MODELING THE CENTRAL PATTERN GENERATOR OF HUMAN LOCOMOTION USING NONLINEAR OSCILLATORS

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Abstract. *Nervous nets in the spinal marrow are capable to produce rhythmic movements, such as: the locomotion. These specialized systems are known as nervous oscillators or central pattern generators (CPGs). Oscillators can be used as pattern generators similar to the human CPG; such oscillators obtain the approximate trajectories of the legs. The objective of this work is to present the modeling of the human CPG using a set of nonlinear oscillators. We consider a 2D model, with the three most important determinants of gait, that performs motions parallel to the sagittal plane. Using oscillators such as: van der Pol and Rayleigh oscillators, we determine the transient motion and the stable limit cycles of the oscillators, showing the behavior of the hip and knee angles. By changing a few parameters in the oscillators, modification of the step length and the frequency of the gait can be obtained. A comparison of the plotted graphs reveals that the system provides excellent results when compared to experimental analyses. Based on this results, we conclude that the use of coupled nonlinear oscillators can represent an excellent method for signal generation, allowing their application for simulate the CPG in a walking machine.*

Keywords*: CPG, oscillator, locomotion.*

1. INTRODUCTION

Nervous nets in the spinal marrow are capable to produce rhythmic movements, such as: to swim, to jump, and to walk, when isolated from the brain and sensorial inputs. These specialized nervous systems are known as *nervous oscillators* or *central pattern generators* (CPGs)(Mackay-Lyons, 2002).

According to Moraes (1999), the relation between spinal marrow and encephalus in domestic animals is most significant than relation in human beings. The animals perform motor activities by reflexes and not by the cerebral activity. It is estimated that exist approximately ten times more activity in the spinal marrow of dogs than in humans. Grillner (1985), Pearson (1993) and Collins and Richmond (1994) are some interesting works about the locomotion of vertebrates controlled by central pattern generators.

The human locomotion is controlled, in a way, by a CPG, which is evidenced in works as Calancie *et al.* (1994) and Dimitrijevic *et al.* (1998). Nonlinear oscillators can be used in control systems of locomotion as pattern generators, providing approximate trajectories for the legs. The CPG is formed by a set of oscillators, where each oscillator generates angular signals of reference for the movement of the legs. Each oscillator has its proper amplitude, frequency and parameters, and coupling terms makes the linking to the other oscillators. Bay and Hemami (1987), Dutra (1995), Zielinska (1996), and Pina Filho (2005) are some works about CPG formed by oscillators, applied in the locomotion.

The objective of this work is to present the modeling of a central pattern generator formed by a set of coupled nonlinear oscillators, applying this system to a bipedal robot model. We present some concepts about the spinal marrow of human being, including its main structures and characteristics, as well as its relation with the motor functions. In the application, we consider a 2D model, with the three most important determinants of gait (the compass gait, the knee flexion, and the plantar flexion of stance ankle), that performs motions parallel to the sagittal plane. Using nonlinear oscillators with integer relation of frequency, we determine the transient motion and the stable limit cycles of the network formed by coupled oscillators, showing the behavior of the hip and knee angles. By changing a few parameters in the oscillators, modification of the step length and the frequency of the gait can be obtained.

The study of the utilization of this system in the locomotion has great application in the project of autonomous robots and in the rehabilitation technology, not only in the project of prosthesis and orthesis, but also in the searching of procedures that help to recuperate motor functions of human beings.

2. SPINAL MARROW

The spinal marrow is formed by nerves from the cerebral cortex or in some areas of the cerebral trunk, and prolonged, in great part, to the somatic motoneurons (which make connection with the muscles that performing the conscientious movements). The bones of the spinal column protect the spinal marrow, and its nervous fibers pass through small gaps between each vertebra. In the superior vertebrates, the spinal marrow is more strong subordinated to the cerebrum, executing its orders.

The forepart of the spinal marrow contains the motor nerves (motoneurons), which transmit information to the muscles and stimulate the movement. The posterior part and the lateral parts contain the sensitive nerves, receiving information from the skin, joints, muscles and viscera (Fig. 1).

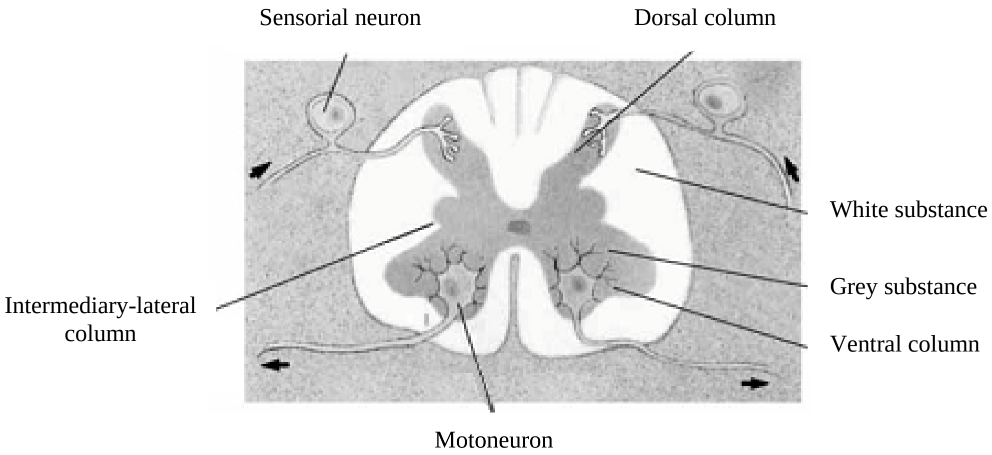

Figure 1. Spinal marrow (Brandão, 2004).

The human gait requires a coordination of the muscular activity between the two legs, which is made by a flexible neural coupling to the level of the spinal marrow (Dietz, 2003). Thus, in the course of the locomotion, a disturbance in one of the legs leads to a pattern of purposely reply of the spinal marrow, characterizing the existence of the so-called central pattern generator.

3. PATTERNS OF LOCOMOTION

The choice of an appropriate pattern of locomotion depends on the combination of a central programming and sensorial data, as well as of the instruction for a specific motor condition. This information determines the way of organization of the muscular synergy, which is planned for adequate multiple conditions of posture and gait (Horak and Nashner, 1986).

Figure 2 presents a scheme of the control system of human locomotion, controlled by the central nervous system, which the central pattern generator supplies a series of pattern curves for each part of the locomotor. This information is transmitted to the muscles by means of a network of motoneurons, and the conjoined muscular activity performs the locomotion. Sensorial information about the conditions of the environment or some disturbance are supplied as feedback of the system, providing a fast action proceeding from the central pattern generator, which adapts the gait to the new situation.

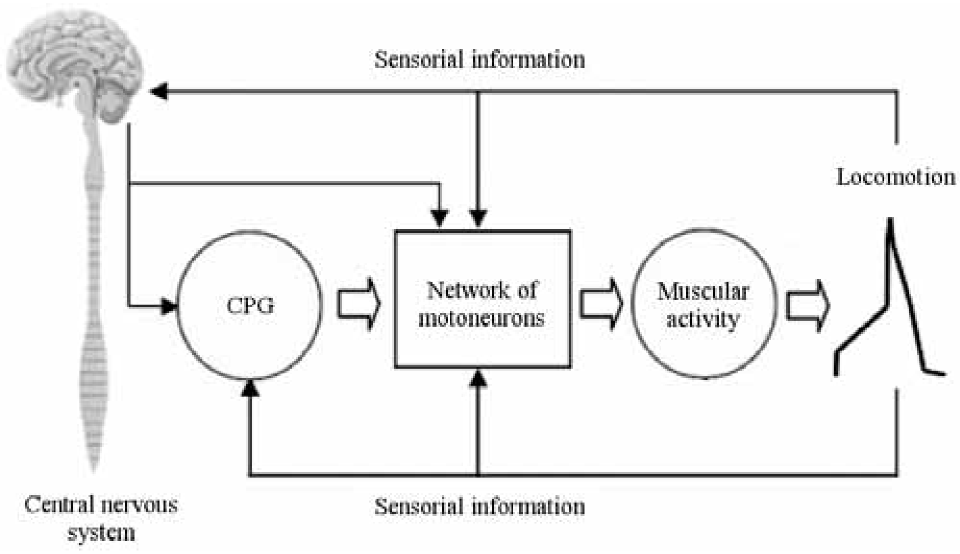

Figure 2. Control system of human locomotion.

In spite of the people not walk in completely identical way, some characteristics in the gait can be considered universal, and these similar points serve as base for description of patterns of the kinematics, dynamics and muscular activity in the locomotion.

In the study presented here, the greater interest is related to the patterns of the kinematics, in particular, of the hip and knee angles. From the knowledge of these patterns of behavior, the simulation of the central pattern generator using the system of coupled oscillators becomes possible.

Thus, considering the movements in the sagittal plane, the hip performs flexion and extension (Fig. 3). According Raptopoulos (2003), the configuration of the knee has direct influence on the amplitude of flexion of the hip. With the extension of the knee, the maximum flexion angle of the hip is 90 degrees, while for the flexion of the knee, the amplitude reaches or exceeds 120 degrees.

In relation to the knee, its articulation have two degrees of freedom, being the flexion-extension the main movement, and the rotation around of the longitudinal axis of the leg is a auxiliary movement, which only appears when the knee is bent. The flexion of the knee is a movement that approaches the posterior region of the leg to the posterior side of the thigh. The amplitude can reach 140 degrees with the hip in flexion, but it does not exceed 120 degrees with the hip in extension. The extension of the knee is defined as the movement that moves away the posterior side of the leg to the posterior side of the thigh. When the extension is extreme, this receives the name of *genu recurvatum* and has pathological causes. Figure 4 shows the movements of the knee in the sagittal plane.

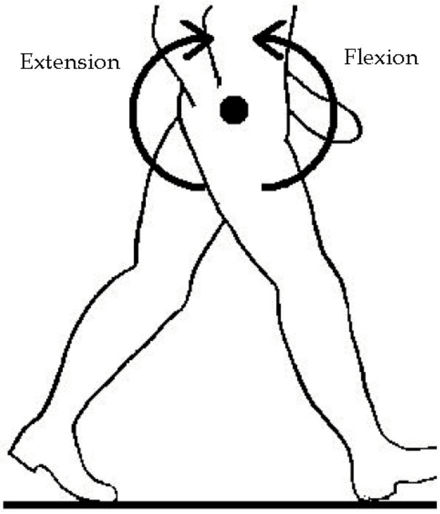

Figure 3. Movements of the hip in the sagittal plane (Raptopoulos, 2003).

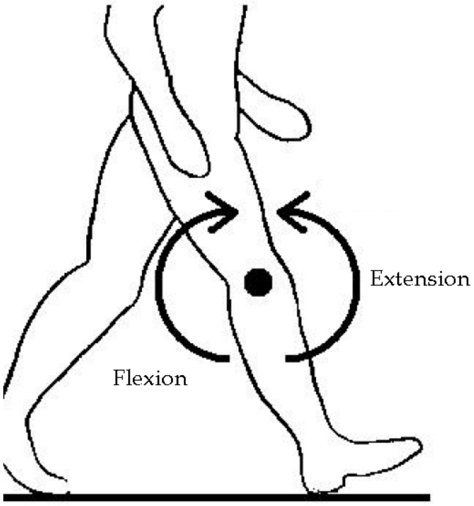

Figure 4. Movements of the knee in the sagittal plane (Raptopoulos, 2003).

From the use of an optic-electronic system of three-dimensional kinematical analysis, Raptopoulos (2003) define the angular behavior of the hip and knee in the course of the locomotion cycle. Twenty-four healthy young male volunteers participated in this work. They had no previous history of surgery or musculoskeletal problems that could affect their walking pattern. They were asked to walk at their normal cadence. Figure 5 presents the graphs of angular displacement and phase space of the hip related to the movements of flexion and extension. Figure 6 presents the graphs of angular displacement and phase space of the knee. These figures are related to stance phase.

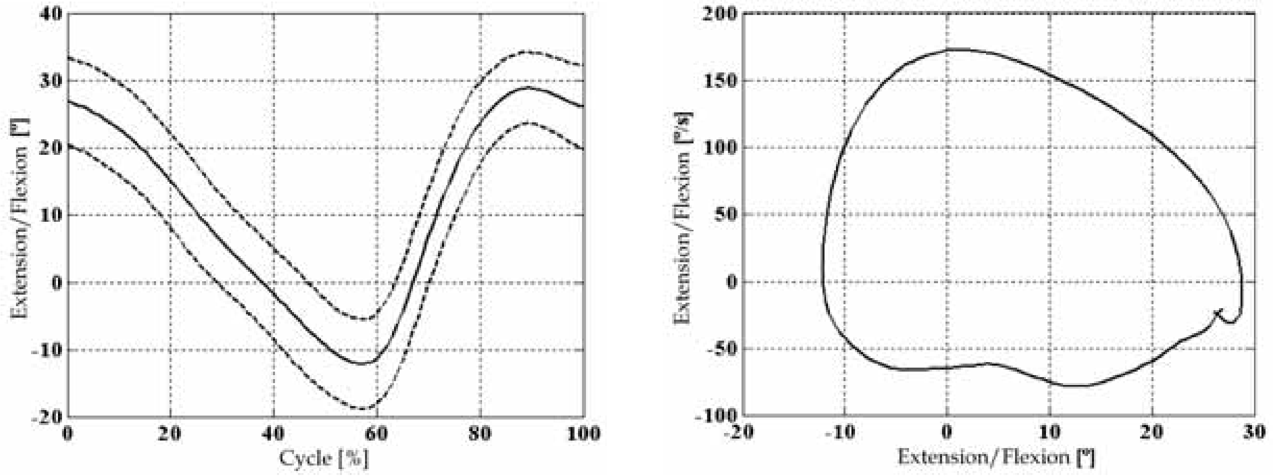

Figure 5. Angular displacement and phase space of the hip (mean ± deviation)(Raptopoulos, 2003).

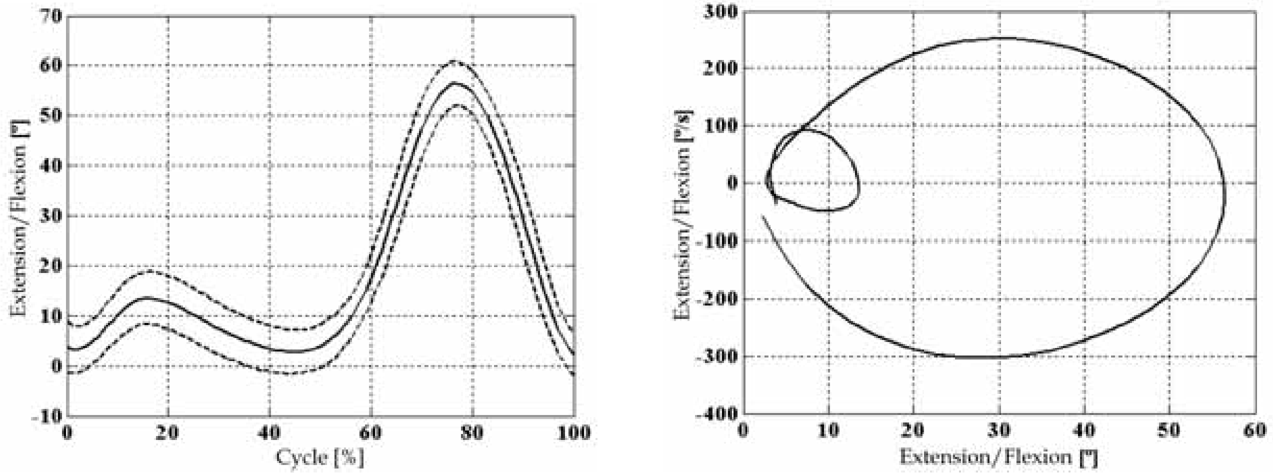

Figure 6. Angular displacement and phase space of the knee (mean ± deviation)(Raptopoulos, 2003).

4. NONLINEAR OSCILLATORS SYSTEM

Oscillators are used to describe mechanisms that repeat its action periodically, such as: some neurons, electric circuits, waves, cells, etc. The behavior of an oscillator can be described by a differential equation, whose solution presents cyclical behavior. Thus, nonlinear oscillators can be represented by nonlinear differential equations.

A question of particular interest in nonlinear systems is the existence of limit cycles. One of the oscillators with limit cycle more known and used in diverse works about locomotion is the van der Pol oscillator. Another similar oscillator to the van der Pol, the Rayleigh oscillator, is less known and it was little explored, as well as its application in the locomotion. The system of coupled oscillators proposed in this work uses these Rayleigh oscillators.

Considering a similar system to that proposed by Pina Filho and Dutra (2006) using Rayleigh oscillators, we have:

$$\ddot{\theta} - \delta\left(1 - q\dot{\theta}^2\right)\dot{\theta} + \Omega^2\left(\theta - \theta_o\right) - coupling\ term = 0 \qquad (1)$$

where: θ represents each one of the angles in study; δ, q and Ω are the parameters of the oscillator. The coupling term represents the way each oscillator interacts with the others. In this work, the term $c_{k,i}[\dot{\theta}_i(\theta_i - \theta_{io})]$ is responsible for the coupling between two oscillators with different frequencies, while the term $c_{i,j}\left(\dot{\theta}_i - \dot{\theta}_j\right)$ makes the coupling between two oscillators with the same frequencies.

Figure 7 shows the structure of coupling between oscillators, where *c* is a constant, *h* is related to hip, *lk* is the left knee and *rk* is the right knee.

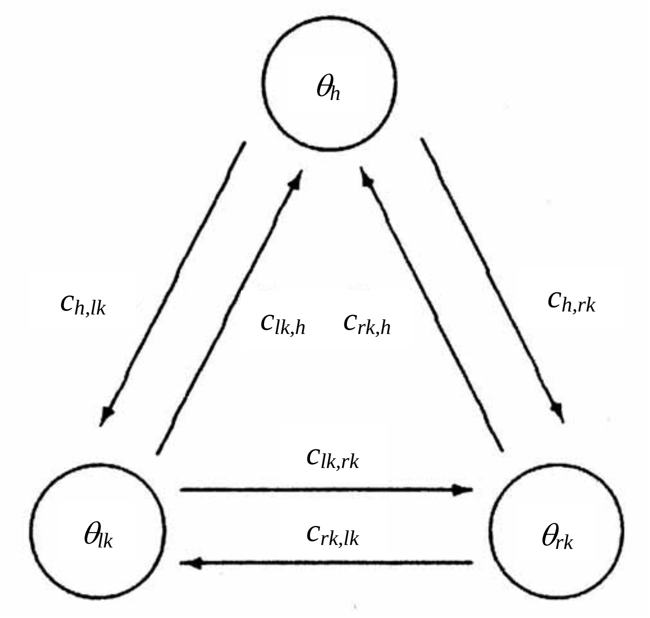

Figure 7. Coupling between oscillators.

Applying the Eq. (1) to the proposed problem, we have:

$$\ddot{\theta}_{lk} - \delta_{lk}\left(1 - q_{lk}\dot{\theta}_{lk}^2\right)\dot{\theta}_{lk} + \Omega_{lk}^2\left(\theta_{lk} - \theta_{lko}\right) - c_{lk,h}[\dot{\theta}_h\left(\theta_h - \theta_{ho}\right)] - c_{lk,rk}\left(\dot{\theta}_{lk} - \dot{\theta}_{rk}\right) = 0 \tag{2}$$

$$\ddot{\theta}_h - \delta_h\left(1 - q_h\dot{\theta}_h^2\right)\dot{\theta}_h + \Omega_h^2\left(\theta_h - \theta_{ho}\right) - c_{h,lk}[\dot{\theta}_{lk}\left(\theta_{lk} - \theta_{lko}\right)] - c_{h,rk}[\dot{\theta}_{rk}\left(\theta_{rk} - \theta_{rko}\right)] = 0 \tag{3}$$

$$\ddot{\theta}_{rk} - \delta_{rk}\left(1 - q_{rk}\dot{\theta}_{rk}^2\right)\dot{\theta}_{rk} + \Omega_{rk}^2\left(\theta_{rk} - \theta_{rko}\right) - c_{rk,h}[\dot{\theta}_h\left(\theta_h - \theta_{ho}\right)] - c_{rk,lk}\left(\dot{\theta}_n - \dot{\theta}_{lk}\right) = 0 \tag{4}$$

The synchronized harmonic functions corresponding to the desired movements are:

$$\theta_{lk} = \theta_{lko} + A_{lk}\cos\left(2\omega t + \alpha_{lk}\right) \tag{5}$$

$$\theta_h = A_h\cos\left(\omega t + \alpha_h\right) \tag{6}$$

$$\theta_{rk} = \theta_{rko} + A_{rk}\cos\left(2\omega t + \alpha_{rk}\right) \tag{7}$$

where: ω is the gait frequency, and α is the phase value.

Considering $\alpha_{lk} = \alpha_h = \alpha_{rk} = 0$ and deriving the Eqs. (5-7), inserting the solution into the differential Eqs. (2-4), the necessary parameters of the oscillators (q_i and Ω_i, $i \in \{lk, h, rk\}$) can be determined. Then:

$$q_{lk} = \frac{4c_{lk,rk}\left(A_{lk} - A_{rk}\right) + 4A_{lk}\delta_{lk} + A_h^2 c_{lk,h}}{12\omega^2 A_{lk}^3 \delta_{lk}} \tag{8}$$

$$\Omega_{lk} = 2\omega \tag{9}$$

$$q_h = \frac{4}{3\omega^2 A_h^2} \tag{10}$$

$$\Omega_h = \omega \tag{11}$$

$$q_{rk} = \frac{4c_{rk,lk}\left(A_{rk} - A_{lk}\right) + 4A_{rk}\delta_{rk} + A_h^2 c_{rk,h}}{12\omega^2 A_{rk}^3 \delta_{rk}} \tag{12}$$

$$\Omega_{rk} = 2\omega \tag{13}$$

From Eqs. (2-4) and (8-13), and using the MATLAB, more specifically the ODE45 method of solution, the graphs shown in Fig. 8 were generated, and represent, respectively, the behavior of the angles as function of the time and the stable limit cycles of the oscillators.

These results were obtained by using the parameters showed in Tab. 1, as well as the initial values provided by Tab. 2. All values for the model were experimentally identified through tests performing in the MATLAB.

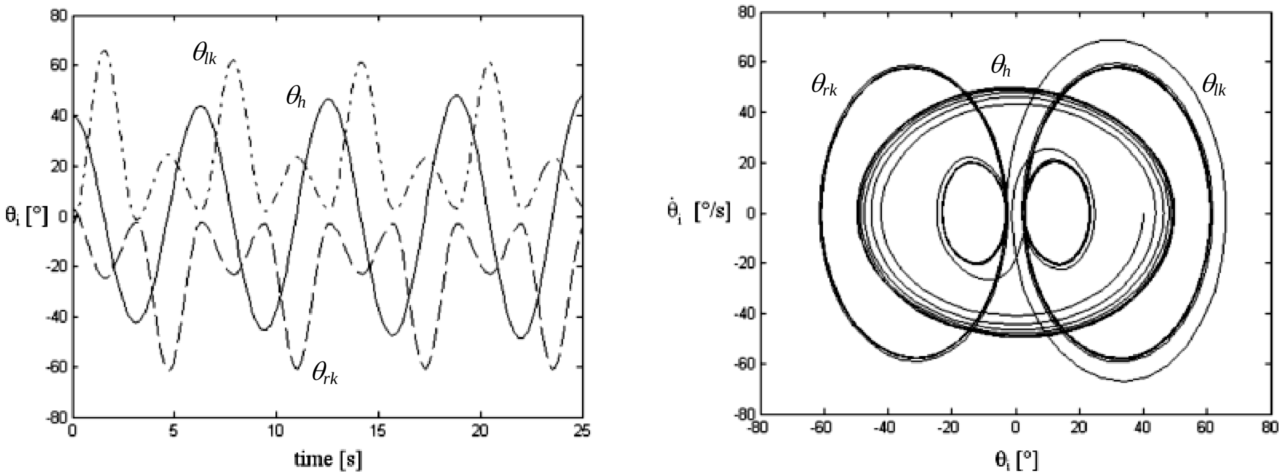

Figure 8. Behavior of the hip and knees as function of the time and stable limit cycles.

Table 1. Parameters of Rayleigh oscillators.

$c_{lk,h}$	$c_{h,lk}$	$c_{lk,rk}$	$c_{rk,lk}$	$c_{h,rk}$	$c_{rk,h}$	δ_{lk}	δ_h	δ_{rk}
0.001	0.001	0.1	0.1	0.001	0.001	0.01	0.1	0.01

Table 2. Experimental initial values.

Cycle	A_{lk}	A_h	A_{rk}	θ_{lko}	θ_{ho}	θ_{rko}
$0 < \omega t \leq \pi$	–29	50	10	32	0	–13
$\pi < \omega t \leq 2\pi$	–10	50	29	13	0	–32

Comparing the graphs of Fig. 8 with the graphs presented in Figs. 5 and 6, in spite of the different amplitudes demonstrated by the experimental tests and by nonlinear oscillators system, taking into consideration only the cycle of locomotion, where 100% of cycle in the Figs. 5 and 6 is equivalent to 6.28 s in Fig. 8, the graph generated by oscillators system represent the pattern of behavior of the elements (hip and knees), being able to be used to generate the approximate trajectories for the legs. This confirms the possibility of the use of coupled Rayleigh oscillators in the modeling of the central pattern generator.

5. APPLICATION OF THE SYSTEM TO A BIPED MODEL

Considering the 2D model of biped locomotor presented in Fig. 9, with movements in the sagittal plane, capable to represent the three most important determinants of human gait (the compass gait, the knee flexion of stance leg, and the plantar flexion of stance ankle).

The locomotion cycle can be divided in two intervals: single support phase and double support phase. In single support phase, one of the legs performs the swinging movement, while the another one it is responsible for the support. The extremity of the support leg is assumed as not sliding. The double support phase is the phase where the transition of the legs occurs, the swinging leg becomes supporting leg and to another one it gets ready to initiate the swinging movement. This phase is initiated at the moment where the swinging leg touches the ground.

Three pairs of elements form the model: femur, tibia, and foot. The legs have identical lengths. The model dimensions can be seen in Tab. 3.

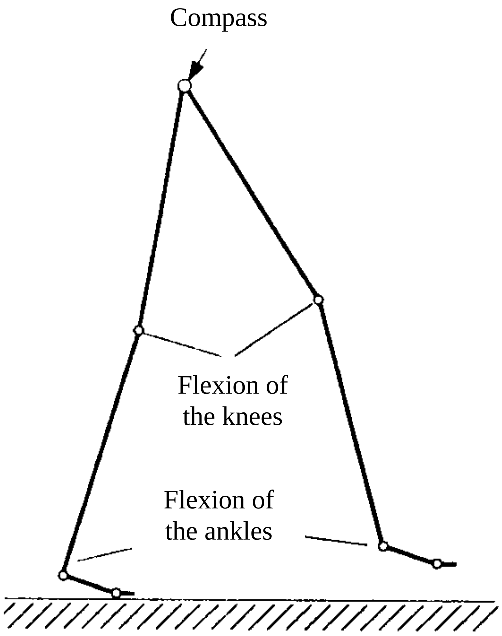

Figure 9. 2D model of biped locomotor.

Table 3. Model Dimensions.

Model part	Length [m]
Foot	0.14
Tibia	0.37
Femur	0.37

From the adopted model and applying the coupled oscillators system to generate the degrees of freedom of the locomotor, a simulation was performed take into consideration the Eqs. (2-4) and (8-13), with the values showing in Tabs. 1 to 3. The simulations presented here were performed only through a kinematical analysis, as described in Section 3.

Figure 10 presents the biped gait for angular amplitude of the hip equal to 50°.

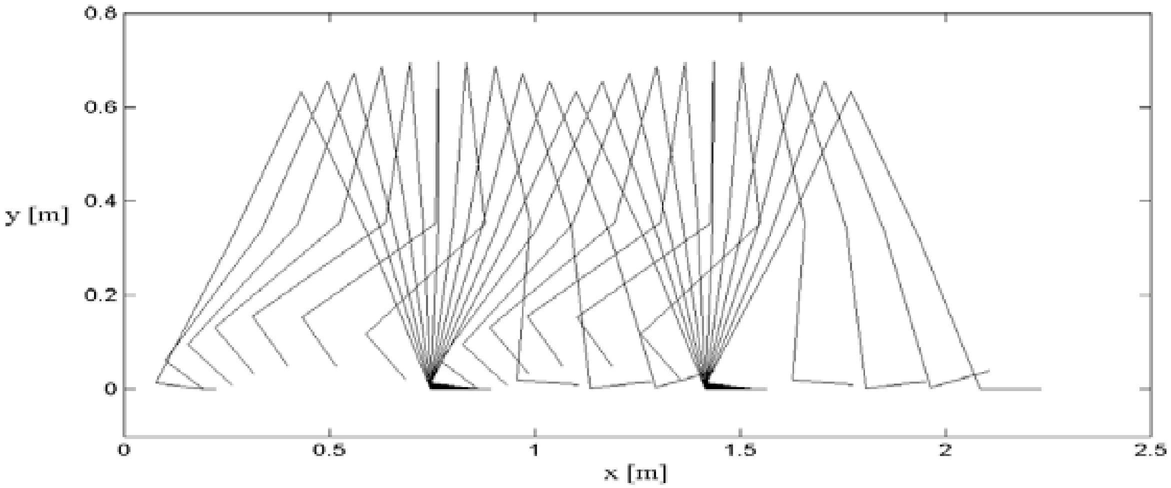

Figure 10. Gait for $A_h = 50^o$.

In this case, the adopted value for amplitude of the hip angle provide a step length equal to 0.63 m. A alteration of this amplitude value cause a change of step length, consequently modifying the gait. Thus, the pattern generator system makes possible the change of step length by means of amplitude alteration.

Figure 11 presents the alteration of the hip angle, with initial amplitude 50º changing to 30º. In this case, for amplitude of 30º the step length is equal to 0.38 m. The gait simulation with these conditions is presented in Fig. 12.

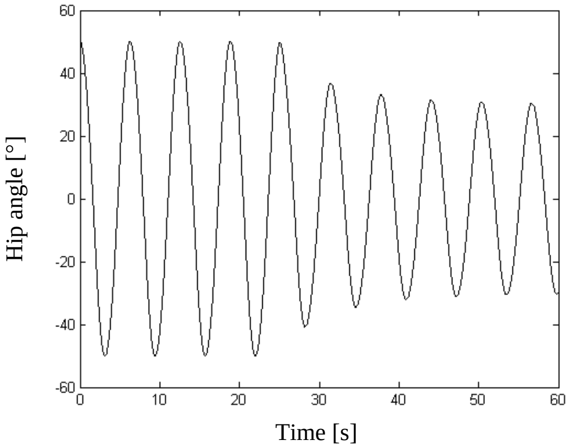

Figure 11. Alteration of locomotion pattern with A_h = 50º to 30º.

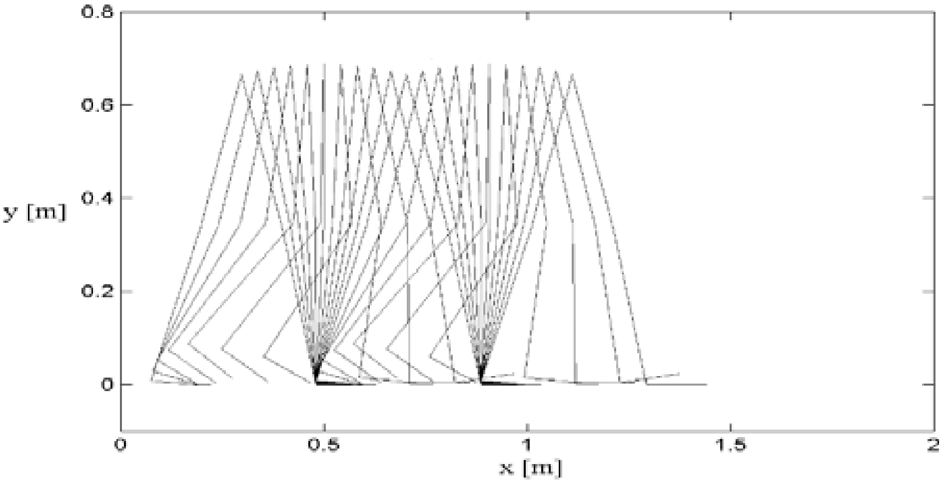

Figure 12. Gait for A_h = 30º.

The system make possible too increases of the step length from increase of the amplitude of hip angle. Figure 13 presents the alteration of pattern locomotion, with initial amplitude 40º changing to 50º. In this case, for amplitude of 40º the step length is equal to 0.5 m. The gait simulation for A_h = 40º is presented in Fig. 14.

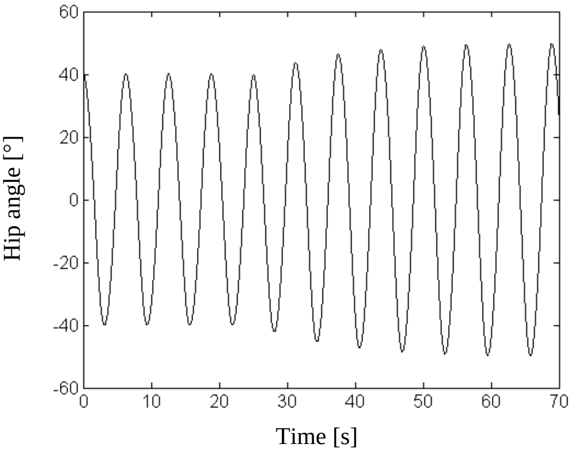

Figure 13. Alteration of locomotion pattern with A_h = 40º to 50º.

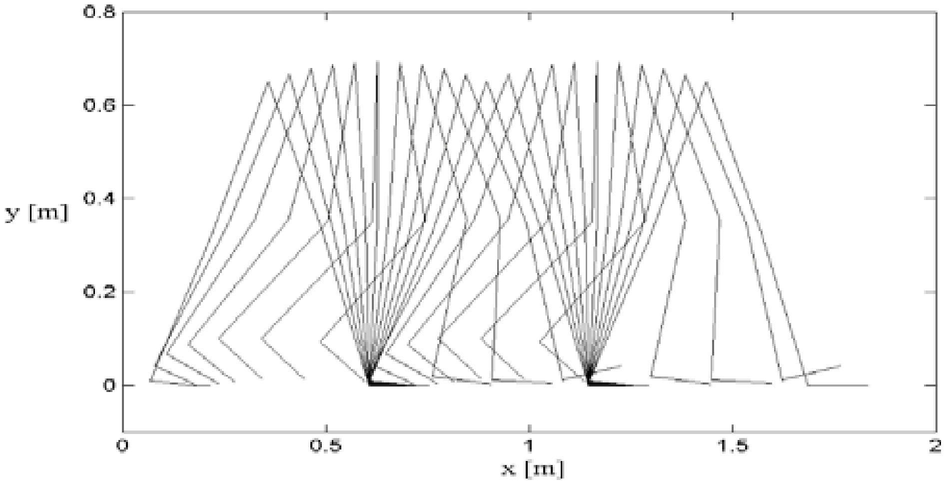

Figure 14. Gait for $A_h = 40^{\circ}$.

Besides the change of step length, the CPG system makes possible too the change in the frequency of the gait, which can be modify by means of the Eqs. (5-7), choosing a new value for ω. Then, modifying the value ω from 1 to 2, we have logically a duplicated gait frequency.

6. CONCLUSION

From presented results and their analysis and discussion, we come to the following conclusions about the modeling of a central pattern generator using nonlinear oscillators, as well as its application to a biped model: the use of coupled nonlinear oscillators, particularly Rayleigh oscillators, can represent an excellent way to signal generation, allowing their application for feedback control of a walking machine by synchronization and coordination of the lower extremities; the adopted model is capable to characterize three of the six most important determinants of human gait; and by alteration of some parameters in the oscillators, modification of the step length and the gait frequency can be obtained.

In future works, we intend to study the behavior of the ankles, as well as simulate the behavior of the hip and knees in the other anatomical planes, thus increasing the network of coupled oscillators, looking for to characterize all determinants of gait, and consequently simulate with more details the central pattern generator of the human locomotion.

7. ACKNOWLEDGEMENTS

The authors would like to express their gratitude to CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico), Brazilian governmental entity promoter of the scientific and technological development, for the financial support provided during the course of this present research.

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