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Preliminary Mechanical Design of a Wearable Parallel-Serial Hybrid Robot for Wrist and Forearm Rehabilitation with Consideration of Joint Misalignment Compensation

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Abstract

This paper presents a preliminary design of a wearable hybrid (parallel-serial) robot for wrist and forearm rehabilitation. The proposed robot design includes novel mechanisms (RRPP and RRRR) for joint misalignment compensation. The prototype of the wearable rehabilitation robot has been manufactured by 3D printing and tested. From the evaluation of the design, the proposed robot is able to assist rotation of the wrist and forearm for rehabilitation. With the features of lightweight, portable and safer design, we expect the proposed wearable robot is suitable for in-home rehabilitation.

Keywords: Rehabilitation Robotics, Mechanism Design, Parallel-serial Hybrid Robot, Wearable Robot, Robot-assisted Therapy

1 Introduction

Patients with upper limb impairment need to regain their lost motor abilities through repetitive and continuous rehabilitation (Klamroth-Marganska et al., 2014). Movement disorders can have a significant impact on a patient's quality of life since many activities of daily living (ADL) require movement of the upper limb. Robot-assisted rehabilitation has been proven to be effective in assisting rehabilitation in clinical practice (Norouzi-Gheidari et al., 2012), not only having the ability to perform repetitive and intensive rehabilitation therapy, but also its rehabilitation outcome is not limited by the shortage of well-trained therapists, or the fatigue of therapists caused by long-term treatment.

Due to the aging of the global population and the rising prevalence of chronic diseases, the need for physical rehabilitation has increased, resulting in the development of a variety of rehabilitation robots in recent years. According to the mechanical structures, rehabilitation robots are usually divided into two types: End-effector type and Exoskeleton type. The end-effector type is in contact with the distal of the human limb, such as the palm. And the posture of the upper limb is changed through the movement of the contacted end-effector without considering the motion of the individual joints of the limb(Qassim and Hasan, 2020). The exoskeleton type has a structure similar to the human limbs and is in contact with the limb through attachments such as cuffs or straps. Exoskeletons can provide direct force and motion to specific impaired joints, which are thought to be beneficial for rehabilitation (Gull et al., 2020).

In recent years, more and more attention has been paid to the development of exoskeleton type rehabilitation robots, especially their wearable feature has the potential to benefit in-home rehabilitation compared to those fixed on the ground, which are usually larger and heavier (Gull et al., 2020). However, since they are worn on a patient's limbs, the robot joints need to be carefully aligned with the human joints in order to avoid misalignment between the two joints, which may cause the generation of unwanted forces (Näf et al., 2018). Unwanted forces will make the user feel uncomfortable or even painful, therefore they should be reduced during the design phase. (Tucan et al., 2020) indicate that attention should be concentrated to assured safety of the medical device and the design should follow a risk assessment process to identify and overcome the risk. Indeed, a safe rehabilitation robot should provide movement supporting without causing any pain, inconvenience, or movement disturbance of the user. If the user feels uncomfortable when using the robot, it will significantly lower the user's willingness to use it and thus reduce the rehabilitation effects. Many researchers have studied how to solve the misalignment problem. However, due to the complex structure of human joints and the soft nature of the human body, ensuring joint alignment remains a challenging problem for robot-assisted therapy (Näf et al., 2018).

In this paper, we propose a wearable hybrid robot for forearm and wrist rehabilitation. Specifically, the 3-RPS parallel module is aimed at flexion/extension (FE) and radial/ulnar deviation (RUD) movements of the wrist and the serial module targets pronation and supination (PS) movements of the forearm, as depicted in Figure 1(a). The design of the 3-RPS parallel module has been described in our previous study (Liu et al., 2021) and the optimized design has been carried out considering the user's comfort and safety. The objective of this work is to propose the design of the

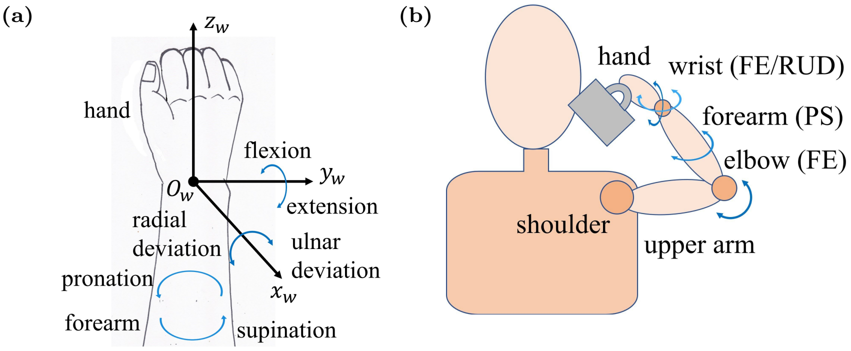

Figure 1. (a) Rehabilitation movements; (b) ADL movements.

novel mechanisms into the serial module to compensate for joint misalignment between human and robot to fulfill a safer robot design for rehabilitation.

2 Design and Implementation

2.1 Requirement to the Wearable Robot

In general, robot-assisted therapy includes two main application fields: providing physical therapy and supporting to perform some ADLs. Precise rehabilitation movements of the robot are required for rehabilitation treatment. In addition, with appropriate assistive forces or torques, the patient should not feel discomfort or any pain during the rehabilitation process. Furthermore, in order to perform many ADLs, FE and RUD movements of the wrist and PS movements of the forearm are necessary. Some basic movements of ADL, such as eating with a spoon or drinking a cup of tea, also need to include FE movements of the elbow as illustrated in Figure 1(b).

The wearable feature of the robot is also a valuable property, since it can benefit for in-home rehabilitation. It is necessary and important to perform the rehabilitation in a safe environment, especially in the current severe COVID-19 epidemic. As a wearable robot, it is worn by the user and has direct contact with the human limb. Therefore, to design considering lightweight, portable, comfort, and safety is required. One potential risk is the misalignment of robot and human joints, which can have serious impacts on comfort and safety, as unwanted forces are generated. Some rehabilitation robots are designed considering wrist, elbow or shoulder alignment (Näf et al., 2018), however, the alignment for the forearm PS motion is often

Movements	Range of motion (degree)	Required Max continuous torque (Nm)
Wrist Flexion/Extension	80 (50F, 30E)	1.5
Wrist Radial/Ulnar Deviation	60 (30R, 30U)	1.5
Forearm Pronation/Supination	100 (50P, 50S)	2.0

Table 1. Range of motion and required torques of the hybrid robot.

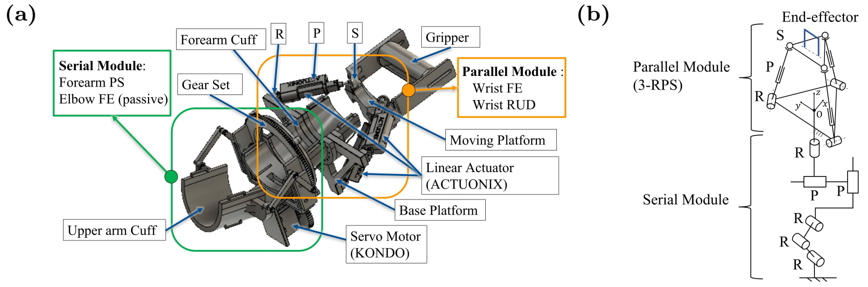

Figure 2. (a) 3D CAD model of the hybrid robot; (b) Schematic diagram of the hybrid robot.

ignored.

The PS movement of the forearm plays an important role in the functionality of the upper limb, and if it is hindered, it will have a serious impact on performing ADL. For robot-assisted rehabilitation of forearm PS movement, it is usually achieved by rotating the rigid links or attachments which are fixed to the forearm and rotated around the rotation axis of robot. However, the PS movement is a complex movement that couples the rotation between humerus, ulna and radius. The rotation is around an axis that runs from the head of the radius to the head of the ulna. In other words, the axis of rotation is not purely straight along the forearm. In addition, the rotation axis of the forearm is not constant during the movement (Lees, 2016). Therefore, in such a situation, joint misalignment may easily occur which leads to generate unwanted forces and cause safety problems. The desired ROM and torques of the robot is shown in Table 1, and the requirements are according to the values given in (Krebs et al., 2007) and the calculations of the current design.

2.2 Details of Mechanical Design

The wearable hybrid robot was designed using a computer-aided design tool, and its components were manufactured using 3D printing in onyx material reinforced with carbon fiber, having both appealing features as

Description	Value	Unit
Radius of moving platform (MP)	40	mm
Radius of base platform (BP)	110	mm
Initial distance between BP and MP	110	mm
The arrangement angle of the revolute joints	90	degree

Table 2. The structural parameters of the parallel module.

lightweight and high strength. The 3D CAD model of the device is shown in Figure 2(a) and the schematic diagram is depicted in Figure 2(b). The robot is attached to the user's upper arm and forearm by means of Velcro straps with cuffs and the palm of the user is fixed to the end-effector. The total weight of the robot including the actuators is about 1.05 kg, which is expected to have portability and is suitable for in-home rehabilitation. The proposed robotic system is composed of two main parts: a parallel module and a serial module.

The parallel module is a 3-RPS robot which can realize two independent rotations and one translation. Two rotational degrees of freedom are used to implement FE and RUD movements of the wrist and the translational degree of freedom is beneficial for adapting to different upper limb lengths. The robot includes a moving platform (MP) and a base platform (BP) which are connected by three limbs and each limb is composed of a revolute joint (R), a prismatic joint (P), and a spherical joint (S) in sequence from BP to MP. The joints of BP and MP are placed at the vertices of the triangle platforms. The prismatic joint is driven by an Actuonix P16-50-22-12-P linear electric motor, which is controlled through an Actuonix Linear Actuator Control Board (LAC) and connected to an Arduino Mega board. The 3-RPS is a lower-mobility parallel robot which has fewer links and actuators, therefore reducing the cost and weight of the robot. However, the occurrence of the parasitic motions in the constrained DOF leads to undesired motions of the MP, which reduce the accuracy and safety of the robot. The parasitic motion of the 3-RPS and the forces\torques applied to the human limb was investigated in our previous study (Liu et al., 2021). In this research, the design of the 3-RPS robot is based on the approach proposed in our previous study and the design parameters are shown in Table 2.

The serial module is connected to the BP of the 3-RPS and is attached to the user forearm and upper arm through the forearm cuff and upper arm cuff, respectively. It performs PS movements of the forearm through a bayonet mount composed of a cylindrical forearm cover with an external gear and a drive pinion gear (gear ratio 1:2.5) directly connected to a servo motor KONDO-KRS-2542R2HV-ICS. The forearm cuff connected with the

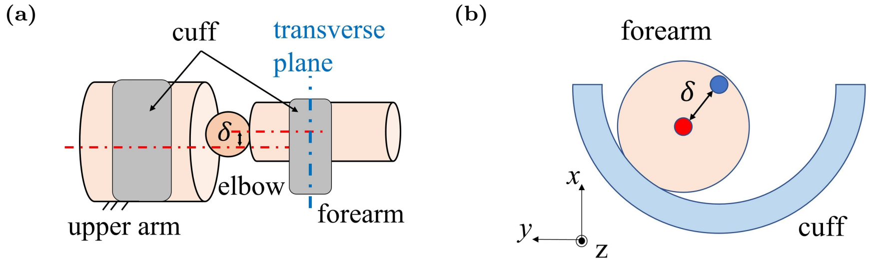

Figure 3. (a) Conceptual model of the axis misalignment; (b) Transverse plane model of the upper limb with the cuff.

cylindrical forearm cover and the fixed upper arm cuff are assembled through a bearing and the user's forearm can insert through the hole of a cylindrical forearm cover. By rotating the cylindrical forearm cover, the forearm can be rotated with respect to the fixed upper arm cuff. In addition, to attach the robot to the upper arm has the advantage of effectively distributing the reaction forces on the user body to avoid any injury or any unpleasant feeling. Moreover, the elbow is included into the wearable device, therefore it has potential for providing elbow assistance.

2.3 Design of Joint/Axis Compensation Mechanisms

Although the size and weight of the wearable robot may increase, it has been proved that adding passive joints to the robot is an effective solution to compensate for the misalignment of human–robot joints (Näf et al., 2018). Inspired by these studies, we propose a novel design that combines the RRPP and RRRR mechanisms to compensate for joint misalignment of the robot with both forearm rotation axis and the elbow joint. We will discuss in detail in the following to describe the design of compensation for different targets.

Misalignment Compensation Mechanism (RRPP) for Rotation Axis of Forearm The robot relies on the rotation of the attached cuff to rotate the forearm and due to the complex anatomy of the forearm mentioned previously, it is difficult to have a good alignment between the rotation axis of the cuff and the forearm, as shown in Figure 3(a). Here we consider a maximum misalignment (δ) between human and robot rotation axis as 10 mm. The mechanism is aligned within the transverse plane of the forearm which is in X-Y plane, and the location of the transverse plane

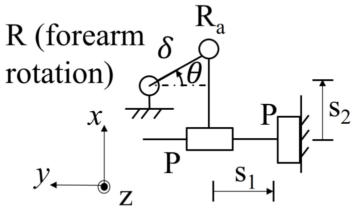

Figure 4. Analytical model of RRPP mechanism.

is set as 110 mm from the wrist joint. The red point and the blue point marked in Figure 3(b) represent the rotation centers of the forearm and of the robot joint, respectively. We regard the forearm rotation as a rotation around a virtual revolute joint and form a four-bar linkage as RRPP with the actuated revolute joint and the added two prismatic joints shown in Figure 4. Through Gruebler's equation, we can find that the DOF of the mechanism is 1. This means that the PS movement of the forearm can be achieved by the one active revolute joint as an actuator of this mechanism regardless of the dimensions of each link. Hence, the proposed mechanism can be adapted to the position of the rotation axis of the forearm.

Next, about kinematic analysis of RRPP mechanism, its geometry is shown in Figure 4, and we can solve the position of two prismatic joints, s_1 and s_2, by using a vector-loop method for given δ, and variable θ. The solutions are as follows:

$$s_1 = \delta \cos\theta, \quad s_2 = \delta \sin\theta \tag{1}$$

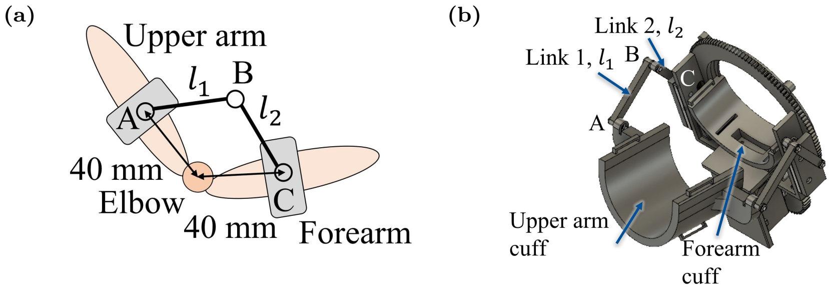

Figure 5. (a) Analytical model of the RRRR mechanism; (b) 3D CAD model of the RRRR mechanism.

From above equations, we can find that the maximum displacement change of the prismatic joints is 20 mm, which is twice the maximum allowable value of axis misalignment. The prismatic joint we used has a 30 mm stroke, therefore 10 mm of the axis misalignment can be fully compensated.

Misalignment Compensation Mechanism (RRRR) for Elbow Joint The elbow joint is viewed as a virtual revolute joint. Three passive revolute joints are added including the elbow joint to form a four-bar mechanism, RRRR, shown in Figure 5(a) by using a similar approach described above. The links l_1 and l_2 are connected to the forearm and the upper arm by the cuffs, respectively. We set the location of the cuff for the forearm and the upper-arm to be 40 mm from the elbow joint in order to have a small volume of the mechanism. Although for the current prototype shown in Figure 5(b), the elbow is not actuated by the actuator and we keep it as a passive joint during the movement, it is possible to add an actuator at

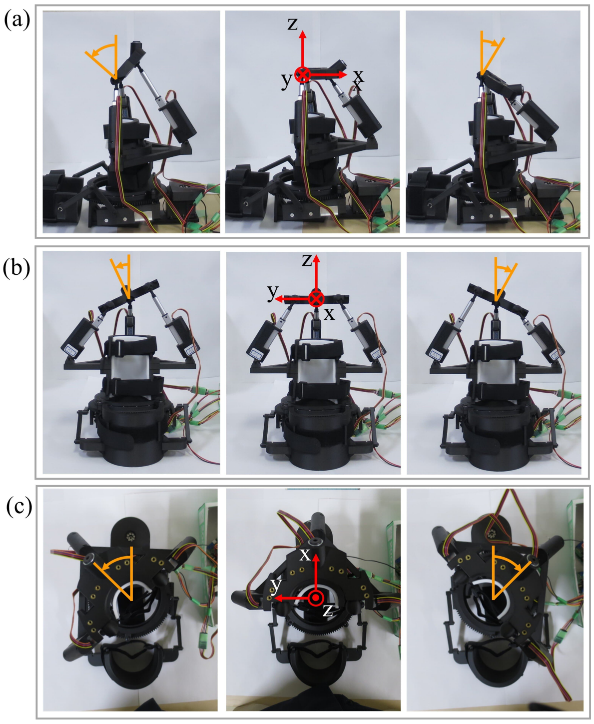

Figure 6. Movements evaluation for: (a) FE (b) RUD (c) PS movements.

point A to rotate the elbow for the next prototype. The link lengths of l_1 and l_2 are set as 60 mm and 55 mm, respectively.

3 Evaluation of the Robot Design

In this section, we evaluate the design of the hybrid robot by setting different configurations of the prototype as shown in Figure 6. A wireless accelerometer, ACL500 (Biometrics Ltd.), is used to measure the rotation angle of moving platform of the 3-RPS in 3 planes simultaneously. From the results, the robot can achieve the desired range of motion of FE, RUD and PS movements without large angular error which is less than 3 degrees. Therefore, the proposed robot design satisfies the specified rehabilitation requirements.

4 Conclusion

We proposed a wearable parallel-serial hybrid robot for wrist and forearm rehabilitation with novel RRPP and RRRR mechanisms for joint misalignment compensation to improve the comfort and safety of the user. The robot is lightweight and portable, which is suitable for in-home rehabilitation. In addition, the robot workspace of the FE, RUD and PS movements are confirmed. It is shown that the proposed robot meets the requirement of rehabilitation of wrist and forearm. Further studies to include some ADL movements will be conducted in the next version of the robot design.

For future works, an experimental investigation to evaluate the effectiveness of the proposed design will be done. Moreover, through questionnaire surveys, we can evaluate the comfortability of the proposed robot. With the measurement data and the feedback of the subjects, the proposed design and further improvements for designing a safer and more comfortable rehabilitation robot will be clarified, prototyped and tested.

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