Pre-therapeutic Device for Post-stroke Hemiplegic Patients’ Wrist and Finger Rehabilitation

Jihun Kim¹, Eun-Taek Woo¹, Jae-Won Seo¹, Jaehyo Kim¹
¹School of Mechanical and Control Engineering, Handong Global University, Pohang, Republic of Korea

ABSTRACT

Background/Objectives: This paper suggests a pre-therapeutic device for post-stroke hemiplegic patients’ wrist and finger rehabilitation both to decrease and analyze their muscle tones before the main physical or occupational therapy.

Method/Statistical Analysis: We designed a robot which consists of a BLDC motor, a torque sensor, linear motion guides and bearings. Mechanical structure of the robot induces flexion and extension of wrist and finger (MCP) joints simultaneously with the single motor. The frames of the robot were 3D printed. During the flexion/extension exercise, angular position and repulsive torque of the joints are measured and displayed in real time.

Findings: A prototype was 3D printed to conduct preliminary experiment on normal subject. From the neutral joint position (midway between extension and flexion), the robot rotated 120 degrees to extension direction and 30 degrees to flexion direction. First, the subject used the machine with the usual wrist and finger characteristics without any tones. Second, the same subject intentionally gave strength to the joints in order to imitate affected upper limb of a hemiplegic patient. During extension exercise, maximum repulsive torque of the normal hand was 2 Nm whereas that of the firm hand was almost 5 Nm. The result revealed that the device was capable enough to not only rotate rigid wrist and fingers with the novel robotic structure, but also present quantitative data such as the repulsive torque according to the joint orientation as an index of joint spasticity level.

Improvements/Applications: We are planning to improve the system by applying torque control and arranging experiments at hospitals to obtain patients’ data and feedbacks to meet actual needs in the field.

Keywords: Stroke, Hemiplegia, Rehabilitation, Robotics, Wrist, Finger

Introduction

Thanks to advanced medical treatments, the death rate of chronic and acute stroke has been gradually reduced. Since the brain injury usually accompanies loss of motor functions, increasing population of hemiplegic patients is naturally inevitable. More than months or even years of rehabilitation is mandatory because repetitive movements of affected joints and muscles practiced in hospitals stimulate neuroplasticity so that normal neurons nearby damaged ones would replace the lost functions¹,²,³.

The ultimate purpose of post-stroke hemiplegia rehabilitation is to recover performance of activities of daily lives(ADL) improving patient’s quality of life (QoL)⁴. Recovery of wrist and finger functions is important to QoL because use of the joints is closely related to interactions with objects. However, those joints are considered most time-consuming and difficult to be fully recovered because restoration of upper limb functions starts from mesial to distal joints, hence from shoulder, arm, wrist, and finally to fingers. In addition, since wrist and fingers have multiple degree-of-freedoms actuated by multiple musculoskeletal systems and since they are quite sensitive compare to other upper limb
joints, it is demanding both to patients and therapists to practice physical and occupational therapies on the very specific joints\cite{5}.

Figure 1: Target ROM of wrist and MCP joints and possible mechanical structures of therapeutic robots. (a) Wrist flexion/extension ROM. (b) MCP flexion/extension ROM. (c) Combined joint ROM. (d) Conventional exoskeleton structure. (e) Proposing structure. Conventional exoskeleton robots restrict all skeletal joints to the robot linkages, so they usually lack flexibility regarding user’s body size. The proposing structure let MPC joint free and allow the tips of fingers slide back and forth. Therefore, the new robot has increased flexibility.

Today, more and more therapeutic robots are introduced to relieve their burden. The robots are considered useful because they 1) provide intensive and repetitive trainings, 2) suggest quantitative assessment about patient’s motor functions, and 3) help build database\cite{6}. However, complex structure of the robots and expensive prices make them impractical to use at small or medium hospitals. As a result, simple therapeutic robots are reported to be more patient- and therapist-friendly as well as easier to commercialize than complex robots\cite{6}. In addition, a recent study on robot-assisted exercise suggests that 10 minutes of simple wrist flexion/extension are sufficient enough to temporarily reduce the joint tone of patients especially on Brunnstrom stage 3\cite{8}. Therefore, we propose a simple and affordable robot that helps reduce the high wrist and finger spasticity before the main physical or occupational therapies.

Materials and Method

Mechanical Structure: One of the easiest yet effective ways to design a therapeutic robot would be following a similar pattern of physical therapy practiced by therapists over the past decades. When they perform the basic wrist/finger stretching exercise on patients, they gently and quite evenly apply a pushing force on the patients’ palm and fingers. As a result, wrist joint is fully extended followed by finger joint extension. The target range of motion (ROM) of wrist and MCP is presented in figure 1 (a) and (b)\cite{7}. To imitate the stretching exercise, we considered the combined ROM of the therapeutic robot as shown in figure 1 (c).

Conventional exoskeleton-type finger robots locate their actuators right beside desired human joints to apply torque thus to induce rotational movements\cite{4,5}. The basic operation algorithm of the conventional method is shown in figure 2 (a). Although this method is intuitive to engineers, the robots become rather inconvenient for most hemiplegic patients with distorted joints. In addition, since users have different hand sizes, alignments between the robot linkages and human joints take too much time. Therefore, most exoskeleton robots are difficult to commercialize\cite{6}. To overcome the difficulties, we considered a novel mechanical structure presented in figure 2 (b). Rather than restricting MCP
joint to the robot, we let them free. Instead, we installed linear motion guides to allow the fingertips freely move back and forth. Finally, wrist joint shares the same rotational axis with BLDC motor. Due to this mechanical structure, it is possible to move the two degrees of freedom with one driving actuator.

The power of the motor was selected based on the maximum wrist torque of healthy person\textsuperscript{9,10}. A BLDC motor MW-VBL24D030S-M-G with rated torque of 24Nm and rated rotational speed of 12.5 rpm was used. Too fast rotational speed is unnecessary to give patients a sense of safety and comfort. A torque sensor TCN16 (Dacell) with capacity of 49.03N-m was used in order to monitor and collect user’s repulsive torque applied to the wrist pivot. The motor is linked to the torque sensor by coupling. A variable resistor was installed on the wrist pivot as a position sensor. Based on the torque and the joint angle data, spasticity level of the patient is expected to be estimated.

Control Algorithm: For wrist and finger flexion/extension exercise, angular position PID control was implemented to the BLDC motor. Underdamped control usually provides a fast response with low rising time and settling time, but overshoots should always be avoided due to a possible risk of fracture since most patients’ joints are distorted. Since the maximum angular speed of the motor was quite slow (12.5 rpm) with a very high gear ratio (1:200), stable overdamped control was promising. Therefore, PID parameters were carefully chosen to be overdamped response. As shown in figure 3, USB-6009 (National Instrument) with C language on Visual Studio (Microsoft) was used to collect sensor data and control the motor with a sample rate of 100 Hz.
Results and Discussion

Preliminary Experiment: Base on the hardware model in figure 2, a prototype was 3D printed as presented in figure 4. Prior to performing clinical trials on hemiplegic patients, we conducted a preliminary usability evaluation. From the neutral position, the device rotated 120 degrees to extension direction and 30 degrees to flexion direction with a constant speed of 7.5 deg/s over 60 seconds. First 22 seconds were assigned to full extension, next 10 seconds to holding, and last 28 seconds to full flexion.

Two preliminary experiments were conducted on a normal subject. A 25-year-old, right-handed man equipped the therapeutic robot on his left hand. First, the subject used the therapeutic device normally. Second, the same subject used the robot again with a moderate repulsive torque as if he had spasticity on his wrist and finger joints.

Torque and angular position data collected during the two experiments are depicted in figure 5. Figure 5 (a) shows data on ordinary joint stiffness in normal subjects during the first experiment. As the robot rotate to the extension direction, only wrist is extended and small increase in repulsive torque up to 0.5 Nm is observed. After the angular position pass by -90 degree, fingers start to extend as well. Together, wrist and fingers show maximum repulsive torque of 2 Nm at full extension position of -120 degrees. The repulsive torque slowly reduces to zero as the joints come back to the neutral position.

Figure 5 (b) illustrates data on moderate joint stiffness intended by the normal subjects during the second experiment. Up to -90 degrees, wrist alone shows a higher repulsive torque of 2 Nm. As the wrist and fingers start to stretch out together, the repulsive torque increase almost to 5 Nm which is 2 times more than the normal joints without spasticity in figure 5 (a). The result show that our device is possible to extend paralyzed wrist and fingers with spasticity as well as monitor tone characteristics based of robotic measures in terms of repulsive torque according to joint orientation.

Future plans and Improvements: We categorized our robot as a pre-therapeutic device because we know that robots cannot perform perfect wrist and finger treatments due to complex and sensitive characteristics of the joints. Therefore, the role of therapists and conventional therapies are still very important. Thus, what we are looking forward with our robot is to reduce the tones of the joint even temporarily before the main therapies to ease therapists’ work load. The research about decrease in wrist stiffness after 10-minute robot-assisted exercise suggests the basis for the concept our robot.[8]

We expect that our robot would also provide a quantitative assessment about user’s joint condition and even motor function ability based on the short pre-therapeutic exercise. The data collected during the exercise is expected to be further processed. A research on cerebellum patients suggest that one’s angular stiffness and viscosity can be derived from angular position, velocity, and torque data[11]. We can directly apply the method to our data to present spasticity in terms of the kinematic constants. A patient with severe spasticity would show a high magnitude in the kinematic constant.
particularly a high stiffness due to spring-like nature of the affected joints. The quantitative assessments would help therapists evaluate patient’s current condition and suggest future treatment direction.

In wrist and finger physical and occupational therapies, thumb is an important joint. Since tones of the other joints vary significantly depending on the thumb position, it should also be extended during extension exercise. Our device as of now does not have such component. Therefore, in order to provide more effective therapeutic device to hospitals, we should consider an appropriate thumb rest in the future.

More importantly, feedbacks from therapists and patients at local hospitals are important. Although MOU has been established with a rehabilitation hospital to conduct joint research, consistent comments on the specific robot is still in sufficient. The prototype we developed should be tested to hemiplegic patients, our target, before we finally confirm our hardware model before main clinical test. For example, safety considerations regarding the device are very important because the patients’ hands are passively extended by the robot. Figuring out combination of suitable motor speed and position controls comfortable to patients would be necessary. Although we designed the frame size based on recommended measures from Statistics Korea, the national department of statistics, we observed that patients’ hands were usually swollen due to edema. Therefore, fine tuning of the robot size must be considered.

A long term study should be carefully planned on actual post-stroke hemiplegic patients. Most case studies conduct clinical tests on their therapeutic device more than a month. We should recruit specific subject groups in terms of Brunnstrom stage, Fugl-Meyer assessment, or Modified Ashworth Scale through meetings with hospital doctors and therapists. Comparison between clinical and robotic measurements regarding motor control during and after the experiment would reveal validity and effectiveness of our robot. Also we expect task-oriented comparative experiment between normal people and patients using the robot.

**Conclusion**

In this study, we suggested a therapeutic robot to help hand and finger rehabilitation of post-stroke hemiplegic patients. Unlike previous studies on hand-finger exoskeleton robots, the proposing device was designed to extend the two joints with one actuator thus increasing flexibility and making more affordable to small and medium rehabilitation hospitals. Repulsive torque and angular position are collected by sensors to monitor exercise. A preliminary experiment was conducted on a healthy subject while applying a repulsive torque to the robot as if it was affected. The test revealed that not only the device is useful enough to stretch out the wrist and fingers similar to conventional physical therapies, but also help gather quantitative characteristics about the affected joints.

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**Ethical Clearance:** Not required

**Source of Funding:** Self

**Conflict of Interest:** Nil

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