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A New Compound Model-based Control (NCMC) of an Upper Limb Robot for Rehabilitation

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Abstract **–** Human-Robot Interaction (HRI) is considered a benchmark problem in upper limb rehabilitation. Interaction forces between robot and user play a vital role in terms of safety and effectiveness in HRI. Existing robots for upper limb rehabilitation have not considered interaction forces between robot and user in their control algorithm for passive rehabilitation. This may lead to pain and discomfort for patients. To bridge this gap, in this research, a new compound model-based control (NCMC) is proposed where interaction forces at both upper arm and wrist has been incorporated into the control algorithm. Besides, this algorithm deals with the parameter variation of the user (arm length, weight, height) by including an error-driven portion. The Lyapunov stability analysis of the proposed control was carried out to see its stability. The NCMC was implemented on a seven degrees of freedom (DOF) upper limb rehabilitation robot (u-Rob) with an ergonomic shoulder in doing upper limb rehabilitation exercises with healthy subjects. The experimental results show the effectiveness of the proposed control and validate the stability of the proposed control approach.

Keywords**:** Human-Robot interaction, interaction forces, compound control, rehabilitation, upper limb robot

1. Introduction

Annually, in the United States, 785,000 individuals experience a new or recurrent cerebral vascular accident (CVA) or stroke, and stroke individuals are projected to be doubled by 2030 [1, 2]. The global scenario of stroke occurrence is quite similar to Unites States [3]. Hemiparesis/hemiplegia is the most common consequence of stroke, which leads to movement deficiency in the contralateral limbs to the brain's affected side. It causes the affected individual loss of arm motor function [4]. Stroke is a leading cause of serious long-term disability in the United States [3]. Besides, the human upper limb's motor function can be lost due to sports injuries, trauma, occupational injuries, and spinal cord injuries [5-7]. Moreover, physical disabilities such as full or partial loss of function in the shoulder, elbow, or wrist are common impairments in older adults.

Task-specific and extensive doing of repetitive exercise have been proven to be effective in regaining lost mobility [4]. Recent studies are corroborating that repetitive robot-assisted rehabilitation program significantly improves motor function in the upper limb [8-14]. The conventional therapeutic approach requires a long commitment by both patient and therapist and/or somebody else –who helps the patient in rehabilitation.

Robot-aided rehabilitation has gained much traction these days with the advancement of robotics, mechatronics and sensor technology and automation. Many research groups built prototypes for robot-aided upper limb rehabilitation, e.g., Inmotion, MARSE-7, CADEN-7, CABexo, CAREX-7, etc. [15-20]. Two types of rehabilitation can be carried out with such systems, namely passive and active exercises. In active exercises, a user contributes in reaching a task or goal, whereas in passive exercises, robots carry the user limb and perform the exercise without taking any contribution from the user.

A wide variety of control approaches (e.g. PID [21], Computed Torque Control [22], Sliding mode control[23-27] and hybrid approaches [28-30]) were developed to run existing robots. Though some of the existing robots incorporated user forces into the control algorithm for active exercises, most did not consider interaction forces in passive rehabilitation. It is worth mentioning here that initially, patients need to go through rigorous passive therapy after stroke to regain as much mobility as possible. Not considering interaction forces during robot operation may reach pain, incorrect posture and discomfort to patients. Being motivated by this issue, in this paper, a new compound model-based control (NCMC) algorithm is proposed that takes interaction forces into consideration to improve human-robot interaction (HRI). This algorithm has been implemented on a 7-DOF upper limb rehabilitation robot (u-Rob), and experiments were conducted with healthy subjects. The main contribution of this research is the proposed NCMC control algorithm. The rest of the sections are organized as follows: section-2 presents a brief description about hardware, kinematics, dynamics and Jacobian of the u-Rob robot, section-3 depicts proposed NCMC control law and stability analysis, section-4 presents and discuss experimental results, and lastly paper ends with the conclusion.

2. u-Rob robot

The u-Rob is a 7-DOF robot, as shown in fig. 1, consisting of three modules, namely shoulder module, elbow and forearm module and wrist module [31] with a wide range of motion (ROM). The shoulder module has three degrees of freedom to realize abduction-adduction (A/A), vertical flexion-extension (S F/E) and upper arm internal-external rotation (I/R). Besides, it includes two novel ergonomic mechanisms to provide shoulder elevation-depression and protraction-retraction passively in response to abduction-adduction and vertical flexion-extension, respectively [26]. Two DOF elbow and forearm module realizes elbow flexion-extension (E F/E) and forearm pronation-supination (P/S). Lastly, wrist module has two DOF to provide wrist flexion-extension (W F/E) and radial-ulnar deviation (R/U). Further details can be found in our previous researches [26, 30, 31].

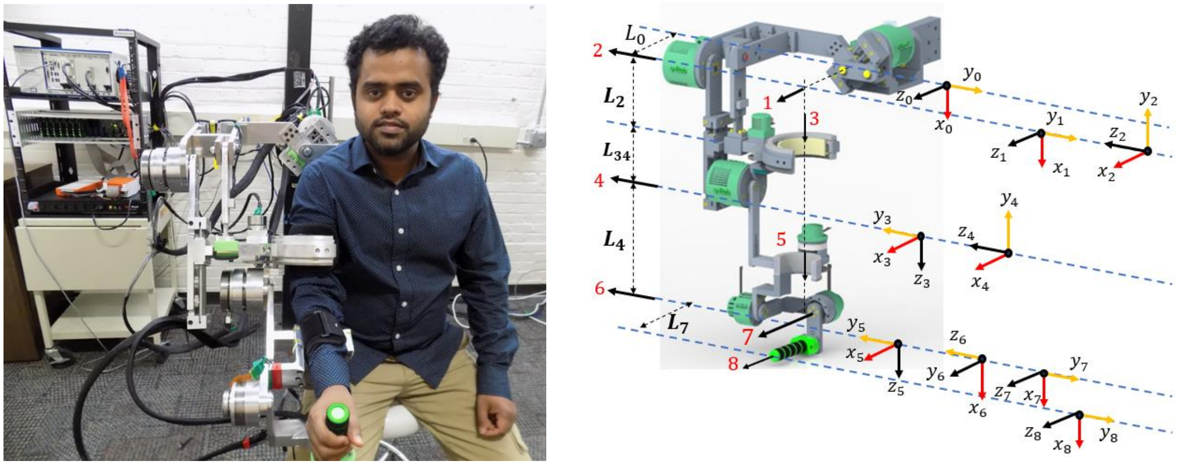

Fig. 1: Seven DOF u-Rob robot with subject (left), coordinate frame assignment of u-Rob (right)

2.1. Hardware Structure

The u-Rob is composed of both serial and parallel linkage. The shoulder module includes two parallel mechanisms of link and slider. To provide upper arm internal-external rotation and forearm pronation-supination, two custom-made cups were designed. To actuate all the joints, Maxon motors coupled with harmonic reducers were used. Three button-type force sensors were placed at the upper arm cup to measure upper arm forces and 3-axis wrist force sensor was placed at the robot's wrist. To ensure safety, position limits, velocity limits and torque limits were included in the control algorithm. Note that each link of u-Rob inherently acts as a mechanical stopper for neighboring link.

2.2. Kinematics

Modified Denavit-Hartenberg (DH) method was used to assign the corresponding coordinate frames of the human upper limb to the u-Rob as shown in fig. 1 [32]. In u-Rob, joint-1, joint-2 and joint-3 correspond shoulder abduction-adduction, vertical flexion-extension, and upper arm internal-external rotation, respectively [31]. The elbow and forearm motion correspond to joint-4 and joint-5 accordingly. The wrist radial-ulnar deviation and wrist flexion-extension correspond to joint-6 and join-7 of the robot joints, respectively. Modified DH parameters were computed, as shown in Table 1 to obtain the position and orientation of u-Rob's hand using homogenous transformation [26]. The homogenous transformation matrices between successive links were computed as shown in equation (1). The kinematics of u-Rob were computed in MATLAB (MathWorks, Natick, MA, USA).

Table 1: Modified DH parameters and range of motion of u-Rob robot.

Upper limb Motion	**Joint** **(*i*)**	α_{i-1} *(Link twist)*	d_i *(Link offset)*	a_{i-1} *(Link length)*	q_i *(Joint variable)*	***Range of Motion*** *(ROM)*
A/A	1	0	0	L_0	q_1	*0 to 90º*
S F/E	2	$\pi/2$	0	0	$q_2 + \pi/2$	*0 to 180º*
I/R	3	$\pi/2$	$L_2 + L_{34}$	0	q_3	*-90º to 90º*
E F/E	4	$-\pi/2$	0	0	q_4	*0 to 135º*
P/S	5	$\pi/2$	L_4	0	q_5	*-90º to 90º*
W F/E	6	$-\pi/2$	0	0	$q_6 - \pi/2$	*-30º to 20º*
R/U	7	$-\pi/2$	0	0	q_7	*-60º to 50º*
End-effector	8	0	0	L_7	0	

$$i-1_{\,i}T = \begin{bmatrix} \cos q_i & -\sin q_i & 0 & a_{i-1} \\ \sin q_i \cos \alpha_{i-1} & \cos q_i \cos \alpha_{i-1} & -\sin \alpha_{i-1} & -\sin \alpha_{i-1}\ d_i \\ \sin q_i \sin \alpha_{i-1} & \cos q_i \sin \alpha_{i-1} & \cos \alpha_{i-1} & \cos \alpha_{i-1}\ d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (1)$$

2.3. Dynamics

The dynamic equations of the u-Rob have been derived from the iterative Newton-Euler formulation as follows [33]:

$$\tau = M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) + F(q,\dot{q}) \qquad (2)$$

Where M(q) is the 7×7 mass matrix of the manipulator, $C(q,\dot{q})$ is a 7×1 dimension vector composed of centrifugal and Coriolis terms, and $G(q)$ is a 7×1 vector of gravity terms. In addition, $F(q,\dot{q})$ is a 7×1 vector of nonlinear coulomb friction and can be expressed by the following relation with a coefficient of friction 'c'. The dynamics were computed in MATLAB (MathWorks, Natick, MA, USA). However, the M, C, G, and F matrix/vectors are so large, and are not included in this work.

$$F(q,\dot{q}) = c.sgn(\dot{q}) \qquad (3)$$

2.4. Jacobian

The linear velocity vector of the end-effector frame (i.e. frame {8}) of the u-Rob robot is comprised of velocities along three Cartesian axes. In contrast, the rotational velocity vector contains angular velocities around three Cartesian axes. From this velocity vector, the Jacobian of the effector velocities (i.e. $J(q)$ is a 6×7 matrix) end- has been computed in MATLAB with respect to the end-effector frame. In addition, Jacobian has also been calculated with respect to the base frame as well. Note that, u-Rob is a redundant manipulator; hence, its Jacobian is not a square matrix. Using equation (4), pseudo-inverse, $J_{pseudo-inverse}$ of the Jacobian can be calculated [34]. In this research, Jacobian of force sensor frame (i.e. frame {8}) and upper arm frame (i.e. frame {3}) have been computed. These two Jacobians were used in proposed NCMC control algorithm.

$$J_{pseudo-inverse} = J^T(q)(J(q)J^T(q))^{-1} \tag{4}$$

3. New Compound Model-Based (NCMC) Control

For rehabilitation, a control approach must ensure safe and effective maneuvering. Since anthropometric parameters (arm's length, arm segment's weight, segment inertia) vary from patient to patient, a model-based controller does not ensure the safe and stable maneuvering of a robot. Besides, the control approach should consider the interactive forces between the user (subject) and the u-Rob robot. Existing exoskeletons have largely ignored the interaction force in passive rehabilitation. Therefore, to take the parameter variation and the interaction forces into the control approach, the error-driven portion of control law and force estimation were included in addition to the model-driven portion. The goal here is to provide a basis to the u-Rob robot (which was given by the model-driven portion), and then any error occurred due to model uncertainty and variation of the anthropometric parameter is for the error-driven portion law to be taken care of. Thus, to control the motion of u-Rob robot, a hybrid approach (based on model-driven computed torque, error-driven proportional derivative torque, and Jacobian-based torque) was used.

3.1. Proposed NCMC control law

The overall control law, model-driven, and error-driven portions were given below.

Error driven portion of control law: $-K_p e - K_v \dot{e}$

Modeldriven portion of control law: $M\ddot{q}_d + C\dot{q}_d + G + F$

Interaction force: $J^T(q, \dot{q})\, F_w$

Modified model driven portion: $M\ddot{q}_d + C\dot{q}_d + G + F - J^T(q)\, F_w$

The overall control law:

$$\tau = -K_p e - K_v \dot{e} + M\ddot{q}_d + C\dot{q}_d + G + F - J^T(q)\, F_w - J_{ua}^T(q)\, F_{ua} \tag{5}$$

Where,

M is a positive definite inertia matrix

$q_d \in \mathbb{R}^{7\times1}$ is the desired joint position vector

$\dot{q}_d \in \mathbb{R}^{7\times1}$ is the desired joint velocity vector

$\ddot{q}_d \in \mathbb{R}^{7\times1}$ is the desired joint acceleration vector

$e = q - q_d$

$\dot{e} = \dot{q} - \dot{q}_d$

$\ddot{e} = \ddot{q} - \ddot{q}_d$

$J^T \in \mathbb{R}^{7\times6}$ is the Jacobian of end-effector expressed in end-effector frame

$J_{ua}^T \in \mathbb{R}^{7\times6}$ is the Jacobian of upper arm frame (i.e. frame 3) expressed in upper arm frame

$F_w \in \mathbb{R}^{3\times1}$ is the Cartesian forces between user and the developed exoskeleton robot at the wrist

$F_{ua} \in \mathbb{R}^{3\times1}$ is the Cartesian forces between user and the developed exoskeleton robot at the wrist

$K_p \in \mathbb{R}^{7\times7}$ is the positive definite diagonal proportional gain matrix

$K_v \in \mathbb{R}^{7\times7}$ the positive definite diagonal derivative gain matrix

3.2. Proof of Lyapunov stability:

From equation (4.6),

$$\ddot{q} = M^{-1}(\tau - C\dot{q} - G - F + J^T(q)\, F_w + J_{ua}^T(q)\, F_{ua})$$

Setting, Lyapunov function, V

$$V = \frac{1}{2} e^T K_p e + \frac{1}{2} \dot{e}^T M \dot{e}$$

$$\frac{dV}{dt} = \dot{V} = \frac{1}{2}\dot{e}^T K_p e + \frac{1}{2} e^T K_p \dot{e} + \frac{1}{2}\ddot{e}^T M \dot{e} + \frac{1}{2}\dot{e}^T M \ddot{e} + \frac{1}{2}\dot{e}^T \dot{M} \dot{e}$$

Thus, $\dot{V} = e^T K_p \dot{e} + \dot{e}^T M \ddot{e} + \frac{1}{2}\dot{e}^T \dot{M} \dot{e}$

$$\Rightarrow \dot{V} = e^T K_p \dot{e} + \dot{e}^T M (\ddot{q} - \ddot{q}_d) + \frac{1}{2}\dot{e}^T \dot{M} \dot{e}$$

$$\Rightarrow \dot{V} = e^T K_p \dot{e} + \dot{e}^T M \left(M^{-1}(\tau - C\dot{q} - G - F + J^T(q)\, F_w + J_{ua}^T(q)\, F_{ua}) - \ddot{q}_d\right) + \frac{1}{2}\dot{e}^T \dot{M} \dot{e}$$

$$\Rightarrow \dot{V} = e^T K_p \dot{e} + \dot{e}^T (\tau - C\dot{q} - G - F + J^T(q)\, F_w + J_{ua}^T(q)\, F_{ua} - M\ddot{q}_d) + \frac{1}{2}\dot{e}^T \dot{M} \dot{e}$$

$$\Rightarrow \dot{V} = e^T K_p \dot{e} + \dot{e}^T (\tau - C\dot{q}_d - G - F + J^T(q)\, F_w + J_{ua}^T(q)\, F_{ua} - M\ddot{q}_d) + \frac{1}{2}\dot{e}^T \dot{M} \dot{e} - \dot{e}^T C \dot{e}$$

$$\Rightarrow \dot{V} = e^T K_p \dot{e} + \dot{e}^T (\tau - C\dot{q}_d - G - F + J^T(q)\, F_w + J_{ua}^T(q)\, F_{ua} - M\ddot{q}_d) + \frac{1}{2}\dot{e}^T \left(\dot{M} - 2C\right)\dot{e}$$

Lemma: If $M(q)$ is a $n \times n$ inertia matrix and $C(q, \dot{q})$ is a $n \times 1$ Coriolis and centrifugal vector, then they satisfy following [36]

$$\dot{e}^T\left[\dot{M}(q) - 2C(q, \dot{q})\right]\dot{e} = 0, \;\; \forall x, q, \dot{q} \; are \; 7 \times 1 \; vectors$$

$$\Rightarrow \dot{V} = e^T K_p \dot{e} + \dot{e}^T (\tau - C\dot{q}_d - G - F + J^T(q)\, F_w + J_{ua}^T(q)\, F_{ua} - M\ddot{q}_d)$$

Choosing $\tau = -K_p e - K_v \dot{e} + M\ddot{q}_d + C\dot{q}_d + G + F - J^T(q)\, F_w - J_{ua}^T(q)\, F_{ua}$

$$\Rightarrow \dot{V} = -\dot{e}^T K_v \dot{e} \leq 0$$

Thus, the stability of the proposed controller is guaranteed.

4. Results and Discussion

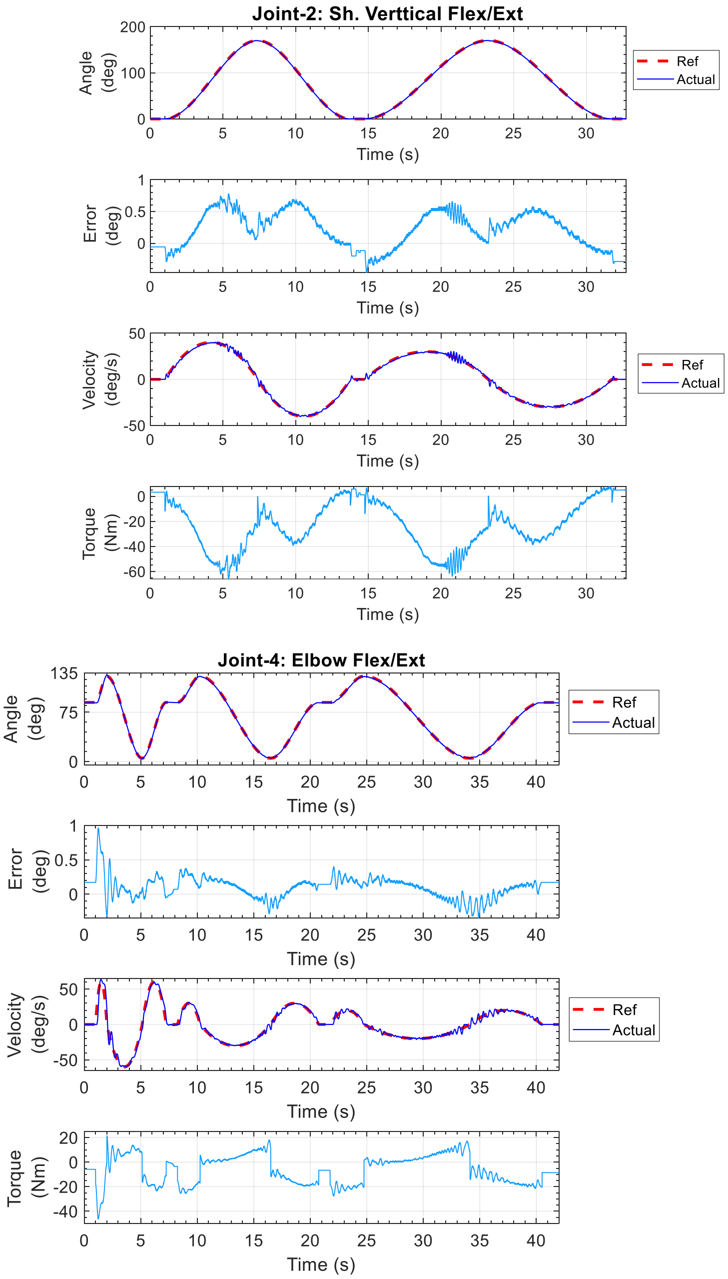

Fig. 2: Result of shoulder exercise (left) and result of elbow exercise (right)

In order to see performance of the proposed control, a wide variety of passive rehabilitation exercises were carried. In the experiments, exercise was given input to the u-Rob robot as a pre-defined trajectory. The performance was measured in termsof tracking of u-Rob's joints' position and velocity. To demonstrate the experimental results, plots of joint position vs. time, error between the reference and actual position, velocity vs. time, and torque vs. time are presented. The red dotted line stands for reference (desired) value in the position and velocity tracking, whereas the solid blue line stands for the actual value. The experiments were conducted with five healthy subjects (age: 28 ± 3 years, weight: 165 ± 30 lbs, height: 5 ft 5 inch ± 5 inch). The Institutional Review Board approved the study (IRB#:19.064; Study title: Experiment of the human natural range of motion with developed robotic device for upper limb rehabilitation).

Though experiments were conducted for a variety of exercises, in order to avoid redundancy, here, only three experimental results are presented. Figure 2 (left) shows the result of the repetitive exercise involving shoulder movements. This exercise was initiated with all joints at zero position, and then the shoulder was vertically flexed to 170º and returned to 0º. The exercise was repeated with a slower velocity to see how proposed NCMC control performs with velocity change. The maximum error for position tracking was found around 0.91º, which shows the excellent tracking performance of the controller. The maximum velocity during the first and second repetition was 60 deg/s and 45 deg/s, respectively. Figure 2 (right) shows the result of an elbow exercise, where the elbow flexion-extension motion was performed and repeated three times. This exercise was initiated with elbow joint angle at 90º; all other joints remained at zero position. From the experimental result, it was seen that the maximum error for position tracking was around 1.17º. The peak velocities for the repetitions were 60 deg/s, 30 deg/s, and 20 deg/s, respectively.

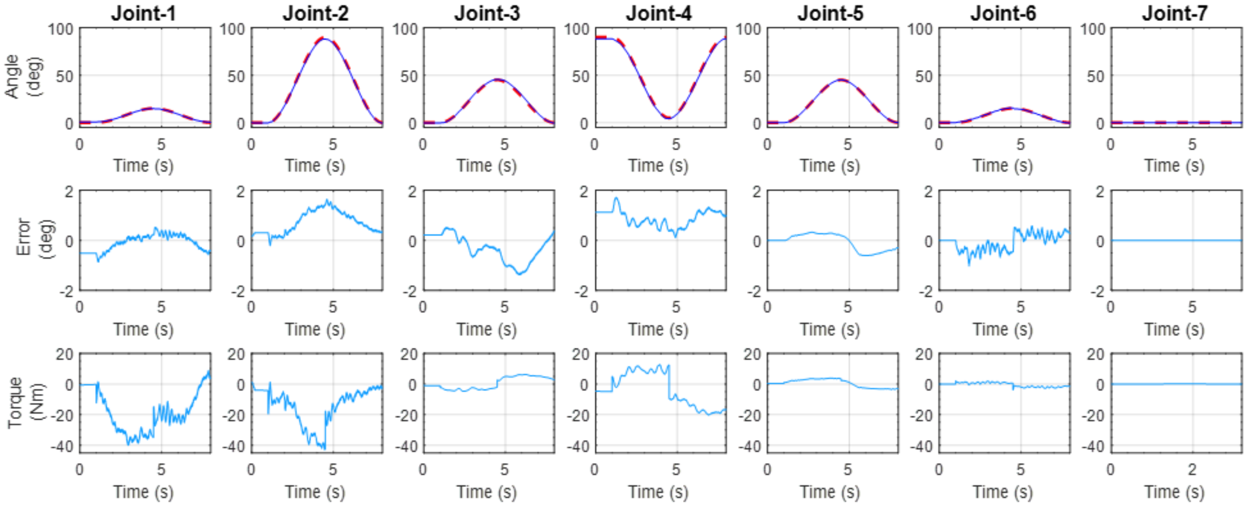

Fig. 3: Result of a diagonal reaching exercise involving simultaneous movement of multiple joints

Figure 3 depicts the result of an experiment involving simultaneous movements of multiple joints. This exercise involves simultaneous movement of all joints except the joint-7 (wrist flexion-extension). It replicates a diagonal reaching movement that starts moving from an initial position (all joints are in 0º while the elbow is at 90º position) to the reaching position (abduction 25º, vertical flexion 90º, external rotation 45º, elbow flexion 10º, forearm pronation 45º and wrist ulnar deviation 15º), and then return to the initial position. As observed from fig. 3, the results show that the NCMC control made u-Robot robot follows the reference trajectory. From the figure, it is also seen that the position for all the joints remained below 2º. The maximum error (1.85º) was found for the elbow joint.

From the results of all three experiments shown in this paper, it is evident that the proposed NCMC has excellent tracking performance and stability; therefore, it can provide robot-aided upper limb rehabilitation.

5. Conclusion

This research proposes a New Compound Model-based Control approach based on robot's and user's interaction forces to improve human-robot interaction. The Lyapunov stability of the proposed control is presented. After that, the proposed NCMC control was experimented with a 7-DOF upper limb rehabilitation robot on healthy subjects to see the controller's performance and stability. The experimental results show that the controller performs well with low tracking error. Besides, the result validates the stability of the controller. Future works remain to conduct a clinical trial with real patients.

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