Journal of Mechanics in Medicine and Biology
Vol. 13, No. 6 (2013) 1340021 (12 pages)

DOI: 10.1142/S0219519413400216

MECHANICAL STRUCTURE IMPROVEMENT OF AN UPPER LIMB REHABILITATION ROBOT: BASED ON AN EQUIVALENT KINEMATIC MODEL

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Received 26 June 2013
Revised 16 September 2013
Accepted 18 September 2013
Published 13 December 2013

Several rehabilitation robots for upper limbs have been introduced so far, and clinical effectiveness was reported in several studies for the aged people or patients with stroke. Upper limb motor deficits of the patients have to be identified during the motor training, which requires the flexibility of mechanical structure. However, the users have difficulties in driving the previous robotic arms precisely because of the previous mechanical structure, especially when they are required to track a circle. This article gives a kinematic analysis on the previous mechanical structure of the previous robot, which is a two bar-linkage, two degrees of freedom mechanism, then solves the force on the handle grip during user's operation based on an equivalent kinematic model. The key of the problem is that force directions exerted by the user are not in the correct directions to drive the robot. Therefore, a new mechanical design using parallel robotic arms is suggested. The improvement is justified by comparing results from tracking circles using different robots.

Keywords: Stroke; upper limb rehabilitation robot; circle tracking task; equivalent kinematic model; parallel robotic arms.

1. Introduction

Approximately two million individuals have a stroke each year in China, and stroke remains the most common cause of disability for adults in China.[1] Hemiplegia caused by stroke brings terrible burden to patients. Therefore, more attention is paid on the recovery of stroke patients. Stroke survivors face various impacts that generate disability in motor, sensory, perceptual and cognitive functioning. Among these disabilities, motor deficits have a large impact on

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managing everyday activities, especially with the impaired upper extremity, because lack of arm-movement control affects activities of daily living (ADL) and independence.[2,3]

It is generally accepted that motor training is an effective way in improving body's function of the stroke patients.[3] According to neuroscience, motor training is built on theories of the brain's own ability to reconstruct.[4] It is testified that after acute brain lesion, motor training has the potential to drive brain reorganization and to optimize functional performance.[5,6] Repetitive motor training forms the basis of plasticity-based motor recovery.[7,8] The recovery is dependent on duration, frequency and intensity in training, which traditional methods done by physicians cannot guarantee.[9,10] Recent studies have suggested that physical rehabilitation performed with robotic devices can enhance arm-movement recovery following stroke.[11]

There are passive mode and active mode in the upper limb rehabilitation robot. In the passive mode, patient's movements are driven by motors, while in the active mode, patient moves voluntarily and the motors only record the position but not enabled. Currently, the upper limb rehabilitation robots are used successfully mainly on early stages of rehabilitation, in which the patient's exercise are driven by the robot. However, passive movement is insufficient to achieve motor recovery.[12] Active engagement and movement attempts are considered to be more important than passive movement.[12] In the later stage of rehabilitation the patients are required to do trajectory tracking tasks, like drawing circles. However, experiments show that they have difficulties in driving the robot precisely with our previous robot, which is a two bar-linkage, two degrees of freedom mechanism (similar to MIT-MANUS[13]). To solve this problem, this article gives a kinematic analysis on the mechanical structure of the previous robot, then uses an equivalent model to solve the force on the handle grip. After the analysis of the results we find that the key of the problem is that the directions of the force exerted by the user at the end point when tracking the circle are not in the expected directions from the robotic arms. Therefore, a new mechanical design using parallel robotic arms is suggested. We justify the improvement by comparing results from tracking circles using different robots.

2. Kinematic Analysis Based On an Equivalent Model

2.1. *Problem with the previous robot-UECM*

UECM (Fig. 1) is a two bar-linkage, two degrees of freedom mechanism. The user's hand should be fixed on the handle grip, when the robot provides shoulder and elbow exercises for hemiplegic upper limb. Trajectory tracking tasks are given for the patients in both passive mode and active mode. When it first engages in the active mode, a certain figure appears on the screen (Fig. 2). Then the patients are required to track the figure by moving the handle grip at the end of the robotic arm.

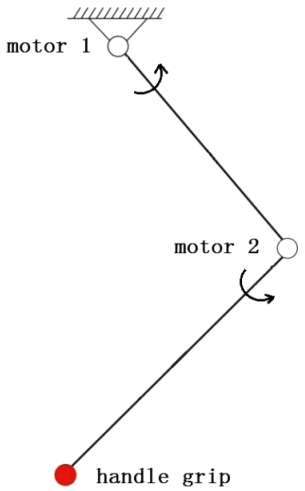

Fig. 1. Kinematic sketch of mechanism of UECM.

Fig. 2. Using UECM to track task circle.

The paths drawn by the handle grip will be shown and recorded along with the displayed trajectories.

While showing no problems for users in drawing straight lines, there are noticeable errors in drawing circles by tracking the displayed trajectories for both healthy and stroke persons (Fig. 3). The circles can be divided into four parts separated by points A, B, C, D (Fig. 4). There are abrupt changes at points A, B, C and D comparing the other points. The data from a two- dimensional force sensor fixed at the handle grip indicate the same problem.

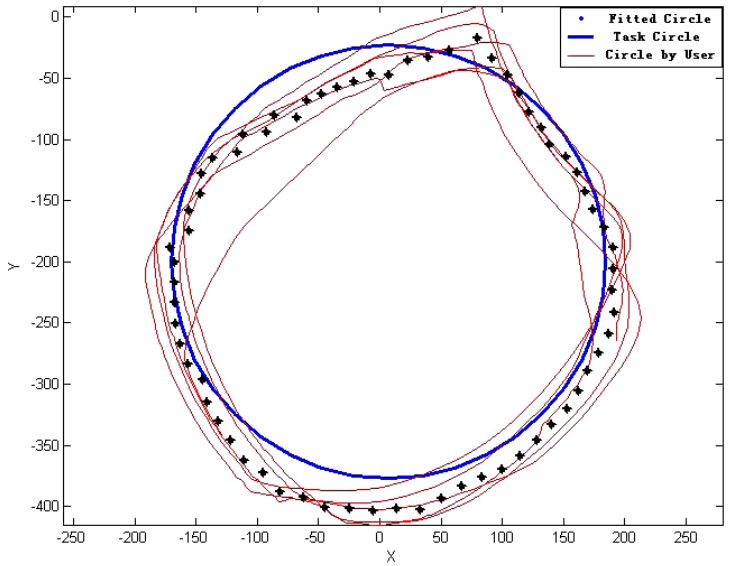

Fig. 3. Task circle (diameter: 350 mm) by healthy object using UECM.

It can be inferred that when the handle grip is near these points, the user exert their force in directions according to their experience. Unfortunately, the handle grip will move almost in a straight line instead of the correct arc. The robot has no repeatability in the active mode, thus it cannot demonstrate the actual motor ability of the user.

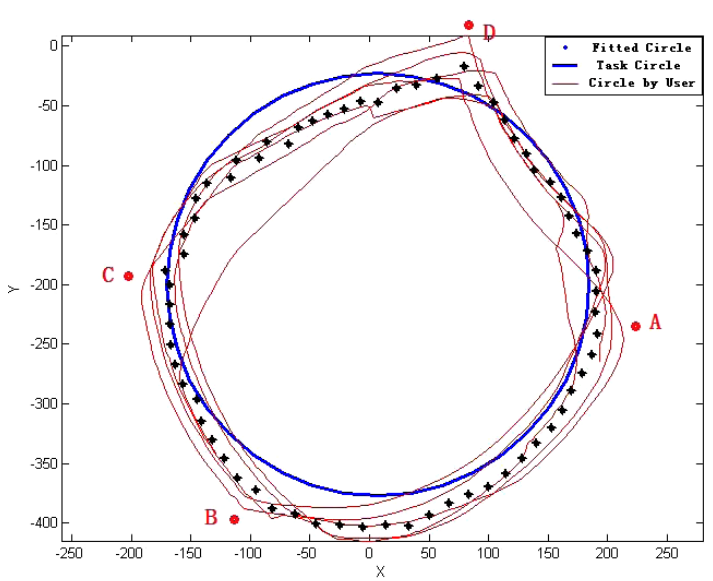

Fig. 4. Four separations of the task circle.

Apparently, if a healthy object draws a circle to follow the track without using the robot, the drawings must be almost the same as the track. Therefore, it can be easily inferred that the reason of the problem must lie in the mechanical structure of the robot.

2.2. *The importance of precise tracking*

As it is mentioned before that passive movement is insufficient to alter motor recovery. Active engagement and movement attempts are thought to be more important than passive movement.

The ultimate objective of motor training for stroke patients is to achieve original functions for the hemiplegic limbs and to recover the ability of motor control, so that the ADL of the patients can be enhanced. The patients' performance of completing the task is used as a motor assessment which can be evaluated by the physical therapists according to the track. In that sense, the tools used in the motor training have to be sensitive to identify motor deficits in order to provide proper prescription for each patient. If there are problems using the previous robot, the ultimate goal would not be achieved, which means it is of significant importance to find an alternative mechanical structure of the upper limb rehabilitation robot.

2.3. *An equivalent model and calculations*

First, we analyze the open-chain two-bar mechanisms when the handle grip can only move along the task circle (Fig. 5). Next, we suppose that there is a power source at the center of the task circle, like a motor. The new equivalent dynamic model, which is now a four-bar mechanism, is shown in Fig. 6. In Fig. 6, ab is the crank of the four-bar mechanism, whose length is the radius of the task circle. The position of point b is the position of the handle grip. In this case, we can calculate the force at point b,

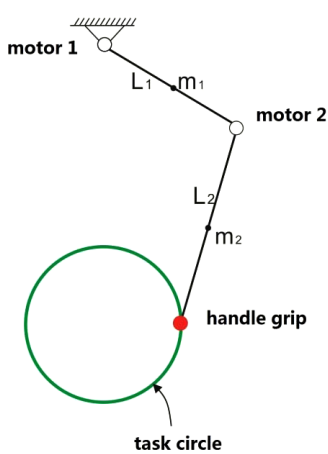

Fig. 5. Sketch map of tracking a task circle.

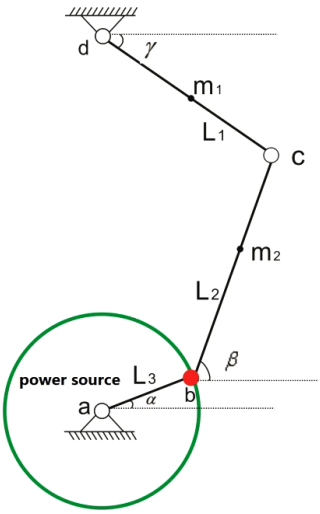

Fig. 6. Equivalent kinematic model.

and it is the force needed from the user's arm to draw the task circle. Thus, force analysis for bar 1 (cd), bar 2 (bc), bar 3 (ab) are presented in Fig. 7.

Point b starts to move ($t = 0\,\mathrm{s}$) when $\alpha = 0°$. Since the forces at a, b, c, d are unknown, we decompose the forces in cartesian coordinate system, broken into $f_{a_x}, f_{a_y}, f_{b_x}, f_{b_y}, f_{c_x} f_{c_y}, f_{d_x}$ and f_{d_y}. Also the accelerations are broken into $a_{1_x}, a_{2_x}, a_{3_x}$ and $a_{1_y}, a_{2_y}, a_{3_y}$. M_a is the torque provided by the power source at point a. I_1 and I_2 are the rotary inertia of bar 1 and bar 2. ε_1 and ε_2 are angular acceleration of bar 1 and bar 2. m_1, m_2 and m_3 are the mass of bar 1, bar 2 and bar 3.

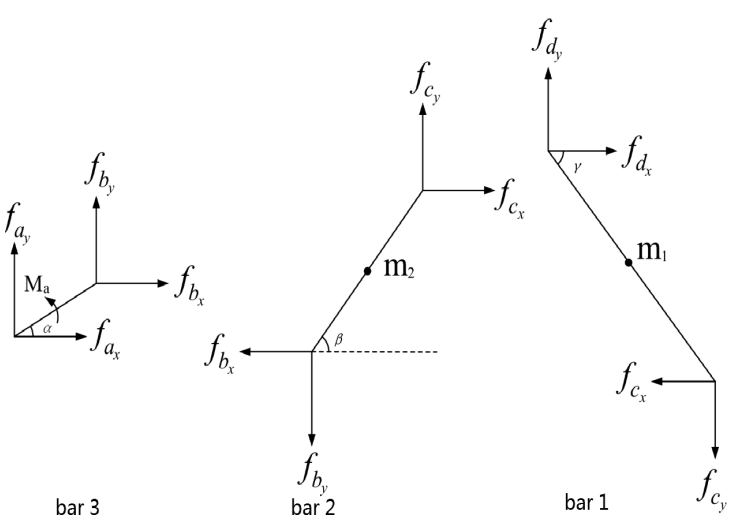

Fig. 7. Force analysis.

Table 1. Parameters.

Parameters	m (Kg)	L (mm)	I
Bar 1	2	400	0.107
Bar 2	1.5	300	ε_2[1]
Bar 3	0.7	150	0.00525

[1] ε_2 changes as α changes according to Ref. 14.

Dynamic equations of bar 3:

$$f_{a_x} + f_{b_x} = m_3 a_{3_x}, \tag{1}$$

$$f_{a_y} + f_{b_y} = m_3 a_{3_y}, \tag{2}$$

$$M_a + f_{b_y} L_3 \cos\alpha - f_{b_x} L_3 \sin\alpha = 0. \tag{3}$$

Dynamic equations of bar 2:

$$f_{c_x} - f_{b_x} = m_2 a_{2_x}, \tag{4}$$

$$f_{c_y} - f_{b_y} = m_2 a_{2_y}, \tag{5}$$

$$(f_{c_y} + f_{b_y}) \frac{L_2}{2} \cos\beta - (f_{c_x} + f_{b_x}) \frac{L_2}{2} \sin\beta = I_2 \varepsilon_2. \tag{6}$$

Dynamic equations of bar 1:

$$f_{d_x} - f_{c_x} = m_1 a_{1_x}, \tag{7}$$

$$f_{d_y} - f_{c_y} = m_1 a_{1_y}, \tag{8}$$

$$f_{c_x} L_1 \sin\gamma + f_{c_y} L_1 \cos\gamma = -I_1 \varepsilon_1. \tag{9}$$

If it takes 5 s to finish the circle, $\omega = \frac{2}{5}\pi \mathrm{rad}/s$. $\alpha = \omega t$.

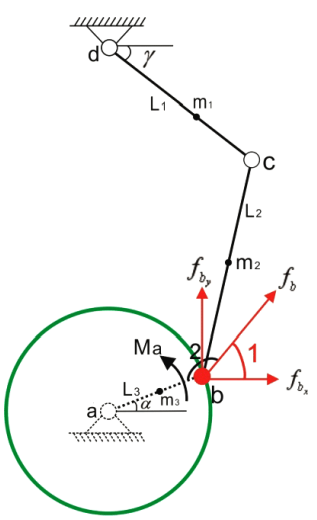

Fig. 8. The force at the handle grip: f_b.

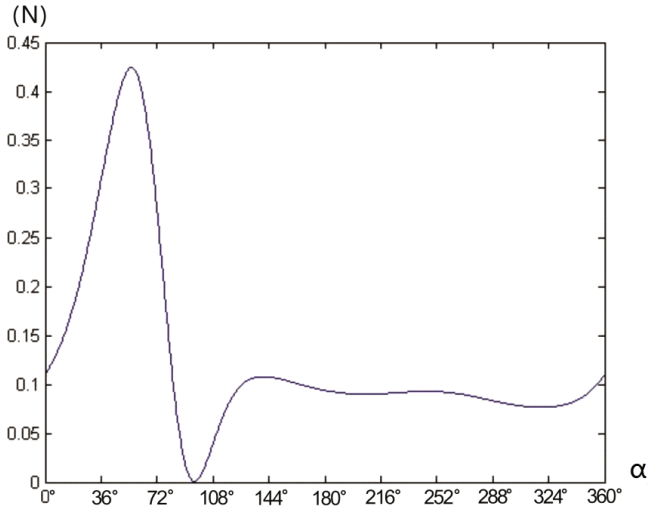

Fig. 9. The amount of f_b (N) as α changes from 0° to 360°.

According to the equations, we can calculate f_b, angle 1 and angle 2 (Fig. 8). Then we can draw the lines of f_b, angle 1 and angle 2 as α changes from to 0° to 360° (Figs. 9–11).

2.4. *Data analysis*

From the results of Figs. 9–11, we know that: 1. f_b is the force required from the user to draw a circle. The amount of the force is small enough for the users to exert. 2. Angle 1 is the angle between the direction of f_b and the horizontal line, and angle 2 is

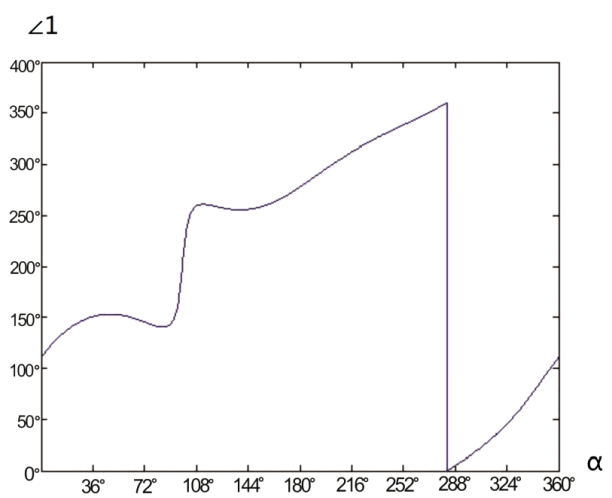

Fig. 10. Plot of angle 1 as α changes from 0° to 360°.

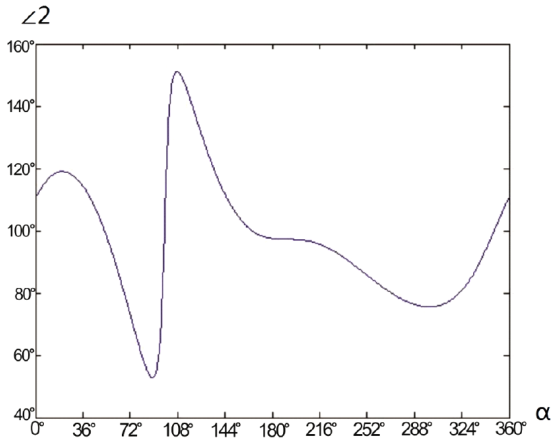

Fig. 11. Plot of angle 2 as α changes from 0° to 360°.

the angle between the direction of f_b and bar 3. It is shown from the picture that the direction of f_b changes α as changes.

These results explain why the users cannot draw the circle precisely according to the task. When the objects track the task circle in the active mode, they exert the force on the handle grip according to the visual feedback. Since the task is a circle, the objects usually exert the force in the tangential direction of the task circle according to their experience. However, the calculated and correct direction of the force to draw the circle changes continuously, no matter how the size of the circle, the center of the circle or the length of the links changes. In addition, there are times that the correct force directions are perpendicular to the user's exertion at some points, which causes the handle grip to get stuck so that the muscle length of the arm remains the same and the muscle tension increases dramatically at a short time. These may lead to spasm of the patients. The handle can only continue if the patients adjust the direction when the handle grip is at these points, as a result, the handle grip slips as Fig. 3 has shown due to the small inertia of the system.

3. A New Mechanical Design and Performance of Circle Tracking Task

Curvilinear motion demands flexibility of the mechanical structure. However, the previous robots, which are based on rigid rod, lack flexibility. As a result researchers at University of Padua come up with the ideas of cable-driven upper-limb rehabilitation robot.[15] Although cable-driven robot has advantages in dexterity, it cannot be used in the active mode as that cable cannot work when relaxed.

Therefore, the idea of parallel robotic arms with variable length is proposed (Fig. 12). There are two slide rails, two sliders and one rod (fixed with one of the sliders) in each arm. The redundant degrees of freedom provide the structure with

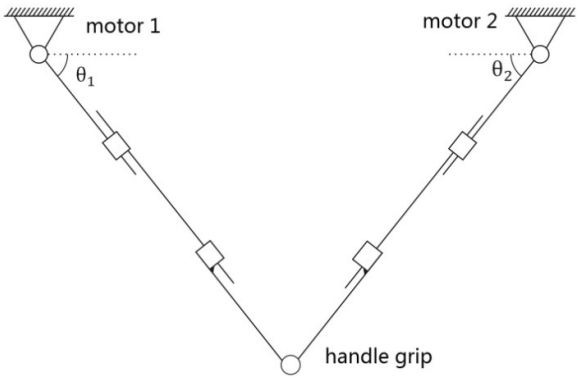

Fig. 12. parallel robotic arms rehabilitation robot.

dexterity and this structure works rigidly. The handle grip will move in the direction of the force exerted by the user, which means when tracking the circle, if the user exert the force in the tangential direction of the task circle, the handle grip will also move in the same direction. Therefore, these robotic arms do not impede the user's force so as to avoid the possibility of spasm on patients.

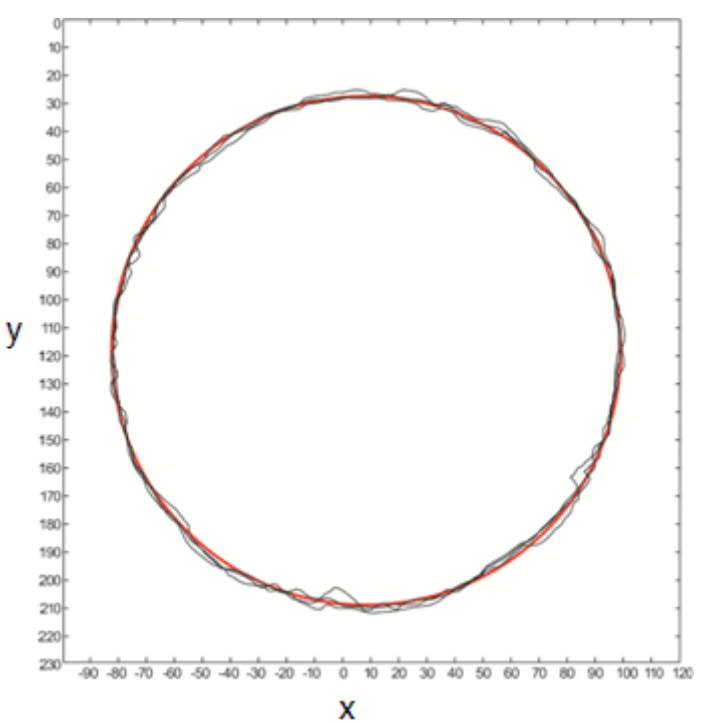

Fig. 13. Task circle (diameter: 180 mm) by healthy object using parallel robotic arms rehabilitation robot.

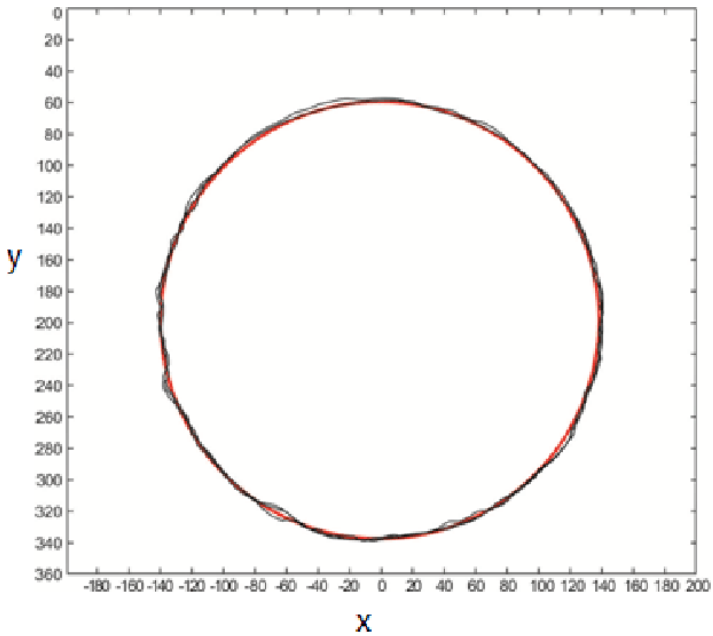

Fig. 14. Task circle (diameter: 280 mm) by healthy object using parallel robotic arms rehabilitation robot.

To compare, we apply the same experiment in tracking the same task circle on the new robot to the previous version. The recoded track performance is shown as the followings (Figs. 13 and 14). The results show that the circle drawn by the user fits the task and there is not any distinct separation in the drawn circle, which means that the mechanical structure of the parallel robotic arms rehabilitation robot is relatively better in use for the active mode of rehabilitation training compared to UECM.

4. Conclusions

The ultimate objective of motor training for stroke patients is to achieve original functions for the hemiplegic limbs and to recover the ability of motor control, so that the ADL of the patients can be enhanced. Therefore, upper limb motor deficits of the patients have to be identified during the motor training. The patients' performance of completing the task is used as a motor assessment which can be evaluated by the physical therapists according to the track. In that sense, the tools used in the motor training have to be sensitive to identify motor deficits in order to provide proper prescription for each patient. However experiments show that users have difficulties in driving the robot precisely with UECM when tracking the task circle under the active mode. Because active engagement and movement attempts are thought to be more important than passive movement, it is of significant

importance to find an alternative mechanical structure for the upper limb rehabilitation robot. With the kinematic analysis of UECM, we find that the key of the problem is that force directions exerted by the user are not correct with the previous mechanical design. Therefore, a new mechanical design using parallel robotic arms is suggested. The improvement is justified by comparing results from tracking circles using the two robots. The results show that the mechanical structure of the parallel robotic arms rehabilitation robot is relatively better in use for the active mode of rehabilitation training compared to UECM.

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