Abstract—An innovative bilateral master-slave control method for an upper limb rehabilitation robot system which can afford training for hemiplegic patients is introduced. The system consists of two identical motors with the master motor working in the generating state and the slave motor working in the electromotion state. Based on hemi-disabled characteristic of hemiplegic patients, the healthy limb is used to operate the master motor to generate electric energy, which in turn powers the slave motor to rotate and support impaired limb in motion imitation, thus realizing rehabilitation training. An experimental prototype with energy supplement control was developed. The appropriate amount of energy is provided for the master-slave closed-loop circuit to compensate the inside energy loss, and further to achieve good motion tracking performance. Test experiments were conducted and the results confirm that the proposed system is capable of achieving motion tracking, energy recycling, and force sensing without force sensors. Thus, this master-slave control system has a great potential for application in rehabilitation robot systems.

I. INTRODUCTION

The percentage of aged persons is continuously increasing in many countries, which is becoming a social problem demanding concern from different fields including social science, medical science and engineering. This trend is particularly rigorous in Japan, where the aged (over 65 years old) accounted for 20.8% of the total population up to 2006 [1]. In the elderly, the prevalence of physical deterioration is sharply high, and their physical deterioration generally leads to degeneration of motor function. Besides, Hemiplegic limb impairment following a traumatic brain injury or a stroke, which is a common disease among the aged individuals, is a global issue recently. Both motor function deterioration and disability have an indirect influence on brain degeneration. Thereby, strength enhancement and function recovery are necessary in our aging society. This emerging requirement has stimulated considerable interest in the development of upper limb rehabilitation robots, which can act as a therapeutic aid for therapists under existing condition that the physical therapy resources are quite limited in many countries.

Among the numerous robots designed to deliver arm therapy, MIT-MANUS [2], [3], ARM-GUIDE [4], [5], and MIME [6]–[8] are three representative devices that have been tested extensively with hemiplegic patients. MIT-MANUS can support patients in executing reaching movements in a horizontal plane. However, a better improvement in shoulder strength and function needs arms to be trained in a vertical direction as well, so ARM-GUIDE and MIME which can give training in a three-dimensional workspace were developed. ARM-GUIDE that allows the subject to exercise against gravity can be used as both a diagnostic tool and a treatment tool for addressing arm impairment in hemiparetics. As a special function of MIME, the limb’s position can be inferred from the robot’s position based on the interaction forces. It was verified that the subjects who received MIME’s therapy had statistically higher gains in arm motor function by having the both upper limbs execute movements that mirror one another. However, these robotic arms are heavy in weight and must be fixed on walls and poles, so the motion space is limited and patients are easily to feel excess fatigue. Otherwise, these robots are complex to set up by patients themselves and are not suitable for a rehabilitation training program at home [9].

A home environment makes it possible to increase duration patients spend in rehabilitation activities, thus, it can ensure a high level of intervention with adequate intensity and frequency to improve the motor recovery [10]. In addition, the home-based rehabilitation can reduce economic burden to a certain extent. Therefore, the development of robots which can be easily used in patients’ home is a new tendency recently. For example, a new human motion tracking system [11] using two body-mounted inertial sensors to measure upper limb motion was developed for home-based therapy. In this system, motion tracking is implemented with a pure position control and a visual feedback but without sensible force feedback, thus operators can not be well informed about the exact status of the impaired limb. Since interaction conditions between the robot and the patient may vary considerably depending on the patient's kinetic capabilities and unpredictable reactions to therapeutic stimuli [12], the security and reliability of the system can not be ensured. A force assistant master-slave tele-rehabilitation robotic system [13], which realizes impedance transfer by means of force transducers, enables therapists to experience the interaction

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force between the robot and the impaired limb. However, the operator of the above robots is the therapist rather than the patient himself/herself. Using these traditional methods, the patient is trained with less motivation and activity, which is unfavorable for acquiring good recovery effect. RoboWear [14], a wearable robotic arm with high force-reflection capability, can be worn by a patient to move around freely and operated by the patient himself. The system realizes force-reflection with two pressure sensors.

In general robotic systems, patients can only be trained passively. A new system which can perform training in both active and passive modes was introduced in [15]. However, except that both a position controller and a force controller are applied, the control strategy in the master and slave sides should be exchanged when the system works in different modes. This increases control complexity seriously. Besides, force feedback in conventional robots is realized with force sensors, which have the drawbacks of introducing control complexity, high system cost, and mounting difficulty. In addition, there is no energy transmission from the operator to the impaired arm in traditional rehabilitation systems.

Working from the above realization, a novel master-slave control scheme utilizing the healthy limb of hemiplegic patients is proposed for home-based rehabilitation robots. With this system, the patients can directly feel the difficulty of driving the impaired limb and sense the degree of comfort of the affected limb, further, make a timely and proper adjustment in the input force from healthy limb, guiding the impaired limb to exercise with relative safety. The system is characteristic of self-assistance, compaction, bilateral control, energy recycling, and force and motion sensing without force sensors or a force controller.

II. METHODS AND MATERIALS

A. Theoretical analysis: force sensing

The master-slave control system contains two identical DC motors with the master motor being operated by the healthy limb and the slave motor tracking the master motor to support the impaired limb to exercise. The master motor as a generator powers the slave motor, which works in the electromotion state, to rotate and support the impaired limb in rehabilitation activities. The equivalent closed-loop circuit of the master-slave system is shown in Fig. 1, where $M_1$ and $M_2$ represent the master motor and slave motor respectively.

Based on the dynamics mechanism, the motion equations of the two motors are written as

$$
\begin{align*}
T_1 &= T_{M_1} + T_0 \\
T_{M_2} &= T_2 + T_0 \\
T_{M_1} &= T_{M_2} = C_T i
\end{align*}
$$

where $T_1$ and $T_2$ are the mechanical torques in the master and slave motor shafts, also represent the input torque obtained from the operator and the output torque provided for driving workload ($T_n$ and $T_out$); $T_{M_1}$ and $T_{M_2}$ are the electromagnetic torques which equals to the multiplication of the motor torque constant $C_T$ and the closed-loop current $i$, and has the same magnitude; $T_0$ is the no-load torque caused by no-load losses including mechanical energy loss, magnetic core loss, and additional loss. According to (1), the relationship between input and output torque can be expressed as

$$
T_1 = T_2 + 2T_0
$$

This indicates that in order to drive workload, the input torque provided for the master motor should be no less than the summation of $T_1$ ($T_{\text{out}}$) and $2T_0$. If the operator input a torque less than this summation, he/she can feel the difficulty and increase the input force accordingly to get balance with the reaction force. Hence, the system is capable of realizing force sensing without a force sensor or a force controller, which simplifies both the hardware and software design greatly. Actually, the force can be reflected in the master site is due to the same working current of the two motors. Besides, no-load torque also has reflection in the master site. When the no-load torque varies following the rotational speed, the operator can feel its change and adjust the input force to obtain an expected motion speed. It implies that the operator can control the input force according to the force and motion sensing.

B. Theoretical analysis: energy recycling

Based on the electrical mechanism, the dynamic voltage balance equation of the master-slave circuit can be written as

$$
Ri + L \frac{di}{dt} = e_1 - e_2 = C_T \omega_1 - C_T \omega_2
$$

where $R$ and $L$ denote the armature resistance summation and inductance summation, respectively; $\omega_1$ and $\omega_2$ are the rotational speeds of the master and slave motors, also are defined as the input and output speeds ($\omega_{\text{in}}$ and $\omega_{\text{out}}$); and $e_1$ and $e_2$ are the armature voltages, which depend on the motor torque constant and the motor speed. As can be seen from (3), the energy generated by the master motor is transmitted to the slave motor except the energy loss in the resistance and inductance, thus realizing a kind of energy recycling. Furthermore, the smaller the energy loss in the electronic closed-loop (energy recycling) circuit will lead to $\omega_2$ with a nearer approach to $\omega_1$. Therefore, a small current is favorable.
C. Master-slave control system design

During rehabilitation operation, in order to drive the impaired limb to imitate the motion of healthy limb correctly, high motion tracking performance is necessary. However, the energy loss in the closed-loop circuit makes it impossible to realize an acceptable motion tracking performance. Hence, the appropriate amount of energy is supplied for the closed-loop circuit to compensate the inside energy loss. On the other hand, it is difficult to drive the impaired limb using a small DC motor directly. Thus, gearbox mechanism is adopted to increase the driving power of the system. The corresponding introduction is given as following:

1) Energy supplement: The master-slave control circuit with energy supplement is shown in Fig. 2. Since the energy supplement control is aimed at achieving precise motion tracking, the input speed and position are the tracking objectives of the output site. The amount of the compensatory energy is regulated according to the speed difference and the position difference between the input and output site. Here a conventional PID (proportional-integral-differential) control is used to construct a basic position-speed feedback (energy supplement) controller. Since the input speed is controlled by the operator, it is not a constant. If the differential control is applied to the speed difference between the input and output site directly, the fluctuation of the input speed may lead to overshoot and oscillation of the whole system. Therefore, the differential control is applied only to the output speed.

The regulation of the supplementary energy is realized by adjusting the duty cycle of a pulse-width modulated (PWM) signal, which is fed to an H-bridge driver to provide moderate energy for the closed-loop circuit. The compensated voltage, $e_{\text{sup}}$, can be calculated using

$$e_{\text{sup}} = (2\alpha - 1)U_s$$

where $\alpha$ is the duty cycle of the PWM signal, and $U_s$ is the supply voltage of the H-bridge driver.

In the system design, a bipolar driving mode is adopted to drive the H-bridge driver. Therefore, when $\alpha = 50\%$, the $e_{\text{sup}}$ equals to zero; when $\alpha > 50\%$, the $e_{\text{sup}}$ is positive; when $\alpha < 50\%$, the $e_{\text{sup}}$ is negative. The amount as well as the direction of the compensated energy can be controlled by the magnitude of $\alpha$ directly. During operation, the energy is compensated in the form of increments. There are three cases as follows:

- When motors rotate with a positive direction (clockwise), $\alpha_{\text{new}} = \alpha_{\text{old}} + \Delta \alpha$.
- When motors rotate with a negative direction (counterclockwise), $\alpha_{\text{new}} = \alpha_{\text{old}} - \Delta \alpha$.
- When motors converse their direction, $\alpha$ is needed to carry out complementation calculation: $\alpha_{\text{new}} = 1 - \alpha_{\text{old}}$, where $\alpha_{\text{old}}$ and $\alpha_{\text{new}}$ represent the duty cycles before the adjustment and after the adjustment, respectively.

2) Gearbox mechanism: In order to acquire a symmetric mechanism, two identical gearboxes are employed in the master and slave sites. The equivalent structure block is shown in Fig. 3. The symmetric structure makes the system can be operated in either direction, thus, hemiplegic patients with the affected arm in either right side or left side can carry out rehabilitation training with this system. Meanwhile, the structure makes the impaired limb can be trained in two modes including passive movement and active movement.

In passive movement mode, the healthy limb exerts more force to overcome the resistant force imposed by the impaired limb, so the impaired limb is moved passively. The patient feels the resistant force reflected in the master site, and controls the movement trajectory as well as the velocities by regulating the input force of the healthy limb. On the other hand, in active movement mode, according to the movement intention of the impaired limb, the patient delivers less resistant force with the healthy limb than the force produced by the impaired limb, and the impaired limb overcomes the force exerted by the healthy limb to move actively.

The gear transmission relationship can be expressed as

$$\begin{align*}
\omega_1 &= N\omega_{in}, \omega_2 = N\omega_{out} \\
T_1 &= NT_1, T_{out} = NT_2
\end{align*}$$

where $N$ is the gear ratio of the two gearboxes; $\omega_1$, $\omega_2$, and $T_1$, $T_2$ are still used to express the rotor speeds and the mechanical torques in the two motor shafts; $\omega_{in}$ and $\omega_{out}$ stand for the input and output speeds; $T_{in}$ and $T_{out}$ represent the input and output (load) torques of the system. The gear ratio can be selected by dividing the motor rated torque into the load torque which can be estimated with the radius of the force arm and the mass of the unhealthy limb. As can be seen in (5), the mechanical torques in the motor shafts is...
minified \( N \) times. Hence, the system can possess sufficient driving power to support the impaired arm even though the load-bearing capability of the DC motors is limited.

Gearbox mechanism also has other influence over the system except increasing load-bearing capability. On one hand, the current is reduced due to the minified mechanical torques in motor shafts (refer to (1) and (5)), thus the energy loss caused by the current, with the resistance loss as the primary portion, is reduced to a certain extent. Therefore, the less supplementary energy is required for realizing motion tracking. However, there is energy loss in the gearboxes because of mechanical friction. That is, the operator is required to deliver more input power to drive the same workload with the same rotational speeds.

On the other hand, the gearboxes make the input and output torque has a new relationship given in
\[
T_{in} = T_{out} + 2NT_0
\]
(6)
The difference between input and output torque is magnified \( N \) times, thus a larger input torque is required for driving the same load. While this does not affect force sensing capability on the premise that \( 2NT_0 \) is not much larger than \( T_{out} \) (\( 2NT_0 \) is smaller than \( T_{out} \) or they are almost in the same magnitude level). However, the reflection of no-load torque related to speed is strengthened, with the motion (speed) sensing capability enhanced relatively.

3) Power transmission analysis: The power transmission flowchart of the master-slave control system is shown in Fig. 4, where the master/gear unit and the slave/gear unit express the sites attached with more active force and less resistant force, respectively; \( P_{in} \) and \( P_{out} \) denote the input power and output power of the system; \( P_{in,1} \), \( P_{out,1} \), and \( P_{out,2} \) represent the input mechanical power, the electromagnetic power, and the output electric power of the master motor, respectively; \( P_{in,2} \), \( P_{out,2} \), and \( P_{out,3} \) are the input electric power, the electromagnetic power, and the output mechanical power of the slave motor, respectively; and \( p_{sup} \) is the compensated energy power for the inside closed-loop circuit. The various energy losses in the system are listed in Table I. Mechanical loss is caused by mechanical fraction, while core loss is induced by the alternative magnetic field towards armature core, and excitation loss is the copper loss in the excitation winding. The above losses are called as no-load loss in general, and are primarily related to the rotational speed. Resistance loss and contact loss are caused by the current and change mainly following the current variation. These two kinds of losses are called as load loss.

<table>
<thead>
<tr>
<th>Gear</th>
<th>Mechanical</th>
<th>Core</th>
<th>Additive</th>
<th>Resistance</th>
<th>Contact</th>
<th>Excitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_g )</td>
<td>( P_m )</td>
<td>( P_{Fe} )</td>
<td>( P_h )</td>
<td>( P_a )</td>
<td>( P_{b} )</td>
<td>( P_f )</td>
</tr>
</tbody>
</table>

The relationship between the input power from the operator and the output electric power of the master motor is given by:
\[
P_{out} = P_{in} - (P_m + P_{Fe} + P_h) - (P_a + P_{b} + P_f)
\]
(7)
In the slave site, there is a reverse energy transmission flow, with the relationship between the input and output power expressed as
\[
P_{out} = P_{in} - (P_a + P_{b} + P_f) - (P_m + P_{Fe} + P_h) - P_g
\]
(8)
As can be seen in Fig. 4, the supplementary energy is used to compensate energy losses including \( p_a \), \( p_b \), and \( p_f \) in the two motors. When the system achieves motion tracking accurately, \( \omega_{out} \) equals to \( \omega_{in} \). According to (5), we can obtain
\[
P_{in,1} = P_{out,1}
\]
(9)
Thus the supplementary energy can be expressed as
\[
p_{sup} = 2(p_a + p_b + p_f)
\]
(10)
where \( p_a \) accounts for the major part among the inside energy losses.

III. EXPERIMENTAL STUDY

A. Experimental platform

In order to verify the effectiveness of the above approach, a preliminary test platform, as shown in Fig. 5, was built for experiments. It was composed of two DC motors (geared DC motor, 1271 series, N=43, McLennan co. UK), an H-bridge driver (TA7267BP, Toshiba co. Japan), two photoelectric encoders (BTE030, Besttechnology co. Japan), and a microprocessor (MC9S08QG8, Freescale co. USA). In order to carry out system performance analysis easily, a DC driving motor (82861010, Crouzet Co. France) instead of a human...
operator was used for driving the master motor in the experiment. It was controlled by a DC power directly, and was coaxially connected to the master motor.

The schematic diagram of the experimental system is shown in Fig. 6. During experiment, workload was attached to the slave part and the motor 82861010 provided driving power for the master part. The speed information was detected with the incremental encoders. The microprocessor collected the speed information through I/O ports, and worked out the duty cycle of the PWM signal with the position-speed control strategy. Then, the microprocessor outputted PWM signal for the H-bridge driver through the PWM output ports. The PWM signal enabled the H-bridge driver to supply compensatory energy for the master-slave circuit.

B. Force sensing test

In this experiment, the input power of the driving motor and the rotational speed of the master motor were tested when different loads were attached to the slave site. The input torque of the master motor was calculated by dividing the tested speed into its corresponding input power, which was deduced from the output power of the driving motor (82861010) and its work efficiency (about 39%) roughly.

The results regarding the relationship between the input and output torque are given in Fig. 7. It can be seen that the input torque increased following the increment of the load torque, verifying that the system has force sensing capability. There was a large difference between the input and output torque, this was caused by no-load torque and torque amplification function of the gearboxes. The load torque ($T_{\text{out}}$) together with the magnified no-load torque ($2NT_0$) are reflected in the master site. In real applications, even though $2NT_0$ is larger than $T_{\text{out}}$, the operator still can sense the load variation if $2NT_0$ and $T_{\text{out}}$ are in the same magnitude level.

C. Energy supplement test

The appropriate amount of energy was compensated for the system with a PID controller to achieve good motion tracking performance. The relationship among the energy loss in the circuit, compensatory energy and the electromagnetic power of the slave motor, $P_2-M$ (equals $P_1-M$ in balance state), was determined by measuring the current, the duty cycle of the PWM signal and the rotational speed of the two motors simultaneously with fixed workload in different input speeds condition. The input speed was regulated by altering the input power of the driving motor directly.

The corresponding powers were calculated using

$$
\begin{align*}
    p_{\text{sup}} &= (2\alpha - 1)U_i i \\
    p_a &= i^2 R \\
    P_{2-M} &= e_i i = C \omega_0 i
\end{align*}
$$

(11)

The calculated results are shown in Fig. 8. It is obvious that the supplementary energy was approximately coincident with the resistance loss. However, the former was slightly larger than the latter because contact loss and excitation loss also occurred in the energy recycling circuit (refer to (10)). In addition, the electromagnetic power of the slave motor was larger than the supplement energy, which confirms that the system has energy recycling capability.

IV. DISCUSSION

The experimental results verify the introduced theory and the feasibility of the proposed control method. However, there are still some drawbacks as follows:

1) The supplementary energy requirement was relatively high. In order to change this situation, we can use
motors with a larger torque constant and a smaller resistance (refer to (1) and (3)). Alternatively, we can increase the gear ratio of the gearbox in the master site. With \( N_1 \) and \( N_2 \) \((N_1 > N_2)\) denoting the gear ratios of the gearboxes in the master and slave sites, the electromagnetic power of the motors can be written as

\[
\begin{align*}
P_{1,M} &= C_f N_1 \omega_{in} \\
P_{2,M} &= C_f N_2 \omega_{out}
\end{align*}
\]

(12)

where \( \omega_{out} \) equals to \( \omega_{in} \), the master motor can generate more electromagnetic power than the power required in the slave site. If the two gear ratios are matched appropriately, the following relation can be achieved

\[
P_{1,M} - P_{2,M} \approx 2(p_o + p_b + p_f)
\]

(13)

Thus the demand for energy supplement can be reduced significantly. The viability of this method has been verified by practical tests with \( N_1 = 43 \) and \( N_2 = 21 \) in our experimental tests.

However, considering force sensing performance, the new relation between input and output torque is given by

\[
\begin{align*}
T_{in}/N_1 &= T_{ML1} + T_{0,1} \\
T_{out}/N_2 &= T_{ML2} - T_{0,2} \\
T_{in} &= N_1 T_{out} / N_2 + N_1 (T_{0,1} + T_{0,2})
\end{align*}
\]

(14)

where \( T_{0,1} \) and \( T_{0,2} \) denote the no-load torque of the master and slave motors. They are not same yet since the different speeds of the two motors. It is evident that force sensing capability is enhanced. However, the system has no symmetric mechanism any more. Hence, when the master part is situated in the impaired limb side, a larger input power of the healthy limb is required to rotate the impaired limb in the passive training mode.

2) In the experiments, encoders were employed to detect the speeds of the two motors and to calculate the required supplementary energy. In the next step, we can try to formulate the relationship between supplementary energy and the current with the method used in the above energy supplement test, and apply the deduced formulation along with detected current to calculate the required supplementary energy in practical applications. Then the system will never require any sensors. This can further improve system cost performance and enhance the potential for extensive applications in control fields.

3) The simple test experiments just preliminarily verified the feasibility of the method. Torque sensors will be used for the next test step to collect the input and output torques and to accurately verify force sensing capability. Besides, proper gearboxes and motors with higher power will be adopted to increase the driving power of the system. Furthermore, in order to make the system more suitable for the rehabilitation robotic application, a robot with multi-DOF mechanism will be developed by adopting a multi-motor combination in the future work.

V. Conclusion

The proposed scheme is characteristic of energy recycling, force sensing without force sensors, and bilateral control. If applying this scheme in the rehabilitation robotic system, the patients will be allowed to perform both the active and passive rehabilitation exercises independently. In addition, since the patient himself/herself controls the training, the input force can be regulated in time according to the feeling of the impaired limb, thus avoiding pain as well as unpredictable reactions, further enhancing the adaptability to the kinetic capabilities of the impaired limb and safety of the system relatively. Besides, this control scheme also has a great potential for applications in the fields of micro-manipulation, micro-assembly and medical surgery assistant.

REFERENCES