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Modelling of the Human Ankle by means of a Nonlinear Oscillators System

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ABSTRACT

A Nonlinear oscillators system can simulate the behaviour of the main elements involved in the human locomotion, as example, the ankle. These oscillators can be used in control systems of locomotion as pattern generators similar to the human gait pattern, providing approach trajectories of the legs. The work presented here demonstrates the application of this system for generating movement pattern of the ankle in the course of locomotion cycle. Taking into consideration previous research about the application of oscillators in the hip and knee, we obtain a more adequate modelling of the human CPG (central pattern generator), allowing its application in the control of bipedal robots for the synchronization and coordination of the legs. This study has applications in the project of autonomous robots and rehabilitation technology.

Keywords: ankle, CPG, oscillators, human locomotion.

1 INTRODUCTION

To become possible the simulation of human locomotion by means of robotic mechanisms, it is fundamental to know some elements and systems involved in the movement, such as: muscles, reflexes, joints and the central pattern generator (CPG), responsible for the production of rhythmic movements, such as: to swim, to walk, and to jump, and that correctly projected it can generate reference trajectories for locomotion, being able to be used in the control of bipedal robots. Some interesting works with detailed description of the rhythmic movement of animals include [1-4], this last one presenting an ample study about the particularities of human locomotion.

In spite of the great number of research in this area, generally, the studies present the modelling of the movement of hips and knees, being the ankle few explored, due to difficulty of standardization of its movement in the course of locomotion. Some other reasons that motivate the choice of the object of study presented here are the fact of the ankles, together with the feet, to belong to vital importance for the sustentation of the body and accomplishment of the locomotion. The ankle is a terminal joint of support, presenting movement practically in one plane with quite complex function, being always exposed to innumerable injuries.

Nonlinear oscillators can be used in control systems of locomotion as pattern generators similar to the human gait pattern, providing approximate trajectories of the legs, including the ankles. The work presented here demonstrates the application of nonlinear oscillators for generating movement pattern of the ankles in the course of locomotion cycle.

2 HUMAN ANKLE

The human ankle is a structure formed by the union of three bones: tibia, fibula and talus, also having three articulations: subtalar, tibiofibular and talocrural, and some ligaments, these ones responsible for the stability of the ankle. Figure 1 presents a frontal view of the human ankle indicating the main elements that form its structure.

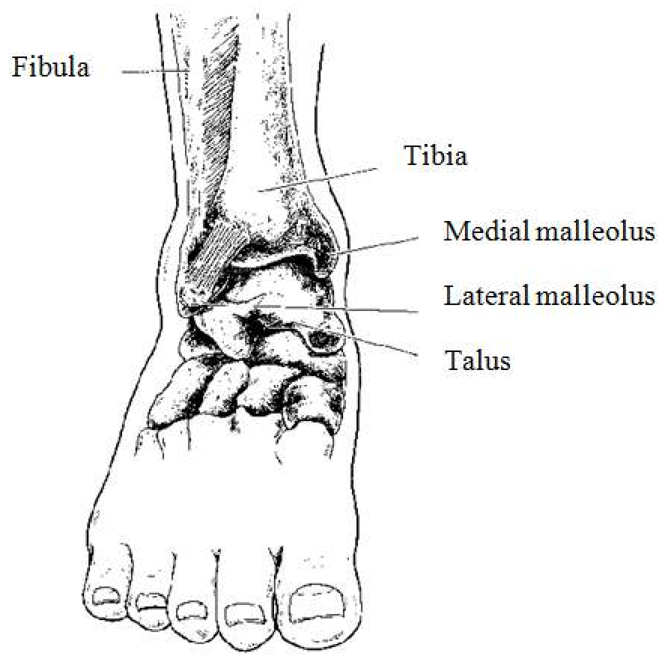

Figure 1: Frontal view of the human ankle.

The subtalar articulation is formed between talus and heel bone. The tibiofibular articulation constitutes the union of the inferior portions of the tibia and fibula. It is a fibrous articulation joined by the interosseous membrane with the anterior and posterior tibiofibular ligaments, firmly coupling the bones. The talocrural articulation is a synovial joint type formed by the superior surface of the convex talus, by the concavity of the distal tibia (medial malleolus) and by lateral malleolus of fibula. These surfaces perfectly fit, allowing the accomplishment of plantar flexion or extension of the ankle, and dorsal flexion or simply flexion of the ankle (Figure 2).

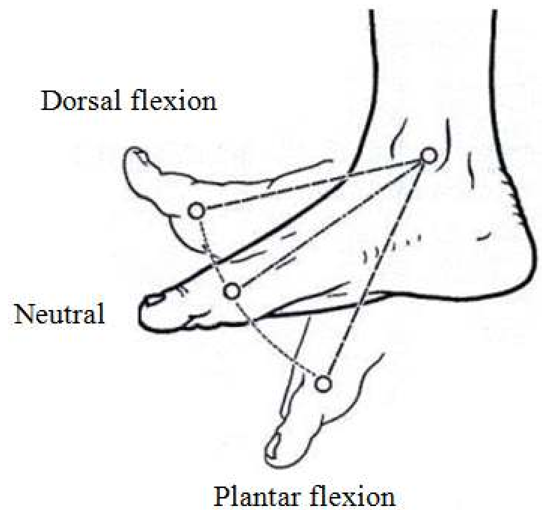

Figure 2: Plantar flexion e dorsal flexion [5].

According Bates and Hanson [6], the medial and lateral malleolus and the strong collateral ligaments stabilize the articulation allowing little or no lateral motion. For Lehmkuhl and Smith [7], the lateral malleolus is projected more distally than the medial one. Thus, the lateral motion of the ankle is more limited than the medial movement. This characterizes a specific axis of movement of the ankle (Figure 3).

Figure 3: Axis of movement of the human ankle [8].

In spite of the plantar flexion and dorsal flexion, that occur in the sagittal plane, to represent the main movements of the ankle, also is possible to observe other movements of lesser amplitude in the other anatomical planes.

According Rosa Filho [9], the involved movements in the articulation of the ankle are: the plantar flexion (extension), the dorsal flexion, the inversion, and the eversion. A definition of each one of these movements is presented to follow:

- Plantar flexion (extension): movement which the plant of the foot is come back toward to the ground. The involved muscles in this movement are: Gastrocnemius and Soleus. The amplitude of movement is 0 to 50º;

- Dorsal flexion: movement which the back of the foot is come back toward to the head. The involved muscles in this movement are: Tibialis anterior and long extensor of the fingers. The amplitude of movement is 0 to 20º;

- Inversion: movement which if turns the plant the foot for "inside" of the leg, in the ankle and intertarsus articulations. The involved muscles are: Tibialis anterior and posterior. The amplitude of movement is 0 to 45º;

- Eversion: movement which if turns the plant the foot for "outside" of the leg, in the ankle and intertarsus articulations. The involved muscles are: long extensor of the fingers and long and short fibular. The amplitude of movement is 0 to 30º.

The movements of flexion and extension occur in the sagittal plane, while the movements of inversion and eversion are related to the frontal plane. Farther these movements, movements of internal and external rotation in the transverse plane exist. Figure 4 shows the movements of the ankle in each one of the anatomical planes.

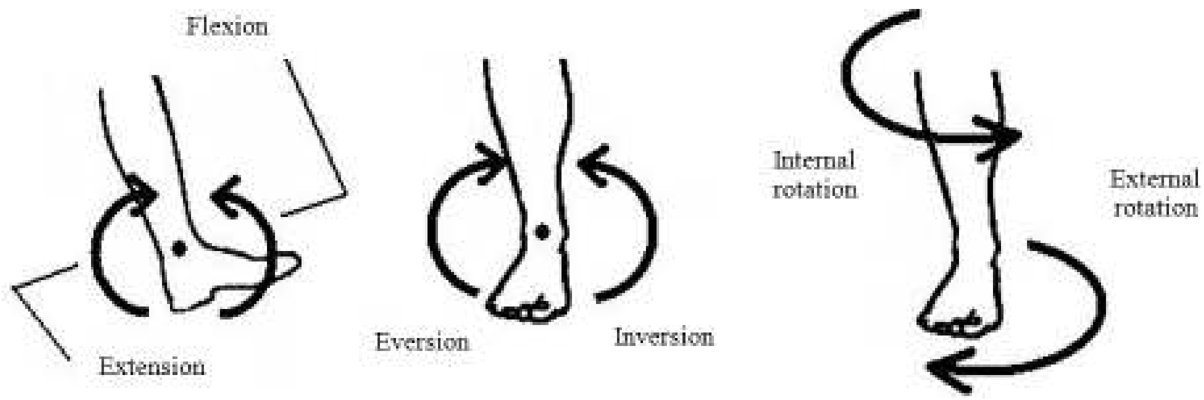

Figure 4: Movements of the human ankle.

In this work the greatest interest is related to the movements of flexion and extension of the ankle, which are linked to the axis of movement defined in Figure 3.

After to verify the main anatomical and movement characteristics of the ankle, to specify its behaviour in the course of locomotion cycle is necessary to know some concepts related to the gait and posture.

3 GAIT, POSTURE, AND LOCOMOTION PATTERNS

The gait can be defined as a way to walk. When compared with the pathological patterns, the normal gait presents a great available band of safe and comfortable speeds. Injuries of the muscle-skeletal system can break the normal pattern of the gait. A great variety of compensatory mechanisms can be placed in action, in an effort to keep the functional deambulation. These compensations are appeared as abnormal patterns of gait, less efficient and with greatest cost in terms of expense of energy, when compared with normal mechanisms.

The normal cycle of locomotion can be divided in two phases (Figure 5):

- Single support phase: in the course of this phase one of the legs performs the balance movement while another one it is responsible for the support.

- Double support phase: it is the phase where the transition of the legs occurs, in other words, the leg in balance becomes support leg and another one it gets ready to initiate the balance movement. This phase is initiated at the moment which the leg in balance touches the ground.

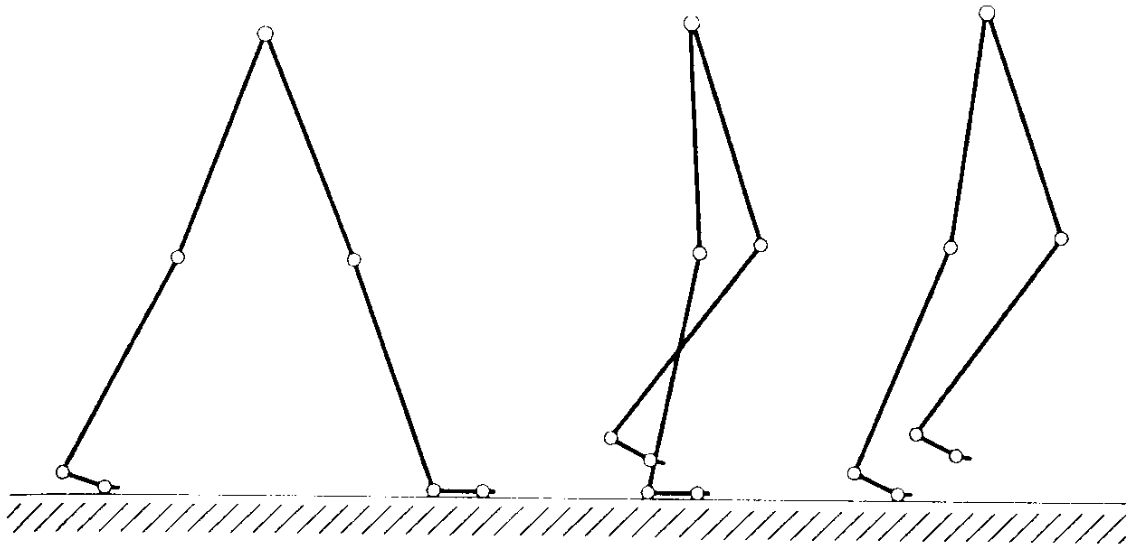

Figure 5: Double and single support phases in the course of locomotion [10].

The articulation between the ankle and the foot has fundamental importance in the sustentation of the body and the locomotion. For Kisner and Colby [11], the ankle and the foot are interrelated structures that have anatomical and functional synchronism, allowing the support, the sustentation and the deambulation. Lehmkuhl and Smith [7] affirm that the posture of the foot and ankle can change, in an only step, to a flexible structure that if conforms to the irregularities of the ground to a rigid structure of sustentation of weight.

The behaviour of the ankle in the course of locomotion cycle, as well as of the other parts of the locomotor, can be showed through graphs. The choice of an appropriate pattern of locomotion depends on the combination of a central programming and input 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 [12].

The central pattern generator supplies a series of pattern curves, which are transmitted to the muscles by means of a network of motor-neurons, and the conjoined muscular activity perform 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 intends adjust the gait to the new situation.

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

In the study presented here the greatest interest is related to the patterns of the kinematics, in particular, of the ankle angle. Only from the knowledge of these patterns it will be possible to evaluate the modelling viability, by means of nonlinear oscillators, of the movement of the ankle in the course of the locomotion cycle.

To specify a pattern of locomotion, either for the ankle or any another element of the locomotor system, is necessary to perform experimental tests using special systems of kinematics analysis, as well as normalization methods, as for example, the use of an optic-electronic system of three-dimensional kinematics analysis [13].

From this system it is possible to define the angular behaviour of the ankle in the course of the locomotion cycle. As the movements of flexion and extension of the ankle are most important in this work, its analysis will be shown with more details. Figure 6 presents graphs of the extension and flexion movements, obtained in the experimental analysis with 24 volunteers. The graphs in full line represent the original movement of each one of the volunteers, while that the graphs in dashed line represent normalized results using the method of Karhunen-Loève. More details about the application of this method can be seen in [13].

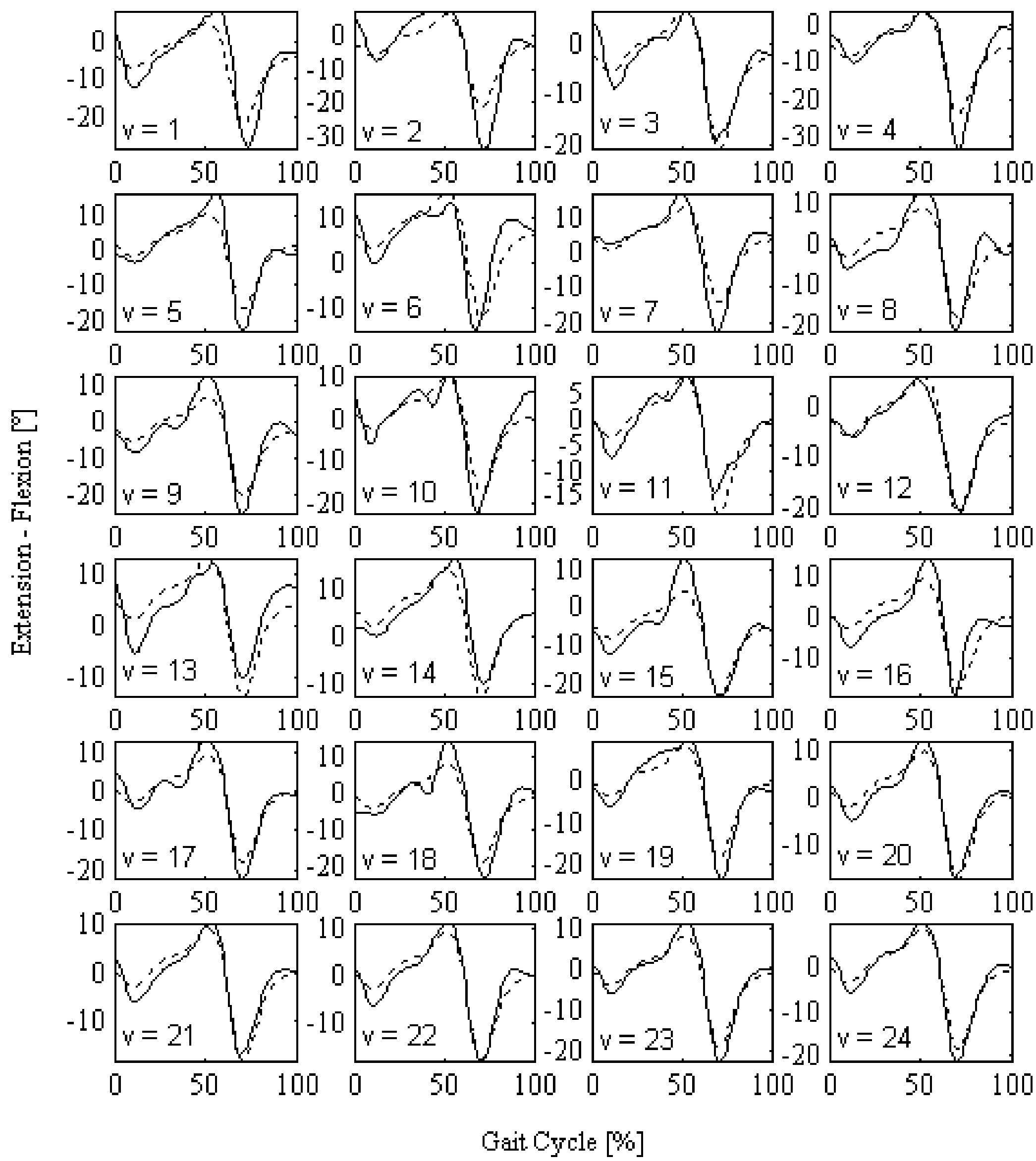

Figure 6: Behaviour of the ankle for 24 volunteers [13].

A standardization of the movement is quite difficult, since some results are much different, but considering all data it is possible to specify a pattern curve to the behaviour of the ankle in the course of a locomotion cycle. This curve can be seen in Figure 7, where the full line represents the average of the values, while the dashed lines represent the extreme values, thus characterizing a pattern of behaviour of the ankle.

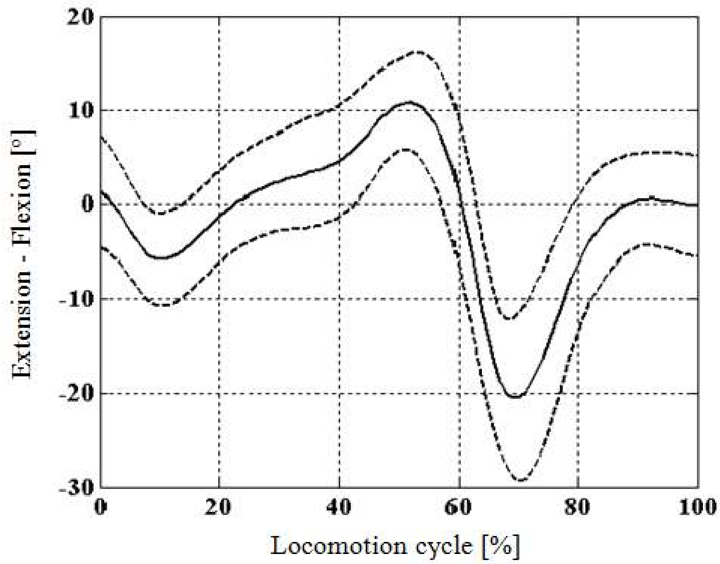

Figure 7: Pattern of behaviour of the ankle.

Figure 8 presents the phase space of the ankle in the sagittal plane, related to the movements of flexion and extension.

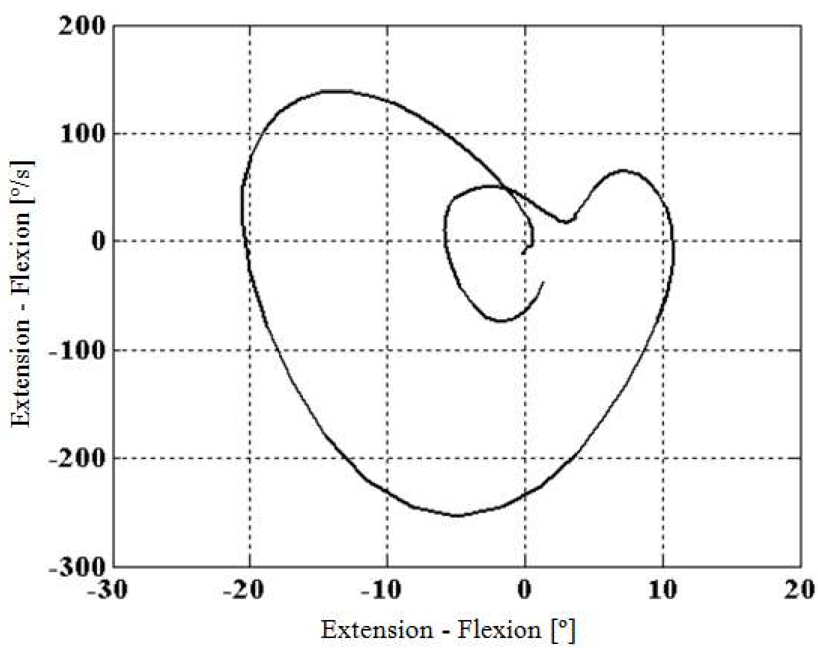

Figure 8: Phase space of the ankle in the sagittal plane.

From the curves defined in the Figures 7 and 8, we can then analyze the possibility of modelling by means of nonlinear oscillators.

4 MODELLING OF THE HUMAN ANKLE

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

One of the oscillators more known and used in diverse works about locomotion is the oscillator of van der Pol. Some previous works about nonlinear oscillators, applied in the locomotion of bipedal robots, can be seen in [10, 14-17].

The equation of van der Pol is well known, originated from a simple circuit RLC in which was inserted an active nonlinear element. The most common configuration of the equation of van der Pol is given by the equation:

$$\ddot{x} + \mu(x^2 - 1)\dot{x} + x = 0 \tag{1}$$

where μ is the damping term. The equation of van der Pol that will be used in the analysis is:

$$\ddot{x} - \varepsilon\left(1 - p(x - x_0)^2\right)\dot{x} + \Omega^2(x - x_0) = 0 \qquad \varepsilon, p \geq 0 \tag{2}$$

where ε, p and Ω correspond to the parameters of the oscillator.

Thus, considering θ the ankle angle, from the equation of van der Pol proposal in (2), we have:

$$\ddot{\theta} - \varepsilon[1 - p(\theta - \theta_0)^2]\,\dot{\theta} + \Omega^2(\theta - \theta_0) = 0 \tag{3}$$

For small values of parameters that determine the nonlinearity of the oscillator, the following approximate periodic solution can be assumed:

$$\theta = \theta_0 + A\cos(4\omega t + \alpha) \tag{4}$$

Deriving the Equation (4), we have the following equations:

$$\dot{\theta} = -4\omega A\sin(4\omega t + \alpha) \tag{5}$$

$$\ddot{\theta} = -16\omega^2 A\cos(4\omega t + \alpha) \tag{6}$$

Considering that the difference of the phase α equal to zero, and substituting the Equation (4), (5) and (6) in (3), the following equation is obtained:

$$\left(A\Omega^2 - 16A\omega^2\right)\cos(4\omega t) + \left(4A\varepsilon\omega - 4A^3\varepsilon\omega p\right)\sin(4\omega t) + \left(4A^3\varepsilon\omega p\right)\sin^3(4\omega t) = 0 \tag{7}$$

We desire to determine the values of parameters p and Ω. Thus two equations are created from (7). That is possible by the application of the method of harmonic balance [18]. In brief, the method consists in quantitatively evaluate the terms in the Equation (7) and, verified the greatest importance of the terms $\cos(4\omega t)$ and $\sin(4\omega t)$, the other terms is ignored, in the case, $\sin^3(4\omega t)$. Then, by the application of this method, we have the linearization of the problem. After that, each one of the terms between parentheses is equalled to zero, and we have the following equations:

$$A\Omega^2 - 16A\omega^2 = 0 \tag{8}$$

$$4A\varepsilon\omega - 4A^3\varepsilon\omega p = 0 \tag{9}$$

Then, solving each one of the equations, the parameters p and Ω are:

$$\Omega = 4\omega \tag{10}$$

$$p = 1/A^2 \tag{11}$$

From the Equation (3), (10) and (11), using the MATLAB, more specifically the ODE45 method of solution, the graphs shown in the Figures 9 and 10 were generated, that they present, respectively, the behaviour of the ankle angle as a function of the time and the stable limit cycle of the oscillator.

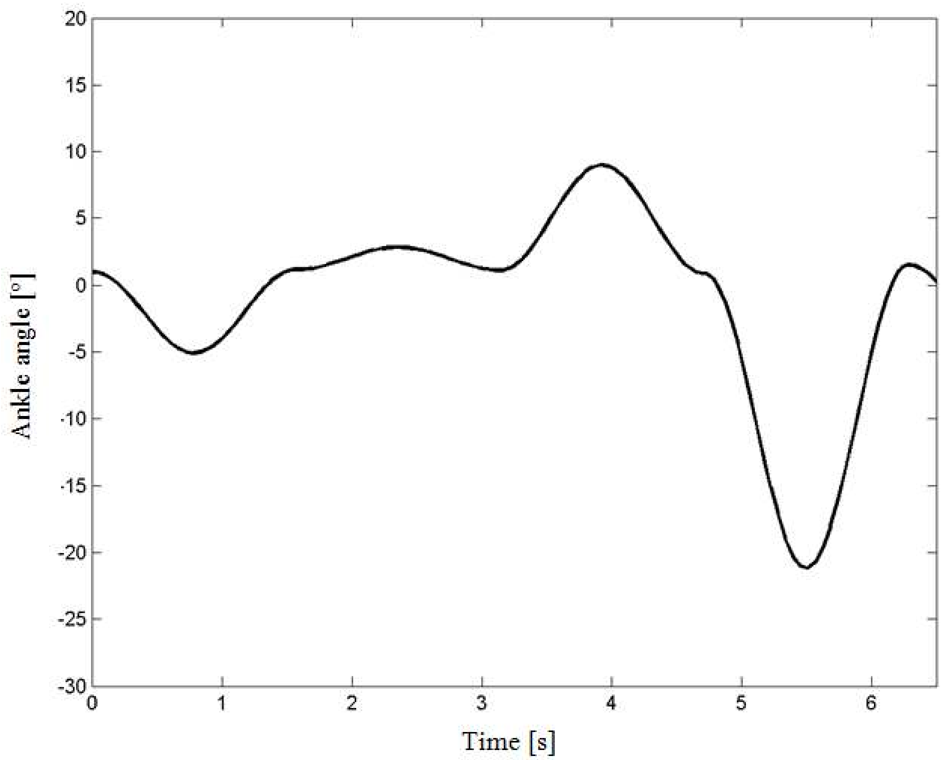

Figure 9: Behaviour of the ankle angle as a function of the time.

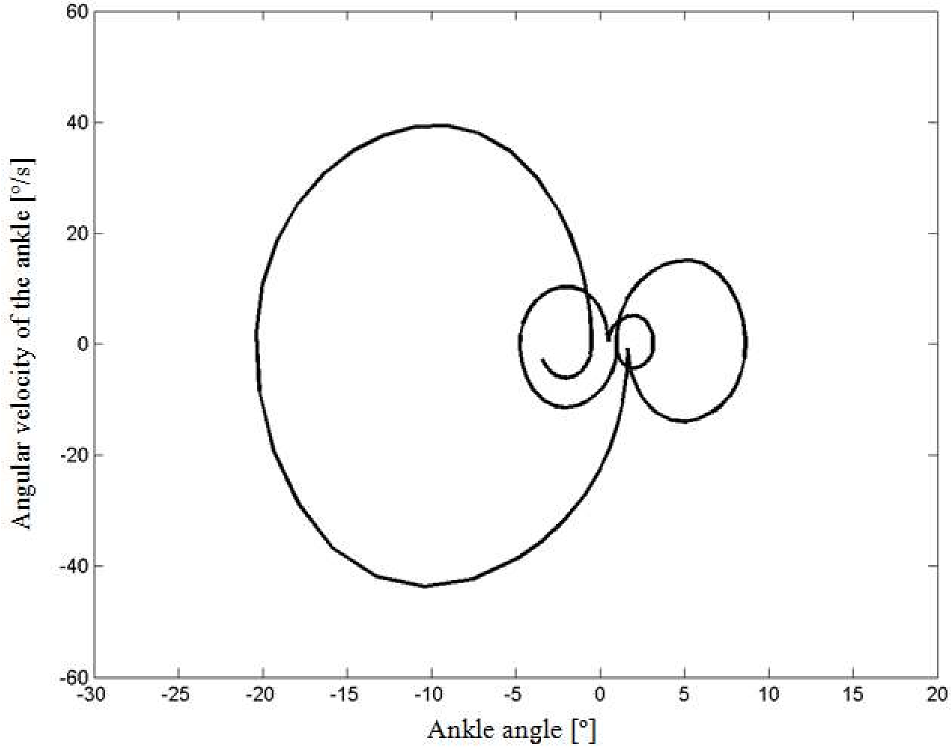

Figure 10: Stable limit cycle of the oscillator.

The results presented here were obtained using the parameter $\varepsilon = 0.1$ and frequency $\omega = 1\ s^{-1}$, as well as the initial values supplied by Table 1. All parameters values for the model were experimentally identified through tests performing in the MATLAB.

Table 1: Experimental initial values.

Cycle	$0 < \omega t \leq \pi/2$	$\pi/2 < \omega t \leq \pi$	$\pi < \omega t \leq 3\pi/2$	$3\pi/2 < \omega t \leq 2\pi$
A	3	-1	-4	11
θ_o	-2	2	5	-10

Comparing the results provided by the oscillator of van der Pol with those presented in the Figures 7 and 8, we verify that the oscillator supplied much similar results, what proves the possibility of use of this system in the modelling of the ankle movement. In Figure 11 we can observe the graphs side by side.

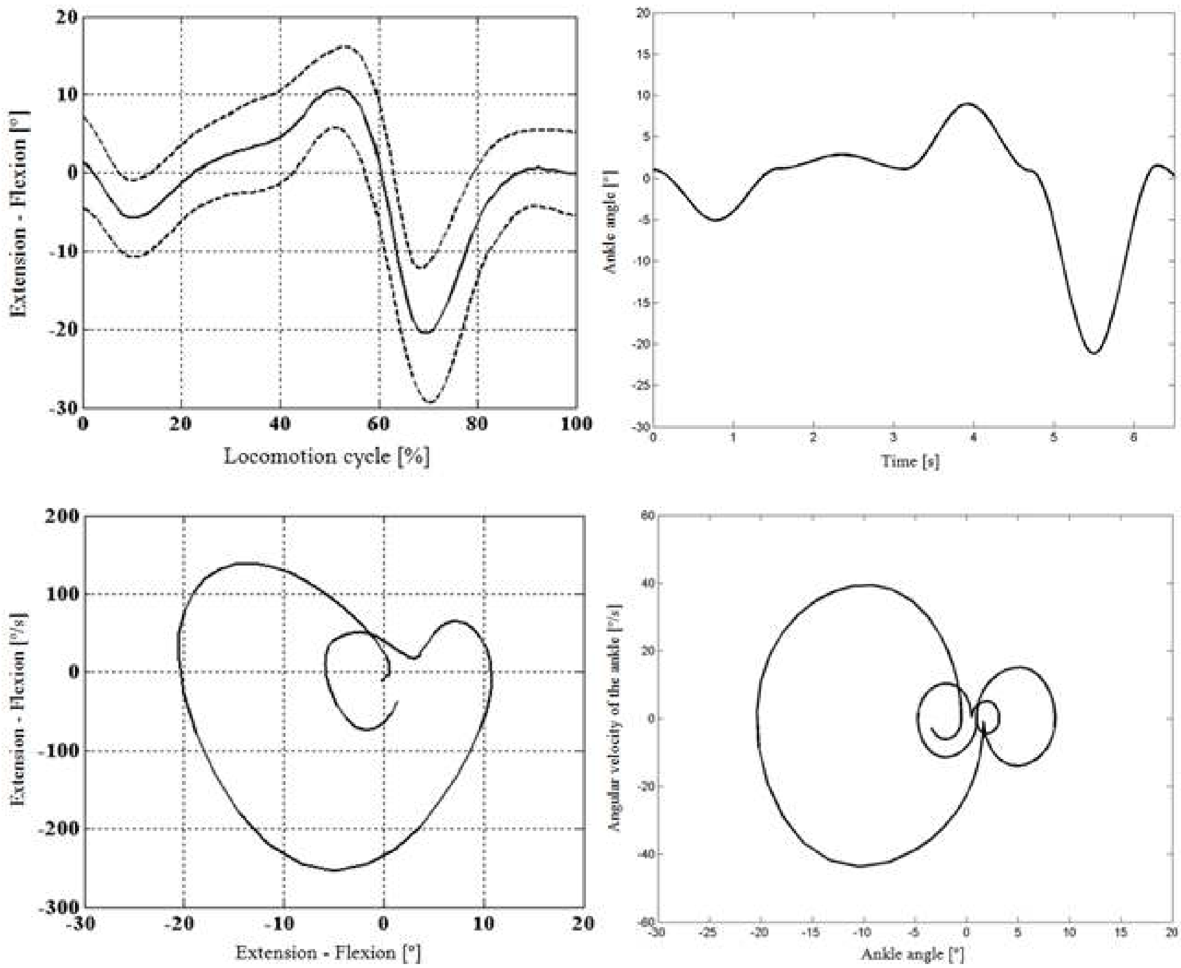

Figure 11: Behaviour of the ankle in the course of a locomotion cycle
(Experimental Analysis versus van der Pol Oscillator).

From the results of the presented analysis with data provided by [17], Figure 12 shows, with a stick figure, the gait with a step length of 0.68 m. The stick figure of a bipedal locomotor with a step length of 0.44 m is represented in Figure 13. The dimensions adopted for the model can be seen in Table 2.

Table 2: Model dimensions.

	length [m]	mass [kg]
Thumb	0.03	0.2
Foot	0.11	0.6
Leg (below the knee)	0.37	4
Thigh	0.37	6

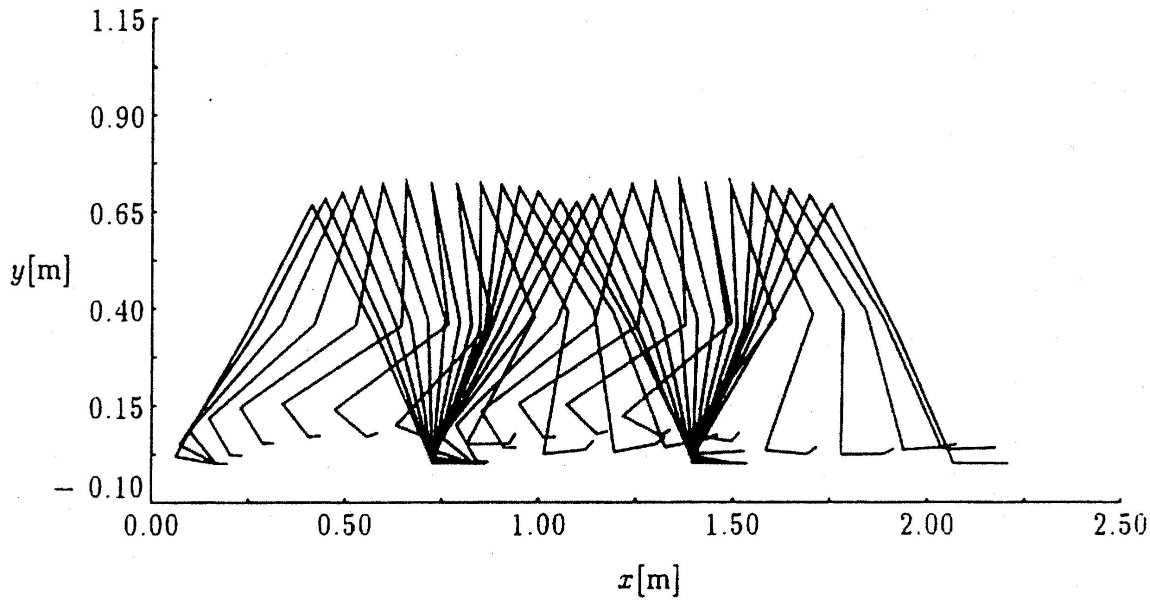

Figure 12: Stick figure showing the gait with a step length of 0.68 m.

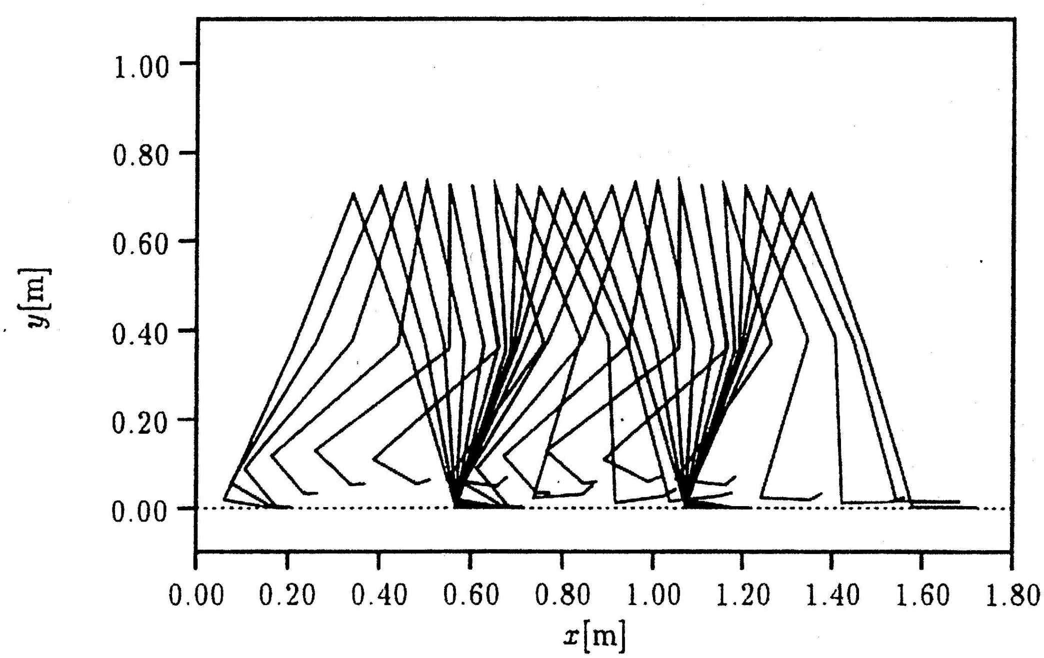

Figure 13: Stick figure showing the gait with a step length of 0.44 m.

5 CONCLUSION

In this work the main characteristics of the human ankle were presented, taking into consideration factors related to the anatomy and movements, and then specifying the pattern of behaviour of the ankle in the course of the locomotion cycle.

With the determination of this pattern, it was possible to simulate the behaviour of the ankle using nonlinear oscillators, of similar way to perform by [17] with hip and knees. The angles of the ankles must be synchronized in order that the locomotion movement will be fluent.

From the results of this work and future studies, we hope to obtain a more adequate modelling of the central pattern generator, responsible for generation of reference trajectories for human locomotion. These studies intend to assist the project of autonomous robots and the rehabilitation technology of human beings.

REFERENCES

[1] Eberhart, H.D., 1976, "Physical principles for locomotion", In: Neural Control of Locomotion, R. M. Herman et al., Eds. New York: Plenum.

[2] Inman, V.T., Ralston, H.J., Todd, F., 1981, "Human Walking", Willams & Wilkins, USA.

[3] Winter, D., 1983, "Biomechanical motor patterns in normal walking", J. Motor Behav., Vol. 15, No. 4, pp. 302-330.

[4] McMahon, T.A., 1984, "Muscles, Reflexes and Locomotion", Princeton University Press, USA.

[5] Kapandji, I.A., 1980, "Fisiologia articular: esquemas comentados de mecânica humana", Ed. 4, Vol. 2, Editora Manole, Brazil.

[6] Bates A., Hanson N., 1996, "Aquatic Exercise Therapy", Philadelphia. W.B. Saunders & Company.

[7] Lehmkuhl, L.D., Smith, L.K., 1989, "Interação dos fatores mecânicos e fisiológicos na função", In: Brunnstroms Cinesiologia Clínica, Ed. 4, F.A. Davis, Philadelphia.

[8] Nordin M., Frankel V., 2001, "Basic Biomechanics of the Musculoskeletal System", Ed. 3, Lippincott, Philadelphia.

[9] Rosa Filho, B.J., 2001, www.wgate.com.br/fisioweb, World Gate Brasil Ltda.

[10] Dutra, M.S., 1995, "Bewegungskoordination und Steuerung einer zweibeinigen Gehmaschine", Aachen, Germany, Shaker Verlag.

[11] Kisner, C., Colby, L.A., 1992, "Exercícios Terapêuticos: Fundamentos e Técnicas", Ed. Manole, São Paulo.

[12] Horak, F.B. and Nashner, L.M., 1986, "Central programming of postural movements adaptation to altered support-surface configurations", Journal of Neurophysiology 55, pp. 1369-1381.

[13] Raptopoulos, L.S.C., Dutra, M.S., Pinto, F.A.N.C., Pina Filho, A.C.de, 2006, "Alternative approach to modal gait analysis through the Karhunen–Loève decomposition: An application in the sagittal plane", Journal of Biomechanics 39, 2898-2906.

[14] Bay, J.S. and Hemami, H., 1987, "Modelling of a neural pattern generator with coupled nonlinear oscillators", IEEE Trans. Biomed. Eng. 34, pp. 297-306.

[15] Zielinska, T., 1996, "Coupled oscillators utilised as gait rhythm generators of a two-legged walking machine", Biological Cybernetics 74, pp. 263-273.

[16] Pina Filho, A.C.de, Dutra, M.S. and Raptopoulos, L.S.C., 2005, "Modeling of a Bipedal Robot Using Mutually Coupled Rayleigh Oscillators", Biological Cybernetics 92(1), pp. 1-7.

[17] Pina Filho, A.C.de, 2005, "Study of Mutually Coupled Nonlinear Oscillators Applied in the Locomotion of a Bipedal Robot", D.Sc. Thesis, UFRJ, COPPE/PEM, Brazil.

[18] Nayfeh, A.H. and Mook, D.T., 1979, "Nonlinear oscillations", John Wiley & Sons, Inc.