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TRAJECTORY GENERATION OF EXOSKELETON FOR LOWER LIMBS USING SYNCHRONIZED NEURAL OSCILLATORS

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Abstract. *This work presents the simulation of a seven degree of freedom exoskeleton for lower limbs which uses synchronized neural oscillators to generate and adapt the joint trajectories regarding the change of the walking velocity. Neural oscillators are sets of differential equations able to produce an oscillatory signal given appropriate values to their parameters. Thus, a curve fitting optimization process is used to guarantee better values to the neural oscillators parameters so that they can reproduce desired joint trajectories and simulate human walking. The parameters should ensure synchronized trajectories for the right and left members with a phase difference that is common for human walking. To do this, the optimization process uses both right and left trajectories and two neural oscillators are synchronized according to the desired trajectory for each joint. In the results, the parameters values were optimized considering a set of different velocities for the human walking, and a dynamic simulator was used considering two types of controllers, being the first based on computed torque and the second one a robust control based on* H_∞*. The results show that is possible to use synchronized oscillators and appropriated feedback signal to change the gait pattern in exoskeleton for lower limbs, based on changes of velocities during the walking.*

Keywords: *optimization, neural oscillator, biped walk, exoskeleton, trajectory generation.*

1. INTRODUCTION

Representation of natural movements of living beings through machines has been one of the most critical and complex study, mainly in the field of robotics. In the last years, *robotic rehabilitation* has used that movements to help people with disabilities. In this case, the kinematics of the robot should be determined on the anatomy of the human body, allowing a relation between the joints of all the members of the human body with the robot. Furthermore, to generate the movements to this kind of robot, techniques that involve *bio-inspired robots*, has been employed, regarding the natural movements found in living beings, (Zhang, 2004; Ijspeert, 2008).

In this context, several studies concerning the generation and control of motor patterns through neural oscillators, called the *Central Pattern Generator - CPG*, Nicholls *et al.* (1992), has been developed in the last years. CPGs are neural networks that can endogenously produce rhythmic patterns in their output, (Hooper, 2000; Matsuoka, 1985). They are based on biological systems that generate basic rhythmic movements of locomotion such as human walk. CPGs comprise non-linear neural oscillators that, in turn, are differential equation systems capable of producing coordinated patterns of rhythmic activities without having any input rhythm pattern, (Wilson, 1961).

The advantage of using neural oscillators and CPGs, compared with the use of dynamic equations and stability criteria, is the fact that they can be employed to control a system without the need a deep understanding of the dynamics of the robot, so, given to the system better performance in a computational point of view. Moreover, the intrinsic characteristics of the oscillators can ensure stability of the system, and these properties are important when considering works with bipedal robots, because stability is a critical point in this study, (Hurmuzlu *et al.*, 2004).

Among the types of oscillators used in researches involving locomotion of bipedal robots, there is the *Matsuoka oscillator*, (Matsuoka, 1985, 1987). Matsuoka oscillators have basic structure and are modeled by a set of differential equations describing the firing rate of the two neurons mutually inhibitory. One important characteristic of these oscillators is the ability to adapt to a sensory input signal which reproduces any design feature or the environment.

But, to give a desired signal, Matsuoka oscillator has several tuning parameters that should be tuned properly. In case of lower limbs representation, movements of left side should be the same of right side. Thus, two neural oscillator should work together given the same signal with phase difference, commom to the human walking.

In this paper, a way to solve the problem of synchronizing two Matsuoka oscillators for trajectory generation for exoskeletons is presented, using a optimization process to approximate desired curves to the neural oscillators outputs. Preliminary works have dealt with this kind of optimization and can be seen in Gomes *et al.* (2011).

This paper is organized as follow: Section 2. describe Matsuoka neural oscillator and the problem of synchronize two oscillators with the same signal; Section 3. shows the exoskeleton model used in this work; Section 4. shows the optimization process used to synchronize the oscillators; Section 5. presents the interface of the simulator and the simulation results; and Section 6. shows the conclusions.

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2. SYNCHRONIZED MATSUOKA NEURAL OSCILLATOR FOR A BIPED WALKING

Matsuoka neural oscillator have been a large use in researches that involves biped walking due its simplicity to be implemented in simulation and physical applications, and its performance to reproduce several kinds of periodic curves. Its basic architecture is shown in Fig. 1. The oscillator is composed by two neurons, E and F, corresponding to the extensor and flexor neurons, respectively. Each neuron is represented by a set of two differential equations, Eq. 1.

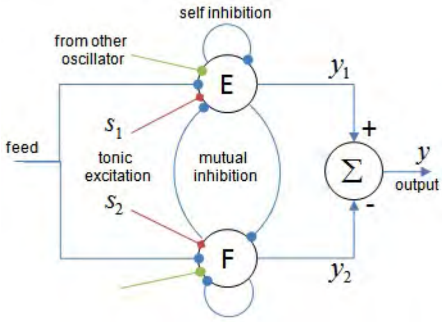

Figure 1. Matsuoka neural oscillator architecture.

$$\begin{cases} \tau_r \dot{x}_i = -x_i + \sum_{j=1}^{n} w_{ij} y_j + s_i - b f_i + feed_i, \\ \tau_a \dot{f}_i = -f_i + y_i, \end{cases} \tag{1}$$

where x_i is a inner state which corresponds to the membrane potential of the neuron; f_i is the degree of adaptation, or self inhibition, in the $i-th$ neuron; b represents the adaptation constant related to self-inhibition f_i; y_i is the output of the $i-th$ neuron and $y_i = \max\{x_i, 0\}$; τ_r is the time constant that specify the rise time when step input is given, where the frequency of output is roughly proportional to $\frac{1}{\tau_r}$, and τ_a specify the adaptation time lag; the inhibitory synaptic connection weight from the $j-th$ neuron to $i-th$ neuron is denoted by w_{ij}, and $w_{ij} \neq 0$ for $i \neq j$, $w_{ij} = 0$ for $i = j$ and $\sum_{j=1}^{n} w_{ij} y_j$ represents the total input from neurons inside a neural network; lastly, s_i is constant drive input. The parameter $feed_i$ is added to represent the input feedback signal to the neuron and represents the interaction between the robot and the environment, (Liu *et al.*, 2008).

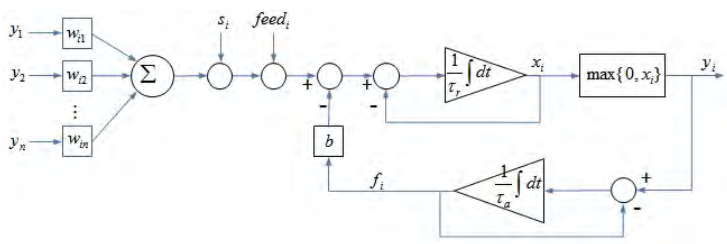

Figure 2. Neuron model (adapted from (Liu *et al.*, 2008)).

Figure 2 shows the block diagram of one neuron, representing the set of equations in Eq. 1. Based on this model and giving appropriate values for each variable, desired output can be obtained to represents the joints trajectories for a bipedal robot. However, to apply Matsuoka oscillator in a bipedal robot, the two legs movements should be synchronized to ensure the walking movements. To do this, two oscillator are coupled, as shown in Fig. 3. In this case, weights w_{e1e2}, w_{e2e1} and w_{f1f2}, w_{f2f1} should has the same value to ensure the syncronization between two oscillators. These values and the phase difference is obtained during the optimization process, described in Section 4.

With this model, it is possible make the exoskeleton for lower limbs, presented in next section, reproduce the movements like a human walking, and according to the desired, change the walking velocity by tuning the parameters. Thus, a net considering two neural oscillators for each pair of joints, being foot, tibia and femur, plus a neural oscillator to control the hip joint, was implemented to generate and adapt the trajectories for the exoskeleton for lower limbs.

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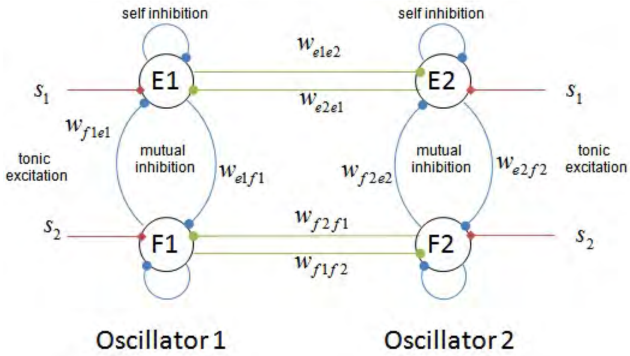
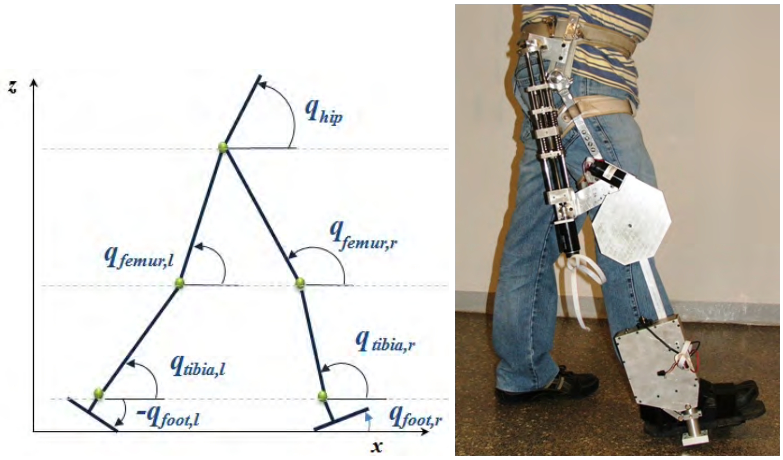


Figure 3. Synchronized Matsuoka oscillator.

3. EXOSKELETON MODEL

Synchronized Matsuoka oscillators has been tested to be implemented in an exoskeleton for lower limbs, named *Exo-Kanguera*, Fig. 4(b). The main purpose of this device is help people with disabilities to walk or help them to recovery lost movements, following rehabilitation protocols, (Siqueira *et al.*, 2013). Exo-Kanguera is driven by series elastic actuators, Jardim and Siqueira (2009), and its model has 7 joints, being 3 for each leg, referring to the foot, tibia and femur joints, plus the hip joint to give the torso balance. The model, with the definition of the absolute angles, can be seen in Fig. 4(a), considering the sagital plane, and the first protype constructed is shown in Fig. 4(b).



(a) Kinematic model of Exo-Kanguera. (b) First version of Exo-Kanguera.

Figure 4. Kinematic model and first model constructed of Exo-Kanguera.

Mathematical model of the exoskeleton is obtained according to the basic robotic equation,

$$M_{ort}(q)\ddot{q} + C_{ort}(q,\dot{q}) + G_{ort}(q) = \tau_a + \tau_{pat} + \tau_d, \tag{2}$$

where $q \in \Re^n$ is the generalized coordinates vector, $M \in \Re^{nxn}$ is the symmetrical, positive definite inertia matrix, $C \in \Re^n$ is the centrifugal and Coriolis torques vector, and $G \in \Re^n$ is the gravitational torques vector. The terms $\tau \in \Re^n$ are the torques acting in orthosis: τ_a is the torque supplied by the actuators, τ_{pat} is the torque generated for the orthosis-patient interaction, and τ_d is the torque generated by any external disturbances acting in the patient-orthosis system. In this paper, τ_{pat} was considered just as a change of velocity, and τ_d was considered in the simulation of the robust control.

Based on Eq. 2, the reference curves to execute the optimization of the neural oscillators parameters are obtained from Gomes *et al.* (2009) that consider Exo-Kanguera exoskeleton and a ZMP stability criterion to generate joint trajectories for the robot. In that case, the algorithm demanded a high computational cost and its implementation render a low performance physical system. Based on this fact, Gomes *et al.* (2011) have used a trajectory generator based on Matsuoka neural oscillator to driven the exoskeleton joints. The parameters of neural oscillators are optimized, finding values that allow the oscillators reproduce the desired trajectories, but within consider left and right synchronism. To the rehabilitation process point of view, the movements should be well determined, so, the oscillators should be synchronized to generate similar trajectories, and then ensuring the stability of the system.

In this paper, it is used an optimization approach that ensure which two neural oscillators are synchronized with them. The same trajectories can be seen to the left and right side of the lower limbs in a simulation system. The main features of

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neural oscillators used for joint trajectories generation are the simplicity and robustness of the resulting neural network. This fact gives the system more feasibility to the computational point of view, allowing its application in real time systems.

4. OPTIMIZATION PROCESS FOR SYNCHRONIZED OSCILLATORS

The optimization process takes account the error between the desired trajectory and the neural oscillator output. This process is described in Gomes *et al.* (2011). The proposed system presented here can be described as a curve-fitting problem between non-linear curves through the Least Mean Squares (LMS) method, given by (3).

$$\min_x ||f(x)||_2^2 = \min_x (f_1(x)^2 + f_2(x)^2 + \ldots + f_n(x)^2), \tag{3}$$

where $x_i = [p_0, p_1, p_2, ..., p_m]$ is the vector that contain the m parameters which need to be adjusted to minimize the function $f(x)$.

However, to ensure the synchrony between two oscillators, that represents the trajectories to the left and the right members, the parameters of two neural oscillator should be optimized at the same time. The cost function (4) is related to the global error is the sum between the error to the first and second neural oscillator and their respective desired trajectories, evaluates in a specific time interval, $[1; k]$. The value of k is determined empirically to avoid transient signal that occurs in the beginning of the output oscillator.

$$f(x) = \sum_{i=1}^{k} \left[(y_1(x)_i - y_1^{d_i})^2 + (y_2(x)_i - y_2^{d_i})^2 \right], \tag{4}$$

where $y_j(x)$ is the $j-th$ neural oscillator output, with $j = 1, 2$, and y_j^d is the desired trajectory.

Thus, the optimization process occurs as shown in Fig. 5. First, initial values to the parameters can be obtained empirically or by a optimization process. In this case, the initial parameters were obtained from the same method, but considering just one oscillator on the each optimization process, (Gomes *et al.*, 2011). Then the oscillators are coupled and their signals are compared with the desired curves. The optmitization method takes the global error as the sum of two oscillator errors, and new parameters are obtained.

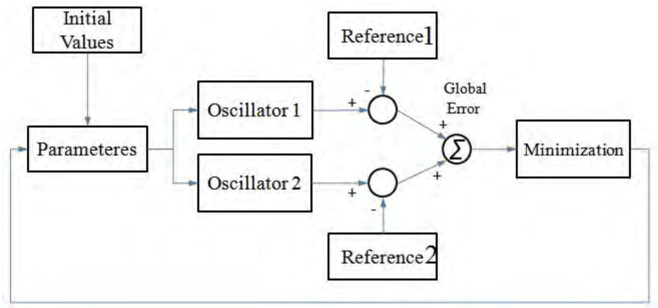

Figure 5. Optimization process diagram.

The optimization method is based on Levenberg-Marquardt, (Marquardt, 1963), and consider a vector error of the curve fitting.

5. SIMULATION TESTS

Simulated tests are performed with a Matlab simulator that considers the robot dynamic and all the forces actuating in the system. To ensure that the robot is following the trajectories, two type of controllers are used. The first one is based on computed torque and takes account the dynamic of the robot plus a PD controller, as shown in Eq. 5.

$$\tau_a = M_{pac,ort}(q)\left(\ddot{q}^d + K_P e + K_D \dot{e}\right) + C_{pac,ort}(q, \dot{q})\dot{q}^d + G_{pac,ort}(q), \tag{5}$$

where e and $\dot{e}$ are the position and velocities errors in the joints, respectively, and $\ddot{e} = -K_P e + K_D \dot{e}$.

The second controller is a robust controller based on $\mathcal{H}_\infty$ used to guarantee that the system are stable even on external disturbances acting in the system or parametric uncertainties. In Siqueira and Terra (2004), the authors present experimental results obtained from the implementation in robot manipulators of a nonlinear $\mathcal{H}_\infty$ control via quasi-linear parameter varying (quasi-LPV) representation. The quasi-LPV representation of a nonlinear system is a state-space equation where

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the system matrices are functions of state-dependent parameters (Wu *et al.*, 1996). In Siqueira and Terra (2006), a similar controller is proposed for disturbance attenuation considering a semi-passive dynamic walking of biped robots.

Considering the dynamical model and the trajectory generator based on neural oscillators, tests are performed with velocity of the walking changing to 0.84m/s until 1.28m/s, considering 9 different values with approximately 5% between each one, i.e., $v = 0.84, 0.89, 0.93, 1.00, 1.04, 1.11, 1.16, 1.23, 1.28$m/s. The reference curves are shown in Figure 6 considering absolute angles (degrees). It can be noted that there are some small deviations because the simulator was reproduced without controller in the system.

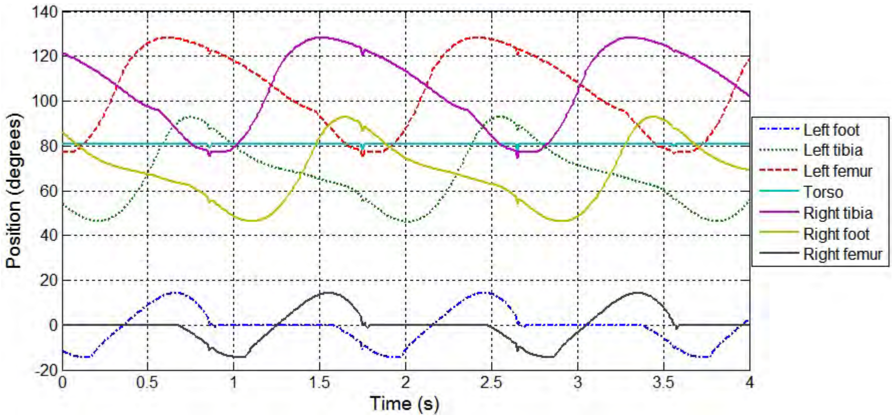

Figure 6. Trajectories generated through synchronized oscillators without a controller.

The interface of simulator is shown in Fig. 7 with curves of trajectories, its velocities and the torques of joints.

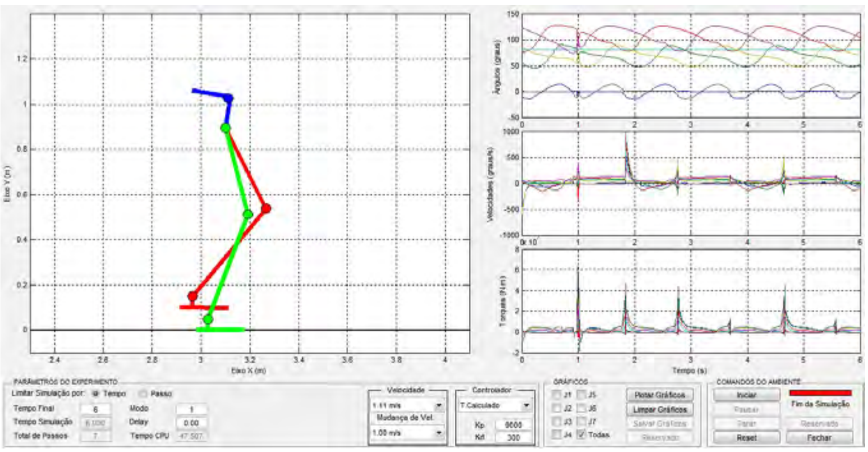

Figure 7. Interface of simulator in Matlab.

The tests are performed as follow: a pattern walk was defined with a velocity of $1, 11$m/s, considering a length of step $Ds = 1.0$m and a time of step 0.90s. The simulation starts with the velocity of 0.84m/s, and then, it is increased for each 0.5s until the last value considered, 1.28m/s. Figure 8 shows this changes without a controller acting on the system.

It can be observed that the foot trajectories deviations are very small, but for the tibia and femur, the deviations should be controlled to avoid instability. Based on this, the CPG efficiency was tested considering the system acting with two types of controllers, as follow.

5.1 First simulation with computed torque controller

According to the changes in the walking velocity, it was performed a simulation considering a controller based on computed torque. Figure 9 shows the trajectories changing. It can be noted small deviations in the trajectories, because the controller is acting to keep the system stable. Also, if the foot of the exoskeleton is in the balance phase and the velocity changes, the system try to go back to a stable point, and then the movements continued.

Thereby, the trajectories to the left and right leg keep synchronized, even if there are changes.

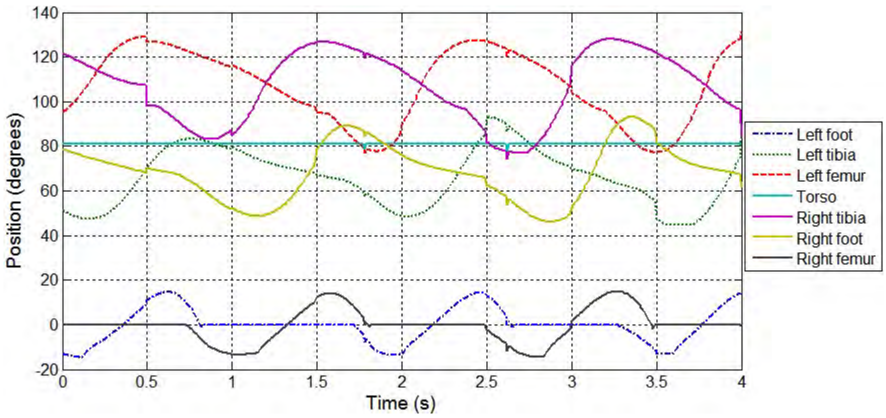

Figure 8. Simulation changing the walking velocity without a controller.

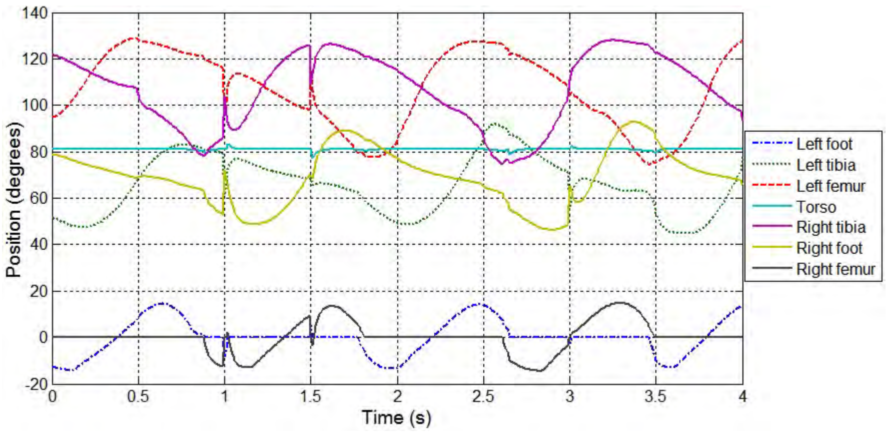

Figure 9. Simulation with Computed Torque controller.

5.2 Second simulation with robust controller

To prevent the system from becoming unstable in the presence of disturbances, it was considered a robust control based on $\mathcal{H}_\infty$, and the same tests presented previously are performed. Figure 10 shows the trajectories changing according to the new parameters to the CPG.

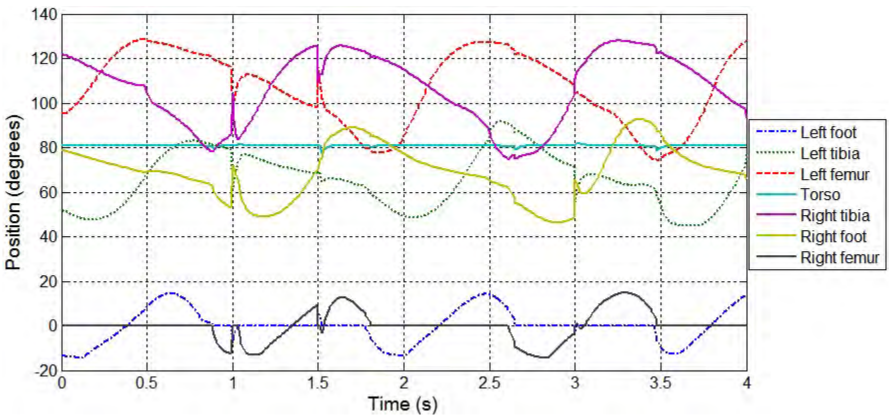

Figure 10. Simulation with H_∞ based controller.

How there are not disturbances, the controller acts as the computed torque. However, if a disturbance is inserted in the system, the controller should be able to keep the stability. Figure 11 shows the trajectories considering a disturbance in the torso joint. It can be observed that there is a small deviation in that trajectory (torso), but the robust control is able to keep the stability to the system and the left and right curves continued with the synchronism.

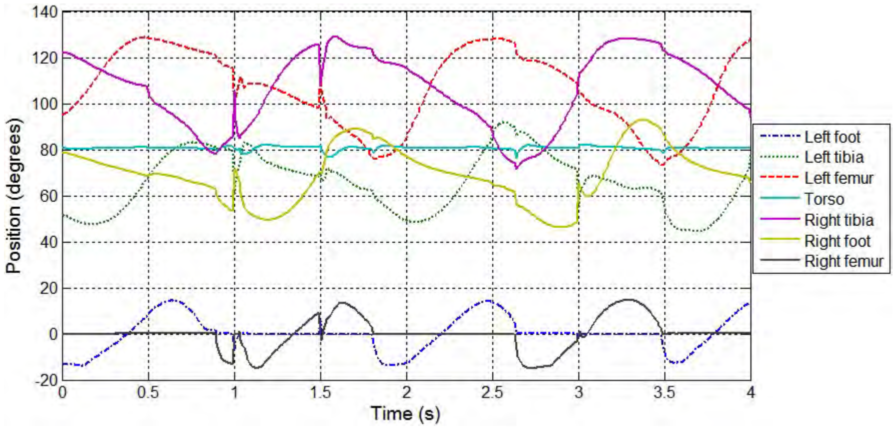

Figure 11. Simulation with H_∞ based controller and a random disturbance.

In all the tests, the synchronism between the right and left members trajectories are ensured, through the CPG structure. Also, the controllers are able to guarantee that the exoskeleton will follow the trajectories.

6. CONCLUSION

This work deals with trajectory generation using synchronized neural oscillators for an exoskeleton for lower limbs. The proposed generator is optimized thought a curve fitting method, and the parameters are changed in the system according to a change of the walking velocity. To guarantee that the system is able to follow the trajectories, two types of controllers are tested. In the first one, computed torque was used, and the system can keep stable and follow the joint trajectories. In the second one a robust control is used and the system keeps stable though there are disturbances. The results show that the synchronized neural oscillators can be used to generate and adapt the exoskeleton trajectories that will be used in rehabilitation process, regarding the adaptation to the rehabilitation process.

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