DESIGN OF A REHABILITATION DEVICE OF BILATERAL UPPER LIMBS FOR POST STROKE PATIENT

THIẾT KẾ THIẾT BỊ HỖ TRỢ ĐIỀU TRỊ PHỤC HỒI CHỨC NĂNG CHI TRÊN HAI BÊN CHO BỆNH NHÂN SAU ĐỘT QUỴ NÃO

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ABSTRACT

Stroke is one of the leading causes of severe impairment in upper limb motor function in patients. Rehabilitation plays a crucial role in helping patients regain their motor capability, maintain muscle and joint flexibility and endurance. This study focuses on designing a 38-degree-of-freedom (DOF) rehabilitation assistance device for both upper limbs. The main part of the device includes eight DOFs that support arm movements, consisting of four movements at the shoulder, two movements at the elbow, and two movements at the wrist. The auxiliary part of the device, which comprises seven positioning DOFs and three moving DOFs, is responsible for position adjustment, helping patients easily perform rehabilitation exercises.

Keywords: *38-dof; Rehabilitation; Upper-limb; Brain stroke.*

TÓM TẮT

Đột quỵ não là một trong những nguyên nhân hàng đầu gây ra ảnh hưởng nghiêm trọng đến chức năng vận động của hai chi trên ở bệnh nhân. Phục hồi chức năng đóng vai trò quan trọng trong việc giúp bệnh nhân lấy lại khả năng vận động, duy trì sự mềm dẻo và sức bền của cơ và khớp. Nghiên cứu này tập trung vào việc thiết kế một thiết bị hỗ trợ phục hồi chức năng 38 bậc tự do cho cả hai chi trên. Trong đó, phần chính của thiết bị bao gồm tám bậc tự do hỗ trợ các chuyển động của cánh tay, gồm bốn chuyển động ở vai, hai chuyển động ở khuỷu tay và hai chuyển động ở cổ tay. Phần phụ của thiết bị, bao gồm bảy bậc tự do định vị và ba bậc tự do di chuyển, có nhiệm vụ hỗ trợ điều chỉnh vị trí, giúp bệnh nhân dễ dàng thực hiện các bài tập phục hồi chức năng.

Từ khóa: *38 bậc tự do; Phục hồi chức năng; Chi trên; Đột quỵ não.*

1. INTRODUCTION

Stroke, also known as a cerebrovascular accident, is a pathological condition that occurs when the blood supply to the brain is obstructed, interrupted, or suddenly reduced, leading to a deficiency of oxygen and nutrients to neural cells. This deprivation causes brain cells to begin necrosis within only a few minutes. According to the World Stroke Organization, stroke is currently the second leading cause of death and the third leading cause of death and disability worldwide, with an estimated global cost of care and treatment of approximately USD 891 billion, equivalent to 1.12% of the global gross domestic product (GDP) [1].

Rehabilitation plays a crucial role in restoring motor function of body parts (such as the arms, legs, and neck) following injuries caused by accidents, stroke, or neuromusculoskeletal disorders [2]. This field represents a strong interdisciplinary convergence between medicine and engineering, particularly in the areas of mechatronics and biomedical robotics.

Rehabilitation robots are currently classified into two main categories: end-effector robots and exoskeleton robots. Exoskeleton robots enable accurate replication of the physiological motion of individual joints through their complex mechanical structures and multi-degree-of-freedom control systems. However, their disadvantages include bulky designs, high manufacturing and operational costs, and the requirement for sophisticated control algorithms.

In contrast, end-effector robots do not directly model joint-level motion but instead apply forces or control position at the distal endpoint of a limb. Although their ability to reproduce physiological joint motion is not entirely precise, this class of robots is well-suited for end-point-based exercises. It offers advantages such as simpler design, lower cost, and ease of implementation in clinical environments [3].

Commonly used physical rehabilitation training devices include quadriceps strengthening chairs, parallel bars for gait rehabilitation, and safety-assisted step stairs, among others (Figure 1).

However, current rehabilitation assistive devices still do not fully meet the eight degrees of freedom required for upper-limb movement. In addition, patients are required to stand or sit while using these devices, which limits their applicability to individuals who can maintain an upright posture independently or with assistive support. For bedridden patients who are unable to stand, these devices are therefore not a suitable solution.

To address these limitations, this paper focuses on the design and development of an upper-limb rehabilitation assistive device for post-stroke patients. The proposed device offers the following advantages: it is capable of natural upper-limb movements, enabling patients to perform exercises in an optimized manner. Furthermore, patients can train in various body postures owing to the device's adjustable positional degrees of freedom.

2. DESIGN

2.1. Overview

The device is designed based on an exoskeleton robot architecture and is intended for passive rehabilitation training (Figure 2). The upper-limb rehabilitation assistive system comprises a total of 38 degrees of freedom (DOF) and is divided into three main modules: ☞

the exercise arm module, the positioning module, and the translation (movement) module.

The exercise arm module incorporates 9 DOF to simulate the motions of the shoulder, elbow, wrist, and hand joints. The positioning module provides 7 DOF to adjust the exercise components to accommodate the patient's posture. The translation module enables vertical lifting and linear motion along the three Cartesian axes (Ox, Oy, Oz), allowing the device to be positioned optimally for rehabilitation training.

The device employs a structural frame with joints actuated by brushless DC motors (Maxon) and harmonic drive gear reducers, selected for their suitability to the system requirements, including:

+ High accuracy and resolution;
+ Zero backlash;
+ High efficiency and low maintenance;
+ Smooth operation with low noise;
+ Compact design and low weight.

The motors and gear reducers used in the system include:

+ Motors: Maxon EC 45 flat (30 W), EC 90 flat (90 W), and EC 60 flat (200 W);

+ Harmonic drives: CFS-11-50-2XH-F, CFS-17-120-2UH, CSF-20-160-2UH, and CSG-32-160-2UH.

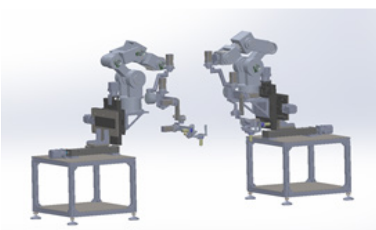

Figure 1. 3D Design of the 38-Dof bilateral upper-limb rehabilitation Device.

2.2. Exercise Arm Module

The exercise arm system is designed with nine degrees of freedom (DOF) for each arm, corresponding to nine functional joint modules that fully replicate the natural physiological movements of the human upper limb. Consequently, the overall system achieves a total of 38 DOF for bilateral arms, ensuring accurate reproduction of the motion range and movement trajectories required for rehabilitation exercises.

Compared with previous rehabilitation assistive device designs, the proposed model in this study introduces an additional degree of freedom. This added DOF is incorporated into Module 1, enabling horizontal elevation and depression of the shoulder joint, thereby enhancing the capability to simulate natural upper-limb motion. Furthermore, Module 2 has been redesigned to improve aesthetic appearance while expanding the relative displacement range between the device and the user, thus increasing flexibility and adaptability to different patient profiles. The remaining functional modules retain the same design, positioning, and operational roles as those reported in previous studies; therefore, they are not reiterated in this paper. The functions and ranges of motion of the modules are summarized in the following Table 1.

2.2.1. Horizontal Arm Module

The horizontal rotation module performs flexion and extension in the horizontal plane, with a range of motion from 0° to 140°. As the first component of the robotic arm, this module also serves as the structural interface and fixation point connecting to the 7-degree-of-freedom positioning module. To ensure mechanical strength and structural rigidity, the primary construction material for Module 1 is stainless steel (INOX 304).

Structurally, the module consists of a mounting bracket for connection to the positioning module, a drive motor, a motor support plate, and a coupling plate that interfaces with the shoulder elevation/depression module.

2.2.2. Shoulder Elevation and Depression Module

The shoulder elevation/depression module describes the lifting and lowering of the arm, with a range from 0° to 70°. It is the second component of the robotic arm and connects the mechanism to the positioning module.

Accordingly, the shoulder elevation/depression module not only contributes to motion generation but also ensures system stability and structural rigidity during operation, thereby providing a foundation for the subsequent movements of the entire robotic arm. The primary structural components of this module include a connecting link to the positioning module, a joint coupled with the harmonic gear reducer, and a linkage to the shoulder abduction module.

2.2.3. Shoulder Abduction Module

The shoulder abduction module enables horizontal expansion of the shoulder with a 0° to 45° range of motion. Its primary components include a drive motor, interconnected linkages, and a protective shoulder cover.

2.2.4. Upper Arm Flexion/Extension Module

The upper arm flexion/extension module describes vertical-plane flexion and extension of the arm, with a range of motion from 0° to 140°. Its primary structural components include a drive motor, a coupling to the gear reducer, and a mounting flange. It also features a slotted linkage that connects to the upper arm internal/external rotation module. This slotted mechanism allows flexible length adjustment to accommodate variations in individual patient arm dimensions during use.

2.2.5. Upper Arm Internal Module

The upper arm internal/external rotation module is responsible for describing internal and external rotational motion of the upper limb, with a range of motion from −85° to +75°. The primary structural components of this module include a drive motor, an upper-arm support ring, a sliding joint, and a cable latch. The transmission mechanism employs a gear–arc gear assembly, in which the gear is mounted to the lower portion of the motor and rotates around a stationary arc gear fixed beneath the upper-arm support ring.

At the center of the upper-arm support assembly, an intermediate sliding ring is incorporated, consisting of upper and lower grooves. Each groove contains steel balls retained by a ball-retaining ring. This configuration allows the driven rotational assembly to move synchronously with the intermediate sliding ring and the retaining ring as the gear rotates, assisted by eight steel balls in each of the upper and lower grooves. The driven assembly also incorporates a sliding joint with a safety pin, allowing for guided rotational motion along the groove to ensure operational safety.

2.2.6. Elbow Flexion Module

The elbow flexion/extension module describes flexion and extension motion at the ☞

elbow joint, with a range of motion from 0° to 120°. The primary structural components of this module include a drive motor, the elbow joint, a gear-reducer support joint, a mounting flange, and an intermediate coupling joint between the shoulder and elbow assemblies.

2.2.7. Forearm Module

The forearm pronation/supination module enables rotational motion of the forearm, including pronation and supination, with a range of motion from −85° to +85°. Structurally, this module is fundamentally identical to the upper arm internal/external rotation module. The primary distinction lies in its reduced range of motion compared to that of the upper arm rotation module.

2.2.8. Wrist Abduction Module

The wrist abduction module describes radial and ulnar deviation of the wrist, with a range of motion from −25° to +20°. The primary structural components of this module include a drive motor, a support assembly, a linkage connecting to the wrist horizontal rotation module, and a mounting flange.

2.2.9. Wrist Flexion Module

The wrist flexion/extension module is responsible for flexion and extension of the wrist, with a range of motion from −50° to +60°. The primary structural components of this module include a drive motor, a wrist linkage, a handle linkage, a mounting flange, and a hand grip.

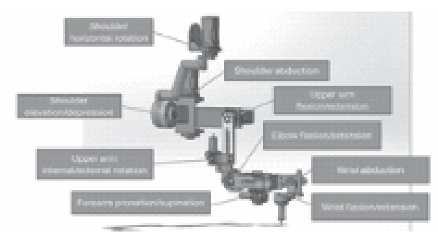

Figure 2. Robot Arm Structures.

2.3. Positioning Module

A key feature that clearly distinguishes this system from previously published upper-limb rehabilitation device designs is the incorporation of a positioning module. The positioning module is designed with seven degrees of freedom for each side, primarily employing revolute joints, which enables flexible and precise positioning and orientation of the exercise arm relative to the patient's upper limb.

The positioning module is primarily fabricated from stainless steel (INOX 304), providing high aesthetic quality, good corrosion resistance, and ease of cleaning, thereby meeting the stringent requirements of hospital and physical therapy environments, as well as being suitable for home-based use.

In total, the system's positioning module provides 14 degrees of freedom for bilateral operation, corresponding to the left and right arms, which significantly enhances adaptability to individual patients and optimizes the overall rehabilitation process.

2.4. Support Base

The support base serves as the structural interface connecting to the exercise arm. In addition, it enables positional adjustment of the device to accommodate the user.

Linear translation is provided along the Cartesian axes as follows:

+ X-axis: Forward/backward translation with a travel range of ±1000 mm;
+ Y-axis: Forward/backward translation with a travel range of ±1000 mm;
+ Z-axis: Vertical translation with a travel range of ±449 mm.

Table 1. Functions and ranges of motion of the modules.

Function	Range of Motion
Shoulder horizontal rotation	0° – 140°
Shoulder elevation/ depression	0° – 70°
Shoulder abduction	0° – 45°
Upper arm flexion/ extension	0° – 90°
Upper arm internal/ external rotation	-45° – 45°
Elbow flexion/extension	0° – 90°
Forearm pronation/ supination	-85° – 85°
Wrist abduction	0° – 35°
Wrist flexion/extension	-25° – 20°

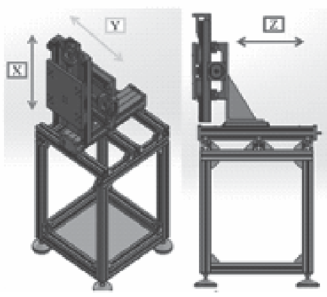

Figure 3. Support Base.

3. DEVICE SETUP AND EXERCISE

3.1. Instructions For Installing Equipment With The Patient

3.1.1. Device Installation

Step 1: Place the translation (movement) module at the intended location of use.

Step 2: Sequentially assemble the joints of the positioning module in the order from Module 7 to Module 1 on both sides.

Step 3: Sequentially assemble the joints of the exercise arm in the order from Module 1 to Module 8 on both sides.

3.1.2. Patient Positioning

Step 1: Adjust the distance of the translation module to match the patient's position.

Step 2: Adjust the positioning module to bring the exercise arm into the appropriate position relative to the patient's arm for training.

Step 3: Secure the patient's upper arm to Module 4 and adjust the clamp position to fit the patient's upper-arm size.

Step 4: Secure the patient's forearm to Module 6 and adjust the clamp position accordingly. The distance can be adjusted to best match the patient's arm condition.

Step 5: Instruct the patient to grasp the hand grip associated with Module 8. The size and spacing of Module 8 are adjustable.

Step 6: Configure the system and initiate the exercise programs integrated into the device.

*All dimensions of the modules are adjustable to accommodate variations in patient physique, clinical condition, and limb size. If the configuration remains excessively large or distant, further adjustments can be made using the translation module and the positioning module.

3.2. Selected Exercises

The device can integrate a set of recommended passive range-of-motion (PROM) exercises. These exercises are illustrated in the figure 4 below.

The exercises integrated into the device replicate nearly the full range of upper-limb movement patterns required for post-stroke rehabilitation. Therefore, training duration and load levels should be adjusted in accordance with the prescriptions of healthcare professionals, including physicians and physical therapists, to ensure patient safety and optimal therapeutic outcomes. In addition, to enhance user engagement and reduce monotony during training, the device can be integrated with interactive and entertainment-oriented software. For example, motion-controlled tasks such as hair-combing simulations, object throwing and releasing, or other interactive games may improve training motivation and increase patient participation.

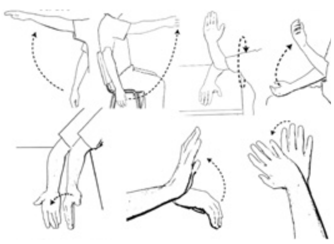

Figure 4. Exercises integrated into Rehabilitation Device [5].

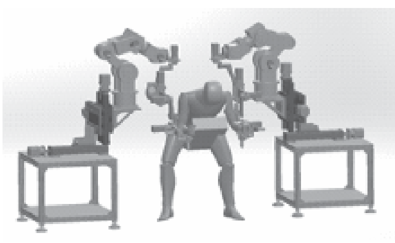

Figure 5. 3D showing the device mounted on a patient in the prone position.

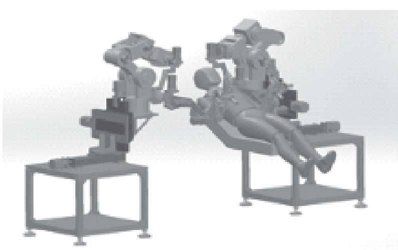

Figure 6. 3D Showing the device mounted on a patient in the supine position.

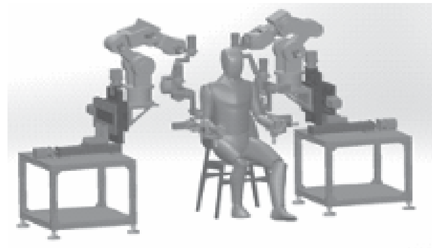

Figure 7. 3D showing the device mounted on a patient in a seated position.

4. CONCLUSION

This paper has presented the design and development of a bilateral upper-limb rehabilitation assistive device for post-stroke patients, highlighting its key advantages over previously reported systems. The device employs stainless steel (INOX 304), which provides high mechanical strength, good corrosion resistance, and compliance with aesthetic and hygiene requirements, making it suitable for both hospital environments and home-based use.

The design enables flexible dimensional adjustment, combined with seven degrees of freedom in the positioning module and three translational degrees of freedom in the movement module, thereby ensuring adaptability to a wide range of patient body types, limb sizes, and training postures.❖

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