Design Process of Exoskeleton Rehabilitation Device and Implementation of Bilateral Upper Limb Motor Movement

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Abstract

With the development of neurorehabilitation, physical rehabilitation strategies for the upper limbs have become gradually accepted by therapists and researchers. These strategies include intensive intervention, task-oriented training, and bilateral training. Most upper limb rehabilitation systems have been developed for unilateral training. This paper develops an upper limb exoskeleton rehabilitation device (ULERD) that can be used for bilateral training. The device has three active degrees of freedom (DoFs) in the elbow and wrist joints, and an additional four passive DoFs at these joints to correct any misalignment between the human and device joints. A bilateral training strategy is implemented with the developed ULERD and a haptic device according to neurorehabilitation theory. In a preliminary study, a healthy user was able to manipulate the haptic device with one hand (intact hand for hemiplegic patients) when the upper arm was fixed, and the ULERD assisted in moving the other hand (impaired upper limb for hemiplegic patients). To implement bilateral training, the kinematics of one upper limb (intact limb) and the haptic device is analyzed, respectively. The angles of the three active DoFs are determined via integration. An inertia sensor is used to evaluate the kinematics resolution. The ULERD was evaluated by experienced therapists during the design process to determine its potential for clinic application. Experimental results indicate that the kinematics resolution is effective and that this type of bilateral movement can be implemented using the ULERD and the haptic device.

Keywords: Phantom premium, MTx sensor, Exoskeleton device, Bilateral training

1. Introduction

Stroke, or cerebrovascular accident, is the leading cause of disability. Approximately 800,000 people suffer a stroke each year in the United States [1]. A stroke can result in decreased motor function, which directly influences the daily activities of patients [2]. Rehabilitation is thus an important research topic. Previous studies have reported the brain neurons of some animals and humans exhibit plasticity [3-6] and that motor cortex functions can be altered by individual motor experiences [7]. Based on this, some strategies that benefit the recovery of stroke patients have been reported, including intensive intervention [8], task-orientation training [9,10], and bilateral training [11]. Most studies have focused on unilateral training, which is performed on the impaired upper limb. In some training methods, the intact upper limbs of stroke survivors have to be restricted because they unconsciously compensate for the impaired upper limbs to complete the task, which is known as constraint-induced movement therapy (CIMT) [12]. This method effectively forces impaired limb recovery, but many patients have stated that they were not interested in participating in this kind of therapy [13]. Bilateral training can be adopted because over half of stroke suffered hemiparesis and unimpaired side can guide the training of impaired side [1]. One of the advantages of bilateral training is that training strategy comes from the individual [14].

The motor function of the impaired limb recovers during bilateral training while the intact limb guards and compensate its performance. Reported the interlimb coupling on the performance of bilateral limbs could enhance recovery of the impaired limb. [15,16]. With the development of robotics and mechatronics, some neurorehabilitation strategies can be implemented using robots. Robotic rehabilitation can provide more intensive, longer-duration, and higher-level training compared with manual arm training. Upper limb robots that are currently in use can be classified into two groups: end-effector type and exoskeleton type. An example of the former is the MIT-Manus [17,18]. It allows two degrees of freedom (DoFs) for movement of the upper limbs, including wrist, elbow, and shoulder movements, by performing task-oriented training. Another robot, the Mirror-Image Motion Enabler (MIME),
provides bilateral movements that the impaired upper limb can perform as the intact upper limb moves [19,20]. A third robot, Gentle/s, was developed for machine-mediated therapy for the neurorehabilitation of stroke patients aiming to improve the quality of treatment and reduce costs [21]. Most commercial devices for upper limb rehabilitation or assistance are end-effector type. Although such devices may be simple to use, arm posture cannot be confirmed and there is a risk of joint injury [22].

Exoskeleton devices can drive individual joint to perform the training of human upper limb. A typical exoskeleton device, the MEDARM, is based on a cable-driven, curved track mechanism that provides independent control of all five major DoFs at the shoulder complex [23]. The ARMin [24] is an exoskeleton device with six independently actuated DoFs and one coupled DoF. It can provide passive and active rehabilitation to stroke patients and can significantly improve motor function of the paretic arm in some stroke patients, even those in a chronic state [25]. These systems allow passive and active rehabilitation and provide an adequate range of movement. However, most of them are heavy and thus cannot be moved easily, making them unsuitable for home rehabilitation. Few rehabilitation robots have been adopted for bilateral training. One example, the MIME, is an adapted PUMA robot, not an exoskeleton device, which restricts the intact limb by a forearm splint. Another bilateral arm training robot was developed based on a master-slave control method. It mainly is used for training elbow joints [26]. An upper limb exoskeleton rehabilitation device (ULERD) is proposed in the present study (ULERD) that can potentially be used to assist the elbow and wrist of the impaired limb of mild stroke patients [27]. A haptic device (Phantom Premium) is adopted here for the intact side to guide the motion of impaired limb. It was easy for subjects to manipulate it. The rehabilitation strategy is implemented by calculating two forward kinematics equations and avoiding complex inverse kinematics of motion, which improves efficiency.

2. Materials and methods

The proposed ULERD is lighter than existing devices, actuated by motors, compact, and able to be pucked around the elbow joint. Bilateral training is implemented using the ULERD and a commercial haptic device (Phantom Premium 3.0). ULERD design was evaluated by physical therapists with a lot of experience in upper limb rehabilitation. Considering the critical requirement of safety, preliminary experiments were performed on a healthy user to evaluate the system. The user manipulated the handle of the haptic device with the left hand (representing an intact hand). The ULERD was worn on the right limb (representing an impaired limb). The manipulating information was obtained using a motion solution unit (MSU) and the ULERD was driven by three motors using a control unit (CU). A 3D animation based on OpenGL was created to show the motion of the upper limb in real-time. Bilateral synchronous movement was then implemented. To evaluate the resolution accuracy of the intact upper limb when using the Phantom Premium, an inertia sensor (MTx, Xsens Technologies B.V.) was used to detect the three motions of the intact upper limb.

2.1 Human upper limb anatomical analysis

As an exoskeleton device, the ULERD was designed considering the results of an anatomical analysis of the human upper limb. The motions performed by a human upper limb at the elbow and wrist were identified from the literature. The motions include elbow flexion/extension (F/E), forearm pronation/supination (P/S), and wrist flexion/extension. The motion mechanism of forearm pronation/supination decides the place where the ULERD is fastened to the forearm. Unlike other systems, the variation of the flexion/extension axis (FEA) in the wrist and elbow is considered. The range of each motion was also confirmed, which is important for designing the motion range of each joint and the safety mechanism.

2.2 Design requirements and description of the ULERD

The major design requirements were: (1) wearability, (2) low weight, (3) compliant mechanism for human upper limbs, (4) reasonable assistance torque and range of motion, (5) suitability and (6) safety. Since the user has to support the device, wearability is very important. To improve wearability, the motor installation strategy and method of fixing the ULERD to the upper limb are considered.

The counter torque is considered during motor installation. If motors are mounted in unreasonable places, the ULERD will move in relation to the upper limb, especially at the elbow joint. Therefore, the direction of the counter torque of motors in the elbow joint should be perpendicular to the axis of the upper arm. Because the required torque derived from the motors of the forearm and wrist is low, the forearm and wrist components remain stable with relation to the upper limb where they are fixed, as shown in Fig. 1(a).

The upper arm is fixed to the device using elastic belts that pass through slotted holes in the upper arm part, as shown in Fig. 1(a). This type of fastening method provides adequate support and decreases the influence of biceps brachii muscle constriction. Anatomically, forearm pronation/supination are mainly caused by rotating the distal end of the radius around the head of the ulna. Therefore, the forearm component is fastened near the elbow joint to facilitate forearm pronation/ supination. A handle is commonly used in some devices for hand fixation [28,29]. However, a handle is not suitable for a patient who is not able to grasp it; therefore, in the ULERD, the user’s hand can be fixed to frame 3 with an elastic belt. Based on our experience of wearing the ULERD, it can be easily worn.

(2) low weight: It is necessary to minimize the weight of an exoskeleton device to minimize power consumption and maximize patient comfort.

To decrease the weight of the device, brushless DC (BLDC) motors (Maxon Technology), which have a high power density and high-gear-ratio gearheads, are utilized. Power is transmitted via a cable drive, which is lighter than a gear or chain drive. The main frames of the device are made of aluminum. The total
weight of the device body is 1.3 kg.

The cable-drive transmission was improved compared with that commonly used in haptic devices, whose cable drives are limited by the friction of the intertwist in the helically grooved shaft. The middle of the cable was fixed to the helically grooved shaft by means of a mechanical method [27,30].

(3) compliant mechanism for human upper limbs: The ULERD is an exoskeleton device that is aligned with the anatomical joints above it. Unlike other exoskeleton devices for the upper limbs [31,32], the ULERD provides two passive DoFs (one translation and one rotation) at the elbow joint and two DoFs (one translation and one rotation) at the wrist joint through shafts and slides, respectively [33].

There are several reasons for adding passive DoFs. First, previous anatomical analysis studies have indicated that human joint motion, including that of the elbow joint, is complex, and that the FEA of the elbow joint is spatially variable [34]. This could result in additional direct influence on the forearm during training. Second, supposing that the FEA of the elbow joint is ideally stable, the position of the user’s elbow joint with respect to the rotation center of the device varies, and even a given user’s elbow joint can be positioned differently between trials. Finally, adding passive DoFs can make the motion of the elbow joint of the device independent from that of the wrist. Above all, it is necessary to add this type of passive DoF.

(4) reasonable assistance torque and range of motion: As a portable exoskeleton device for upper limb rehabilitation, sufficient assistance should be provided, but excessive torque should be avoided. According to physicians’ experience and our experiments results, the continuous maximum torque in the elbow is 15 Nm and those in the other two DoFs are 7 Nm, which is sufficient for stroke survivors who have no severe ankylosis. Range of motion is another important requirement. Generally speaking, the device should provide enough range of motion to the upper limbs. The range of motions of the human upper limbs and the device are shown in Table 1.

(5) suitability: To ensure that most users’ limbs are properly aligned with the exoskeleton, some adjustable mechanisms have been designed in certain exoskeleton devices. The pons are connected to frame 2 by two bolts passing through the curved holes in the frame and the slotted holes in the pons (Fig. 1(b)). By adjusting the position of the bolts in the holes, the variation in the position between the wrist components and the elbow joint of the device is 40 mm, and the variation in the angle between the pons and frame 2 is 20 degrees, which satisfies the carrying angle of the human elbow joint [35].

(6) safety: As the system is in direct contact with the human operator, safety is very important for a rehabilitation device. A safety program reads data derived from a load cell to detect the force between the forearm and frame 2 (Fig. 1(b)). Besides the programmed safety precautions, a mechanical mechanism was designed to prevent overload during rehabilitation. The helical capstan shaft is set apart from the motor shaft during overload or when a preset load is reached for a particular patient. Specifically, the axle sleeve of the motor is connected to the helical capstan shaft by the friction derived from adjusting an outer thumbnut (Fig. 1(b)).

The proposed rehabilitation device has several advantages. First, it is light, compact, and can be puckered around the elbow joint. Second, it is more compliant to human joints by the addition of four passive DoFs. Third, it is more intuitive and simpler to use than existing devices because it was designed for the human upper limbs; little time is required to understand how to interact with it. It is also easy to wear. Finally, the hardware and software setup ensure safety.

2.3 Methodology of bilateral training

This research focused on bilateral training using the ULERD as a rehabilitation device on the impaired side and the Phantom Premium as a manipulator on the intact side. There are several types of bilateral training. This study considers joint space symmetry, in which the motions are mirrored and the joints of each limb follow the same angles [14]. This allows synchronous motion between the intact and impaired sides, as in mirror training. This type of training has been proven effective in previous research [36]. The precondition for implementing bilateral training using these devices is detecting the motion of the intact limb. This is done by integrating a forward kinematics equation for the human upper limbs and the
Phantom Premium in the MSU. The angle velocity of each joint is sent to the CU to complete bilateral training. Figure 2 shows a detailed schematic diagram of bilateral training.

2.3.1 Motion solution unit

The MSU has three main parts, namely the forward kinematics equations for the upper limbs and Phantom Premium, respectively, and their integrals.

![Figure 2. Schematic diagram of bilateral training.](image)

(1) Forward kinematics equation for the upper limbs

Rigid-body frames are assigned for the forearm and hand on the intact side following the convention for modified Denavit-Hartenberg (DH) parameters [37]. As shown in Fig. 3, the origins of these frames were assigned as \( \{O_0\}, \{O_1\}, \{O_2\}, \{O_3\}, \) and \( \{O_4\} \). Frame 0 is fixed at the elbow joint, which is immobile in this system. The origin of frame 4 was positioned at the rotation center of the end-effector of the Phantom Premium when a user grips it with the left hand, and frame 4 was fixed on frame 3. A convenient relationship between the user’s hand and the end-effector of the Phantom Premium was thus created. It was assumed that the position and posture of the hand in Fig. 3 are the initial status. The geometric parameters for the upper limbs, namely the angle of elbow extension/flexion \((\theta_2)\), the angle of the forearm pronation/supination \((\theta_3)\), and the angle of the wrist extension/flexion \((\theta_4)\).

The forward kinematics equation for the upper limbs can be obtained as:

\[
^jA_i = ^{i-1}A_{i-1}^{i-1}A_{i-2}^{i-2}A_{i-3}^{i-3}A_{i-4}^{i-4}A_i
\](1)

where \(c\) and \(s\) represent cosine and sine, respectively. \(^jA_i\) is the transform matrix from frame \(i\) to frame \(j\), and \(1, 2, 3\), and \(4\) correspond to \(\theta_2, \theta_3, \) and \(\theta_4\), respectively. The variables \(d_i, d_{i-2}, d_{i-4}\), and \(d\) are shown in Fig. 3.

(2) Forward kinematics equation for Phantom Premium

The forward kinematics equation is used to obtain the position and posture of the end-effector of the Phantom Premium. The Application Programming Interface (API) toolkit provides a \(4 \times 4\) transformation matrix that includes the roll, pitch, and yaw of the end-effector; however, it is difficult to use it to transform the relationship for the user’s left limb. Therefore, the kinematics are calculated from the base to the end-effector using DH algorithms based on the encoder installed at each joint. Figure 4 shows one frame for the base and six frames for each link.

The entire transformation matrix for the Phantom Premium is:

\[
^0A_4 = ^0A_3^0A_2^0A_1^0A_0^0A = \begin{bmatrix}
  n_x & o_x & a_x & p_x \\
  n_y & o_y & a_y & p_y \\
  n_z & o_z & a_z & p_z \\
  0 & 0 & 0 & 1
\end{bmatrix}
\](2)

where

\[
\begin{align*}
  n_x & = c_{\epsilon_{62}} c_{\epsilon_{53}} c_{\epsilon_{63}} - c_{\epsilon_{62}} s_{\epsilon_{53}} s_{\epsilon_{63}} + s_{\epsilon_{62}} s_{\epsilon_{53}} c_{\epsilon_{63}} \\
  o_x & = c_{\epsilon_{62}} s_{\epsilon_{53}} c_{\epsilon_{63}} - c_{\epsilon_{62}} c_{\epsilon_{53}} s_{\epsilon_{63}} - c_{\epsilon_{62}} s_{\epsilon_{53}} c_{\epsilon_{63}} \\
  a_x & = s_{\epsilon_{62}} c_{\epsilon_{53}} c_{\epsilon_{63}} + c_{\epsilon_{62}} s_{\epsilon_{53}} s_{\epsilon_{63}} + s_{\epsilon_{62}} c_{\epsilon_{53}} s_{\epsilon_{63}} \\
  p_x & = s_{\epsilon_{62}} c_{\epsilon_{53}} c_{\epsilon_{63}} + c_{\epsilon_{62}} s_{\epsilon_{53}} s_{\epsilon_{63}} + s_{\epsilon_{62}} c_{\epsilon_{53}} s_{\epsilon_{63}} \\
  n_y & = c_{\epsilon_{62}} s_{\epsilon_{53}} - c_{\epsilon_{62}} c_{\epsilon_{53}} s_{\epsilon_{63}} + c_{\epsilon_{62}} s_{\epsilon_{53}} c_{\epsilon_{63}} \\
  o_y & = s_{\epsilon_{62}} c_{\epsilon_{53}} - s_{\epsilon_{62}} c_{\epsilon_{53}} s_{\epsilon_{63}} + c_{\epsilon_{62}} s_{\epsilon_{53}} c_{\epsilon_{63}} \\
  a_y & = s_{\epsilon_{62}} s_{\epsilon_{53}} c_{\epsilon_{63}} + c_{\epsilon_{62}} s_{\epsilon_{53}} s_{\epsilon_{63}} - s_{\epsilon_{62}} s_{\epsilon_{53}} c_{\epsilon_{63}} \\
  p_y & = s_{\epsilon_{62}} s_{\epsilon_{53}} c_{\epsilon_{63}} + c_{\epsilon_{62}} s_{\epsilon_{53}} s_{\epsilon_{63}} - s_{\epsilon_{62}} s_{\epsilon_{53}} c_{\epsilon_{63}} \\
  n_z & = s_{\epsilon_{62}} - c_{\epsilon_{62}} s_{\epsilon_{53}} c_{\epsilon_{63}} - c_{\epsilon_{62}} s_{\epsilon_{53}} s_{\epsilon_{63}} - s_{\epsilon_{62}} s_{\epsilon_{53}} c_{\epsilon_{63}} \\
  o_z & = \epsilon_{62} - c_{\epsilon_{62}} c_{\epsilon_{53}} - c_{\epsilon_{62}} s_{\epsilon_{53}} c_{\epsilon_{63}} - s_{\epsilon_{62}} s_{\epsilon_{53}} c_{\epsilon_{63}} \\
  a_z & = \epsilon_{62} - c_{\epsilon_{53}} - c_{\epsilon_{62}} c_{\epsilon_{53}} - c_{\epsilon_{62}} s_{\epsilon_{53}} c_{\epsilon_{63}} - s_{\epsilon_{62}} s_{\epsilon_{53}} c_{\epsilon_{63}} \\
  p_z & = \epsilon_{62} - c_{\epsilon_{53}} - c_{\epsilon_{62}} c_{\epsilon_{53}} - c_{\epsilon_{62}} s_{\epsilon_{53}} c_{\epsilon_{63}} - s_{\epsilon_{62}} s_{\epsilon_{53}} c_{\epsilon_{63}}
\end{align*}
\]

where \(\epsilon_{62}\) and \(\epsilon_{63}\) are the sine and cosine of the summation of angles \(\theta_2\) and \(\theta_3\) according to Fig. 4, respectively.

(3) Integration of the upper limb and Phantom Premium forward kinematics equations

Figure 5 shows the initial state when the user grips the end-effector of the Phantom Premium with his left hand. According to this figure, the transformation matrix from the original frame of the upper limbs to the Phantom Premium is:

\[
^0A_y = \begin{bmatrix}
  0 & 0 & -1 & -r \\
  -1 & 0 & 0 & n \\
  0 & 1 & 0 & m \\
  0 & 0 & 0 & 1
\end{bmatrix}
\](3)

where \(n, r, \) and \(m\) are the displacements between the original coordination of the Phantom Premium and the upper limbs along the \(x, y, \) and \(z\) axes, respectively.
also be obtained using this technique, since it is quite complicated, a program is used to determine its value.

2.4.2 Control unit (CU)

For joint space symmetry of bilateral training, angle tracking is considered. Since the angle is the time integral of velocity, the velocity control model is chosen in the CU.

The general equation of a proportional-integral-derivative (PID) controller is given in Eq. (9). \( U(t) \) is the output signal of the PID controller, which is the summation of the proportional, integral, and derivative terms.

\[
U(t) = K_r \epsilon(t) + K_i \int \epsilon(t) dt + K_d \frac{d\epsilon(t)}{dt}
\]  

(9)

With a large proportional gain \( K_r \), the system response is faster, leading to higher error. An excessively large proportional gain leads to system instability. With a large integral gain \( K_i \), the steady-state errors of the system are reduced more quickly. With a large derivative gain \( K_d \), the overshoot of the system can be reduced. In this research, the controller of the Maxon motor has a user interface for setting the relative parameters, including the parameters of PID, so it is open and easy to use. The API function provided by Maxon Technology can also be called directly. The parameters were obtained using a query command and then modified based on the original parameters.

3. Results and discussion

A detection algorithm was developed for the upper limbs using the six-DOF Phantom Premium and a visual interface was created for observing the experiments. The intact upper arm was kept immobile, and an inertia sensor (MTx sensor) evaluated the forearm angle and posture of the palm during the experiments. A healthy subject manipulated the Phantom Premium using his left limb (representing an intact limb), and wore the ULERD on his right limb (representing an impaired limb). The experiments required the subject to perform an elbow extension, a forearm pronation, a wrist extension, a wrist flexion, a forearm supination, and an elbow flexion in that order. Figure 6 shows the subject performing bilateral training using the Phantom Premium and an exoskeleton device. Table 2 lists the experimental parameters.

![Figure 5. Frame assignment for the upper limb and the Phantom Premium.](image)

![Figure 6. Self-rehabilitation training using the Phantom Premium and an exoskeleton device.](image)
Table 2. Geometric parameters for Phantom Premium

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (mm)</th>
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<tr>
<td>l</td>
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<td>k</td>
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<td>130</td>
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Figure 7(a) shows the elbow extension and flexion angles of the left limb, which were detected using the Phantom Premium, MTx sensor, and rotation angles of the joint of the ULERD. The rotational angles detected by the Phantom Premium and obtained through the MSU are close to those detected by the MTx sensor at a given angle. The small deviations between the two trajectories can be caused by various factors. In this case, it is thought that the rotation axis of the elbow joint changed during extension and flexion, so that the upper arm was not stable and the MTx sensor was not stable during wrist pronation and supination. Data derived from the Phantom Premium were processed as an input signal and an output motor rotation of the elbow joint in synchronization with the CU, so that these two trajectories remained close to each other. Figures 7(b) and (c) show the forearm pronation/supination and wrist extension/flexion detected by the Phantom Premium, the MTx sensor, and the joint angles of the ULERD. Figure 7(c) indicates more consistent angles trajectories detected by the MTx sensor and Phantom Premium than those in Fig. 7(b). In other words, the posture of the palm was detected more accurately. These results also indicate that the algorithm is effective and can be used to detect upper limb motion.

The ULERD was designed as a wearable exoskeleton device for upper limb rehabilitation. The mechanism and materials can be further optimized since the ULERD was manually designed and fabricated. The proposed device is still at the laboratory level and cannot be directly used in application. Although the trajectories from the Phantom Premium and the inertia sensor had some deviations, this would be permitted because physical rehabilitation does not require high accuracy. The errors were partly caused by the motion of the skin, muscles, and bones of the upper limbs. To implement the preliminary bilateral training and evaluate the kinematics analysis of the proposed system, a healthy user participated in the experiment. The limb was derived by the ULERD and the subject does not contract the muscle to perform the motion. Even under these conditions, it was difficult to analyze the dynamics of the system. Therefore, only the kinematics was considered, which can be implemented by using velocity and position loop control.

4 Conclusion

Rehabilitation based on robots is an important field of research. This study implemented bilateral training using the developed ULERD and the Phantom Premium. The ULERD has three active DoFs and four passive DoFs. A portable and wearable exoskeleton device for the upper limbs was designed. The ULERD was evaluated by physical therapists with a lot of experience in upper limb rehabilitation. Considering the critical requirement of safety, preliminary experiments were performed by a healthy user to evaluate the system. According to the results of mirror training of bilateral limbs focused on the elbow and wrist joints, the proposed algorithm was effective and could be used to detect upper limb motion. The accuracy of bilateral training was feasible according to the therapist. Unlike a general joystick, a haptic device not only exerts force on users, but can also detect the movement of the upper limb if the upper arm is stable because of its six DoFs and adequate work range. Therefore, the system can potentially monitor the impaired upper limb’s performance by following the intact upper limb. This study focused on the design process of the ULERD under the constructive advice from experienced therapists and motion detection of the user’s left upper limb (intact limb for patients) because it is important in bilateral rehabilitation. Experimental results show that the algorithms worked effectively. Moreover, the proposed system could be used for remote rehabilitation.
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References


