the index finger and thumb are both modeled as a serial four-bar linkage with four DOFs. The DIP and PIP joints of index finger, and the IP and MCP joints of thumb are modeled as one-DOF hinges to realize the flexion/extension motions, while the MCP joint of index finger and CMC joint of the thumb are respectively simplified as two one-DOF hinges (denoted by MCP1 and MCP2, CMC1and CMC2, respectively) with orthogonal and intercrossing rotating axis to realize the corresponding motions of flexion/extension and adduction/abduction. We assume that the index finger is in the palm plane when stretch straight. The inclination angle of thumb plane $\alpha_t$ is measured to be 30 degrees with respect to the palm plane. Meanwhile the angle $\gamma_t$ between the central lines of the index finger and thumb is measured to be 45 degrees.

And the anthropometric data, including the average length of finger phalanges, and ROM of finger joints [3], [8], [9],[11] are listed in Table I. These data are the design parameters of exoskeleton device and are used later to calculate the workspaces of the index finger and thumb, and to implement the simulation experiment.

TABLE I
ANTHROPOMETRIC DATA OF HAND

| Digit | Parameter | | | | |
|---|---|---|---|---|---|
| Thumb | Joint | IP | MCP | CMC1 | CMC2 |
| | ROM(Degree) | 0～80 | 0～50 | -30～15 | 0～45 |
| | Phalange | Distal | Proximal | | Radial |
| | Length(mm) | 28 | 35 | | 45 |
| Index Finger | Joint | DIP | PIP | MCP1 | MCP2 |
| | ROM(Degree) | 0～80 | 0～100 | 0～85 | 0～25 |
| | Phalange | Distal | Middle | | Proximal |
| | Length(mm) | 17 | 25 | | 43 |

## B. *Design of the Hand Exoskeleton*

The hand exoskeleton includes the index finger part and the thumb part, and both are assembled on the same base which is fixed on the back of the palm by Velcro. The virtual prototype is shown in Fig.2. The physical prototype of index finger has been developed [10] (see Fig.3) and the detail is not presented here.

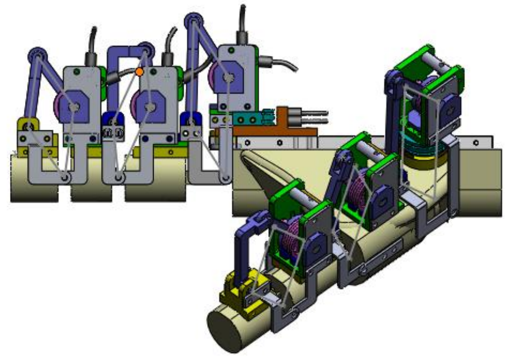


Fig.2 Virtual prototype of the exoskeleton

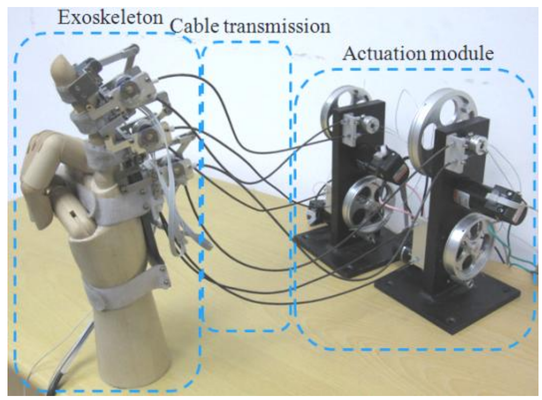



Fig.3 Physical prototype of the index finger of exoskeleton

We apply the design to the thumb by adding additional attachment for the consideration of assembling. The exoskeleton module for thumb is to be manufactured soon.

# III. KINEMATICS AND WORKSPACE ANALYSIS

## A. *Kinematic Analysis of exoskeleton*

The kinematic sketch of the exoskeleton for the digit is shown in Fig. 4, which can be considered a serial four-bar linkage combined with the closed chain parallelogram mechanism at each phalange. The target of the kinematic analysis is to determine the relationship between the digit-tip position and the joint angles.

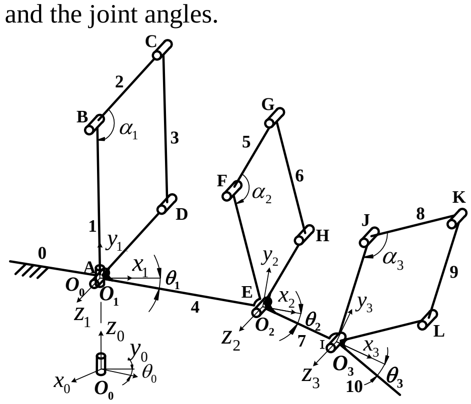


Fig. 4 Kinematic sketch of exoskeleton for the digit

With the advantage of the parallelogram mechanism, the kinematic sketch can be simplified as that of the serial mechanism, as demonstrated in Fig.5, when considering the aforementioned kinematics.

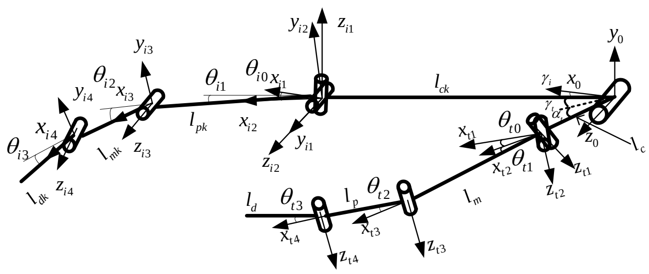



Fig.5 Kinematic sketch and D-H representation

We use the well-known D-H method to establish the coordinate systems on each link and the fixed coordinate system, the origin of which is located on the center of the wrist joint. The positions of thumb-tip and the index fingertip can be calculated as follows.

$$\begin{bmatrix} x_t \\ y_t \\ z_t \end{bmatrix} = \begin{bmatrix} A\cos\gamma_t\cos\theta_{t0} + B\sin\gamma_t + l_c\cos\gamma_t \\ A\sin\theta_{t0} \\ -A\sin\gamma_t\cos\theta_{t0} + B\cos\gamma_t - l_c\sin\gamma_t \end{bmatrix} \quad (1)$$

$$A = l_d\cos(\theta_{t1} + \theta_{t2} + \theta_{t3}) + l_p\cos(\theta_{t1} + \theta_{t2}) + l_m\cos\theta_{t1}$$
$$B = l_d\sin(\theta_{t1} + \theta_{t2} + \theta_{t3}) + l_p\sin(\theta_{t1} + \theta_{t2}) + l_m\sin\theta_{t1}$$

$$\begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix} = \begin{bmatrix} C\cos(\gamma_i - \theta_{i0}) + l_{ck}\cos\gamma_i \\ D \\ -C\sin(\gamma_i - \theta_{i0}) - l_{ck}\sin\gamma_i \end{bmatrix} \quad (2)$$

$$C = l_{dk}\cos(\theta_{i1} + \theta_{i2} + \theta_{i3}) + l_{mk}\cos(\theta_{i1} + \theta_{i2}) + l_{pk}\cos\theta_{ii}$$
$$D = l_{dk}\sin(\theta_{i1} + \theta_{i2} + \theta_{i3}) + l_{mk}\sin(\theta_{i1} + \theta_{i2}) + l_{pk}\sin\theta_{ii}$$

where

$[x_t \quad y_t \quad z_t]^T$ denotes the coordinate of thumb-tip;

$[x_i \quad y_i \quad z_i]^T$ denotes the coordinates of index fingertip;

$\theta_i$ denotes the joint angle of the thumb and index finger;

$l_i$ denotes the length of phalanx.

$\gamma_t$ , $\gamma_i$ denote the angles of thumb and index finger at the root segment with respect to axis $x_0$ .

For the subscription meanings of $\theta_i$ and $l_i$, please see Fig.5.

### B. Opposition Space of the exoskeleton

The palmar opposition is the fundamental manipulation for human hand, and the quantification of opposition function is still an open issue. Without losing the universality, we take the thumb and index finger for example to discuss the issue. We define the term 'opposition space' to express the range that the opposition exists and the metric 'opposition degree' to represent the relative extent that the opposition space accounts for the whole workspace of fingers.

#### 1) Opposition Space

Apparently the opposition requires that the intersection of the workspaces of thumb-tip and index fingertip is the non-null set. We define the intersection as the 'opposition space'. The opposition space can be represented as follows:

$$\boldsymbol{OS} = \{\boldsymbol{x} | \boldsymbol{x} \in \boldsymbol{WS}_i, \boldsymbol{x} \in \boldsymbol{WS}_t\} \quad (3)$$

where

$OS$ denotes the opposition space;

$x$ denotes the point in the opposition space;

$WS_i$ denotes the workspace of the index fingertip;

$WS_t$ denotes the workspace of the thumb-tip.

From (1) and (2) we know that the opposition space is determined by the joint angles of digits, which can be formulated from the following equations.

$$\begin{bmatrix} x_t \\ y_t \\ z_t \\ 1 \end{bmatrix} = \begin{bmatrix} x_i \\ y_i \\ z_i \\ 1 \end{bmatrix} \text{ or } \begin{cases} x_t = x_i \\ y_t = y_i \\ z_t = z_i \end{cases} \quad (4)$$

Substituting (4) into (1) and (2), three equations are obtained with eight joint angle variables (four for thumb and four for index finger). It is an under constraint equation with five independent variables. Given the limits of the independent variables, the opposition space is derived.

#### 2) Opposition degree

We define 'opposition degree' as the volume ratio of opposition space to the volume of the index fingertip workspace. The metric can be used as the criterion to instruct the design of the hand rehabilitation device or to evaluate the ergonomic performance of the device. According to the definition, we have

$$\eta = \frac{V_{OS}}{V_{WS_i}} \quad (5)$$

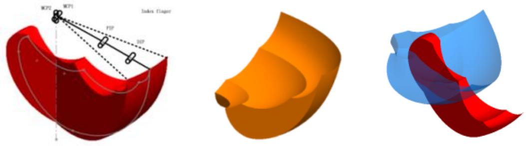
where $\eta$ is the opposition degree;

$V_{OS}$ is the volume of opposition space;

$V_{WS_i}$ is the volume of the index fingertip workspace.

#### 3) Solution implementation

As described aforementioned, equation (4) is a trigonometric equation with high dimensional independent variables. Therefore it is difficult to represent the opposition space in an explicit analytical function. We solve the equation with the aid of SolidWorks software to get the opposition space and then calculate the opposition degree. We use the data listed in table I for example. The workspaces are shown in Fig.6, and the volumes of the index finger workspace and opposition space are $V_{WS_i} = 65503\,\text{mm}^3$, $V_{OS} = 9582\,\text{mm}^3$. Therefore the opposition degree is $\eta = 14.6\%$.



(a) (b) (c)

Fig.6 Workspaces:(a) index finger (b)thumb (c) opposition space

To further illustrate the utility of the proposed method, we analyze the impact that the exoskeleton imposes on the opposition space by comparing the results in two conditions: the index finger wears and doesn't wear the exoskeleton which is developed by our research group. The joint angles of index finger when wearing the exoskeleton is listed in table II.

TABLE II
JOINT ROM OF INDEX FINGER WITH EXOSKELETON

| Joint | DIP | PIP | MCP1 | MCP2 |
|---|---|---|---|---|
| ROM(Degree) | 0~65.5 | 0~95 | 0~80 | 0~25 |

The comparison result is shown in Fig. 7. With the exoskeleton, the volume of the index finger workspace is $v_{ws_i} = 56190\,mm^3$ which is about 14percent smaller than the volume without the exoskeleton. This result is accords with the fact that the ROM with exoskeleton is less than the ROM without exoskeleton which results in the decrease of the workspace. As so far, we cannot calculate the opposition degree since the physical prototype of thumb exoskeleton is not available yet.

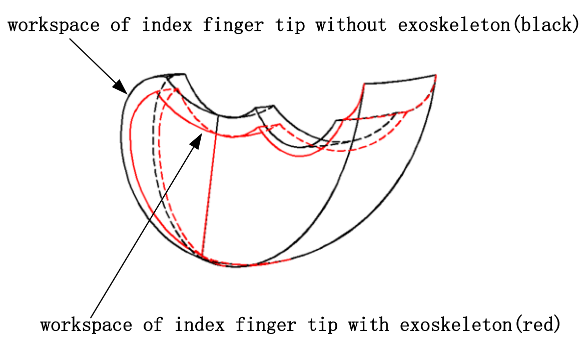
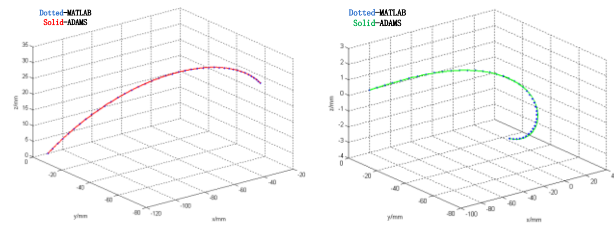



Fig.7.Comparison of workspaces of index finger tip

## IV. SIMULATION EXPERIMENTS

### A. *Kinematic Verification of index finger and thumb*

The kinematics of index finger and thumb are verified by simulation experiments which are conducted in ADAMS software. The hand model is built with the data listed in table I. The positions of index fingertip and the thumb-tip are measured during the simulation. The positions are also calculated in MATLAB according to the proposed kinematics equations (1) and (2). The results are shown as Fig. 8.




(a)Thumb (b) Index finger

Fig.8 Positions of index fingertip and thumb

Both the inputs of thumb and index finger in ADAMS are the maximal joint angles that are listed in Table I and II. It can be seen that the results calculated in two ways accord with each other well, therefore the kinematic analysis of the thumb and index finger is verified.

### B. *Opposition simulation*

The opposition is also simulated in ADAMS to verify the workspace analysis. In order to derive the solution of (4) and the corresponding joint angles, we first calculate (1) and (2) respectively in MATLAB. If (4) is satisfied, the fingertip coordinates and the corresponding joint angles are recorded. Then an arbitrary set of recorded joint angles are input into the simulation model of ADAMS to check whether the index finger and thumb can accomplish the opposition. The result is shown as Fig. 9. At the simulated configuration, the joint angles of the thumb are $\theta_{t0} = 16°$ , $\theta_{t1} = 10°$ , $\theta_{t2} = 30°$ , $\theta_{t3} = 60°$ ; while the joint angles of the index finger are $\theta_{i0} = 25°$ , $\theta_{i1} = 66°$ , $\theta_{i2} = 32°$ , $\theta_{i3} = 36°$

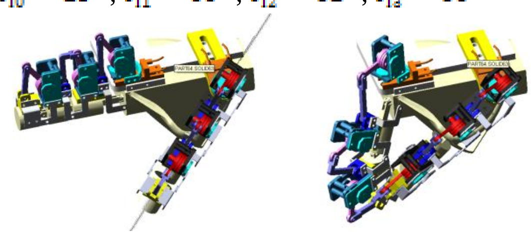


Fig.9 Opposition simulation results

## V. CONCLUSION AND FUTURE WORK

The kinematic and workspace of an exoskeleton for thumb and index finger rehabilitation is analyzed. Meanwhile, the "opposition space" is defined to quantify the opposition function of the hand. The metric "opposition degree" is proposed on the purpose of instructing the design and evaluating the ergonomic performance of hand rehabilitation device. It can also be used to rate the motor function recovery of impaired hand. The proposed idea of opposition space and opposition degree is preliminary demonstrated by an example and the kinematics is verified by simulation experiments.

For the future work, we are going to apply the exoskeleton scheme to all the fingers and conduct more experiments to verify the proposed method and to improve our design.

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