

Iterative Estimator-Based Nonlinear Backstepping Control of a Robotic Exoskeleton

Brahmi Brahim, Mohammad Habibur Rahman, Maarouf Saad, Cristóbal Ochoa Luna

Abstract—A repetitive training movement is an efficient method to improve the ability and movement performance of stroke survivors and help them to recover their lost motor function and acquire new skills. The ETS-MARSE is seven degrees of freedom (DOF) exoskeleton robot developed to be worn on the lateral side of the right upper-extremity to assist and rehabilitate the patients with upper-extremity dysfunction resulting from stroke. Practically, rehabilitation activities are repetitive tasks, which make the assistive/robotic systems to suffer from repetitive/periodic uncertainties and external perturbations induced by the high-order dynamic model (seven DOF) and interaction with human muscle which impact on the tracking performance and even on the stability of the exoskeleton. To ensure the robustness and the stability of the robot, a new nonlinear backstepping control was implemented with designed tests performed by healthy subjects. In order to limit and to reject the periodic/repetitive disturbances, an iterative estimator was integrated into the control of the system. The estimator does not need the precise dynamic model of the exoskeleton. Experimental results confirm the robustness and accuracy of the controller performance to deal with the external perturbation, and the effectiveness of the iterative estimator to reject the repetitive/periodic disturbances.

Keywords—Backstepping control, iterative control, rehabilitation, ETS-MARSE.

I. INTRODUCTION

Any stroke is caused by the interruption of the blood supply to any portion of the brain, which controls all the functions of the organisms including thought, gesture and activities of daily living [1]. Stroke is the fourth leading cause of mortality and the primary cause of long-term disability in Canada. Every year, nearly 16000 Canadians die as a consequence of a stroke. Yearly, between 40000 and 50000 new strokes are reported in Canada [2]. Although stroke is more prevalent in the elderly, it can strike at any age, even children [3]. The most frequent after effects of a stroke are the loss of muscle control and sensation, often on one side of the body. Stroke victims find it difficult to assess the distance, the position and the velocity of movement [3]. Rehabilitation programs are considered the main methods to help stroke victims to recover their lost motor function and obtain new skills [3]. However, to get maximum benefits from the rehabilitation programs, an early therapeutic intervention is necessary because the

improvement becomes slower over time. Recently, a new method of rehabilitation based on robotic applications has attracted a lot of attention among the research community. This method relies principally on the ability of the robot to repeat accurately the therapeutic tasks (such as a rehabilitation activity) for a longer period of time allowing unlimited repetition of the rehabilitation activities.

Many researchers have been developing rehabilitation robots, for instance: InMotion [4] has two DOF, Assisted Rehabilitation and Measurement Guide (ARMin) [5] have six DOFs, intelligent Pneumatic Arm Movement (iPAM) [6] have five DOFs. These robots are connected to the subject upper-limb. The patient can move his arm in the workspace depending on the available DOF of the exoskeleton [7]. To assist stroke survivors with upper limb dysfunction, we have created a novel seven DOFs exoskeleton robot called ETS-MARSE [8], [9]. It can perform a variety of arm movements (Table I) and is able to perform passive and active rehabilitation activities.

Numerous control techniques have been developed to control the exoskeleton robots for providing rehabilitation therapy, such as a simple PID control implemented in [10]; an intelligent PID control that combines neural networks with PID, implemented in [11]; a nonlinear modified computed torque control which requires good estimation of robot dynamic parameters implemented in [12]. Besides those, a robust sliding mode control with exponential reaching law was proposed in [13] to improve the performance of the robot and limit the chattering problem generated by the high-frequency activity of the control signal. However, there are new nonlinear control techniques that do not require accurate estimation of parameters of robot dynamic model; such as a fuzzy controller based on sliding mode control proposed in [14], where the adaptation of the dynamic parameters was done by using a fuzzy controller. This approach is aimed to ameliorate the performance of the robot and limit the chattering phenomenon that could produce damage to the motors.

An adaptive control based on neural network is presented in [15] to estimate the uncertain parameters and external disturbances. Neural networks and fuzzy logic are powerful tools used to estimate the dynamic parameters [16]. However, fuzzy logic has a slow response time as the advanced nonlinear technique need bulky calculation [8]. Practically, the trajectories of rehabilitation therapy are repetitive; that make a robotic exoskeleton subject to a periodic and/or repetitive perturbation and uncertainties caused by the variation of dynamic parameters of the robot (such as ETS-MARSE) and

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from the environment (such as a different bodily condition of patients) [17]. Moreover, when a robot is tracking/following a desired trajectory, particularly a complex motion, the uncertainties and the external perturbation can be turned into a nonlinear dynamic term with unknown parameters that causes problems on the control which negatively impact the performance and even the stability of the robot.

To ensure the asymptotic stability and the robustness of the exoskeleton robot, a new nonlinear iterative backstepping control was implemented on the ETS-MARSE. This approach permits to design the control law in several steps based on a Lyapunov candidate function which is positive definite and its derivative is always decreasing [18], [19]. Moreover, the iterative backstepping control is capable of supplying a high degree of accuracy in the presence of uncertainties and external disturbances and reject them [17], [20]. A few techniques have been found to combine nonlinear control and iterative control [21], [22]. The main advantage of the iterative estimator control is that it does not require precise knowledge of the robot model's dynamic parameters and provides good tracking performance despite the presence of disturbances.

To evaluate the accuracy and the robustness of the controller we have implemented trajectory tracking conforming to prescribed passive therapeutic activities [13]. All the experiments were performed with healthy subjects. In the next section, the kinematics and workspace of ETS-MARSE are presented and the control approach is described. Experimental results are exhibited in Section III; finally, the conclusion and future work are presented in Section IV.

II. CONTROL DESIGN

A. Description of ETS-MARSE Robot

The modeling of the exoskeleton was done based on the joints and movements of the human upper-limb. In the model shown in Fig. 1, joints one, two and three represent the scapulohumeral joint (shoulder joint). Joints one and two correspond respectively to the horizontal and vertical extension/flexion of the shoulder joint, while joint three corresponds to the external/internal rotation of the shoulder joint. The joint four corresponds to the elbow flexion/extension. The joint five represents supination/pronation of the forearm and joints six and seven correspond respectively to ulnar/radial deviation, and flexion/extension of the wrist joint [9]. The workspace of the exoskeleton is presented in Table I. The kinematic analysis of the exoskeleton ETS-MARSE is based on the frames [23] attached as shown in Fig. 1.

B. Control

The technique of the iterative backstepping control is proposed for the dynamic of the exoskeleton ETS-MARSE. The dynamic behavior can be expressed as:

$$M(\theta)\ddot{\theta} + C(\theta, \dot{\theta})\dot{\theta} + G(\theta) + F(\theta, \dot{\theta}) + P(t) = \tau \quad (1)$$

where $\theta \in R^7$ is the joint angles vector, $M(\theta) \in R^{7 \times 7}$ is the inertia matrix, $C(\theta, \dot{\theta}) \in R^{7 \times 7}$ is the Coriolis/centrifugal

matrix, $G(\theta) \in R^7$ is the gravity vector, τ is the generalized torques vector, and $F(\theta, \dot{\theta})$ is nonlinear vector of friction. The Coulomb friction model can be written as:

$$F(\theta, \dot{\theta}) = \tau_{\text{friction}} = cf * \text{sign}(\dot{\theta}) \quad (2)$$

where cf is the Coulomb constant friction. $P(t) \in R^7$ is the unknown bounded perturbation which represents nonlinear dynamic perturbations, assumed to be bounded and satisfies the following hypothesis.

Theorem 1: [24], [25] the perturbation varying in time $P(t)$ is continuous and periodic in time with known period T . It can be expressed as:

$$P(t) = P(t - T) \quad (3)$$

Equation (1) can be expressed as:

$$\ddot{\theta} = M(\theta)^{-1}\tau - M(\theta)^{-1}[(C(\theta, \dot{\theta})\dot{\theta} + G(\theta) + F(\theta, \dot{\theta}) + P(t)] \quad (4)$$

The objectives of the control are to ensure the global stability of the robot by using the backstepping control, and reject the external disturbances and uncertainties by integrating powerful iterative control. The first step in this strategy is to choose the dynamic of the errors. We can determine the error as following:

$$e_1 = \theta - \theta_d \quad (5)$$

where, $\theta_d = [\theta_{1d} \dots \dots \theta_{7d}]$ is the desired trajectory for all joints. Considering the Lyapunov function candidate:

$$V_1 = \frac{1}{2} e_1^T e_1 \quad (6)$$

Differentiating (5) with respect to time yields:

$$\dot{e}_1 = \dot{\theta} - \dot{\theta}_d \quad (7)$$

The derivative of V_1 is given by:

$$\begin{aligned} \dot{V}_1 &= e_1^T \dot{e}_1 \\ &= e_1^T (\dot{\theta} - \dot{\theta}_d) \end{aligned} \quad (8)$$

The stabilization of \dot{V}_1 can be obtained by introducing a virtual control input γ_1 :

$$\gamma_1 = \dot{\theta}_d = \dot{\theta} + k_1 e_1 \quad (9)$$

where k_1 is a 7×7 diagonal positive-definite matrix. Substituting (9) in (8) we obtain:

$$\dot{V}_1 = -e_1^T k_1 e_1 \quad (10)$$

The second error variable is considered:

$$e_2 = \dot{\theta} - \dot{\theta}_d \quad (11)$$

Consider the second Lyapunov function candidate:

$$V_2 = V_1 + \frac{1}{2} e_2^T M(\theta) e_2 \quad (12)$$

The derivative of V_2 is written as:

$$\begin{aligned} \dot{V}_2 &= \dot{V}_1 + e_2^T M(\theta) \dot{e}_2 + \frac{1}{2} e_2^T \dot{M}(\theta) e_2 \\ &= \dot{V}_1 + e_2^T M(\theta) (\ddot{\theta} - \ddot{\theta}_d) + \frac{1}{2} e_2^T \dot{M}(\theta) e_2 \\ &= -e_1^T k_1 e_1 + e_2^T M(\theta) (M(\theta)^{-1} \tau - M(\theta)^{-1} (C(\theta, \dot{\theta}) \dot{\theta} + G(\theta) + F(\theta, \dot{\theta}) + P(t))) - e_2^T M(\theta) \ddot{\theta}_d + \frac{1}{2} e_2^T \dot{M}(\theta) e_2 \\ &= -e_1^T k_1 e_1 + e_2^T \left(\tau - C(\theta, \dot{\theta}) \dot{\theta} - G(\theta) - F(\theta, \dot{\theta}) - P(t) \right) - e_2^T M(\theta) \ddot{\theta}_d + \frac{1}{2} e_2^T \dot{M}(\theta) e_2 \end{aligned} \quad (13)$$

From (11) we can obtain: $\dot{\theta} = e_2 + \dot{\theta}_d$

$$\begin{aligned} \dot{V}_2 &= -e_1^T k_1 e_1 + e_2^T \left(\tau - C(\theta, \dot{\theta}) e_2 - C(\theta, \dot{\theta}) \dot{\theta}_d - G(\theta) - F(\theta, \dot{\theta}) - P(t) \right. \\ &\quad \left. - M(\theta) \ddot{\theta}_d + \frac{1}{2} \dot{M}(\theta) e_2 \right) \end{aligned} \quad (14)$$

Theorem 2: the derivatives of the inertia matrix $M(\theta)$ with the matrix $C(\theta, \dot{\theta})$ satisfies [17]:

$$y^T [\dot{M}(\theta) - 2 * C(\theta, \dot{\theta})] y = 0, \quad \forall y, \theta, \dot{\theta} \in R^n \quad (15)$$

Using Theorem 2 we obtain:

$$\dot{V}_2 = -e_1^T k_1 e_1 + e_2^T (\tau - C(\theta, \dot{\theta}) \dot{\theta}_d - G(\theta) - F(\theta, \dot{\theta}) - P(t) - M(\theta) \ddot{\theta}_d) \quad (16)$$

Consider the control law that stabilizes the system as:

$$\tau = -k_2 e_2 + C(\theta, \dot{\theta}) \dot{\theta}_d + G(\theta) + F(\theta, \dot{\theta}) + M(\theta) \ddot{\theta}_d + P(t) \quad (17)$$

where k_2 is a 7×7 diagonal positive-definite matrix.

Substituting (17) in (16), we find $\dot{V}_2 \leq -e_1^T k_1 e_1 - e_2^T k_2 e_2$. But the term $P(t)$ is not known, so the control law (14) of joint-based control is not appropriate. To solve this problem, an estimator of unknown parameter was integrated in control law as:

$$\hat{\tau} = -k_2 e_2 + C(\theta, \dot{\theta}) \dot{\theta}_d + G(\theta) + F(\theta, \dot{\theta}) + M(\theta) \ddot{\theta}_d + \hat{P}(t) \quad (18)$$

with:

$$\hat{P}(t) = \hat{P}(t - T) + k_3 e_2; \hat{P}(t) = 0, \forall t \in [-T, 0] \quad (19)$$

where: $\hat{P}(t) = [\hat{P}_1(t) \dots \dots \dots \hat{P}_7(t)]^T$ and k_3 is a 7×7 diagonal positive-definite matrix.

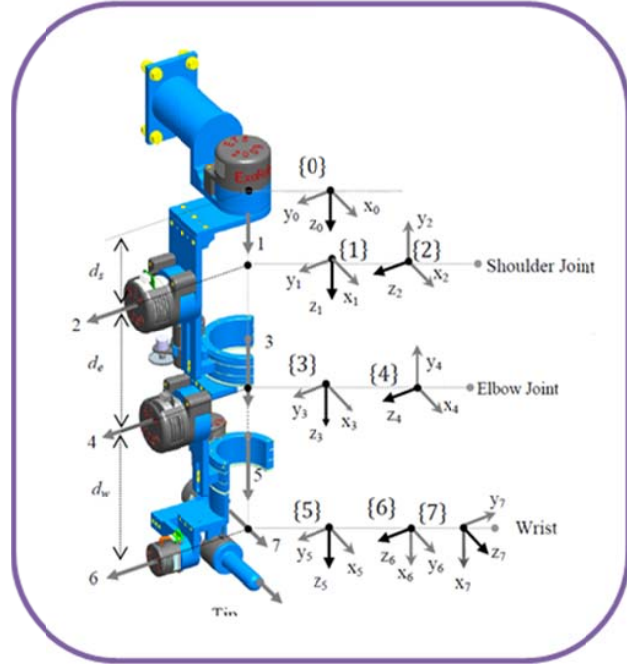


Fig. 1 Link frame attachment to ETS-MARSE [8]

TABLE I
MOVEMENTS OF ETS-MARSE

Joints	Motion	Workspace
1	Shoulder joint horizontal flexion/extension	0°/140°
2	Shoulder joint vertical flexion/extension	140°/0°
3	Shoulder joint internal/external rotation	-85°/75°
4	Elbow joint flexion/extension	120°/0°
5	Forearm joint pronation/supination	-85°/85°
6	Wrist joint ulnar/radial deviation	-30°/20°
7	Wrist joint flexion/extension	-50°/60°

We observe that the control law (18) consists of two terms: the first term ensures the global stability of the robot and the second term estimates the repetitive/periodic perturbations.

We can define the term of estimation error of perturbation as following:

$$\tilde{P}(t) = P(t) - \hat{P}(t) \quad (20)$$

Substituting (19) in (20), using Theorem 1 we obtain:

$$\tilde{P}(t) = P(t - T) - \hat{P}(t - T) - k_3 e_2 \quad (21)$$

Theorem 3: (see [21]): Considering:

$$\begin{cases} P_i(t) \in P(t) \\ \hat{P}_i(t) \in \hat{P} \\ \tilde{P}_i(t) \in \tilde{P} \\ g(t) \in R \end{cases} \quad (22)$$

where $i \in \{1, \dots, 7\}$, i is number of joints and suppose:

$$\begin{cases} P_i(t) = P_i(t-T) \\ \bar{P}_i(t) = P_i(t) - \bar{P}_i(t) \\ \bar{P}_i(t) = \bar{P}_i(t-T) + g(t) \end{cases} \quad (23)$$

Then the right hand derivative of equation: $\int_{t-T}^t \bar{P}^2(s)ds$ is $-2\bar{P}_i(t) * g(t) - g^2(t)$.

Proof: the right hand derivative of equation: $\int_{t-T}^t \bar{P}^2(s)ds$ is $\bar{P}_i^2(t) - \bar{P}_i^2(t-T)$. Considering $\bar{P}_i(t) = \bar{P}_i(t-T) + g(t)$:

$$\begin{aligned} \bar{P}_i^2(t-T) &= [P_i(t-T) - \bar{P}_i(t-T)] * [P_i(t-T) - \bar{P}_i(t-T)] \\ &= [P_i(t) - \bar{P}_i(t) + g(t)] * [P_i(t) - \bar{P}_i(t) + g(t)] \\ &= \bar{P}_i^2(t) + 2g(t)\bar{P}_i(t) + g^2(t) \end{aligned} \quad (24)$$

Thus, we can obtain:

$$\bar{P}_i^2(t) - \bar{P}_i^2(t-T) = -2g(t)\bar{P}_i(t) - g^2(t) \quad (25)$$

Consider a new Lyapunov function candidate as:

$$V_3 = V_1 + \frac{1}{2}e_2^T e_2 + \frac{1}{2k_3} \int_{t-T}^t \bar{P}^T(s)\bar{P}(s) ds \quad (26)$$

The derivative of V_3 is given by:

$$\begin{aligned} \dot{V}_3 &\leq -e_1^T k_1 e_1 - e_2^T k_2 e_2 - e_2^T \bar{P}(t) + \frac{1}{2k_3} \bar{P}^T(t)\bar{P}(t) - \\ &\frac{1}{2k_3} \bar{P}^T(t-T)\bar{P}(t-T) \end{aligned} \quad (27)$$

Using the proof of the Theorem 3 to demonstrate the stability of V_3 and considering :

$$g(t) = -k_3 e_2 \quad (28)$$

where $e_2 = [e_{21} \dots \dots e_{27}]$. Substituting (28) in (25) we obtain:

$$\bar{P}_i^2(t) - \bar{P}_i^2(t-T) = 2k_3 e_2 \bar{P}_i(t) - k_3^2 e_2^T e_2 \quad (29)$$

One can obtain:

$$\begin{aligned} \frac{1}{2k_3} \bar{P}^T(t)\bar{P}(t) - \frac{1}{2k_3} \bar{P}^T(t-T)\bar{P}(t-T) &= \bar{P}^T(t)e_2 - \\ \frac{k_3}{2} e_2^T e_2 \end{aligned} \quad (30)$$

So, we can write (27) as following:

$$\dot{V}_3 \leq -e_1^T k_1 e_1 - e_2^T k_2 e_2 - e_2^T \bar{P}(t) + \bar{P}^T(t)e_2 - \frac{k_3}{2} e_2^T e_2 \quad (31)$$

We obtain:

$$\dot{V}_3 \leq -e_1^T k_1 e_1 - e_2^T (k_2 + \frac{k_3}{2}) e_2 \quad (32)$$

with k_1, k_2, k_3 positive gains, it is easy to conclude that the control law (18) assures stability of the robot. The overall scheme of the proposed control technique is exhibited in Fig. 2.

TABLE II
THE CONTROL GAINS

Gains	Test 1	Test 2
k_1	Diag [15 15 16 15 15 16 16]	same
k_2	Diag[50 50 50 60 80 80 80]	same
k_3	Without estimator	Diag[3 3 3 4 3 3.5 3]

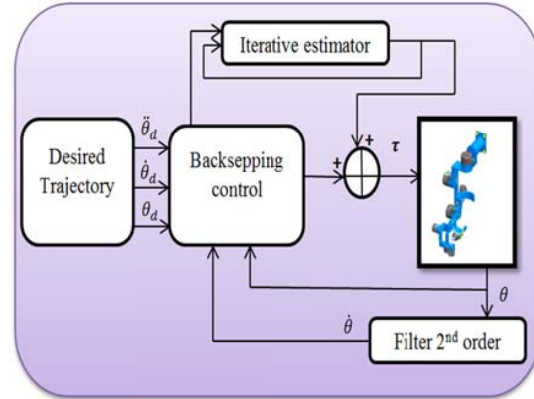


Fig. 2 General schematic of the iterative backstepping control

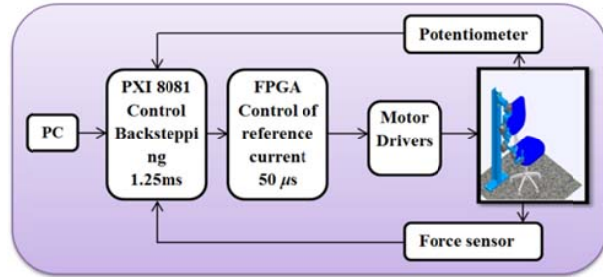


Fig. 3 Control architecture

III. EXPERIMENTS AND RESULTS

The control of the exoskeleton ETS-MARSE robot was implemented in a LabView (National Instruments) PXI system. A PXI card performs the control design and was used as the robot operating system. The control architecture and experimental setup for the ETS-MARSE is designed in three blocks shown in Fig. 3. First, the user interface is connected to the ETS-MARSE for selection of the control technique and the predetermined rehabilitation activity (desired trajectory); it also feedbacks the experimental data from the robot system to analyze the exoskeleton performance. The second block is the PXI-8108, where the proposed control was realized with a period of 1.25 ms (sampling time).

In the experimental setup, we assess the performance of the controller using a repetitive task exercise. In first test, we used in the desired passive trajectory only elbow joint: flexion/extension (see Fig. 4). The control gains utilized for the tests were determined experimentally in (Table II).

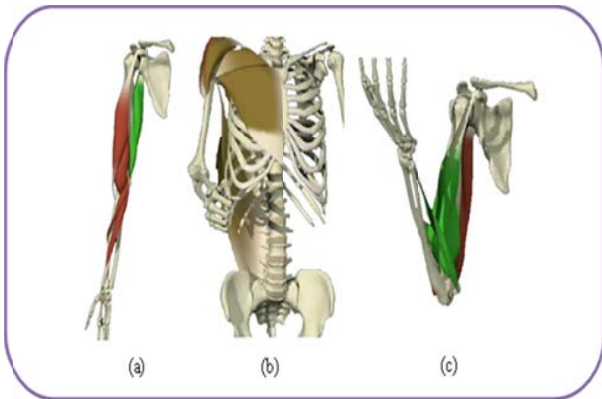


Fig. 4 The proposed elbow joint movement [26]. (a) Extension; (b) Initial position; (c) Flexion

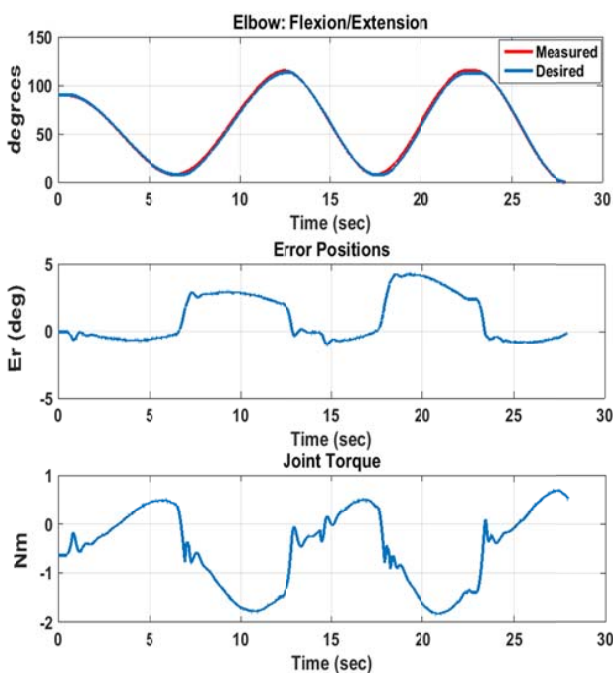


Fig. 5 Performance tracking of repetitive task training conducted with subject-A (age: 30 years; height: 177 cm; weight: 75 kg)

The experimental results of the exercise performed with subject-A (age: 30 years; height: 177 cm; weight: 75 kg) are displayed in Fig. 5. It is obvious that the performance of backstepping control was satisfactory, where the controller has kept stability on the stretch of path with dynamic error (2nd row of the Fig. 5) less than 2.5 degrees. The latest row corresponds to the generated joint torques. To verify the robustness and the precision of the controller with the estimator proposed, the same trajectory was conducted with subject-B (age: 27 years; height: 170 cm; weight: 79 kg). From Fig. 6, we can clearly see that the measured trajectories overlap with the desired trajectories meaning the control proposed provided an excellent tracking performance. We observe that the tracking error (2nd row of Fig. 6) was reduced compared with the first test (Fig. 5).

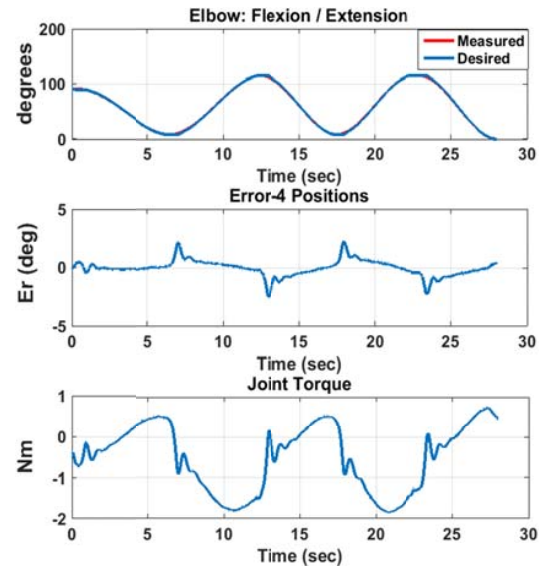


Fig. 6 Performance tracking of repetitive task training conducted with subject-B (age:27 years; height: 170 cm; weight: 79 kg)

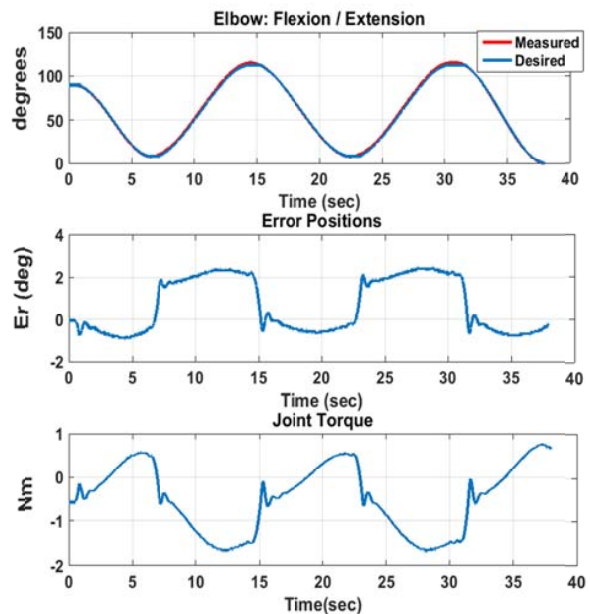


Fig. 7 Performance tracking of repetitive task training conducted with subject-A (age: 30 years; height: 177 cm; weight: 75 kg) various velocity

We observe that we have an error less than 2 degrees only in the instant in which the robot changes its direction from flexion movement to extension movement or vice versa; and during the trajectory, the error converged to zero. We can say that the proposed control provides an excellent tracking performance and it is suitable to limit the influence of periodic perturbations and compensate them.

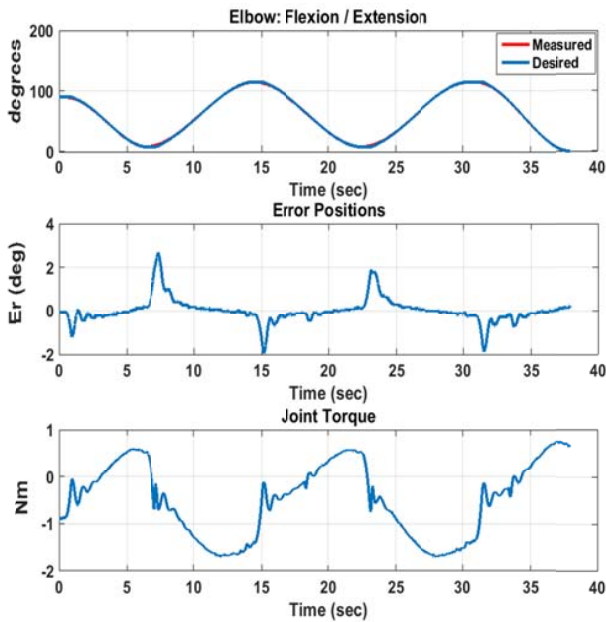


Fig. 8 Performance tracking of repetitive task training conducted with subject-B (age:27 years; height: 170 cm; weight: 79 kg) various velocity

In the second test, we have repeated the previous trajectory but with various velocity. We consider the change of speed in the same trajectory as an external disturbance [27].

The test results of the task conducted with subject-A (age: 30 years; height: 177 cm; weight: 75 kg) are illustrated in Fig. 7. It is obvious that the performance of backstepping control was good, where the controller has kept stability during the sequence of the desired trajectory with dynamic error (2nd row of Fig. 7) relatively less 2.1 degrees. The latest row corresponds to the generated joint torques. To confirm the robustness and the accuracy of the controller with the estimator proposed, the same trajectory was conducted with subject-B (age: 27 years; height: 170 cm; weight: 79 kg). From Fig. 8, we can view that the measured trajectories are identical to the desired trajectories meaning that the control proposed gave a satisfactory tracking performance. We remark that the tracking error (2nd row of the Fig. 8) was decreased compared to the first test (Fig. 7); we note that there is an error of less than 2.1 degrees in the moment the robot changes its direction from flexion movement to extension movement or vice versa; and during the desired trajectory, the error converged to zero. Also, the generated torque joint (3rd row of Fig. 8) is smooth compared with previously generated torque (3rd row of Fig. 7).

Despite the change of speed, the estimator forces the error to converge to zero. We can easily conclude that the proposed control provides an excellent tracking performance and it is able to limit and reject the influence of the periodic disturbance.

IV. CONCLUSION

In this paper, we proposed a new controller based on backstepping control to manipulate an exoskeleton called ETS-MARSE to be able to achieve passive rehabilitation activities. To reduce the influence of disturbances and external forces, we integrated an estimator that does not require precise knowledge of the robot model's dynamic parameters. All desired trajectories were examined with different subjects to prove the accuracy and the robustness of the controller. Experimental results presented an excellent tracking performance and confirmed the efficient of the control proposed in presence of disturbances and external disturbances.

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