

STUDY AND MODELING OF THE ANKLES MOVEMENT PATTERN IN THE COURSE OF HUMAN LOCOMOTION

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Abstract. *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 movement. This CPG correctly projected can generate reference trajectories for locomotion. 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. A coupled oscillators system can simulate the behavior of the main elements involved in the locomotion, such as: hip, knees and ankles. The work presented here demonstrates the application of nonlinear oscillators for generating movement pattern of the ankles in the course of locomotion cycle. Together with previous research related to the application of oscillators in the hip and knees, we can obtain a more adequate modeling of the CPG, allowing its application in the control of bipedal robots for the synchronization and coordination of the legs. This study have great application in the project of autonomous robots and in the rehabilitation technology.*

Keywords: *ankle, CPG, oscillator, locomotion.*

1. INTRODUCTION

In the course of many years the human being comes trying, using diverse forms, to recreate the complex mechanisms that form the human body. Such task is extremely complicated, and the results are unsatisfactory for many times. However, with greater technological advances each time, from theoretical and experimental research, the man succeeds, in a way, to copy or to imitate some systems of the human body, for example, the locomotion.

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 Eberhart (1976), Inman *et al.* (1981), Winter (1983) and McMahon (1984), 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 modeling 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. ANATOMY OF THE ANKLE

The 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 ankle indicating the main elements that form its structure.

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 (Fig. 2).

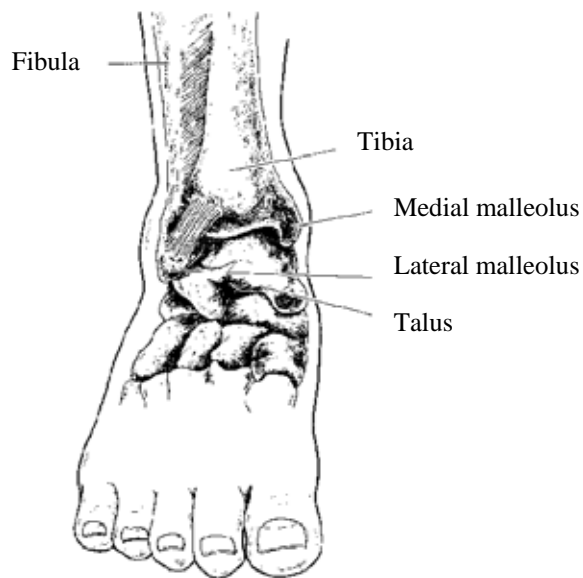


Figure 1. Frontal view of the ankle.

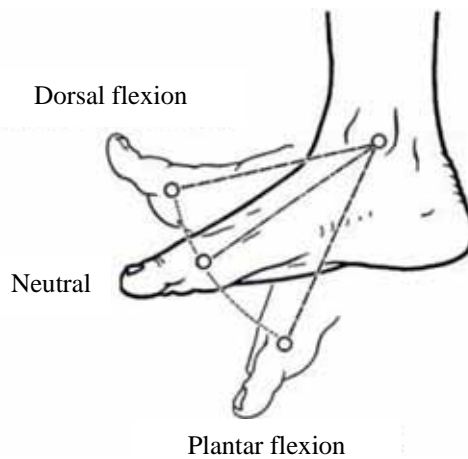


Figure 2. Plantar flexion e dorsal flexion (Kapandji, 1980).

According Bates and Hanson (1996), the medial and lateral malleolus and the strong collateral ligaments stabilize the articulation allowing little or no lateral motion. For Lehmkuhl and Smith (1989), 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 (Fig. 3).



Figure 3. Axis of movement of the ankle (Nordin and Frankel, 2001).

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, what it will be presented in the section to follow.

3. MOVEMENTS OF THE ANKLE

According Rosa Filho (2001), 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 50°;
- 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 20°;
- 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 45°;
- 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 30°.

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.

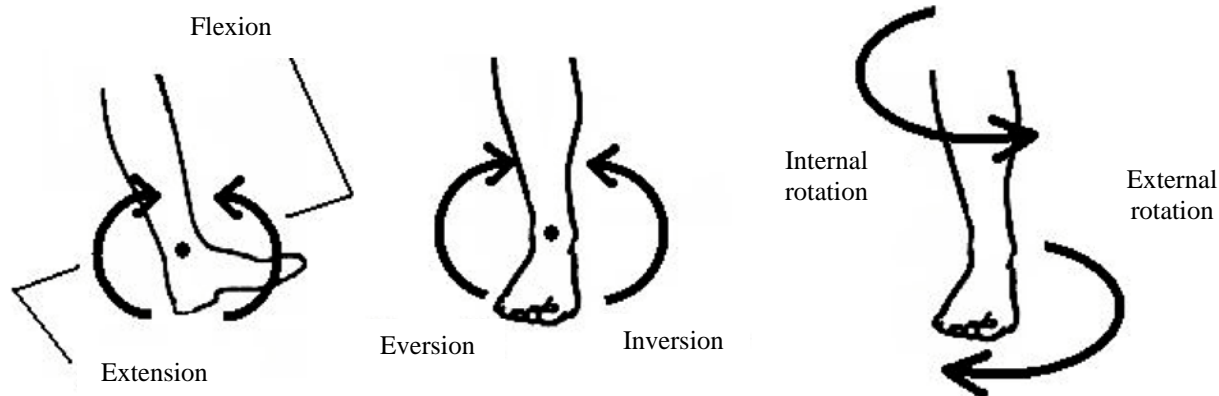


Figure 4. Movements of the ankle.

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 Fig. 3.

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

4. GAIT AND POSTURE

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 (Fig. 5):

- Single support phase: in the course of this phase one of the legs perform the balance movement while the 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 the 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.

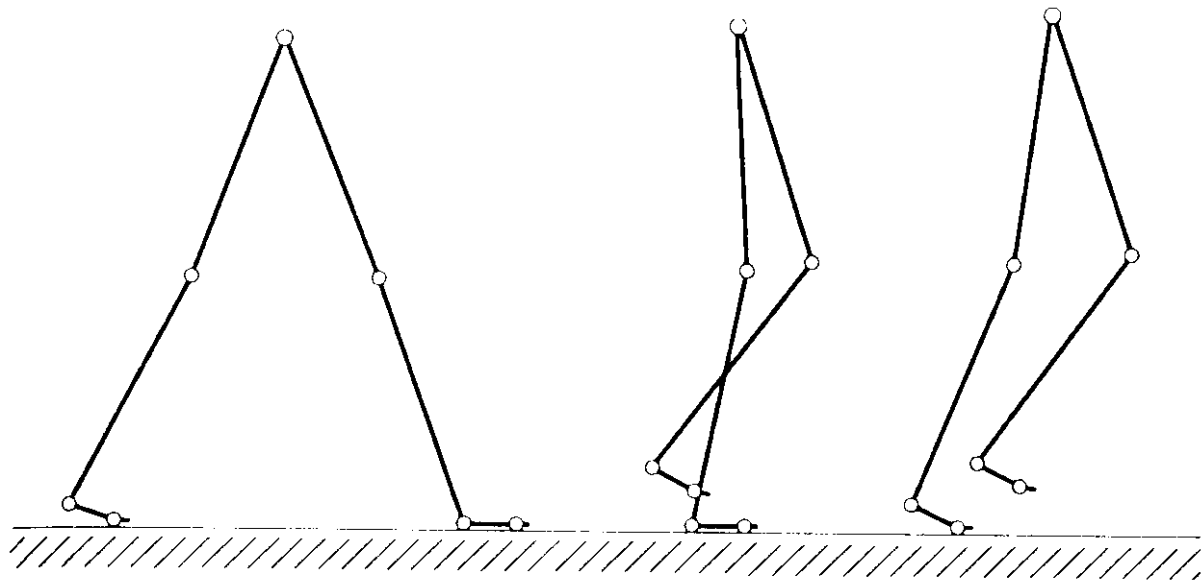


Figure 5. Double and single support phases in the course of locomotion (Dutra, 1995).

The articulation between the ankle and the foot has fundamental importance in the sustentation of the body and the locomotion. For Kisner and Colby (1992), 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 (1989) 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 behavior of the ankle in the course of locomotion cycle, as well as of the other parts of the locomotor, can be showed through graphs, as it will be seen to follow.

5. PATTERNS OF LOCOMOTION

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 (Horak and Nashner, 1986).

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 modeling 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 (Raptopoulos *et al.*, 2006).

From this system it is possible to define the angular behavior 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 Raptopoulos *et al.* (2006).

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 behavior of the ankle in the course of a locomotion cycle. This curve can be seen in Fig. 7, where the full line represents the average of the values, while the dashed lines represent the extreme values, thus characterizing a pattern of behavior of the ankle.

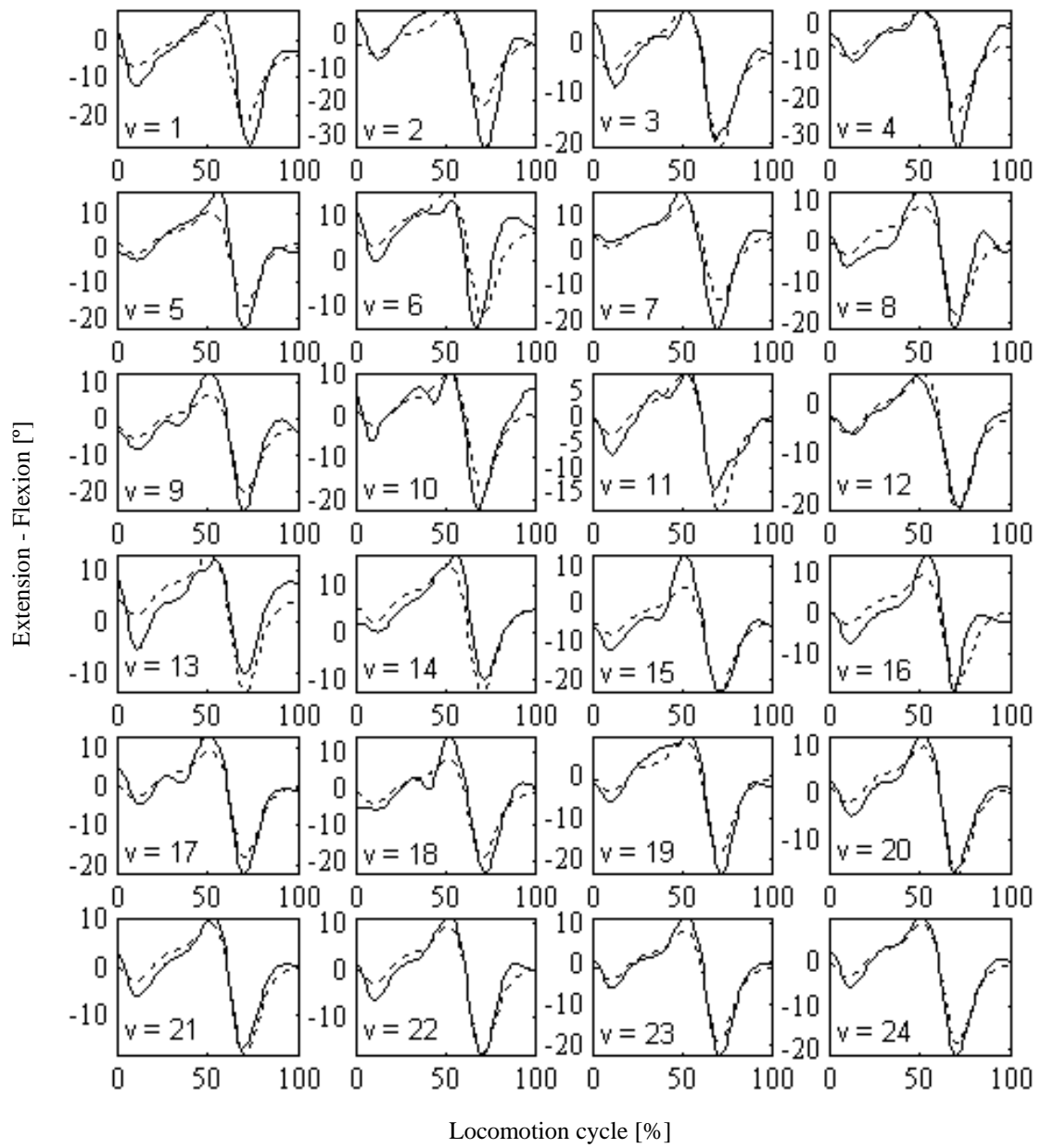


Figure 6. Behavior of the ankle for 24 volunteers (Raptopoulos *et al.*, 2006).

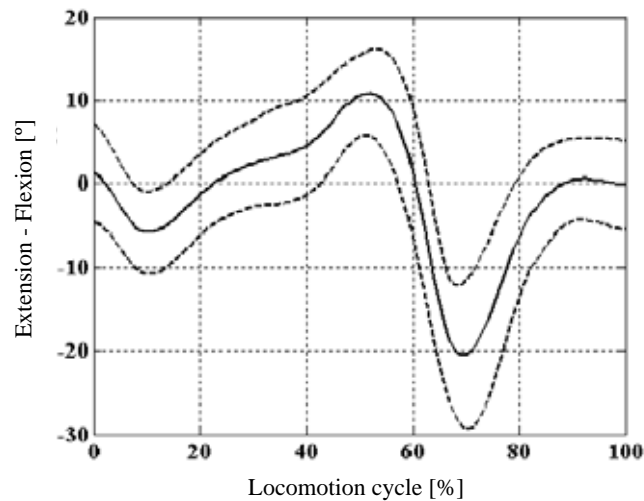


Figure 7. Pattern of behavior of the ankle.

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

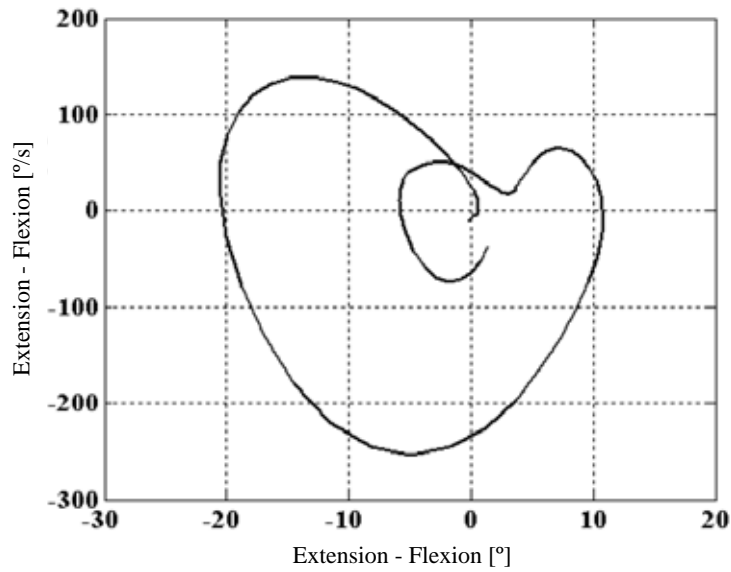


Figure 8. Phase space of the ankle in the sagittal plane.

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

6. MODELING OF THE ANKLE MOVEMENT

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.

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 Bay and Hemami (1987), Dutra (1995), Zielinska (1996), Pina Filho *et al.* (2005), and Pina Filho (2005).

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

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

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

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

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:

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

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

$$\theta = \theta_0 + A \cos(4\omega t + \alpha) \quad (4)$$

Deriving the Eq. (4), we have the following equations:

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

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

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

$$(A\Omega^2 - 16A\omega^2)\cos(4\omega t) + (4A\varepsilon\omega - 4A^3\varepsilon\omega p)\text{sen}(4\omega t) + (4A^3\varepsilon\omega p)\text{sen}^3(4\omega t) = 0 \quad (7)$$

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 (Nayfeh and Mook, 1979). In brief, the method consists in quantitatively evaluate the terms in the Eq. (7) and, verified the greatest importance of the terms $\cos(4\omega t)$ and $\text{sen}(4\omega t)$, the other terms is ignored, in the case, $\text{sen}^3(4\omega t)$. Then, by the application of this method, we have the linearization of the problem. After that, each one of the terms between parentheses is equaled to zero, and we have the following equations:

$$A\Omega^2 - 16A\omega^2 = 0 \quad (8)$$

$$4A\varepsilon\omega - 4A^3\varepsilon\omega p = 0 \quad (9)$$

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

$$\Omega = 4\omega \quad (10)$$

$$p = 1/A^2 \quad (11)$$

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

The results presented here were obtained using the parameter $\varepsilon = 0.1$ and frequency $\omega = 1 \text{ s}^{-1}$, as well as the initial values supplied by Tab. 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_0 | -2 | 2 | 5 | -10 |

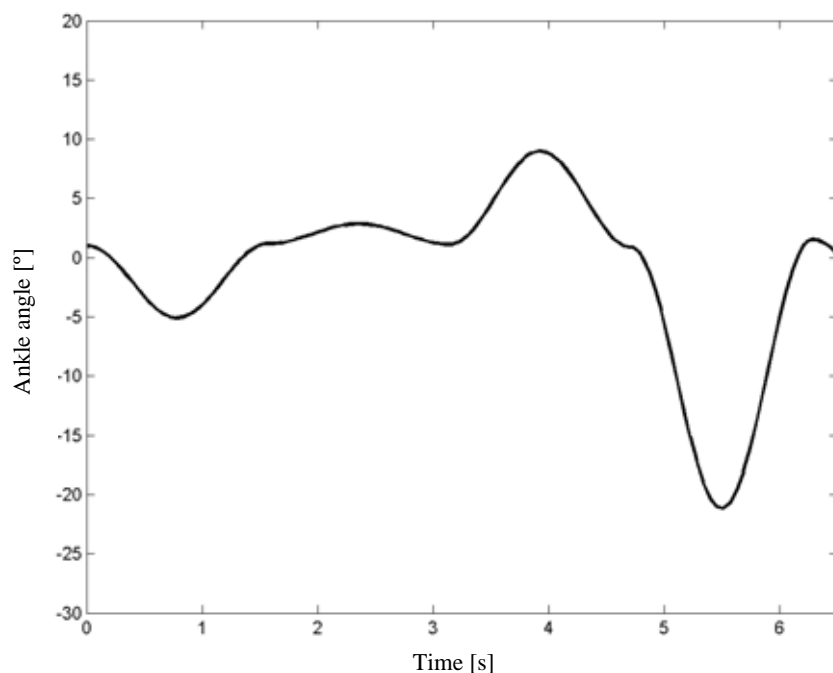


Figure 9. Behavior of the ankle angle as a function of the time.

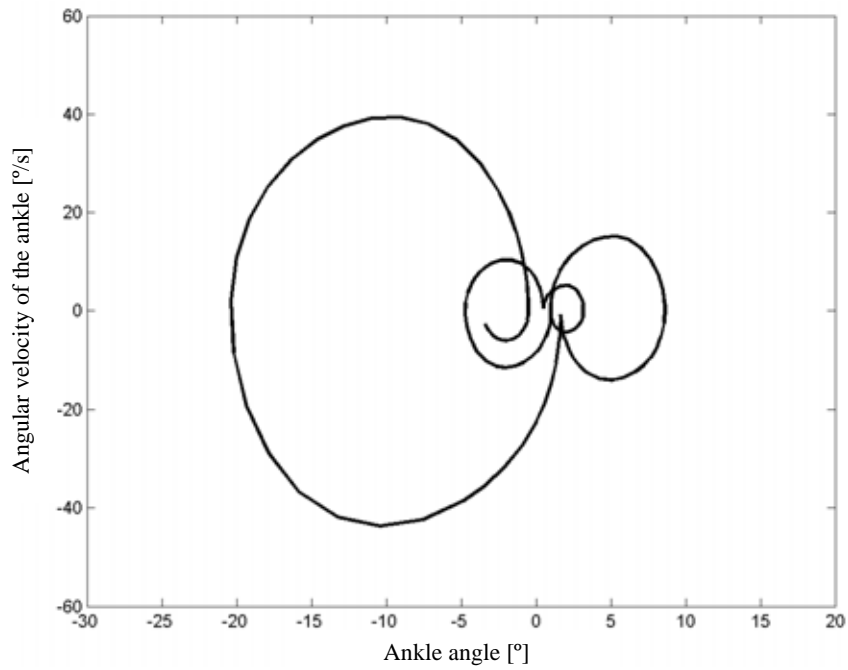


Figure 10. Stable limit cycle of the oscillator.

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

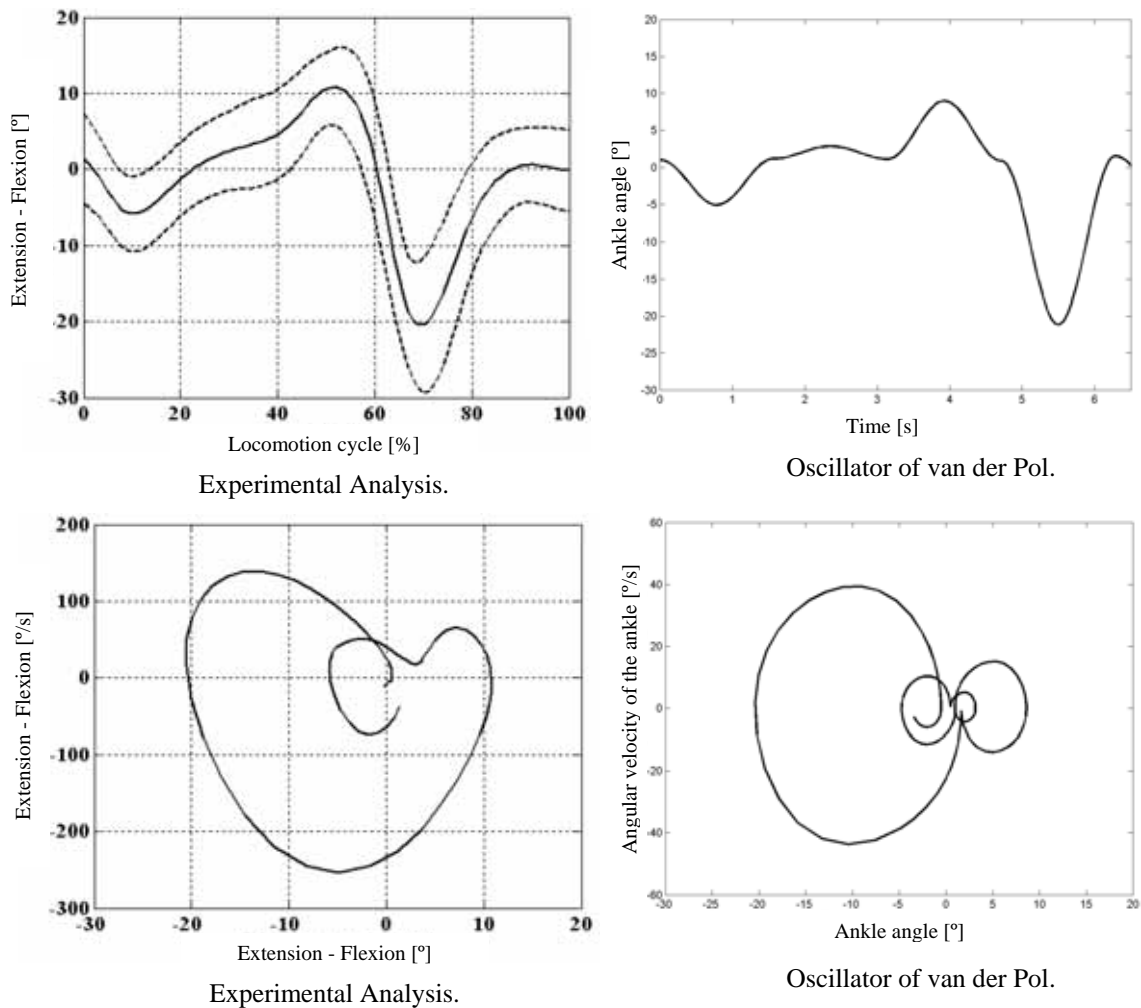


Figure 11. Behavior of the ankle in the course of a locomotion cycle.

7. CONCLUSION

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

With the determination of this pattern, it was possible to simulate the behavior of the ankle using nonlinear oscillators, of similar way to perform by Pina Filho (2005) 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 modeling 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.

8. ACKNOWLEDGEMENTS

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