ABSTRACT

This paper proposes a wearable upper-limb rehabilitation device, DULEX, to increase the range of motion of the finger and wrist joint gradually. DULEX has three degrees of freedom for the wrist, the index finger, and a mechanism enclosing other three fingers except the thumb. The motion trajectory of DULEX is aligned to the user’s hand motion by using a parallel mechanism designed. The design parameters such as length and location of links are determined by kinematics analysis and an optimal technique. We use artificial air muscles to actuate each joint motion to reduce total weight. The motion angle of joint is indirectly estimated from muscle length controlled by air pressure. From experimental results, we show that DULEX is applicable to the upper-limb rehabilitation exercise.

KEY WORDS

Upper-limb paralysis, rehabilitation device, artificial muscle, and stroke patients

1. Introduction

Stroke is one of disease on the circulatory system. It causes a functional paralysis disorder to disable voluntary muscle contraction. Upper-limb disorder is a typical aftereffect by stroke. It is known that a repetitive rehabilitation with therapist is effective to improve the functional disabilities after stroke. However such rehabilitation therapy needs for much physical labors of therapists and costs. Consequently a novel rehabilitation therapy using assistive devices to reduce the physical efforts and costs are necessary.

Recently, there were researches on the rehabilitation therapy using assistive systems such as stretching and strengthening muscles [1], power-assisting to flexion motion [2], and correcting the affected part after surgery [3]. It showed that imitation exercise such as stretching the abnormal part from the normal motion is effective in rehabilitation therapy [4]. In these exercises high concentration, repeatability, and specified exercise motion should be considered.

Marvelous results in rehabilitation system were shown in robotics. There were various robotic upper-limb rehabilitation devices to assist exercises effectively instead of therapists [5-11]. The devices performed upper-limb movement well, but they were working on fixed position only. Therefore patients must be placed under restraint during exercises.

In recent, there were lightweight wearable devices for the rehabilitation of the hand including the wrist. Mentor [1] performed flexion and extension of the finger and the wrist synchronously. But it is impossible to exercise the finger and the wrist independently. RUPERT [12] was also an upper-limb exercise robot that could perform various arm rehabilitation motions. However it was not adequate for the finger rehabilitation because it was too bulky to wear.

In this paper, we proposes a wearable upper-limb rehabilitation device, DULEX (Dong-eui Upper Limb EXerciser), to increase the range of motion of the finger and wrist joint gradually. To improve the therapy effect we design the DULEX to move the index finger independently. DULEX has three degrees of freedom for the motions of the wrist, the index finger, and a mechanism enclosing other three fingers except the thumb. The motion trajectory of DULEX is aligned to the user’s hand motion by using a parallel mechanism. The design parameters such as length and location of links are determined by kinematics analysis and an optimal technique. We use artificial air muscles to actuate each joint motion in order to reduce the total weight. Because the range of motion depends on muscle length, the motion angle of joint can be indirectly estimated from muscle length to be controlled by air pressure.

This paper is organized as follows. Section 2 describes a static modeling of the artificial muscle and its preliminary experiments. Section 3 presents a kinematics analysis of the finger and the wrist extension motions. In section 4 and 5 design and control for DULEX are described. Then the experimental results using DULEX developed in this study are shown in section 6. Finally we conclude this study.

2. Artificial muscle actuator

We use the air muscle produced by Shadow Robot as actuators to flex the finger and the wrist of DULEX. The
air muscle is composed of a rubber tube, nylon fiber shell, a seal cap and a metal end ring (see Fig. 1). Contraction of the air muscle is controlled by changing inner pressure of the rubber tube. The behavior of air muscle is similar to the human muscle’s one. Chou and Hannaford proposed an analysis model from the relations of length, pressure, and expansive force of the air muscle [13].

In this study we introduced the Chou’s analysis model to our study for preliminary experiments, but we assumed the muscle shape is a complete cylinder model without diameter variation. Fig. 2 shows the geometry of the air muscle. Let \( L \) and \( D \) be length and diameter of muscle. And \( \theta \) is the angle between braided thread and cylinder long axis. Then \( L \) and \( D \) can be obtained as follows,

\[
L = b \cos \theta, \quad \text{(1)}
\]

\[
D = \frac{b \sin \theta}{n\pi}. \quad \text{(2)}
\]

In above equations, \( n \) and \( b \) are the number of turns and the length of thread. By the energy conservation that the input work equals the output work if system is lossless and without energy storage, the relations can be expressed as follows,

\[
dW_{in} = P_g dV, \quad dW_{out} = -FdL. \quad \text{(3)}
\]

\[
dW_{in} = dW_{out} : F = \frac{P_g b^2 (3 \cos^2 \theta - 1)}{4\pi n^2}. \quad \text{(4)}
\]

From equation (1) to (4), the force related to the pressure and the length is obtained as the following equation,

\[
F = \frac{p_g b^2 (3L^2 - b^2)}{4\pi n^2}. \quad \text{(5)}
\]

In this study, we set the constant value \( n \) and \( b \) in Eq. (5) to 3.0588 and 17.368, respectively.

2.1 Static verification

We performed preliminary experiments to verify the obtained analysis model to real behavior of the air muscle. Fig. 3 shows the muscle characteristics according to the air pressure when a fixed load is given. Dotted lines are simulation results, and the solid lines are measured data. In the measured results the maximum standard deviation of the length was 2.41mm, and the maximum average error compared with the simulation was 4mm. This means that the analysis model is well established. Consequently, we can estimate the length of air muscle by measuring the current air pressure of the muscle.

3. Kinematics of hand

3.1 Kinematics of finger mechanism

We apply a muscle-wire mechanism to DULEX. The mechanism is similar to the muscle-tendon structure of human finger. The index finger, the other three fingers, and the wrist are designed on the basis of the muscle-wire mechanism. The main design concept of DULEX is to align the center of rotation to human joint so as to align the motion trajectory of DULEX to the user’s hand motion. In this study, we introduce a parallel mechanism into DULEX to align the motion trajectory. The mechanism is designed to revolve on the finger and the wrist joint as shown in Fig. 4. The designed finger mechanism is shown in Fig. 5. The finger is realized by using the parallel link mechanism. When the muscle linked to the proximal phalange is contracted, the proximal phalange link \( r_2 \) rotates to the clockwise direction, and then the distal-middle phalange link \( r_{fd} \) is extended. In this motion, the center of rotation of the vector \( \vec{r}_{fp} \) and \( \vec{r}_{fd} \) were aligned to the PIP joint and MCP joint respectively. The vector \( \vec{r}_{fp} \) corresponding to the proximal phalange can be found as follows,

\[
\vec{r}_{fp} = \vec{r}_0 + \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \end{bmatrix} \vec{r}_2, \quad \left( \vec{r}_2 = \vec{r}_1 \right). \quad \text{(6)}
\]

The link length, \( r_0, r_2 \) and \( r_1, r_3 \) are set to 42.67mm and 10mm based on the Korean standard anthropometric data. We set the angle of proximal phalange as \( \theta \) then, the
is the sum of the vectors $\mathbf{v} \times \mathbf{w}$ and $\mathbf{r}$. Are known.

When the vectors $\mathbf{v}$ and $\mathbf{w}$ are parallel, the direction vector $\mathbf{u}$ can be obtained from $\mathbf{v}$, vectors $\mathbf{r}$.

The direction vector $\mathbf{u}$, and select the length $\mathbf{r}$ corresponding to the distal-middle phalange.

3.2 Determination of design parameters

Vector $\mathbf{r}_{d1}$ is corresponding to the distal-middle phalange of finger. When the proximal phalange is extended by the muscle contraction, the trajectory of link $\mathbf{r}_{d1}$ is determined by the length $r_1, r_5$ of the links and the angle $\alpha$ between the link $r_5$ and vector $\mathbf{r}_{d1}$ (see Fig. 4).

Consequently, we select the length $r_1, r_5$ and the angle $\alpha$ as design parameters, and then we obtain the values of parameters using optimal design techniques as follows. We first set the ROM of proximal phalange to $90^\circ$. And the ROM of the distal-middle phalange is also set to $90^\circ$, when the angle of proximal phalange to be completely stretched is $0^\circ$ ($\theta = -30^\circ$). We give the boundary conditions of the angle $\alpha$ and the length $r_4$ as $30 \text{ mm} \leq r_4 \leq 60 \text{ mm}$ and $30^\circ \leq \alpha \leq 90^\circ$, and select the direction vector $\mathbf{r}_4$ when the vectors $\mathbf{r}_{fp}$ and $\mathbf{r}_{d1}$ are conformable at the maximum spread angle ($\theta = -30^\circ$) of the hand. Then, we set other conditions that the range of distal-middle vector $\mathbf{r}_{d2}$ is $90^\circ \leq r_{d2} \leq 90.1^\circ$, and the transmission angle between vectors $\mathbf{r}_4$ and $\mathbf{r}_5$ is larger than $40^\circ$. Consequently the link $r_5$ can be obtained from the $\mathbf{r}_{d2}$, direction vector $\mathbf{r}_5^\prime$, and length of link $r_4$ by the following equation,

$$
\mathbf{r}_5 = \left[ -\mathbf{r}_{d2} \mathbf{r}_5^\prime + \sqrt{4\mathbf{r}_{d2}^2 - (\mathbf{r}_{d2} \mathbf{r}_5^\prime \times \mathbf{k})} \right] \mathbf{r}_5^\prime .
$$

Using these conditions, we obtained two solutions to satisfy the ROM of distal-middle phalange when the flexion angle of proximal phalange is ($\theta = 60^\circ$). We selected the final solution to make the length of links minimize. The solution is expressed by solid line in Fig. 6, and the parameters are $r_4 = 47 \text{ mm}$, $r_5 = 9.16 \text{ mm}$, $\alpha = 40^\circ$.

Then the vector $\mathbf{r}_{d2}^\prime$ corresponding to the distal-middle phalange can be obtained by the following equation because the inner angle $\alpha$ and vector $\mathbf{r}_5$ are known.

$$
\mathbf{r}_{d2}^\prime = \mathbf{r}_5 \left[ \begin{array}{c} \cos(\pi - \alpha) \\ -\sin(\pi - \alpha) \\ \cos(\pi - \alpha) \end{array} \right] \mathbf{r}_5^\prime .
$$

3.3 ROM of finger

We designed the ROM of the wrist, the proximal phalange, and the distal-middle phalange to be $90^\circ$ as shown in Table 1. The ROM of the distal-middle phalange is $90^\circ$.

<table>
<thead>
<tr>
<th>Angle</th>
<th>distal-middle phalange</th>
<th>proximal phalange</th>
<th>wrist</th>
</tr>
</thead>
<tbody>
<tr>
<td>initial position angle</td>
<td>90</td>
<td>60</td>
<td>48</td>
</tr>
<tr>
<td>extension angle</td>
<td>0</td>
<td>-30</td>
<td>-42</td>
</tr>
</tbody>
</table>
from the initial angle ($\theta = 60^\circ$) to the maximum extended position ($\theta = 30^\circ$). We performed a simulation to verify the ROM of fingers designed by the obtained parameters. The result showed that the ROM of the proximal phalange was $90^\circ$ at which the initial position of the distal-middle phalange was $\theta = 60^\circ$ (see Fig. 7).

### 3.4 Kinematics of wrist mechanism

The wrist mechanism is designed to enable wrist flexion (see Fig. 8). Here, the flexion angle, $\gamma$, is the same as the following equation.

$$\gamma = \beta + \theta_1 + \theta_2 - 180^\circ.$$  \hspace{1cm} (13)

In Eq. (13), $\beta$ and $\theta_2$ are design parameters obtained from the fixed length $d_1$, $d_2$. And $\theta_1$ is calculated by the following equation using the muscle length $l_1$ and $d_1$, $d_2$.

$$\theta_1 = \cos^{-1}\left(\frac{d_1^2 + d_2^2 - l_1^2}{2d_1d_2}\right).$$ \hspace{1cm} (14)

As a result, the fixed angle was $\beta = 59.46^\circ$, $\theta_2 = 13.44^\circ$ when the lengths $d_1$, $d_2$ are given as 38.42mm and 150.59mm, respectively.

### 3.5 Relations of joint angle and wire length

Fig. 9 shows kinematics analysis to measure the angle of proximal phalange according to the muscle length. $x$ is the wire length from the proximal phalange to the pulley, a, b are constant lengths as $a = 28$mm and $b = 88.6$mm. Given the wire length $x$, the motion angle of the proximal phalange can be obtained by using a fixed inner angle as follows.

$$\rho = \cos^{-1}\left(\frac{a^2 + b^2 - x^2}{2ab}\right).$$ \hspace{1cm} (15)

$$\varphi = 360^\circ - (129.52^\circ + \rho).$$ \hspace{1cm} (16)

$$\theta = 180^\circ - (\varphi + 16.2^\circ).$$ \hspace{1cm} (17)

By comparing the simulation results we can see that the ROM of the proximal phalange is $85^\circ$.

### 4. Design of DULEX

#### 4.1 Design of finger parts

After analyzing kinematics we designed a prototype DULEX based on the Korean standard anthropometric data. As mentioned in section 3, the main design concept is to align the center of rotation to human joint so as to align the motion trajectory of DULEX to the user motion. As additional functions, we designed a Velcro-type band to tie fingers up the distal-middle part [14], and also inserted a stopper structure to prevent over-movement of DULEX when performing flexion and extension motions. The proximal link is composed of the wire-link mechanism. In Fig. 10 the blue arrows show the direction and position of the wire fixed on DULEX. We used pulley structure in the center of wrist joint so as to reduce a friction force to disturb the pulling force. All links composed of the finger parts were made of ABS (acrylonitrile, butadiene and styrene) material and aluminum alloy with 1mm thickness to increase the stiffness (see Fig. 11).
The mechanism to support fingers was designed by edge supporting structure as shown in Fig. 12. Consequently, the thickness of supporter between fingers can be reduced.

4.2 Design of wrist parts

The wrist joint that is the center of flexion and extension motion is designed in the wrist parts. We insert a pulley in the wrist joint to reduce a friction force between the finger mechanism and the wire connected to the muscle. To actuate the finger and the wrist motions, three artificial muscles were attached on the arm part. The muscles are fixed on the elbow position, which are selected by considering the length of maximum contraction and relaxation. A stopper to prevent over-flexion and extension of wrist was designed on the back of the hand. We also designed two holes on the arm part for fixing Velcro-type bands to tie user’s arm flexibly.

5. Control system

In this paper we proposed a kinematic analysis of the relations between the angle of proximal phalange and the length of the artificial muscle. However, the length of the muscle in the developed DULEX system could not be measured directly because it has no sensors to measure length. Therefore we obtained the relations of the inner pressure and the length of muscle. In this study, we first obtained the change of muscle length according to the muscle pressure by preliminary experiments for the air muscle characteristics. Using the results we designed the control system for DULEX. Fig. 13 shows the block diagram of the control system. Given a target angle, the length to be controlled is obtained by the inverse kinematics. Then, the target pressure corresponding to the length is selected from the muscle characteristics, and it is controlled by PD control method. We used a pressure sensor, SPD100GA (Smartec Co.), with measuring range from 100kPa to 600kPa. The controller is implemented by an 8bit RISC type microcontroller. Fig. 14 shows the system configuration for muscle control of DULEX. Fig. 15 shows the developed DULEX that is a lightweight wearable upper-limb rehabilitation device.

6. Experimental results

We first performed experiments for the changes of motion angle and wire length according to the muscle contraction. Fig 16 shows the experimental setup for the experiments.
While controlling extension motions we can verify the muscle pressure on the computer monitor. As a result the ROM of proximal phalange was 85°. Although the tendency to increase is similar to the simulation result, the experimental result has errors of maximum 5° comparing the simulation result at the maximum muscle contraction (see Fig. 17). This is caused by errors in measuring and the length of parts fabricated. In the next experiment, we investigated the ROM under 1.5kg load. Fig. 18 shows the experimental results. The measured angle was well controlled within ROM as shown in Fig. 17. However, the load on DULEX might be different value from the experimental setup because it depends on the ability of user’s hand function.

7. Conclusion

In this paper, we proposed a wearable upper-limb rehabilitation device, DULEX, to increase the extension range of motion of the finger and wrist joint gradually. To improve the therapy effect we designed the DULEX to move the index finger independently. The motion trajectory of DULEX was aligned to the user’s hand motion by using a parallel mechanism. The design parameters such as length and location of links were determined by the kinematics analysis and an optimal technique. The artificial air muscles used in DULEX contributed to reduce the body weight. Moreover the main skeleton of DULEX was made of ABS material. As the results, the total weight of developed DULEX was about 504g.

In this study, we assumed the initial hand posture is the flexion with a grasping force. However the user’s hand force must be extremely diverse according to the level of disorder. To control extension motion with considering user’s hand ability is the future work.

References


