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L_1 Adaptive Control of a Lower Limb Exoskeleton Dedicated to Kids' Rehabilitation



Boutheina Maalej, Ahmed Chemori and Nabil Derbel

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 tracking 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

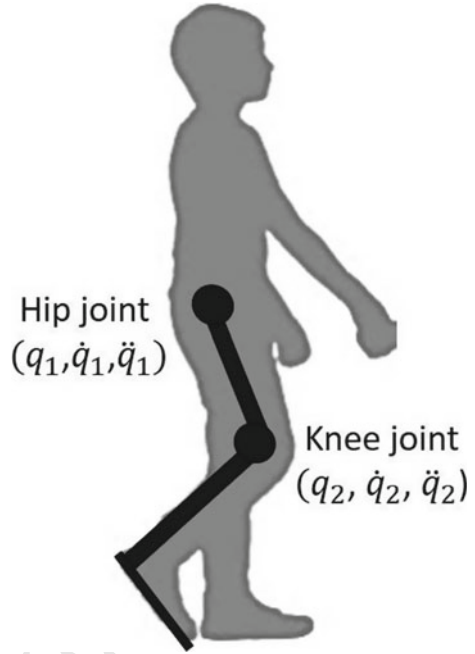
Exoskeletons are made in order to help kids suffering from several diseases, such as the cerebral palsy, to restore their walk again by a cyclical and alternative rhythmic activities. The basic idea is to control the lower limb exoskeleton (Fig. 1) at the hip and knee joints.

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

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

with,

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



$$M_{11} = \frac{1}{8}l_1^2m_1 + \frac{1}{4}m_2 \left(\frac{1}{4}l_2^2 + l_1^2 + l_1l_2 \cos q_2 \right) + \frac{1}{2}m_s(l_1^2 + l_2^2k_2^2 + 2l_1l_2k_2 \cos q_2) + \frac{1}{2}k_1^2l_1^2m_t + \frac{1}{2}(I_1 + I_2 + I_s + I_t)$$

$$M_{12} = M_{21} = \frac{1}{2}m_2 \left(\frac{1}{2}l_2^2 + l_1l_2 \cos q_2 \right) + \frac{1}{2}m_s(l_2^2k_2^2 + 2l_1l_2k_2 \cos q_2) + (I_2 + I_s)$$

$$M_{22} = \frac{1}{8}m_2l_2^2 + \frac{1}{2}m_sl_1^2 + l_2^2k_2^2 + \frac{1}{2}(I_2 + I_s)$$

$$C_{11} = \left(\frac{1}{2}m_2 + m_s k_2 \right) l_1 l_2 \sin q_2$$

$$C_{12} = - \left(\frac{1}{2}m_2 + m_s k_2 \right) l_1 l_2 \sin q_2$$

$$C_{21} = \left(\frac{1}{4}m_2 + 1/2m_s k_2 \right) l_1 l_2 \sin q_2$$

$$C_{22} = 0$$

$$G_1 = - \left(\frac{1}{2}m_1 + m_2 + k_1 m_t + m_s \right) gl_1 \sin q_1 - (1/2m_1 + m_s k_2) gl_2 \sin(q_1 + q_2)$$

$$G_2 = - \left(\frac{1}{2}m_1 + m_s k_2 \right) gl_2 \sin(q_1 + q_2)$$

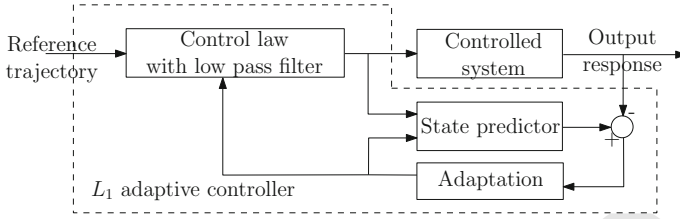


Fig. 2 Block diagram of L_1 adaptive control [7]

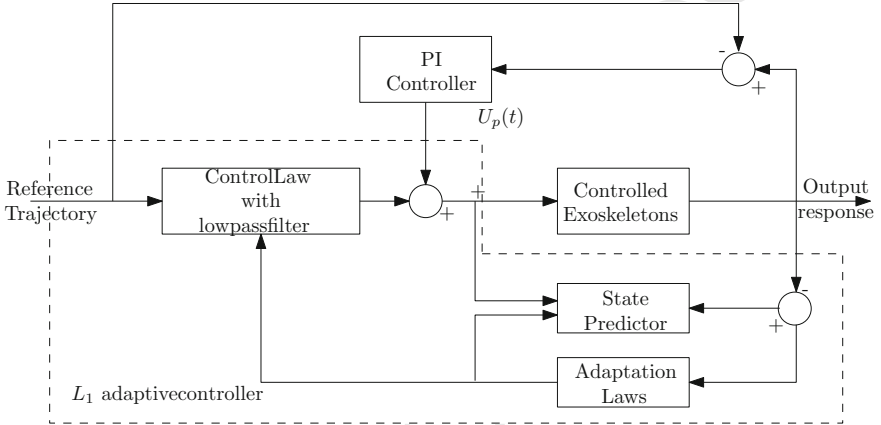


Fig. 3 Block diagram of the augmented L_1 adaptive control [2]

65 where:

66 $q = [q_1 \ q_2]^T \in \mathbb{R}^2$ represents the position vector of the hip and knee joints, respec-
 67 tively,

68 $\dot{q} = [\dot{q}_1 \ \dot{q}_2]^T \in \mathbb{R}^2$ is the speed vector,

69 $\ddot{q} = [\ddot{q}_1 \ \ddot{q}_2]^T \in \mathbb{R}^2$ is the acceleration vector,

70 $M(q) \in \mathbb{R}^2$ is the inertia matrix, which is symmetric, uniformly bounded and positive
 71 definite,

72 $C(q, \dot{q})\dot{q} \in \mathbb{R}^2$ represents the Coriolis, and centrifugal forces and torques,

73 $G(q) \in \mathbb{R}^2$ denotes the gravity torques,

74 $\tau \in \mathbb{R}^2$ is the vector of actuator torques,

75 m_1, m_2, l_1, l_2 represent the mass and length of thigh and shank segments of the
 76 exoskeleton, respectively,

77 m_t, m_s denote thigh and shank masses of human limb,

78 k_1, k_2 are the position of the center of mass of thigh and shank segments, respectively,

79 I_1, I_2, I_s, I_t represent the moments of inertia of thigh and shank of the exoskeleton
 80 and human limb, respectively,

81 g is the gravity acceleration.

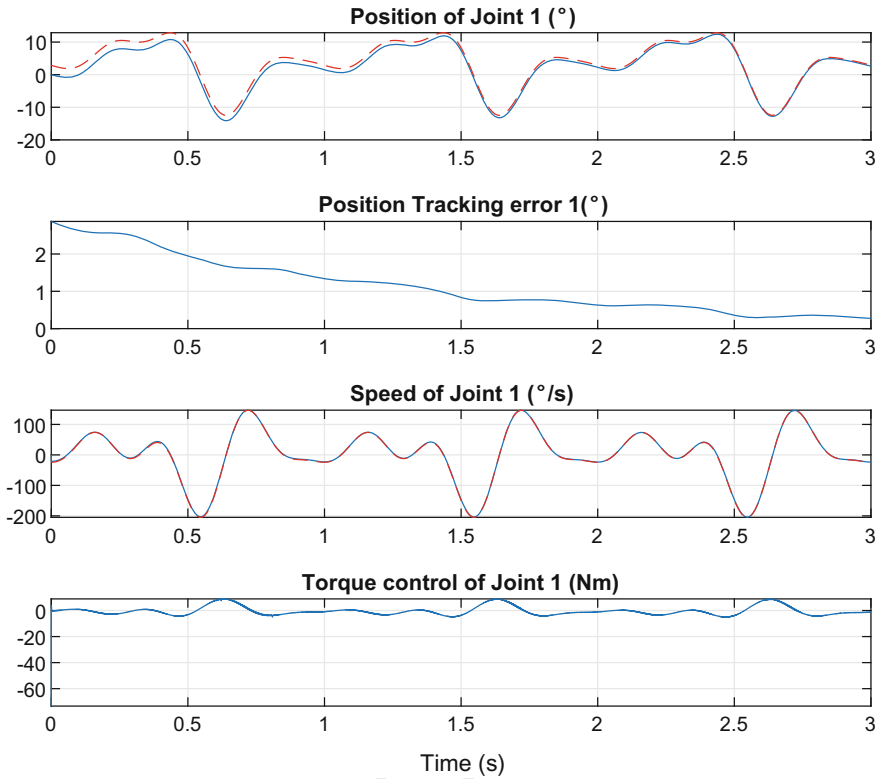


Fig. 4 Classical adaptive control of the hip joint. For the position and the speed, dashed line: desired trajectory, solid line: actual trajectory

82 3 Proposed Control Solution

83 3.1 Adaptive Control [12]

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

$$87 \quad V(t) = \frac{1}{2} \left[\tilde{q}^T M(q) \tilde{q} + \tilde{a}^T \Gamma \tilde{a} + \tilde{q}^T K_p \tilde{q} \right] \quad (2)$$

88 where

89 a : represents the vector of unknown manipulator parameters

90 \hat{a} : represents its estimate

91 $\tilde{a} = \hat{a} - a$: denotes the parameter estimation error vector

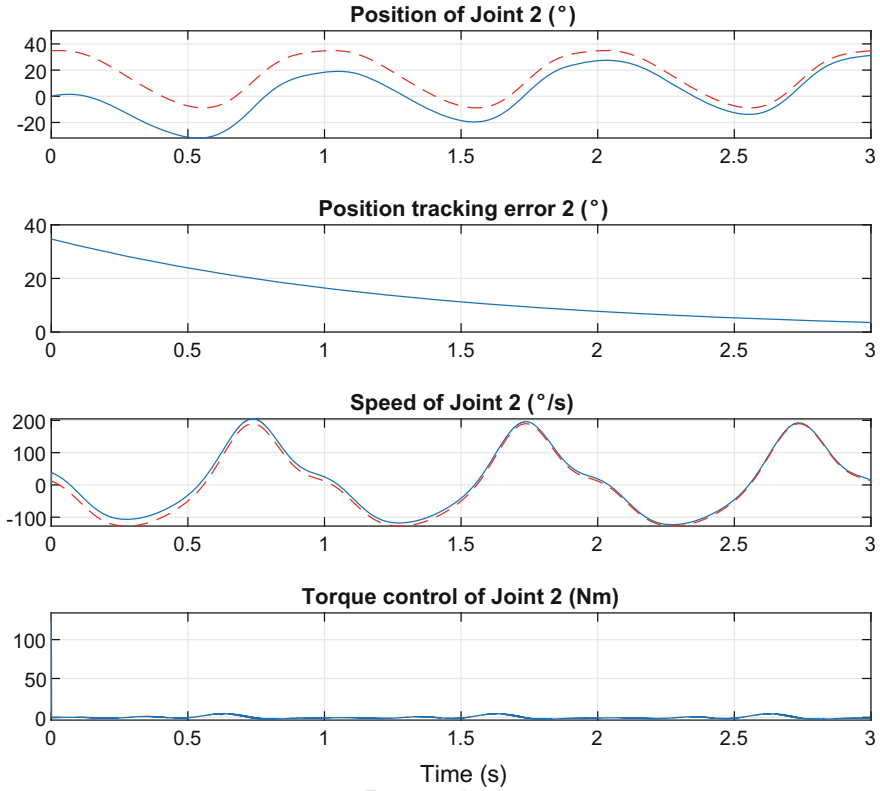


Fig. 5 Classical adaptive control of the knee joint. For the position and the speed, dashed line: desired trajectory, solid line: actual trajectory

92 K_p, Γ : symmetric positive definite matrices

93 $\tilde{q} = q - q_d$: represents the position tracking error

94 $\dot{\tilde{q}} = \dot{q} - \dot{q}_d$: represents the velocity tracking error

95 The derivative of V with respect to time is:

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

100 Using the property of skew symmetric matrix, we have:

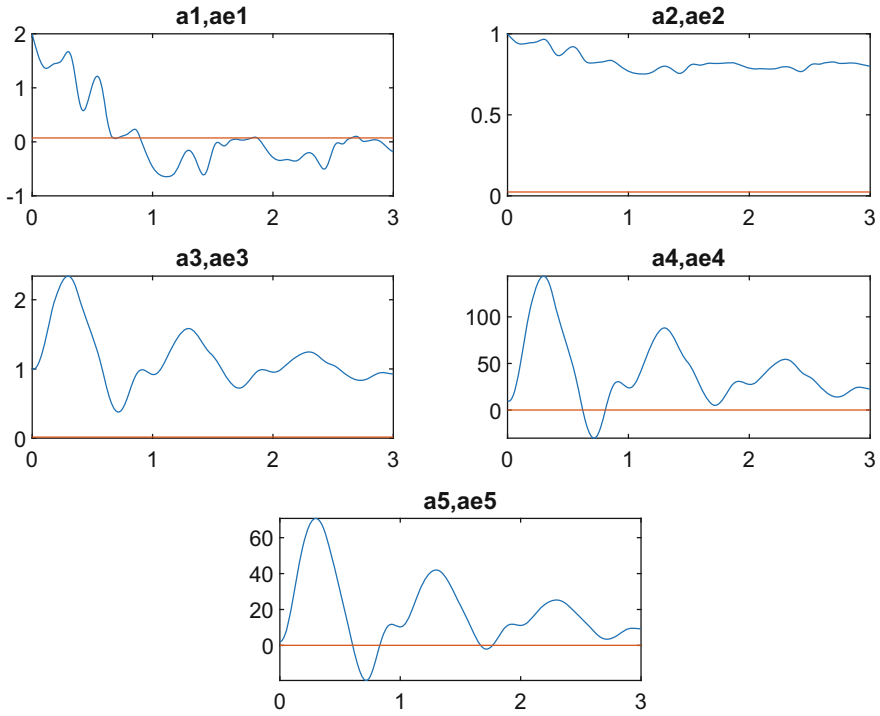


Fig. 6 Evolution of the estimated Parameters for the first approach of Slotine

101
$$\frac{1}{2} \frac{d}{dt} (\dot{q}^T M \dot{q}) = \dot{q}^T (\tau - G(q)) \quad (4)$$

102
$$\dot{q}^T \left(\frac{1}{2} \dot{M} - C \right) \dot{q} = 0 \quad (5)$$

103 Considering the following control law:

104
$$\tau = \widehat{M} \ddot{q}_d + \widehat{C}(q, \dot{q}) + \widehat{G}(q) - K_p \tilde{q} - K_D \dot{\tilde{q}} \quad (6)$$

105 gives

106
$$\dot{V} = \tilde{q}^T \left[\tilde{M}(q) \ddot{q}_d + \tilde{C}(q, \dot{q}) \dot{q}_d + \tilde{G}(q) - K_D \dot{\tilde{q}} \right] + \tilde{a}^T \Gamma \tilde{a} \quad (7)$$

107 where:

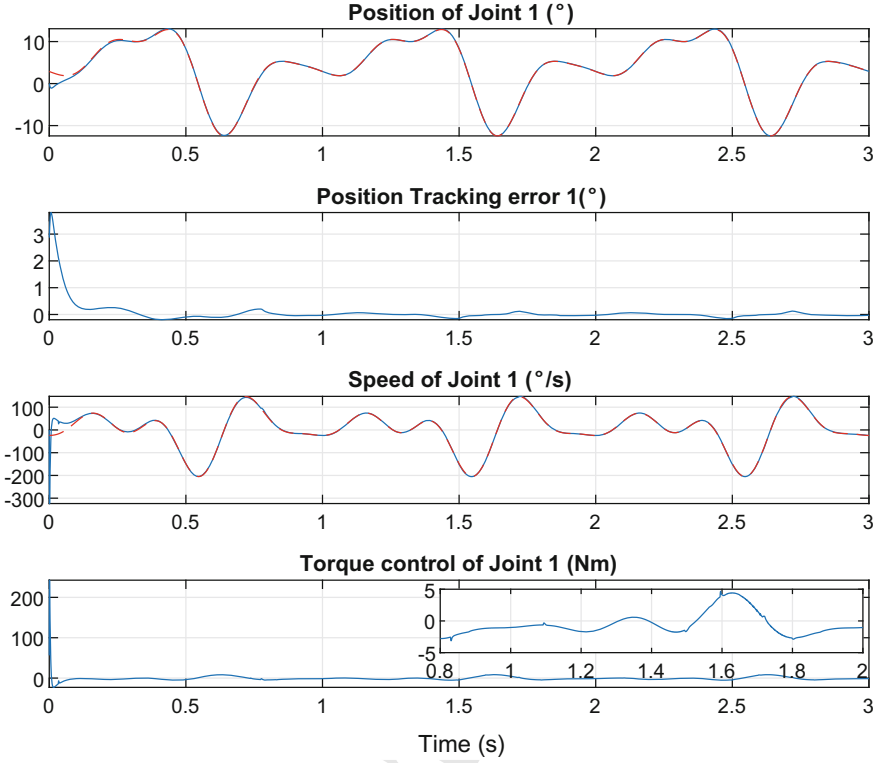


Fig. 7 Adaptive control with integral action of the hip joint. For the position and the speed, dashed line: desired trajectory, solid line: actual trajectory

$$108 \quad \tilde{M}(q) = \hat{M}(q) - M(q) = \sum_i M_i \tilde{a}_i \quad (8)$$

$$109 \quad \tilde{C}(q, \dot{q}) = \hat{C}(q, \dot{q}) - C(q, \dot{q}) = \sum_i C_i \tilde{a}_i \quad (9)$$

$$110 \quad \tilde{G}(q) = \hat{G}(q) - G(q) = \sum_i G_i \tilde{a}_i \quad (10)$$

111 Then, let's write:

$$112 \quad \tilde{M}(q)\ddot{q}_d + \tilde{C}(q, \dot{q})\dot{q}_d + \tilde{G}(q) = Y\tilde{a} \quad (11)$$

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

$$114 \quad \dot{V} = -\tilde{q}^T K_D \tilde{q} + \tilde{a}^T [\Gamma \tilde{a} + Y^T \tilde{q}] \quad (12)$$

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

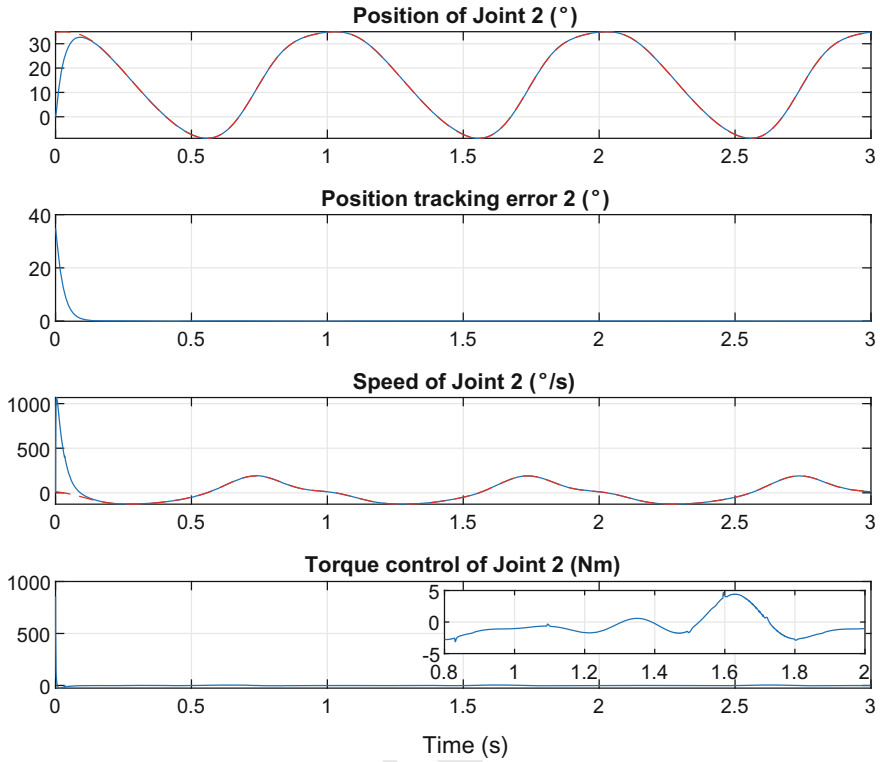


Fig. 8 Adaptive control with integral action of the knee joint. For the position and the speed, dashed line: desired trajectory, solid line: actual trajectory

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
<i>IAE</i>	0.0037	0.0169	0.0972	0.1578	0.0054	0.0609
<i>ISE</i>	0.0062	0.0181	0.0057	0.0279	1.2702×10^{-4}	0.0183
<i>IAER</i>	28.2872	3.1664	0.4075	0.2513	0.0228	0.0970

116

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

117

using the adaptive law of the parameter vector a :

118

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

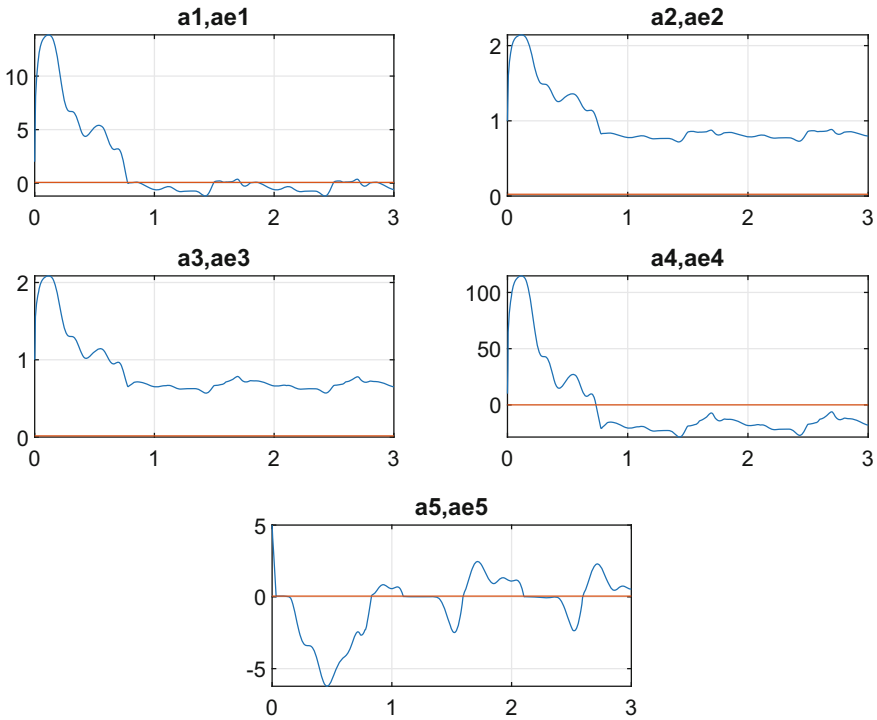


Fig. 9 Evolution of the estimated Parameters for the second adaptive approach of Slotine

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.

$$\tilde{q} + \Lambda \tilde{q} = 0 \quad (15)$$

where Λ is a positive definite diagonal matrix.

The virtual reference trajectory is expressed by

$$q_r = q_d + \Lambda \int \tilde{q} dt \quad (16)$$

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

$$\dot{q}_r = \dot{q}_d - \Lambda \tilde{q} \quad (17)$$

$$\ddot{q}_r = \ddot{q}_d - \Lambda \dot{\tilde{q}} \quad (18)$$

If we define

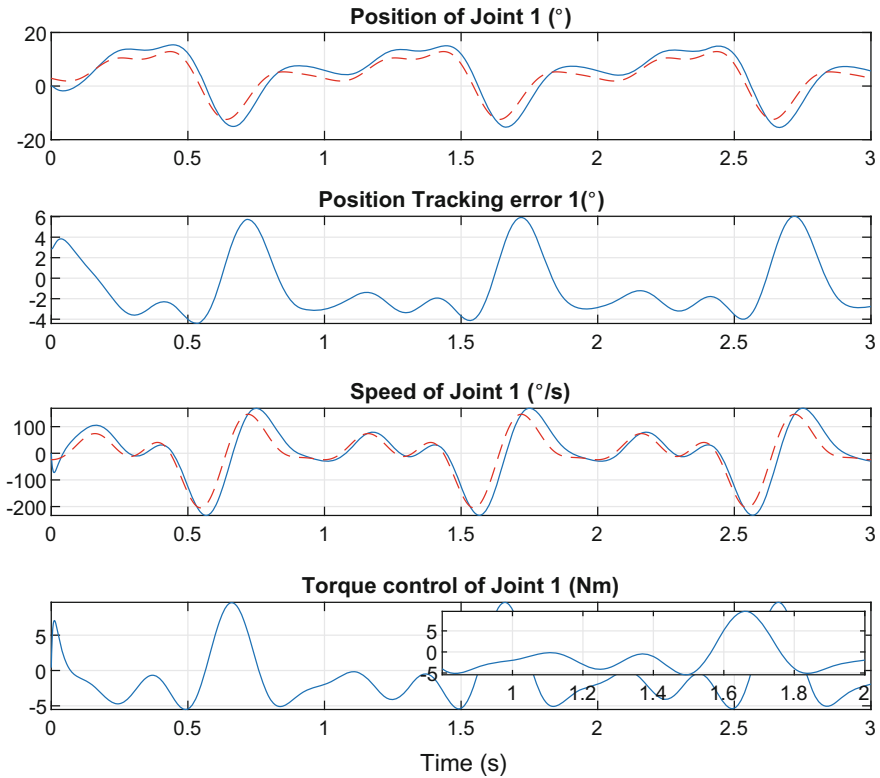


Fig. 10 Classical L_1 adaptive control of the knee joint. For the position and the speed, dashed line: desired trajectory, solid line: actual trajectory

130
$$s = \ddot{q}_r = \dot{q} - \dot{q}_r = \ddot{q} + \Lambda \dot{q} \quad (19)$$

131 The control and the adaptation laws become:

132
$$\tau = \widehat{M}\ddot{q}_r + \widehat{C}(q, \dot{q})\dot{q}_r + \widehat{G}(q) - K_D s \quad (20)$$

133
$$\widehat{a} = -\Gamma^{-1} Y^T(q, \dot{q}, \dot{q}_r, \ddot{q}_r) s \quad (21)$$

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

135
$$V = \frac{1}{2} s^T M s + \frac{1}{2} \widetilde{a}^T \Gamma \widetilde{a} \quad (22)$$

136 Its first time derivative leads to:

137
$$\dot{V} = -s^T K_D s \leq 0 \quad (23)$$

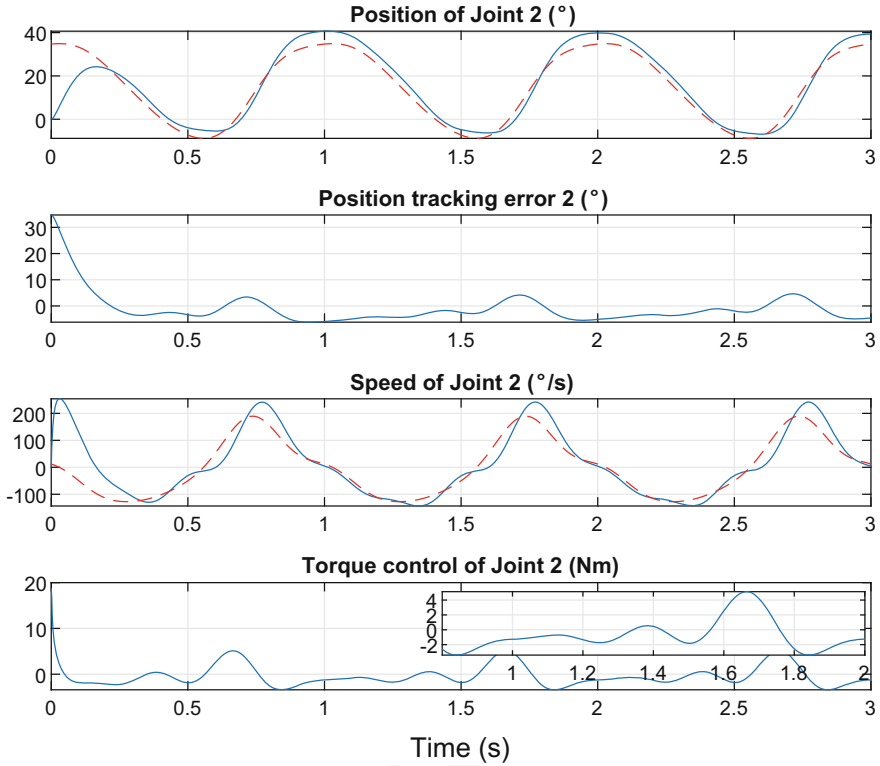


Fig. 11 Classical L_1 adaptive control of the hip joint. For the position and the speed, dashed line: desired trajectory, solid line: actual trajectory

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

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

144 3.3 L_1 Adaptive Control [2]

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

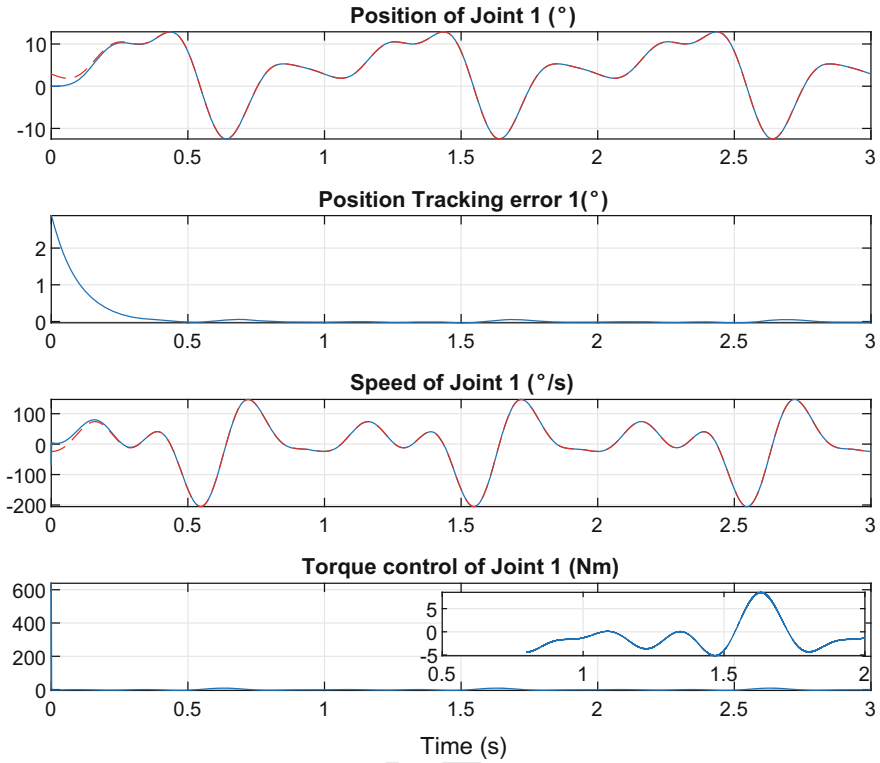


Fig. 12 Position, speed and torque control of the hip joint, obtained with a Augmented L_1 adaptive controller in the nominal case. Solid line: actual trajectory, dashed line: desired trajectory

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

151 The expression of the torque is:

152
$$\tau(t) = A_m r(t) + \tau_{ad}(t) \tag{24}$$

153 where:

154 $A_m \in \mathbb{R}^{2 \times 2}$ is a Hurwitz matrix

155 $\tau_{ad} \in \mathbb{R}^{2 \times 2}$ is the adaptive component

156 The tracking error is expressed as:

157
$$r = (\dot{q} - \dot{q}_d) + \Lambda(q - q_d) \tag{25}$$

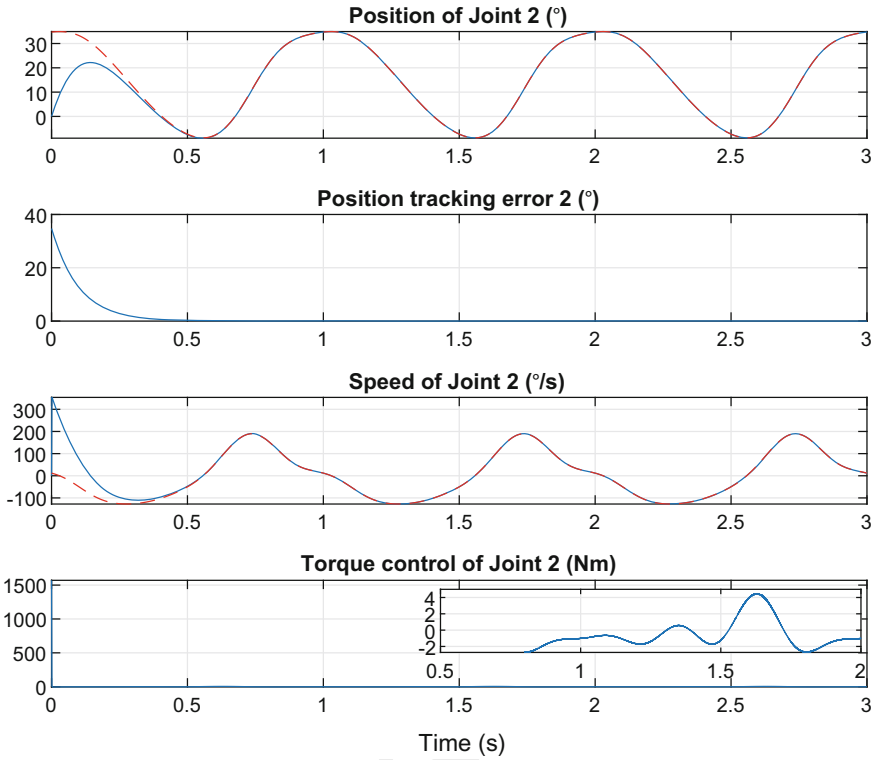


Fig. 13 Position, speed and torque control of the knee joint, obtained with a Augmented L_1 adaptive controller in the nominal case. Solid line: actual trajectory, dashed line: desired trajectory

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

$$162 \quad \hat{r} = A_m \hat{r}(t) + \tau_{ad}(t) - [\hat{\theta}(t) \|r_t\|_\infty + \hat{\sigma}(t)] - K \tilde{r}(t) \quad (26)$$

163 where:

164 $\tilde{r}(t) = \hat{r}(t) - r(t)$ is the prediction error

165 $K \in \mathbb{R}^{2 \times 2}$ used to reject high frequency noises.

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

$$167 \quad \dot{\hat{\theta}}(t) = \Gamma Proj(\hat{\theta}(t), P\hat{r}(t) \|r_t\|_\infty) \quad (27)$$

$$168 \quad \dot{\hat{\sigma}}(t) = \Gamma Proj(\hat{\sigma}(t), P\hat{r}(t)) \quad (28)$$

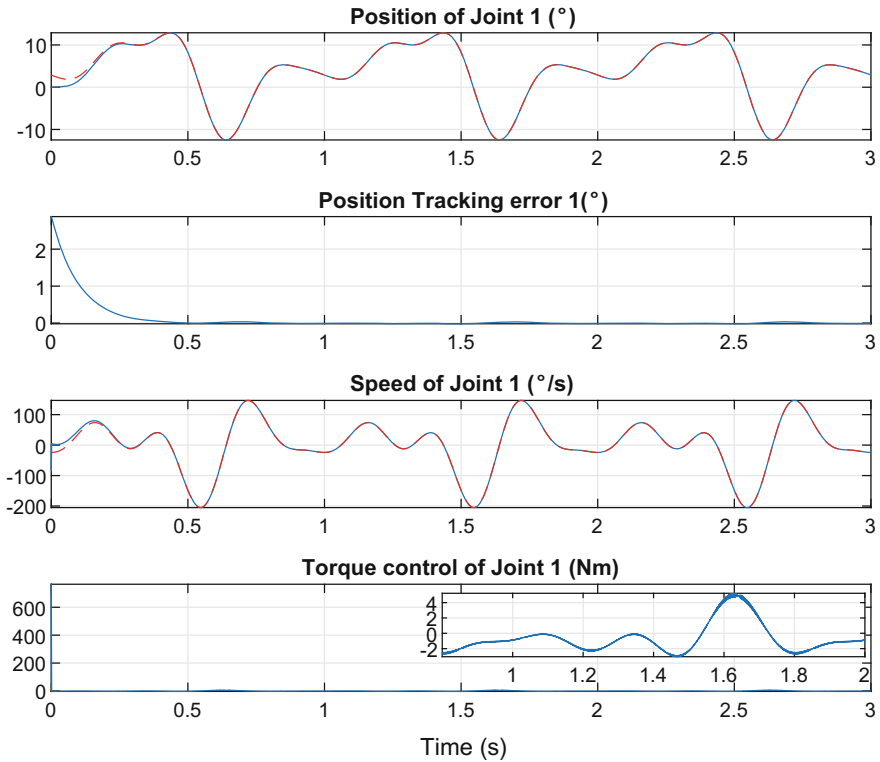


Fig. 14 Influence of -30% of masses and -15% of length uncertainties on the hip joint tracking with augmented L_1 adaptive controller

169 where Γ is the adaptive gain.

170 Let's P the solution of the algebraic Lyapunov equation:

171
$$A_m^T P + P A_m = -Q \tag{29}$$

172 The adaptive control is as follows:

173
$$\tau_{ad}(s) = C(s)\hat{\eta}(s) \tag{30}$$

174 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
 175 bounded-input bounded-output (BIBO) stable strictly proper transfer function.

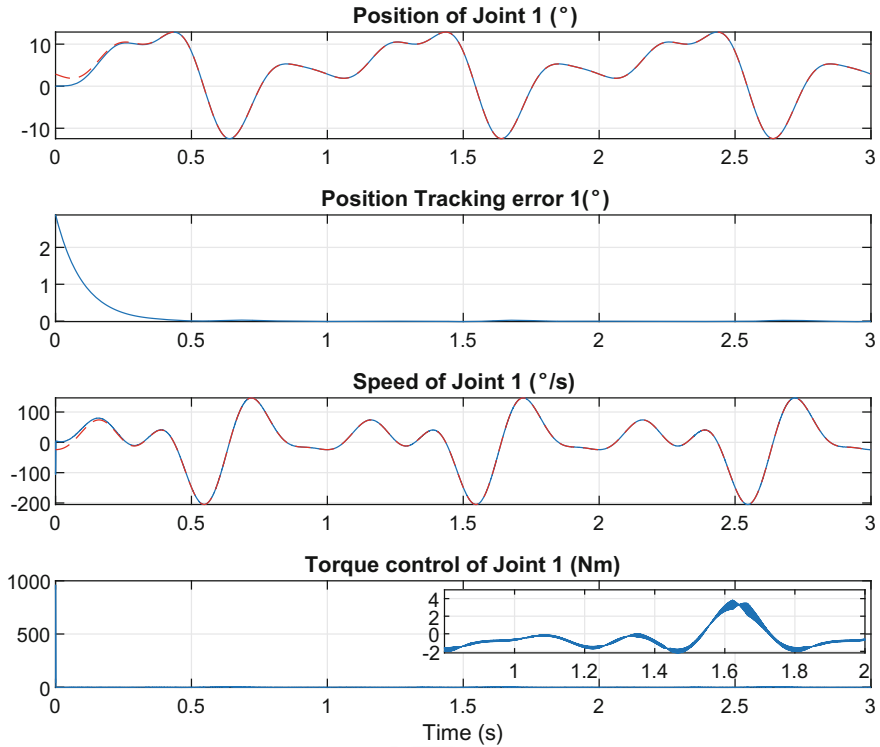


Fig. 15 Influence of -50% of masses and -25% of length uncertainties on the hip joint tracking with augmented L_1 adaptive controller

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:

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

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

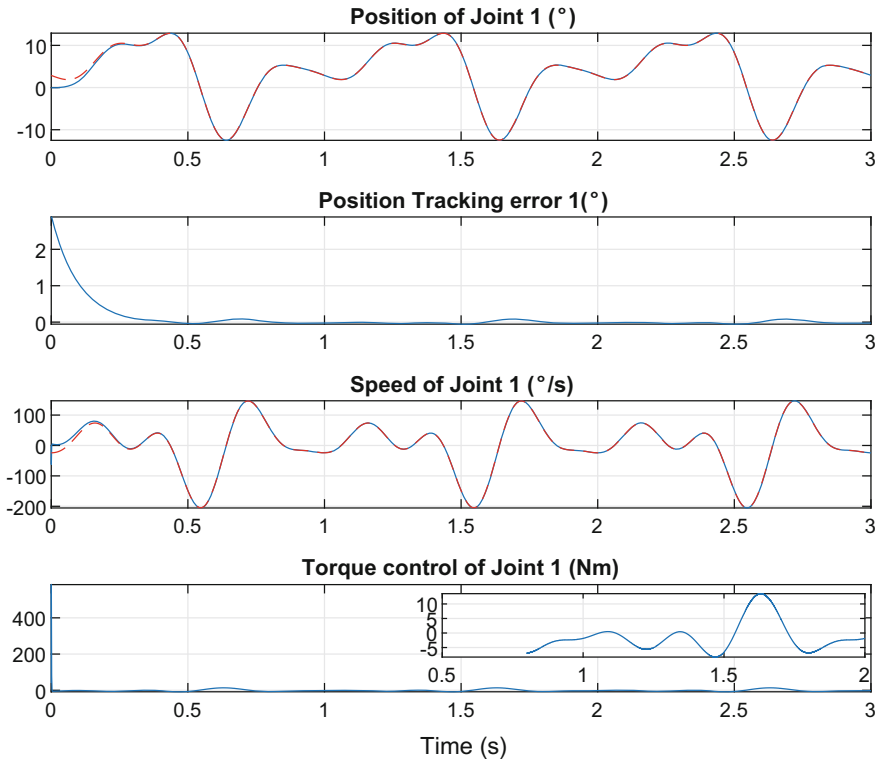


Fig. 16 Influence of 30% of masses and 15% of length uncertainties on the hip joint tracking with augmented L_1 adaptive controller

184 **4 Simulation Results**

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

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

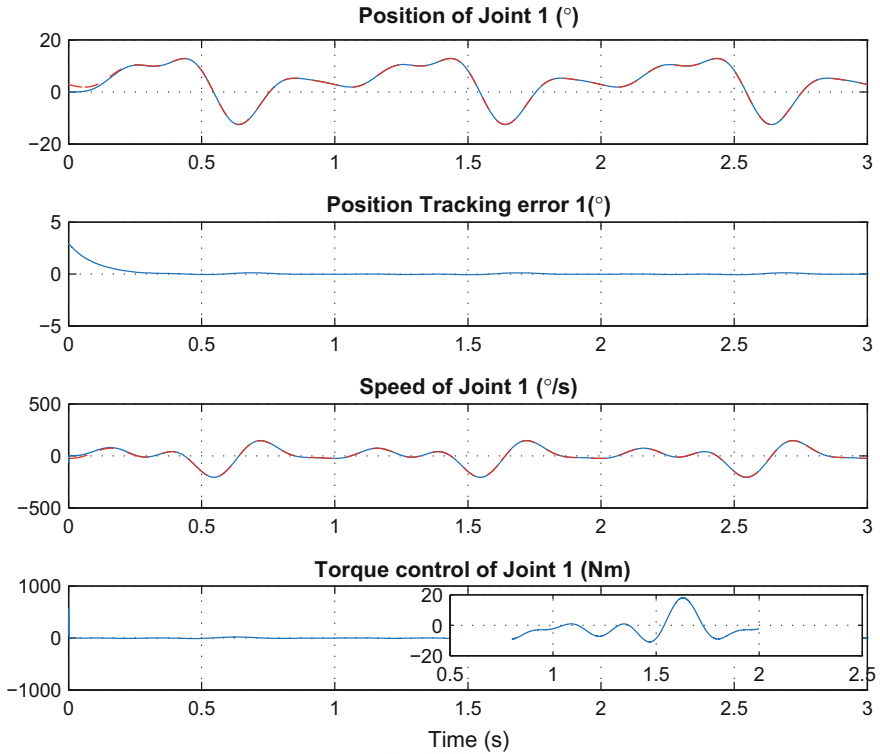


Fig. 17 Influence of 50% of masses and 25% of length uncertainties on the hip joint tracking with augmented L_1 adaptive controller

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

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

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

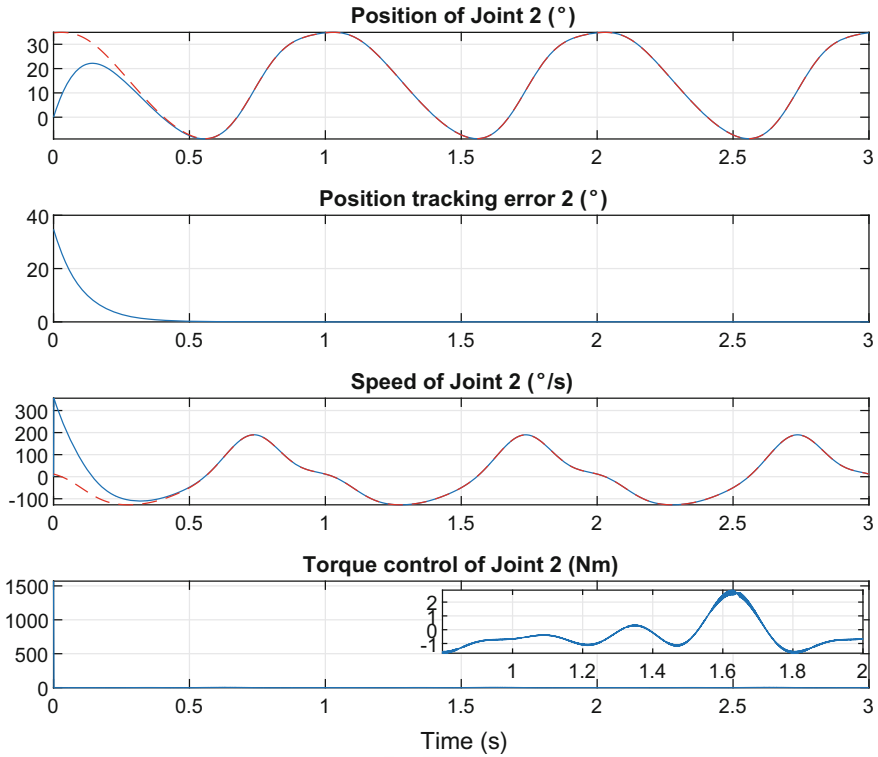


Fig. 18 Influence of -30% of masses and -15% of length uncertainties on the knee joint tracking with augmented L_1 adaptive controller

203

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

204

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

205

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

206

e denotes the tracking error.

207

The obtained results are summarized in Table 1.

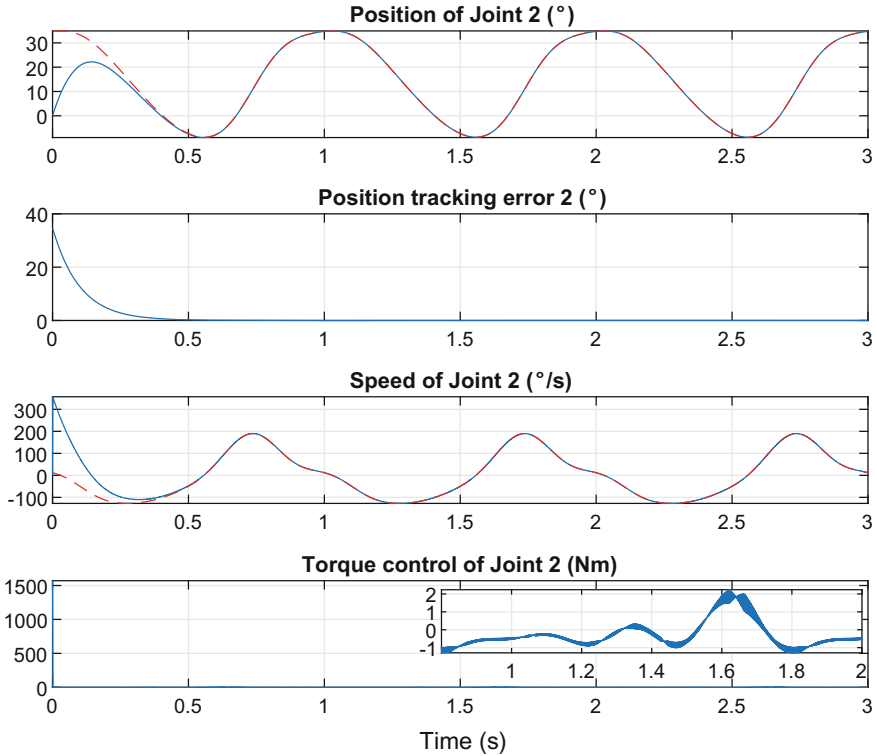


Fig. 19 Influence of -50% of masses and -25% of length uncertainties on the knee joint tracking with augmented L_1 adaptive controller

208

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 $\pm 50\%$ and leg length variations of ± 15 and $\pm 25\%$.

209

210

211

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 $\pm 50\%$ and leg length variations of ± 15 and $\pm 25\%$.

212

213

214

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.

215

216

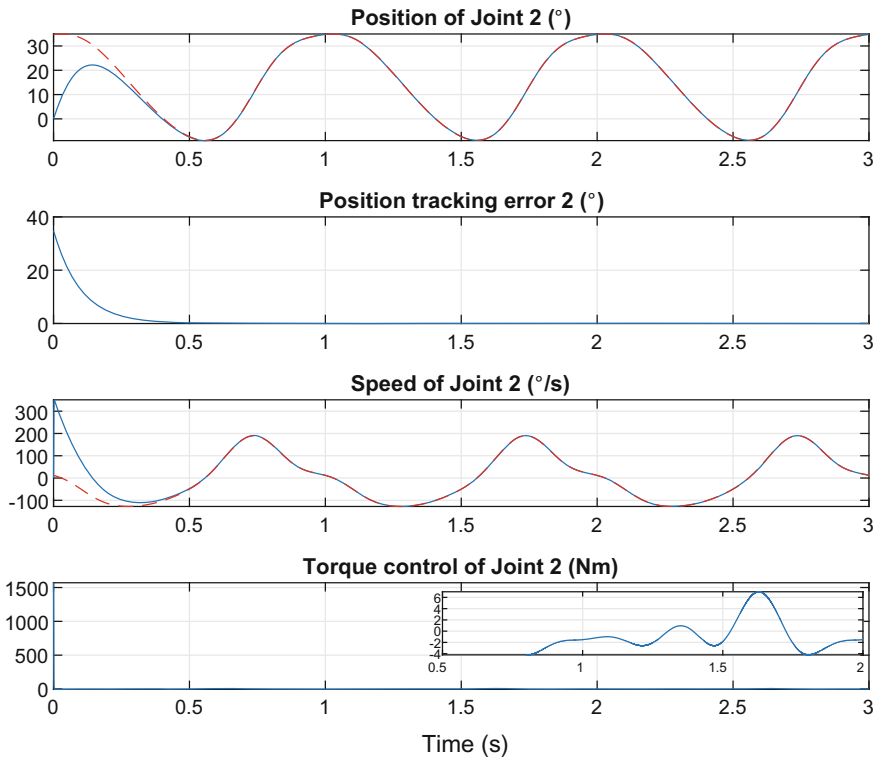


Fig. 20 Influence of 30% of masses and 15% of length uncertainties on the knee joint tracking with augmented L_1 adaptive controller

217 5 Conclusion and Future Work

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

AQ1

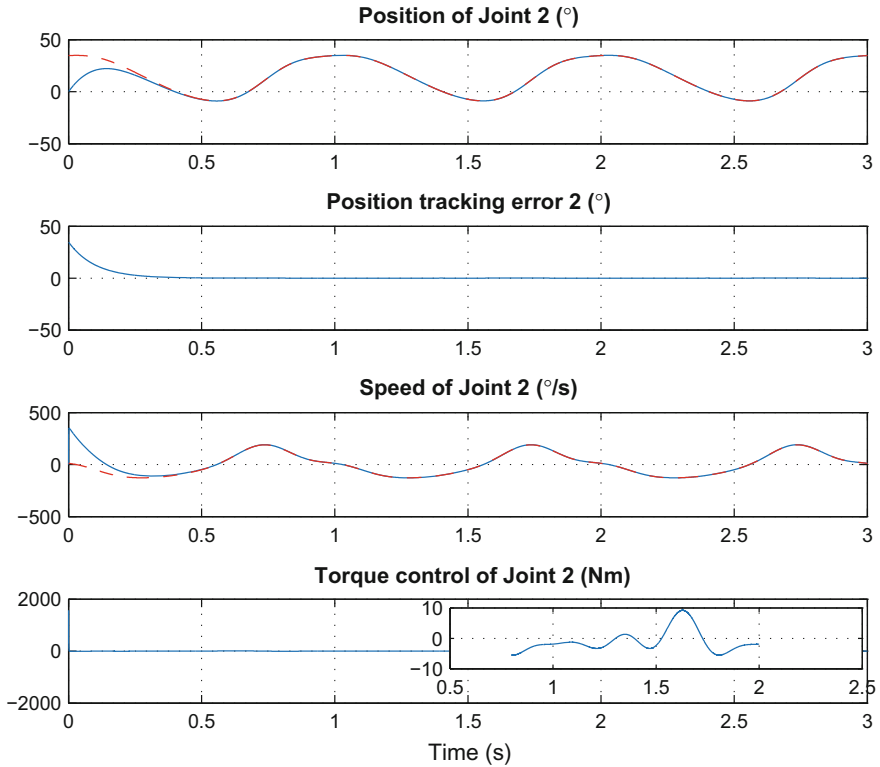


Fig. 21 Influence of 50% of masses and 25% of length uncertainties on the knee joint tracking with augmented L_1 adaptive controller

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Chapter 6

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