$L1$ Adaptive Control of a Lower Limb Exoskeleton Dedicated to Kids' Rehabilitation

Boutheina Maalej, Ahmed Chemori, Nabil Derbel

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Abstract In this chapter, four adaptive controllers have been proposed to control a 2-DOF exoskeleton dedicated to kids' rehabilitation. These control laws are implemented at the hip and the knee joints. In fact, tracking the gait scheme with an intense and a precise work may allow children to increase their brain plasticity. Through the proposed study, it is shown that the augmented L_1 adaptive controller is robust regards to parametric variations. Besides, to validate this controller, different scenarios and simulations were carried out to prove its effectiveness.

Keywords Rehabilitation · Cerebral palsy · Exoskeletons · Classical adaptive control · L_1 adaptive controller

1 Introduction

Robotic systems have recently impacted the human life. Indeed, human-robot interaction in several domains is considered as one of the most remarkable achievement all over the world. Nowadays, exoskeletons can be considered as a significant example of human-robot interaction. Initially, exoskeletons were developed for military applications. Then, for industrial applications and medical uses. Since walking is a key feature of independency, restoring safe walking is one of the main goals of

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robotic rehabilitation. There exist several disabilities that may cause the movement disorders and affect the brain which is the responsible of the body functions. Any damage in the brain tissue before, during or after childbirth may affect certain areas of the brain. Besides, depending on the degree of injury, it can cause permanent disorders, characteristic of a non-progressive injury. Among the potentially determining factors of irreversible brain damage, the most frequently observed include infections of the nervous system, hypoxia (lack of oxygen), head injuries, etc. Children with cerebral motor disorders represent 3 per 1000 newborns. In this context, several medical applications appear in order to help paralyzed kids to restore their locomotion. In this work, we consider the case of lower limb rehabilitation using exoskeletons in order to assist children movements. In the sequel, we will be interested in kids who have between 2 and 13 years old. Hence, we propose to implement robust controllers that can be adapted to the difference of children morphologies [10]. An adaptive control is a controller with adjustable parameters. In fact, it can adapt to changes in the process dynamics and the disturbance characteristics. Moreover, adaptive techniques can also be used to provide automatic tuning of controllers. In this chapter, four control laws are proposed to solve the problem of parametric variations. The chosen controllers include two nonlinear state feedback adaptive controllers, the L_1 adaptive control and augmented L_1 adaptive control. The first approach, based on Slotine works [12], consists in a PD feedback part and a full dynamic feedforward tacking into consideration parametric variations. The second approach is also based on Slotine works [12]. It consists in adding an integral control action to the previous approach in order to eliminate undesirable steady-state position errors. The third approach consists in applying L_1 adaptive control proposed by Naira Hovakimyan [7]. The fourth approach is the augmented L_1 adaptive control [9] which combines the L_1 adaptive control with a Proportional-Integral control to eliminate the time lag and to improve the tracking performances. Simulation results will be presented with a comparative study which aims to show the robustness of the augmented L_1 adaptive control.

2 Description and Modeling of Exoskeletons

Exoskeletons are made in order to help kids suffering from several diseases, such as the cerebral palsy, to restore their walk again by a cyclical and alternative rhythmic activities. The basic idea is to control the lower limb exoskeleton (Fig. 1) at the hip and knee joints.

The dynamic model includes the human limb and the exoskeleton, it is written as follows [5]:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = \tau \tag{1}$$

with,

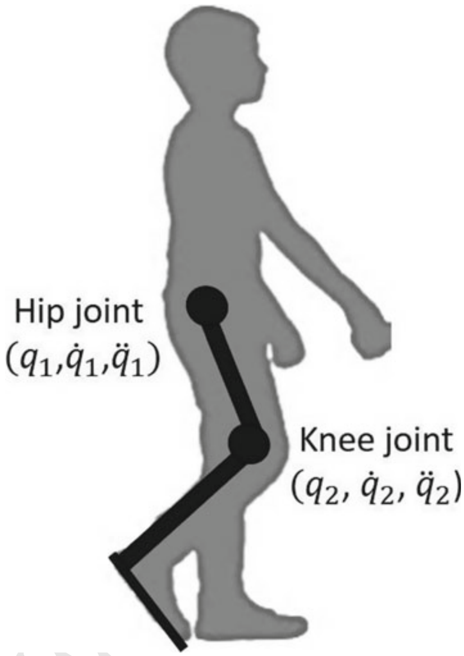

Fig. 1 Concept of the 2-joint lower limb exoskeleton

$$M_{11} = \frac{1}{8}l_1^2 m_1 + \frac{1}{4}m_2\left(\frac{1}{4}l_2^2 + l_1^2 + l_1 l_2 \cos q_2\right) + \frac{1}{2}m_s(l_1^2 + l_2^2 k_2^2 + 2 l_1 l_2 k_2 \cos q_2)$$
$$+\frac{1}{2}k_1^2 l_1^2 m_t + \frac{1}{2}(I_1 + I_2 + I_s + I_t)$$
$$M_{12} = M_{21} = \frac{1}{2}m_2\left(\frac{1}{2}l_2^2 + l_1 l_2 \cos q_2\right) + \frac{1}{2}m_s(l_2^2 k_2^2 + 2 l_1 l_2 k_2 \cos q_2) + (I_2 + I_s)$$
$$M_{22} = \frac{1}{8}m_2 l_2^2 + \frac{1}{2}m_s l_1^2 + l_2^2 k_2^2 + \frac{1}{2}(I_2 + I_s)$$
$$C_{11} = \left(\frac{1}{2}m_2 + m_s k_2\right) l_1 l_2 \sin q_2$$
$$C_{12} = -\left(\frac{1}{2}m_2 + m_s k_2\right) l_1 l_2 \sin q_2$$
$$C_{21} = \left(\frac{1}{4}m_2 + 1/2 m_s k_2\right) l_1 l_2 \sin q_2$$
$$C_{22} = 0$$
$$G_1 = -\left(\frac{1}{2}m_1 + m_2 + k_1 m_t + m_s\right) g l_1 \sin q_1 - (1/2 m_1 + m_s k_2) g l_2 \sin(q_1 + q_2)$$
$$G_2 = -\left(\frac{1}{2}m_1 + m_s k_2\right) g l_2 \sin(q_1 + q_2)$$

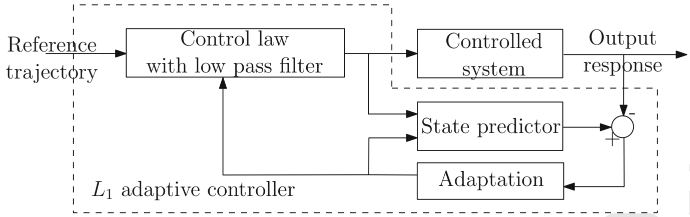

Fig. 2 Block diagram of L_1 adaptive control [7]

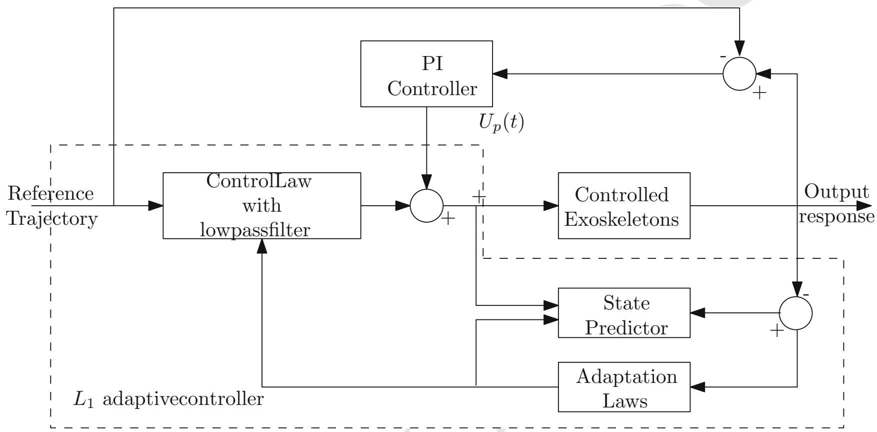

Fig. 3 Block diagram of the augmented L_1 adaptive control [2]

where:

$q = [q_1\ q_2]^T \in \mathbb{R}^2$ represents the position vector of the hip and knee joints, respectively,
$\dot{q} = [\dot{q}_1\ \dot{q}_2]^T \in \mathbb{R}^2$ is the speed vector,
$\ddot{q} = [\ddot{q}_1\ \ddot{q}_2]^T \in \mathbb{R}^2$ is the acceleration vector,
$M(q) \in \mathbb{R}^2$ is the inertia matrix, which is symmetric, uniformly bounded and positive definite,
$C(q, \dot{q})\dot{q} \in \mathbb{R}^2$ represents the Coriolis, and centrifugal forces and torques,
$G(q) \in \mathbb{R}^2$ denotes the gravity torques,
$\tau \in \mathbb{R}^2$ is the vector of actuator torques,
m_1, m_2, l_1, l_2 represent the mass and length of thigh and shank segments of the exoskeleton, respectively,
m_t, m_s denote thigh and shank masses of human limb,
k_1, k_2 are the position of the center of mass of thigh and shank segments, respectively,
I_1, I_2, I_s, I_t represent the moments of inertia of thigh and shank of the exoskeleton and human limb, respectively,
g is the gravity acceleration.

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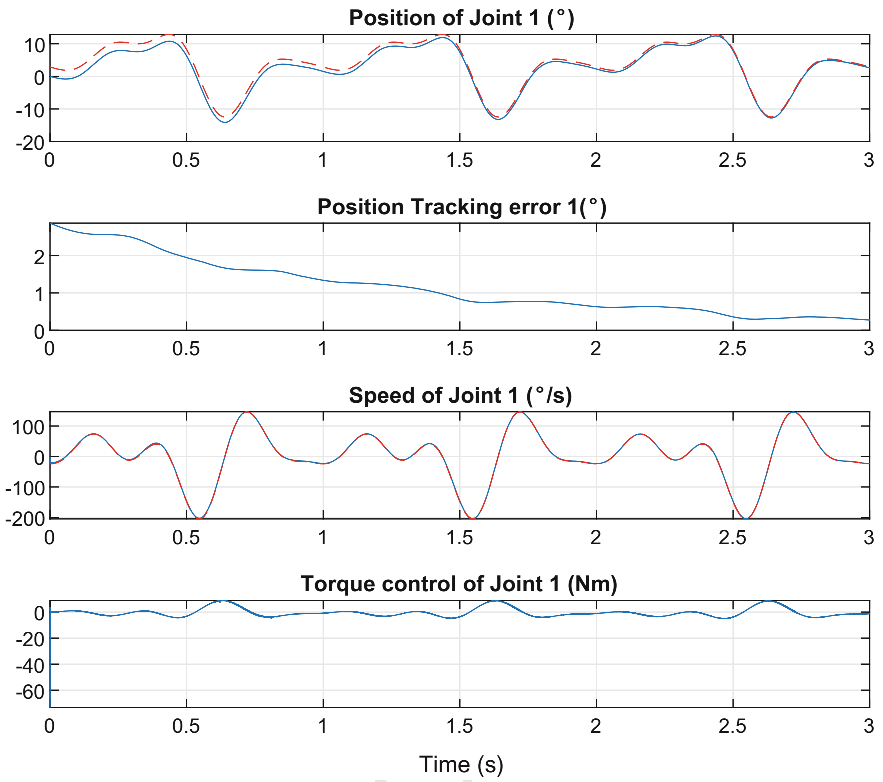

Fig. 4 Classical adaptive control of the hip joint. For the position and the speed, dashed line: desired trajectory, solid line: actual trajectory

3 Proposed Control Solution

3.1 Adaptive Control [12]

Let consider that q_d is the desired joint position and $\dot{q}_d$ is the desired velocity. The main idea is to develop a globally stable adaptive controller which is obtained from a Lyapunov stability analysis. The Lyapunov function associated to the system is:

$$V(t) = \frac{1}{2}\left[\dot{\tilde{q}}^T M(q)\dot{\tilde{q}} + \tilde{a}^T \Gamma \tilde{a} + \tilde{q}^T K_p \tilde{q}\right] \qquad (2)$$

where

a: represents the vector of unknown manipulator parameters
$\widehat{a}$: represents its estimate
$\widetilde{a} = \widehat{a} - a$: denotes the parameter estimation error vector

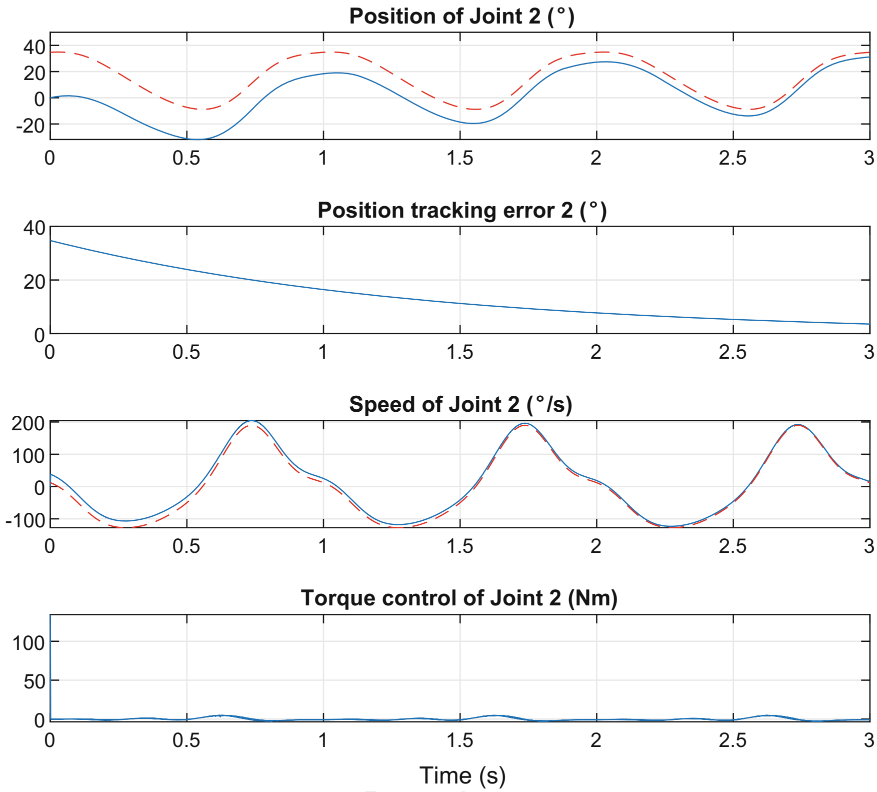

Fig. 5 Classical adaptive control of the knee joint. For the position and the speed, dashed line: desired trajectory, solid line: actual trajectory

K_p, Γ: symmetric positive definite matrices
$\tilde{q} = q - q_d$: represents the position tracking error
$\dot{\tilde{q}} = \dot{q} - \dot{q}_d$: represents the velocity tracking error

The derivative of V with respect to time is:

$$\begin{aligned}
\dot{V}(t) &= \dot{\tilde{q}}^T M \ddot{\tilde{q}} + \frac{1}{2}\dot{\tilde{q}}^T M \dot{\tilde{q}} + \tilde{a}^T \Gamma \dot{\tilde{a}} + \tilde{q}^T K_p \dot{\tilde{q}} \\
&= \dot{\tilde{q}}^T \left(\tau - C(q,\dot{q})\dot{q} - G(q) - M\ddot{q}_d\right) + \dot{\tilde{q}}^T \left(\frac{1}{2}(\dot{M} - 2C) + C\right)\dot{\tilde{q}} \\
&\quad + \tilde{a}^T \Gamma \dot{\tilde{a}} + \dot{\tilde{q}}^T K_p \tilde{q} \\
&= \dot{\tilde{q}}^T \left(\tau - M(q)\ddot{q}_d - C(q,\dot{q})\dot{q}_d - G(q) + K_p \tilde{q}\right) + \tilde{a}^T \Gamma \dot{\tilde{a}} \qquad (3)
\end{aligned}$$

Using the property of skew symmetric matrix, we have:

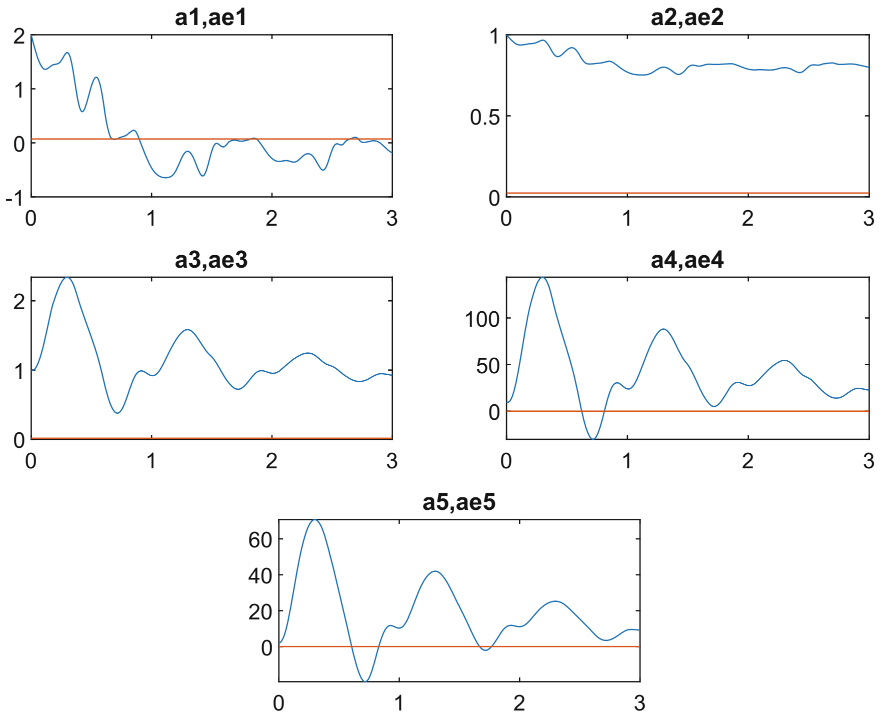

Fig. 6 Evolution of the estimated Parameters for the first approach of Slotine

$$\frac{1}{2}\frac{d}{dt}(\dot{q}^T M \dot{q}) = \dot{q}^T \left(\tau - G(q)\right) \tag{4}$$

$$\dot{q}^T \left(\frac{1}{2}\dot{M} - C\right)\dot{q} = 0 \tag{5}$$

Considering the following control law:

$$\tau = \widehat{M}\ddot{q}_d + \widehat{C}(q, \dot{q}) + \widetilde{G}(q) - K_p\widetilde{q} - K_D\dot{\widetilde{q}} \tag{6}$$

gives

$$\dot{V} = \dot{\widetilde{q}}^T \left[\widetilde{M}(q)\ddot{q}_d + \widetilde{C}(q, \dot{q})\dot{q}_d + \widetilde{G}(q) - K_D\dot{\widetilde{q}}\right] + \widetilde{a}^T \Gamma \dot{\widetilde{a}} \tag{7}$$

where:

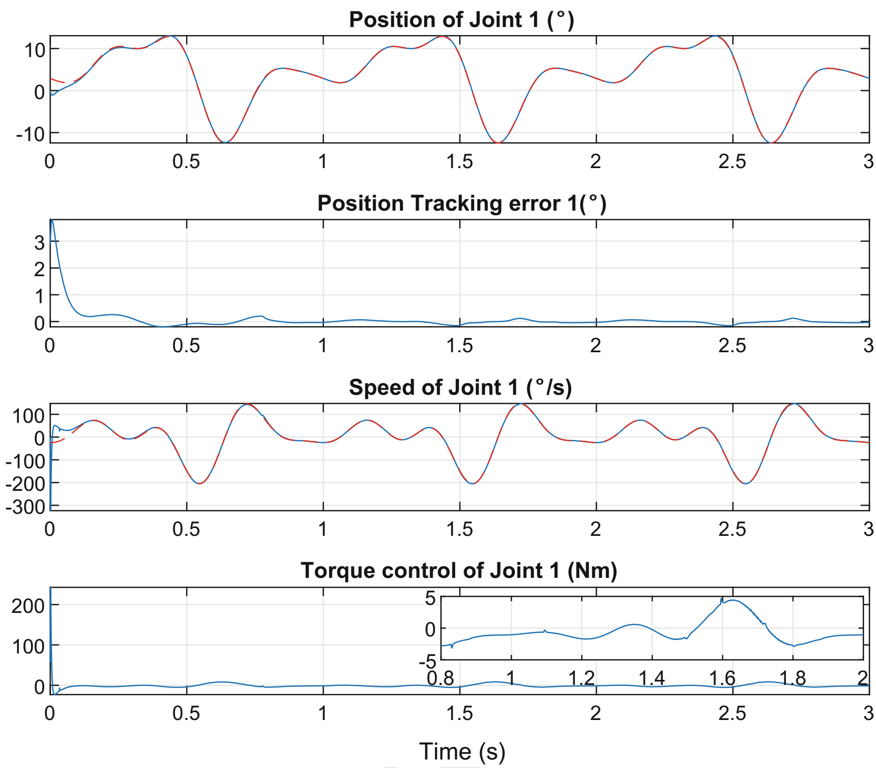

Fig. 7 Adaptive control with integral action of the hip joint. For the position and the speed, dashed line: desired trajectory, solid line: actual trajectory

$$\widetilde{M}(q) = \widehat{M}(q) - M(q) = \sum_i M_i \widetilde{a}_i \tag{8}$$

$$\widetilde{C}(q, \dot{q}) = \widehat{C}(q, \dot{q}) - C(q, \dot{q}) = \sum_i C_i \widetilde{a}_i \tag{9}$$

$$\widetilde{G}(q) = \widehat{G}(q) - G(q) = \sum_i G_i \widetilde{a}_i \tag{10}$$

Then, let's write:

$$\widetilde{M}(q)\ddot{q}_d + \widetilde{C}(q, \dot{q})\dot{q}_d + \widetilde{G}(q) = Y\widetilde{a} \tag{11}$$

where $Y = Y(q, \dot{q}, \dot{q}_d, \ddot{q}_d)$ is an $n \times m$ matrix. Therefore:

$$\dot{V} = -\dot{\tilde{q}}^T K_D \dot{\tilde{q}} + \widetilde{a}^T [\Gamma \dot{\widetilde{a}} + Y^T \dot{\tilde{q}}] \tag{12}$$

Assuming that variations of the unknown vector a can be neglected, we obtain:

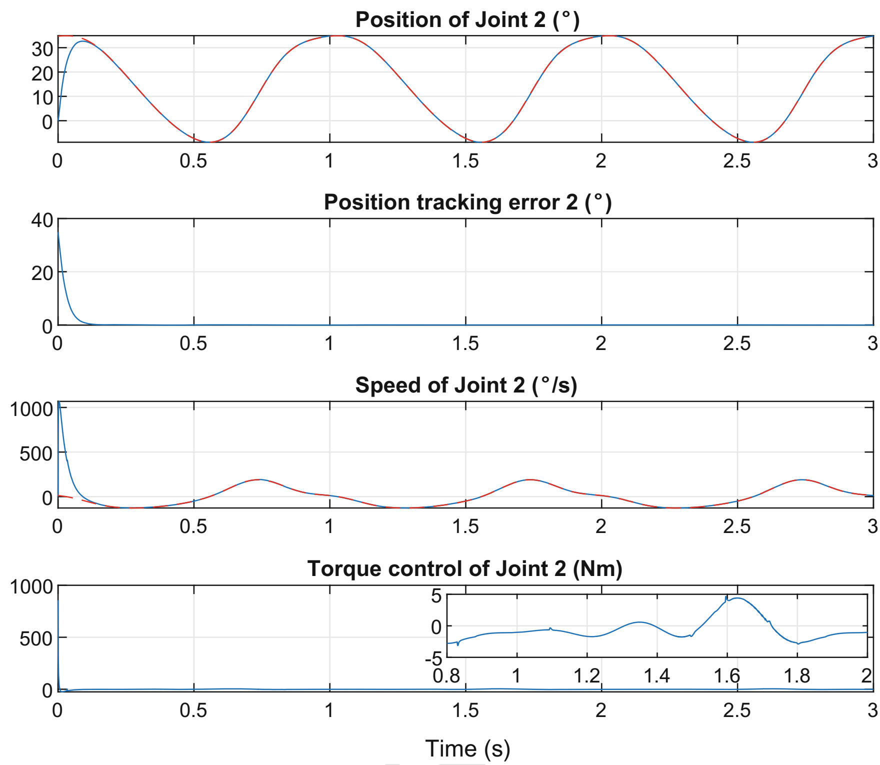

Fig. 8 Adaptive control with integral action of the knee joint. For the position and the speed, dashed line: desired trajectory, solid line: actual trajectory

Table 1 Tracking performance comparison

	Classical adaptive controller		L_1 adaptive controller		Augmented L_1 adaptive controller	
	Joint 1	Joint 2	Joint 1	Joint 2	Joint 1	Joint 2
IAE	0.0037	0.0169	0.0972	0.1578	0.0054	0.0609
ISE	0.0062	0.0181	0.0057	0.0279	1.2702×10^{-4}	0.0183
$IAER$	28.2872	3.1664	0.4075	0.2513	0.0228	0.0970

$$\dot{V} = -\dot{\tilde{q}}^T K_D \dot{\tilde{q}} \leq 0 \tag{13}$$

using the adaptive law of the parameter vector a:

$$\dot{\hat{a}} = -\Gamma^{-1} Y^T \dot{\tilde{q}} \tag{14}$$

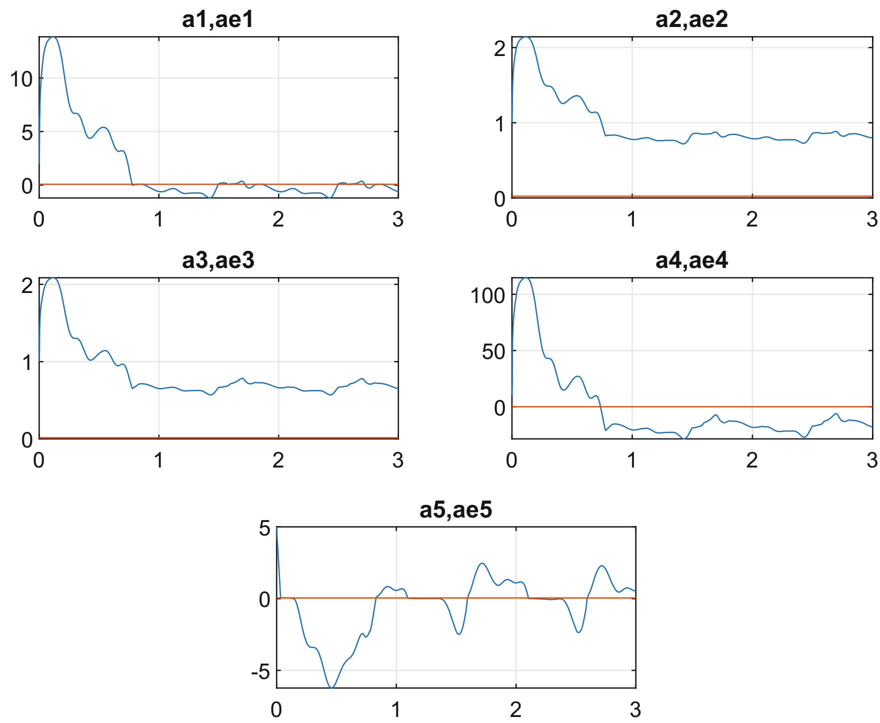

Fig. 9 Evolution of the estimated Parameters for the second adaptive approach of Slotine

3.2 Adaptive Control with an Integral Action [12]

The idea is to eliminate the steady-state position errors by restrict them to lie on a sliding surface.

$$\dot{\tilde{q}} + \Lambda \tilde{q} = 0 \tag{15}$$

where Λ is a positive definite diagonal matrix.

The virtual reference trajectory is expressed by

$$q_r = q_d + \Lambda \int \tilde{q} dt \tag{16}$$

As a consequence, $\dot{q}_d$ and $\ddot{q}_d$ are replaced by

$$\dot{q}_r = \dot{q}_d - \Lambda \tilde{q} \tag{17}$$

$$\ddot{q}_r = \ddot{q}_d - \Lambda \dot{\tilde{q}} \tag{18}$$

If we define

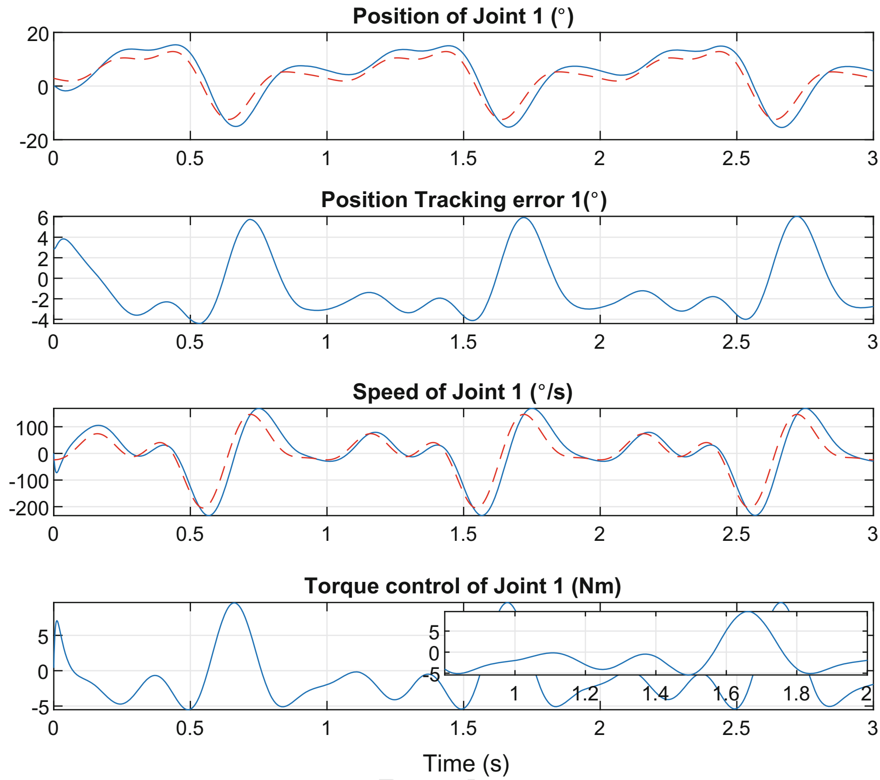

Fig. 10 Classical L_1 adaptive control of the knee joint. For the position and the speed, dashed line: desired trajectory, solid line: actual trajectory

$$s = \dot{\tilde{q}}_r = \dot{q} - \dot{q}_r = \dot{\tilde{q}} + \Lambda \tilde{q} \tag{19}$$

The control and the adaptation laws become:

$$\tau = \widehat{M}\ddot{q}_r + \widehat{C}(q, \dot{q})\dot{q}_r + \widetilde{G}(q) - K_D s \tag{20}$$

$$\dot{\hat{a}} = -\Gamma^{-1} Y^T(q, \dot{q}, \dot{q}_r, \ddot{q}_r)s \tag{21}$$

We use a Lyapunov function to demonstrate the global convergence of the tracking:

$$V = \frac{1}{2}s^T M s + \frac{1}{2}\tilde{a}^T \Gamma \tilde{a} \tag{22}$$

Its first time derivative leads to:

$$\dot{V} = -s^T K_D s \leq 0 \tag{23}$$

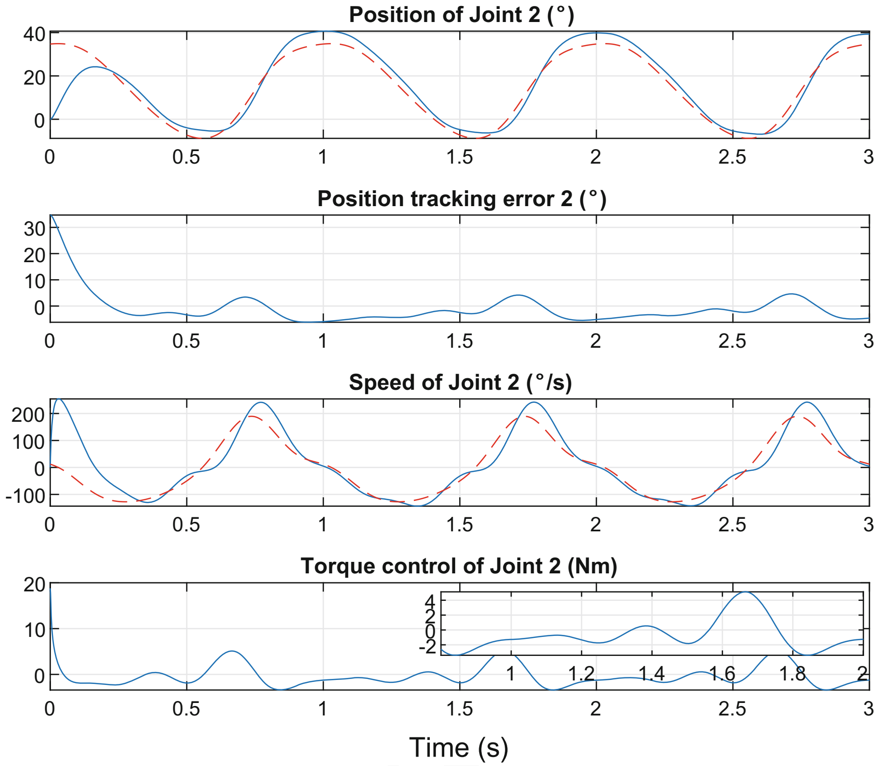

Fig. 11 Classical L_1 adaptive control of the hip joint. For the position and the speed, dashed line: desired trajectory, solid line: actual trajectory

The control law does not contain K_p, since the position error $\tilde{q}$ is already included in $\dot{\tilde{q}}_r$. Moreover where s becomes equal to 0, $\tilde{q}$ converges to 0.

It is well known that the adaptive controller has several limitations such as (i) the initial value of the parameters, (ii) the persistent excitation of the estimated parameters, and (iii) the stability. Hence, L_1 Adaptive controller is presented in the next subsection which overcome these limitations.

3.3 L_1 Adaptive Control [2]

L_1 adaptive control is inspired from the Model Reference Adaptive Control (MRAC), it is structured into four principal parts as illustrated in Fig. 2 namely the controlled system, the state predictor, the adaptation mechanism and the control law including a low pass filter. Considering that the control input vector $\tau(t)$ is a compound of two

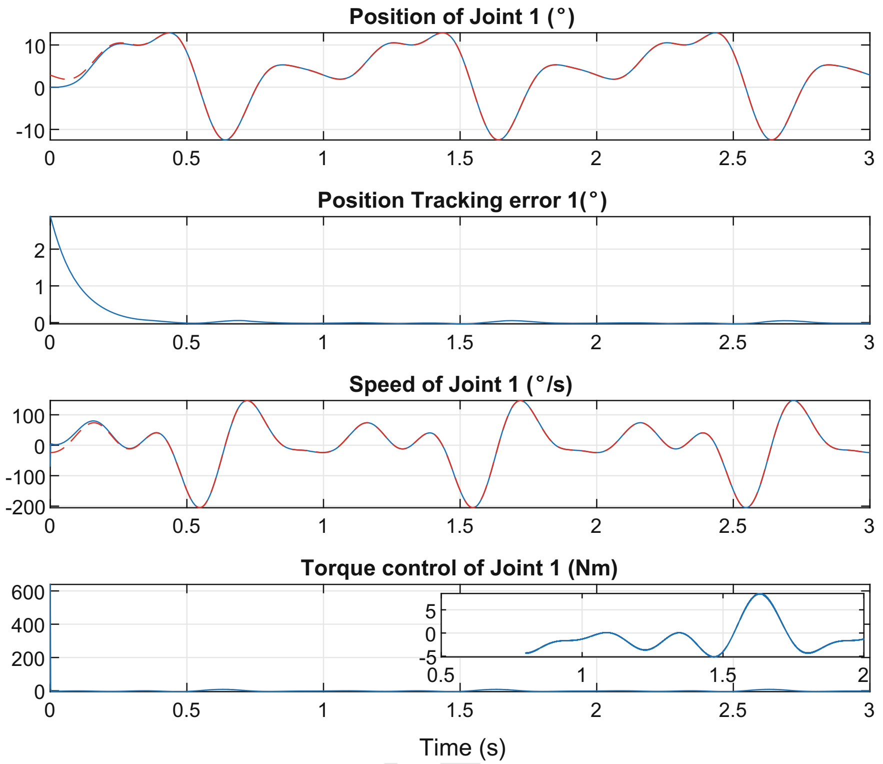

Fig. 12 Position, speed and torque control of the hip joint, obtained with a Augmented L_1 adaptive controller in the nominal case. Solid line: actual trajectory, dashed line: desired trajectory

parts, a fixed state-feedback term that defines the evolution of the transient response and an adaptive term τ_{ad} that compensates the nonlinearities of the system.

The expression of the torque is:

$$\tau(t) = A_m r(t) + \tau_{ad}(t) \tag{24}$$

where:

$A_m \in \mathbb{R}^{2\times 2}$ is a Hurwitz matrix
$\tau_{ad} \in \mathbb{R}^{2\times 2}$ is the adaptive component

The tracking error is expressed as:

$$r = (\dot{q} - \dot{q}_d) + \Lambda(q - q_d) \tag{25}$$

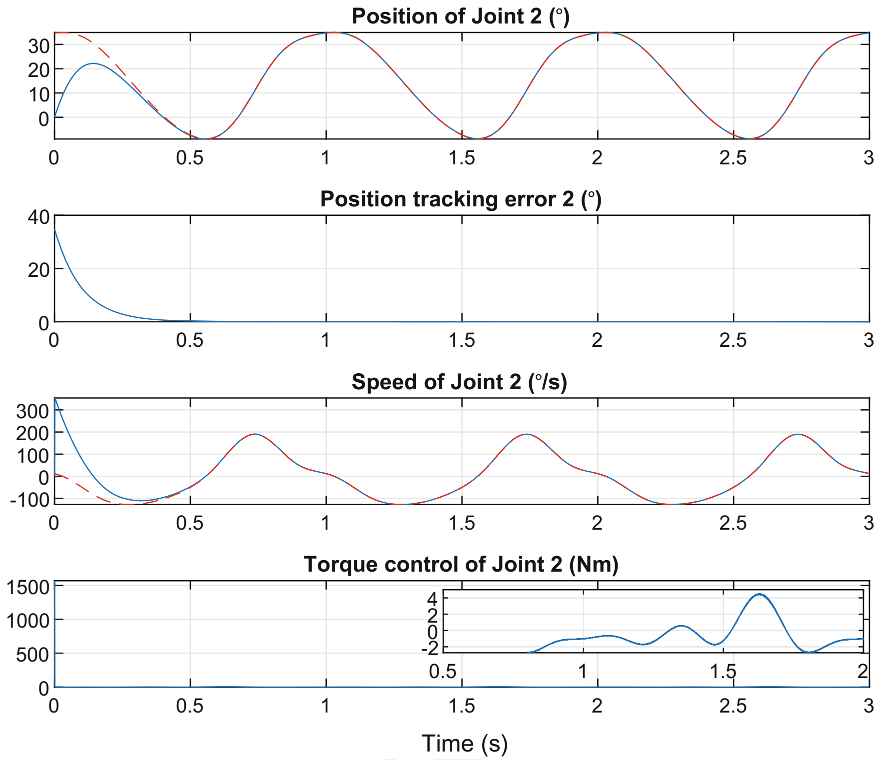

Fig. 13 Position, speed and torque control of the knee joint, obtained with a Augmented L_1 adaptive controller in the nominal case. Solid line: actual trajectory, dashed line: desired trajectory

with $\Lambda \in \mathbb{R}^{2\times 2}$ is a symetric positive definite matrix. It is difficult to know exactly all nonlinearities of the system, hence the adaptive control can be defined in such a way to cancel the effect of these nonlinearities. For that, we consider the state predictor which is based on estimated parameters obtained from the adaptation mechanism:

$$\dot{\hat{r}} = A_m \hat{r}(t) + \tau_{ad}(t) - [\hat{\theta}(t)\|r_t\|_\infty + \hat{\sigma}(t)] - K\tilde{r}(t) \tag{26}$$

where:

$\tilde{r}(t) = \hat{r}(t) - r(t)$ is the prediction error
$K \in \mathbb{R}^{2\times 2}$ used to reject high frequency noises.

Using the projection method, we obtain the estimate of $\theta(t)$ and $\sigma(t)$:

$$\dot{\hat{\theta}}(t) = \Gamma Proj(\hat{\theta}(t), P\hat{r}(t)\|r_t\|_\infty) \tag{27}$$

$$\dot{\hat{\sigma}}(t) = \Gamma Proj(\hat{\sigma}(t), P\hat{r}(t)) \tag{28}$$

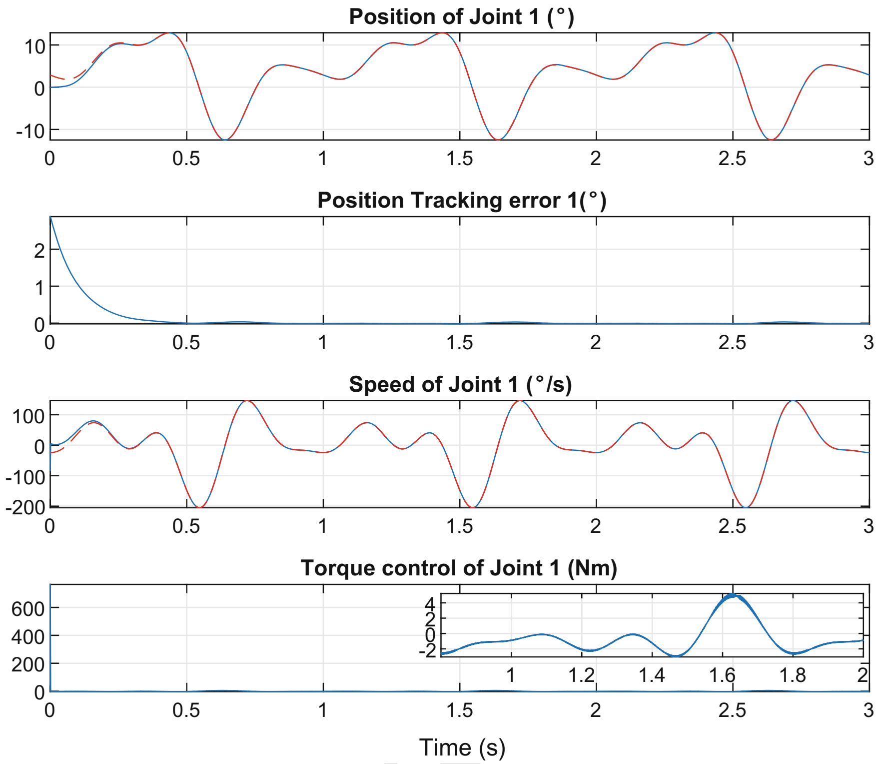

Fig. 14 Influence of −30% of masses and −15% of length uncertainties on the hip joint tracking with augmented L_1 adaptive controller

where Γ is the adaptive gain.

Let's P the solution of the algebric Lyapunov equation:

$$A_m^T P + P A_m = -Q \tag{29}$$

The adaptive control is as follows:

$$\tau_{ad}(s) = C(s)\hat{\eta}(s) \tag{30}$$

where $\hat{\eta}(s)$ is the Laplace transform of $\hat{\eta}(t) = \hat{\theta}(t)\|r_t\|_\infty + \hat{\sigma}(t)$, and $C(s)$ is a bounded-input bounded-output (BIBO) stable strictly proper transfer function.

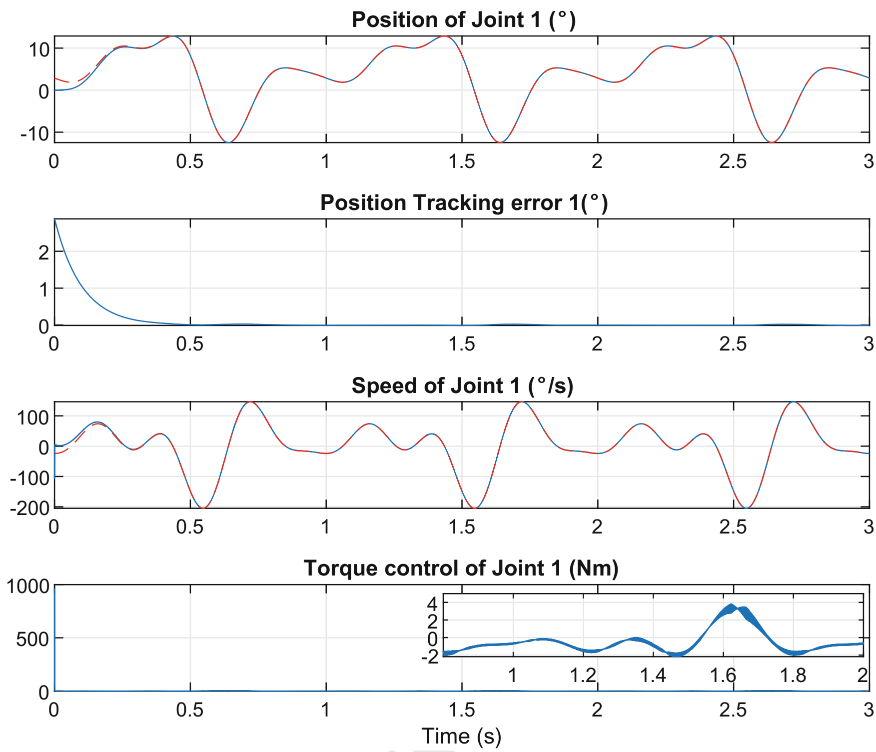

Fig. 15 Influence of −50% of masses and −25% of length uncertainties on the hip joint tracking with augmented L_1 adaptive controller

3.4 *Augmented L_1 Adaptive Control [2]*

The implementation of the classical L_1 adaptive control indicates the presence of a time lag. Hence, the idea is to develop an augmented version of the L_1 adaptive control. Figure 3 shows the block diagram of the augmented L_1 adaptive control. In fact, a linear PI controller is used as an additional part to the filtered control input.

The expression of the torque becomes:

$$\tau(t) = A_m r(t) + \tau_{ad}(t) + K_p(q - q_d) + K_i \int (q - q_d)dt \tag{31}$$

where K_p and $K_i \in \mathbb{R}^{2\times 2}$ are diagonal positive definite matrices.

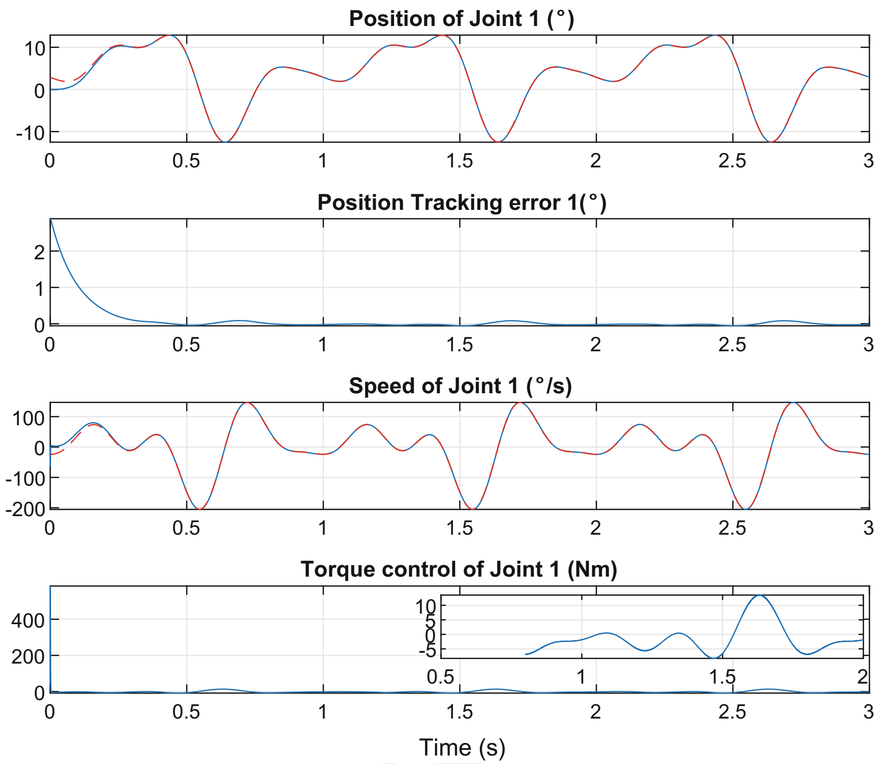

Fig. 16 Influence of 30% of masses and 15% of length uncertainties on the hip joint tracking with augmented L_1 adaptive controller

4 Simulation Results

Lower limb exoskeletons are actuated at the knee and hip joints. To validate the different controllers proposed in the previous section, some simulations are presented. First, Figs. 4 and 5 show respectively the position evolution of the hip and the knee joints, the tracking error, their speed and their applied torques using the first approach of Slotine in the nominal case. Besides, Fig. 6 show the convergence of the estimated unknown parameter to the system parameters.

The second part consists in the adaptive control using an integral action. Results are presented in Figs. 7, 8 and 9.

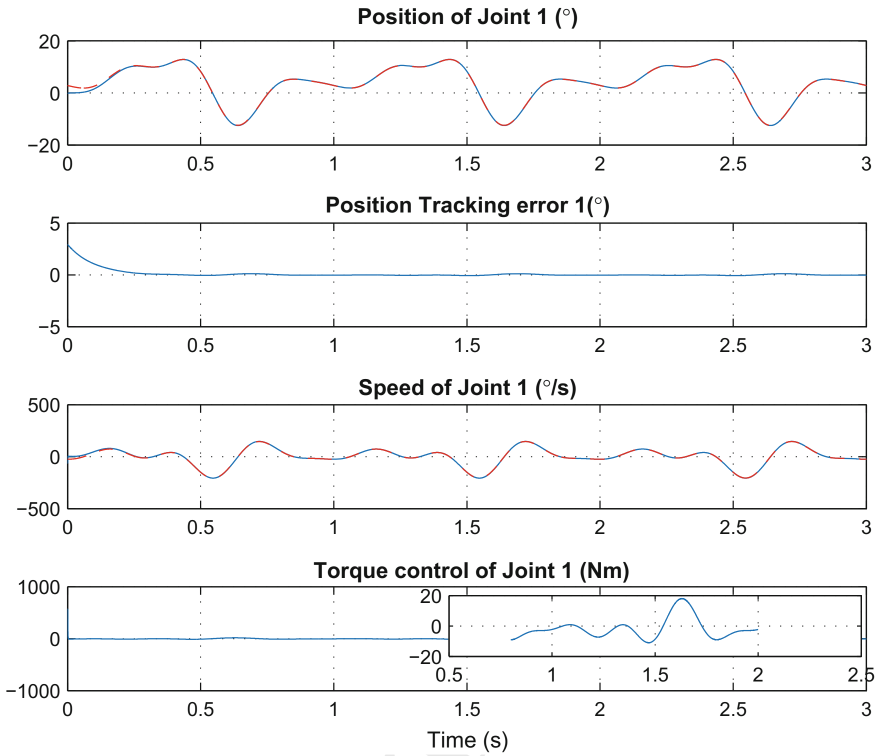

Fig. 17 Influence of 50% of masses and 25% of length uncertainties on the hip joint tracking with augmented L_1 adaptive controller

These figures show a good tracking of the desired trajectories using the second approach of Slotine.

Then, a classical L_1 adaptive control is implemented. Figures 10 and 11 show a time lag between the actual and the desired trajectory. Hence, the idea of implementing an augmented L_1 adaptive control. The obtained results are illustrated in Figs. 12 and 13, and show a good tracking of the desired reference trajectories.

In order to prove the robustness of the proposed extended L_1 adaptive control. First, we demonstrate the performance of the proposed controllers using three criteria named as (i) the Integral of the Absolute Error (IAE), (ii) the Integral of the Squared Error (ISE) and (iii) the relative integral of absolute error (IAER):

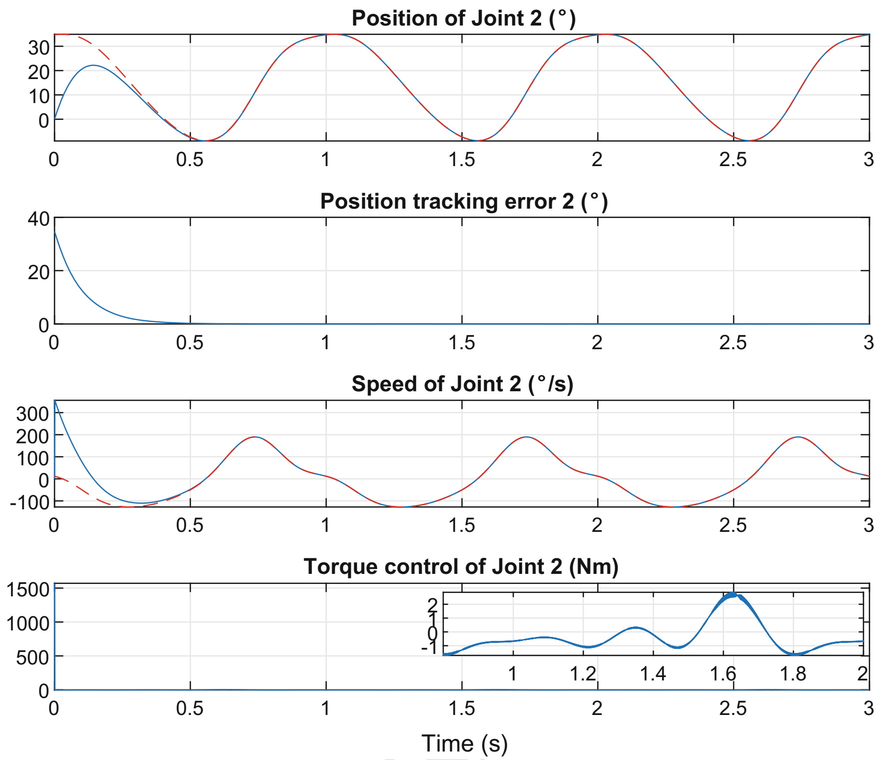

Fig. 18 Influence of −30% of masses and −15% of length uncertainties on the knee joint tracking with augmented L_1 adaptive controller

$$IAE = \int |e|dt \tag{32}$$

$$ISE = \int e^2 dt \tag{33}$$

$$IAER = \frac{\int |e|dt}{\int |q_d|dt} \tag{34}$$

e denotes the tracking error.

The obtained results are summarized in Table 1.

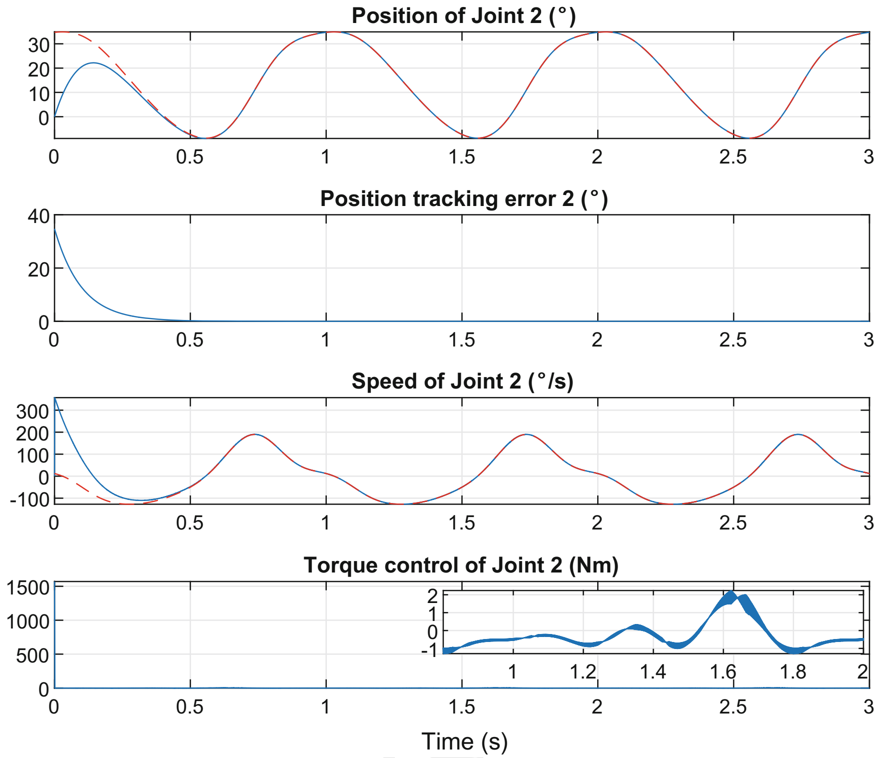

Fig. 19 Influence of −50% of masses and −25% of length uncertainties on the knee joint tracking with augmented L_1 adaptive controller

Figures 14, 15, 16 and 17 present the evolution of positions, velocities, applied torques and position errors of the hip joint in the presence of mass variations of ±30 and ±50% and leg length variations of ±15 and ±25%.

Figures 18, 19, 20 and 21 present the evolution of positions, velocities, applied torques and position errors of the knee joint in the presence of mass variations of ±30 and ±50% and leg length variations of ±15 and ±25%.

In both cases, results show a good tracking of the desired trajectories in the presence of parametric variations with performant torques values. Thus, it is well obvious the good performances observed by the augmented L_1 adaptive control.

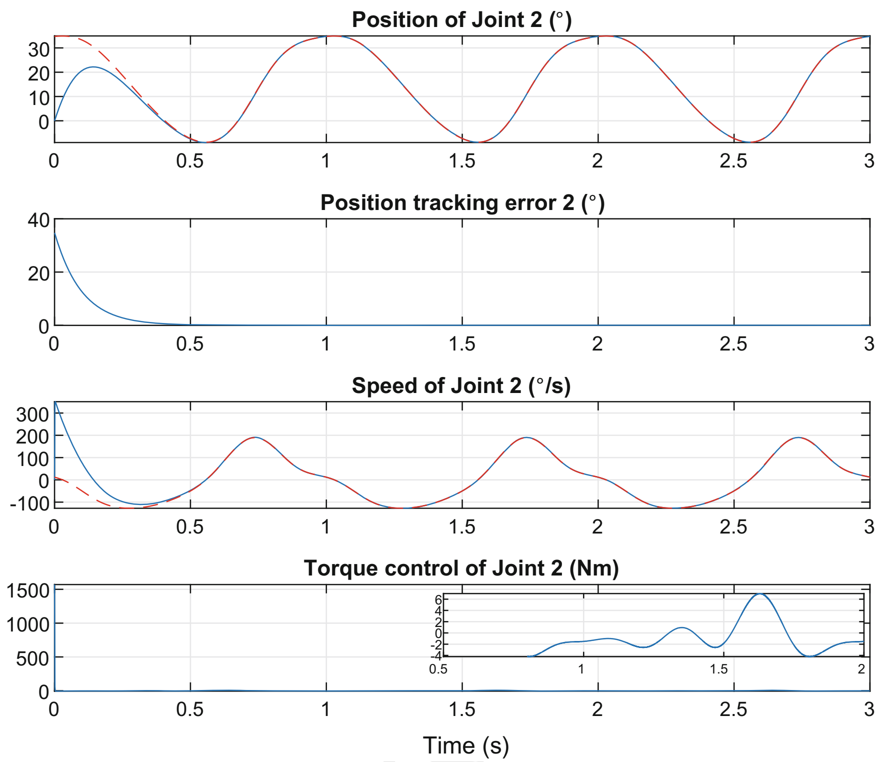

Fig. 20 Influence of 30% of masses and 15% of length uncertainties on the knee joint tracking with augmented L_1 adaptive controller

5 Conclusion and Future Work

In this work, four adaptive controllers have been proposed and implemented to control an exoskeleton for kids rehabilitation. These control laws have been tested for the tracking of walking cycle desired trajectory. This study concerns kids who have between 2 and 13 years old (i.e. with different morphologies). Through numerical simulations, it has been shown that the augmented L_1 adaptive controller is the best one in terms of robustness against these parametric variations. Future works aim to validate the proposed approaches on a real exoskeleton, as well as the application to the targeted kids therapy. AQ1

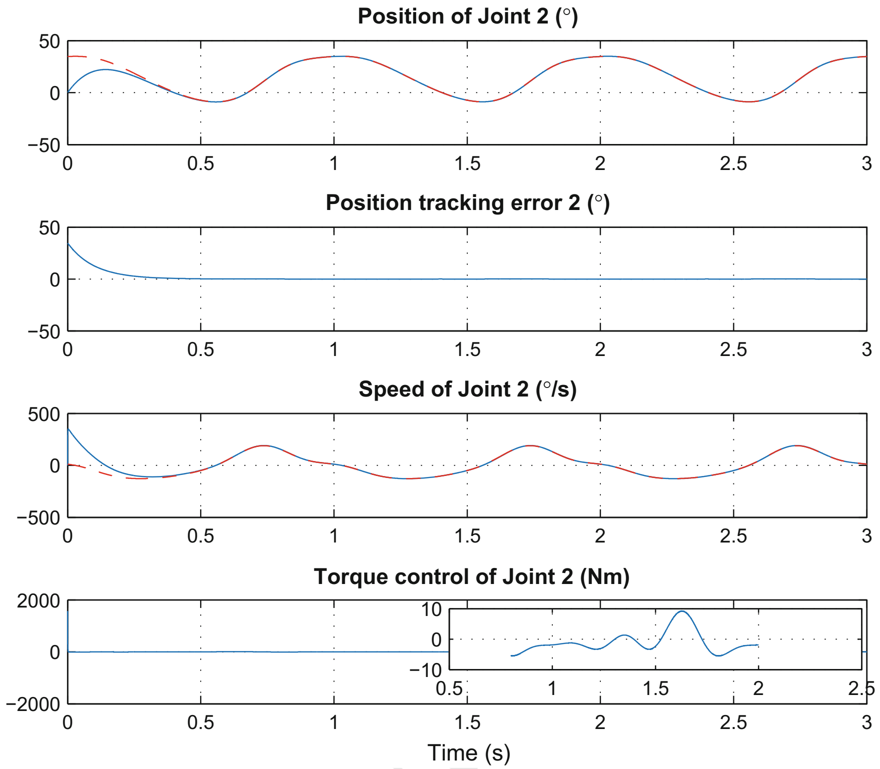

Fig. 21 Influence of 50% of masses and 25% of length uncertainties on the knee joint tracking with augmented L_1 adaptive controller

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Chapter 6

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