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Kinematic Model for Robotic Terrestrial Locomotion Inspired in Doves (*Columba livia*)

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Abstract

Objectives: In this work we create and implement a terrestrial locomotion model inspired in Dove waking scheme and Craig nomenclature for biped robot movement design. **Methods**: For the model implementation we use the Craig method to obtain the transformation matrix that describes position and orientation of leg joints in Doves. We obtain biological experimental results in a group of Doves (*Columbia livia*) in order to contrast and complement previous work in terms of energy efficiency. **Findings**: We propose kinematic models for slow and moderate pace, which were evaluated through energy efficiency analysis. **Application**: The model offers an alternative for design of mobile robots where the locomotion is performed in irregular terrains since the biped model proposed here, has just two discrete support points in comparison with other types of locomotion such as wheels.

Keywords: Biped Locomotion, Biped Robotic, Bio-mechanical Motion, Craig Nomenclature, Denavit Hartenberg

1. Introduction

The terrestrial robot locomotion is a relevant topic of research since it is one of the most determinant aspects to be considered for a suitable remote task execution. In this sense, wheels locomotion has widely studied and implemented since it offers advantages such as less energy consumption, stability and less modeling complexity. However, its implementation in non-uniform terrains generates wheel sliding and velocity reduction that require an increase of energy cost for robots or improvements in mechanical designs to enhance wheels traction[1]. In this regard, biped inspired locomotion offers an alternative that emulates the legs movement of humans and birds, allowing the movement in spite of the terrain irregularities[2]. In this approach we focus on bird inspired locomotion since in comparison with humans, which base their movement in two segments (femur and tibia) and three joints (hips, knees y ankle), they have developed a more complete and sophisticated motion scheme through three segments (femur, tibiotarsus and tarsometatarsus) and four joints (hips, knees, ankle and foot). This can be shown in Figure 1.

In this work, we develop a kinematic model based on the Craig nomenclature and biological experiments made in a group of Doves (*Columba livia*). This model offers a design tool inspired in bird terrestrial motion that can be used for locomotion in robots, which, to the best of our knowledge, have not been discussed in literature. The rest of this article is organized as follows. In Section 2 we describe the most relevant work related to bird movement analysis, kinematic models and bio-inspired robots. Section 3 describes the main concepts related to

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the model implementation. In section 4 we describe the implemented model in a detailed way. Finally, in Sections 5 and 6 we show the results analysis and the conclusions, respectively. In order to describe the terrestrial bird behavior, mathematic models have been complemented with experimental data obtained through multiple acquisition methods. In this sense, the Doves courtship is studied[3] through visual data acquisition and a learning algorithm based on neuronal networks. The implemented model quantifies the head balancing and predicts unable information to minimize the free energy. Additionally, those results are confirm[4] about the patterns in locomotion sequences, both for normal and courtship cycles. A kinematic model is developed using metallic spheres located in strategic points in the body of a quail[5]. Through x-ray and video camera they construct a 3-D description for the bird movement. Between the most important findings are the center of mass localization along with the fact that the stability is improved using a flexed position. Additionally, they show that the modified convention of the Denavit -Hartemberg parameters is suitable for the kinematic description of open and close loop structures and to define the z axis as the articulation axis. On the other hand, the simulation results show that the implemented model is suitable to replicate biped locomotion and can be implemented as a human model.

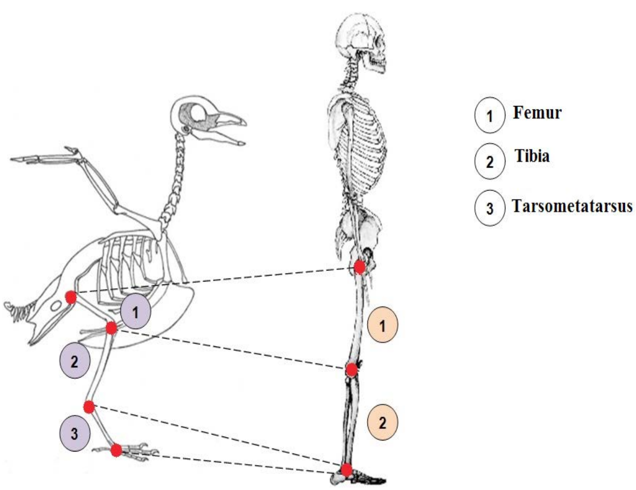

Figure 1. Comparative schemeof posterior limb.

Some cases of biped locomotion models implemented in robots are found in literature as UNROCA I, UNROCA II, UNROCA III[6], Spring Turkey and Spring Flamingo. The case of UNROCA II (an improved version of I), is based on the biped locomotion known as Winter[7], which uses the Denavit-Hartenberg matrices and the Craig nomenclature to define the kinematic model. For the case of UNROCA III[8], it implements additional characteristics in order to maintain the robot equilibrium using balancing weights. The simulations show good performance for locomotion in flat terrains and through few steps of a ladder. In the case of Spring Turkey[9] and Spring Flamingo[10], they were developed as experimental platforms to define control techniques and locomotion algorithms. Another case of bio-inspiration through birds is given in[11]. In this work a robot called Jurassic Chicken uses a rule based on neuronal networks and the biped locomotion of flightless birds in order to control the static equilibrium. Since the robot is modeled as a rigid body, the gravity center was easily determined. A biped robot was designed to climb through rigid surfaces using suction devices[12]. It has a hybrid kinematic structure composed of two modules 3 RPS (Rotational, prismatic and spherical).

Having into account the previous research, in this work we propose an additional scheme for biped locomotion inspired in birds, specifically using information from the *Columba livia* Dove, which offers a general locomotive pattern that allows comparative analysis with other research results. This scheme can be used for the design of biped robots in order to address the drawbacks of locomotion over irregular terrains where wheel-locomotive solutions are insufficient.

2. Preliminaries

In this section we describe relevant concepts used to define the locomotion model of our approach. First, in Section 3.1 we describe general aspects about bird locomotion. Second, in Section 3.2 we show energy and mechanical concepts related to this type of locomotion. Finally, a description about the characteristics for the selectedDove (*Columba livia*) is given.

2.1 General Aspects about Bird Locomotion

The bird locomotion cycle begins when a foot has ground contact and ends when the same foot touches the floor again. This can be shown in Figure 2. ***The foot support period*** is the phase at which a foot is on the floor. This is divided in single and double support. In the single support state, only one foot is working as body support for the bird body. In double support, both feet are supporting the bird body at the same time (the absence of a double foot support period differentiates walking and running movements). The ***foot balancing period*** is the phase at which the foot is not on the floor.

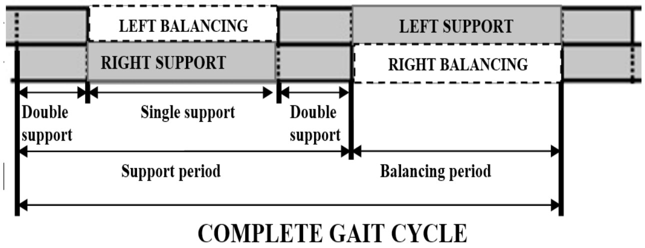

Figure 2. Representation of gait components.

The step length is the lineal distance over the progression plane between the point at which a foot heel touches the floor and the other foot.

Complete step length is the lineal distance over progression plane between the points at which a foot heel touches the floor two times (Figure 3).

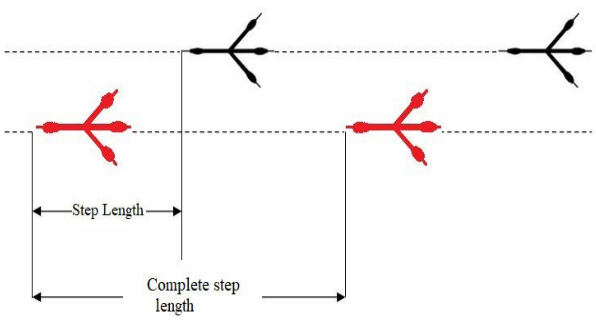

Figure 3. Step length.

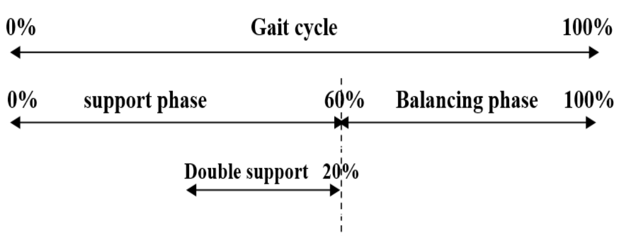

Figure 4. Gait cycle duration.

A detailed description of ***the locomotion period*** shown in Figure 2 is given in Figure 4. Observe how the foot support period takes 60% of it (40% in single support and 20% in double support), and the balancing period takes the remaining 40%.

2.2 Relevant Concepts about Mechanic and Energy for Locomotion

A locomotion scheme is defined through Kinematic and Dynamic models in order to describe joints movements and the required energy. Generally, the mathematical model for locomotion combines the translational and rotational movement of the kinematic chain, i.e., the set of links (bones) connected to each other. This chain can be opened, when only one foot is on the floor (e.g. balancing period), or closed, when both feet are on the floor (e.g. double support period). This means that for a biped model inspired in birds, we have 6 rotational joints (3 for each leg), each one with 3 degrees of freedom when the leg is configured as an open kinematic chain.

2.3 Kinematic and Dynamic Models

A kinematic model is based on transformations between reference systems related to the variables representing joints and their spatial location. It considers the movement description through position, velocity, acceleration and the four quantities related to each joint as is model[13], such as link length a_{i-1}, torsion angle α_i, joint distance d_i and joint angle θ_i. By means of this model, it is possible to describe the spatial location of the posterior limb of a bird in a given time, attributing a rigid coordinated system to each segment of it and a description from any point through a set of transformations, which in our approach follows the process defined by Craig notation[1 14].

It uses a homogeneous transformation matrix composed of a rotation matrix and a position vector. The last row of this matrix has the first three columns set to zero, which correspond to the perspective factor, and the fourth row set to one, which describes the scale factor. This is shown in (1).

$$ {}^{A}_{B}T = \begin{bmatrix} {}^{A}_{B}R & {}^{A}_{Borg}P \\ 000 & 1 \end{bmatrix} \tag{1}$$

which, can be expressed in more detail using (2), where the four quantities established in are included:

$$ {}^{i-1}_{i}T = \begin{bmatrix} c\theta_i & -s\theta_i & 0 & a_{i-1} \\ s\theta_i c\alpha_{i-1} & c\theta_i c\alpha_{i-1} & -s\alpha_{i-1} & -s\alpha_{i-1}d_i \\ s\theta_i s\alpha_{i-1} & c\theta_i s\alpha_{i-1} & c\alpha_{i-1} & c\alpha_{i-1}d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

The complex transformation matrix can be obtain from the last matrix with the objective of build the direct kinematic, this is shown in (3)

$$ {}^{0}_{\mathbf{n}}\mathbf{T} = {}^{0}_{1}\mathbf{T}\,{}^{1}_{2}\mathbf{T}\,{}^{2}_{3}\mathbf{T}\cdots{}^{\mathbf{n}-1}_{\mathbf{n}}\mathbf{T} \tag{3}$$

Regarding to the dynamic model, it is described through the torque that the bird must perform in its joints in order to move the limbs. For an inverse dynamical model, as in the case of this work, this torque is obtained from the kinetic and potential energies, which according to the Lagrange-Euler model are given by the following expressions respectively (4 and 5).

$$E_c = \frac{1}{2} I \dot{\theta}^2 \tag{4}$$

$$E_p = mgl \sin\theta \tag{5}$$

where, $\boldsymbol{I}$ is the inertia moment and $\boldsymbol{\theta}$ is the angle from the link to the ground**m**is the mass, **g** is gravity and **l** is elevation.

Then, the torque is given by (6)

$$\tau_i = \frac{d}{dt}\frac{\delta L}{\delta \dot{q}_i} - \frac{\delta L}{\delta q_i}, i = 1 \ldots n \tag{6}$$

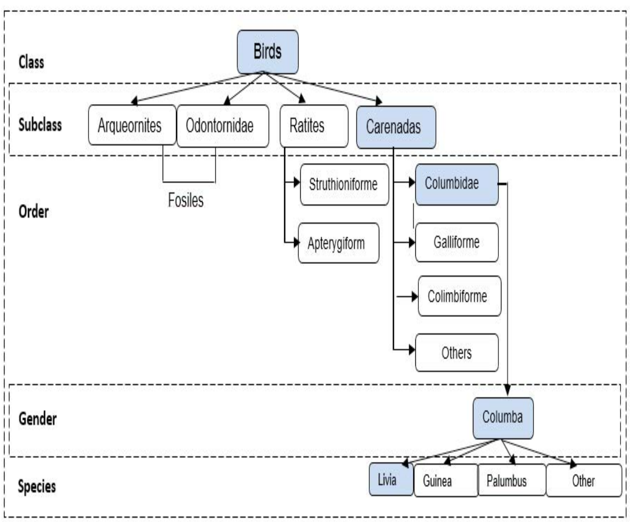

Figure 5. Systematic classification.

2.4 Bird Selection

Doves have inspired different knowledge areas such as optics (radiation and UV filters)[15], textile industry (self-cleaning clothing)[16], magnetic sensors[17] and robotic locomotion models as in this work. In this approach, the Dove species *Columbia livia*, whose classification is shown in Figure 5, is used to inspire the locomotion model because it is a common bird in our city. In this sense, in addition to the studies reported about biped locomotion in Doves[18], head balancing in [4,19–24] and variations of size and form in[25], we took experimental data to complement information about its movement, step length, step frequency, velocity and mass when they walk over a monitored surface. A detailed description of this process is given in Section 4.

3. Methodology and Model Description

The proposed locomotion model is based on experimental data taken by means of a set of tests in a *Columba livia* Dove and the previous results obtained[25,26]. Combining these results we expect to improve the parameter selection and the uniformity in the samples. Finally, through these parameters we define the matrix using the Craig nomenclature in order to describe our locomotion model in a mathematical form.

3.1 Biological Experiments

We measured morphologic parameters in 5 young Doves (*Columba livia*) shooting them using a video camera with 14 mega pixels and 5x of optical zoom. Three of these Doves were captive while the other two were analyzed on the street. In this way, the four tests shown in Table 1, were taken in a young Dove in order to measure full-step length, step frequency, step velocity and mass. If we make a comparison between results, the third test shows more similitude with the results obtained[25,26].

Table 1. Behavior parameters for terrestrial locomotion

Bird	Test 1	Test 2	Test 3	Test 4
Step length (mm)	215	182	274	235
Step frequency (s-1)	2,77	2,27	2,5	2,4
Step velocity (mm/s)	596	414	685	655
Mass (g)	233	233	245	250

In Table 2, we show the bone and posterior limb dimensions for the same bird and two tests, which were obtained using a precision calibrator. Additionally, in Table 3 we show the mass for 4 Doves. The last test focuses on the Dove density measure and in this way the mass and inertial tensor for each bone, which are essential parameters for the kinetic energy calculation. To measure this density, first we had to calculate the bird's volume submerging it in a recipient with a known area and filled with water. In this way, we obtained the 4 results shown in Table 4, which give us an average bird density of $754,22 \frac{Kg}{m^3}$.

Table 2. Bone and posterior limb dimensions

Length	Test 1	Test 2
Femur (mm)	39,8	43,8
Tibiotarsus (mm)	60,8	61,7
Tarsometatarsus (mm)	32,2	32,9

Table 3. Dove mass for 4 individuals

	Bird 1	Bird 2	Bird 3	Bird 4
Mass (g)	250	270	310	368

Table 4. Bird density

	Test 1	Test 2	Test 3	Test 4
Bird's mass (kg)	0,31	0,31	0,31	0,31
Container area (m2)	0,041616	0,041616	0,041616	0,041616
Bird's volume (m3)	0,000332	0,000416	0,000522	0,000416
Density (kg/m3)	931,1322	744,9058	595,9246	744,9058

3.2 Comparative Analysis

A comparison between our results and the results obtained[25-26] is described in this section. First, in Table 5 we compare our experimental results about terrestrial locomotion, specifically those shown in the test 3 of Table 1, with results of Fujita, which were taken in 40 Doves and 113 steps, using video analysis and anatomic measures in dead Doves. Here we can observe that the results of our experiments demonstrate that the step length and velocity are greater that the values measured. Second, in Table 6 we compare our experimental results shown in Tables 2 and 3, and the results of about posterior limb bones dimensions. It is noticeable that there is not a considerable difference for the femur, tibiotarsus and tarsus-metatarsus dimensions between the three authors. However, the difference is considerable in terms of the mass, which is of 77,9 grams between results of Fujita and our results.

3.3 Selection of the Model Parameters

In Table 7 we show a compilation of the most uniform data taken from our biological experiments and the results. In this way, we first use the step length to define the workspace for each step in order to determine the limits for the simulation. Secondly, the dimensions of the posterior limb, composed of the Femur, Tibiotarsus, Tarsometatarsus, are used to define the kinematic model through the matrix using the Craig nomenclature.

Table 5. Behavior parameters for terrestrial locomotion-comparative results

Author	Species	Step length	Step frequency	Step velocity
Masaki Fujita	*C. livia*	237.6 mm	2.593 s-1	628.5 mm/s
Test 3 Table 1	*C. livia*	274 mm	2.5 s-1	685 mm/s

Finally, the step frequency, step velocity, mass and density are used to describe the inertial tensor, which defines the required energy to perform the movement. All this information is used to define the mathematical model of our approach, which is based in two modes, slow and moderate locomotion, as it is established in[18].

4. Results

As we mentioned in the previous section, the locomotion model of this work has into account three concepts, the workspace, the kinematic model and the inertia tensor. Here we describe them along with the simulations results for each case.

4.1 Workspace

The workspace of a full step is determined through the maximum and minimum angles described by the joints during the locomotion process. Figures 6 and 7 shows the workspace for the slow and moderate locomotion, respec-

Table 6. Bone and posterior limb dimensions-comparative results

Author/ source	Species	Femur length	Tibiotarsus length	Tarsometatarsus length	Mass
Masaki Fujita	*C.livia*	45,1mm	59,1 mm	32,6 mm	347,9 g
Richard Johnston	*C. livia*	39,1mm	58.1 mm	31,7 mm	-
Results Table 2	*C. livia*	39,8mm 43,8 mm	60.8mm 61.7mm	32,2mm 32,9 mm	270g

Table 7. Compilation of the model parameters

Parameters	Values		Test
	Slow walking	**Moderate walking**	
Step length	182 mm	237.6 mm	Test 2 Table 1 Fujita (26)Table 5
Gait frequency	2.27 s-1	2.59 s-1	Test 2 Table 1 Fujita (26)Table 5
Step velocity	414 mm/s	628.5 mm/s	Test 2 Table 1 Fujita (26)Table 5
Mass	310 g	310 g	Bird 3 Table 3
Density	$705,56\frac{Kg}{m^3}$	$705,56\frac{Kg}{m^3}$	Table 4
Femur length	43.8 mm	43.8 mm	Test 2 Table 2
Tibiotarsus length	61.7 mm	61.7 mm	Test 2 Table 2
Tarsometatarsus length	32.9 mm	32.9 mm	Test 2 Table 2
Locomotion pattern	Slow walking	Moderate walking	Cracraft (18)

tively. For the slow locomotion case, the leg endpoint is located between the –55.6 mm and 102 mm over the movement line and 75 mm above the floor surface. For the moderate locomotion case, the leg endpoint is located between the –57 mm and 90 mm over the movement line and 76.7 mm above the floor surface.

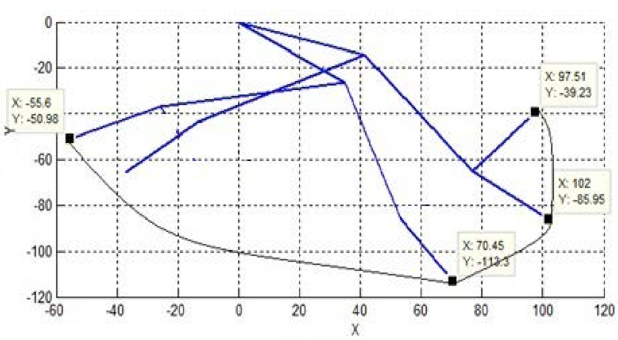

Figure 6. Workspace in slow walking for a Dove (*Columba livia*).

4.2 Kinematic Analysis for the Bird Locomotion

Using the results shown in Table 7, we build the parameters matrix for each link. This matrix is described in Table 8. By means of the Craig procedure we define each reference point for each link as is depicted in Figure 8.

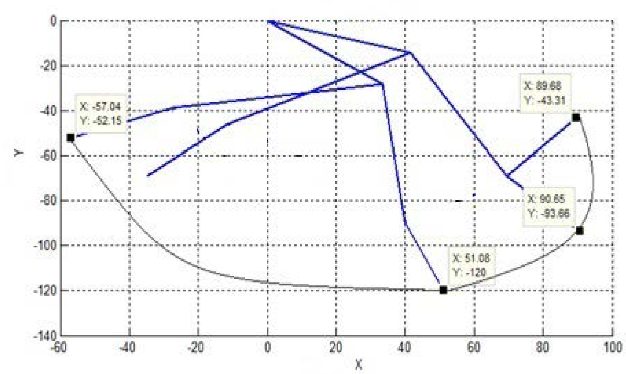

Figure 7. Workspace in moderate walking for a Dove (*Columba livia*).

Table 8. Parameters matrix-dennavit hartenberg

Link	$a_{(i-1)}$	$a_{(i-1)}$ (mm)	θ_i (rad)	
1	0	0	0.7505	0
2	0	0	θ_2	0
3	0	43.8	θ_3	0
4	0	61.7	θ_4	0
5	0	32.9	0	0

The fixed reference point is located on the hip joint. The first reference point is oriented 43 degrees in relation to the fixed point, and its translation is through the bird motion axis (x axis) depending on the type of step being analyzed. The proposed model is bi-dimensional and defined in the sagittal plane of the Dove, which means that the torsion angle (α) and the joint distances (d) are zero. The joint angles vary for each step sample as is established[18] for slow and moderate locomotion.

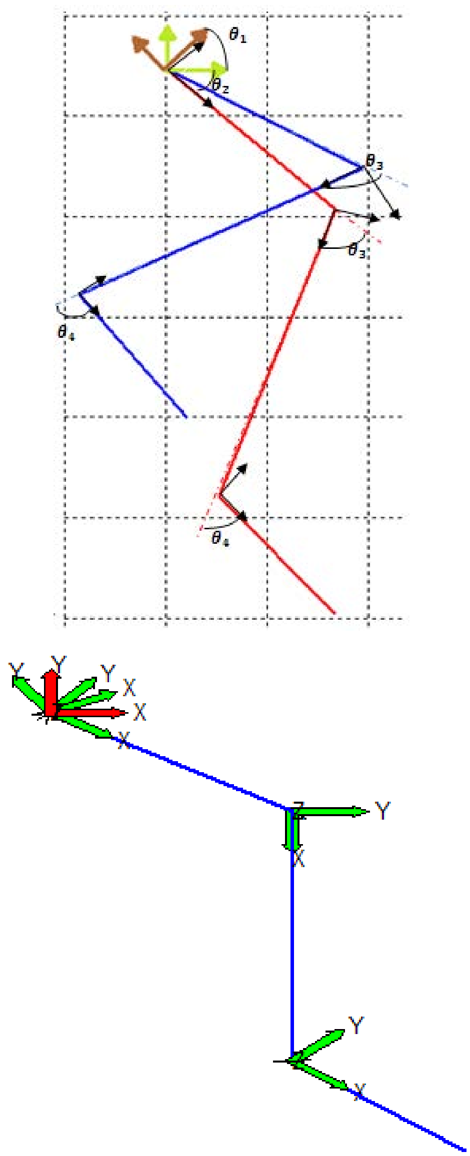

Figure 8. Reference Points and Joint Angles for Posterior Limb.

Now, having the reference points and the necessary parameters for the matrix (Table 8), we obtain the following homogeneous transformation matrix

$$
{}_4^0T = \begin{bmatrix} \cos(\theta_1+\theta_2+\theta_3+\theta_4) & -\sin(\theta_1+\theta_2+\theta_3+\theta_4) & 0 & \begin{matrix} 32.9\cos(\theta_1+\theta_2+\theta_3+\theta_4)+ \\ 43.8\cos(\theta_1+\theta_2)+61.7\cos(\theta_1+\theta_2+\theta_3) \end{matrix} \\ \sin(\theta_1+\theta_2+\theta_3+\theta_4) & \cos(\theta_1+\theta_2+\theta_3+\theta_4) & 0 & \begin{matrix} 61.7\sin(\theta_1+\theta_2+\theta_3)+32.9\sin(\theta_1+ \\ \theta_2+\theta_3+\theta_4)+43.8\sin(\theta_1+\theta_2) \end{matrix} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

With this matrix and the time variation for the joint angles, it is possible to describe the slow and moderate locomotions for a step, as we can see in Figures 9 and 10. The movement including both Dove feet is shown in Figures 11 and 12 for slow and moderate locomotion, respectively.

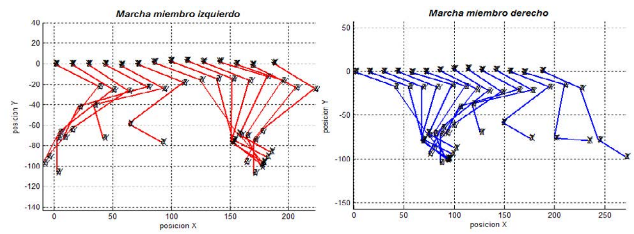

Figure 9. Slow Locomotion (a) walk left limb (b) walk right.

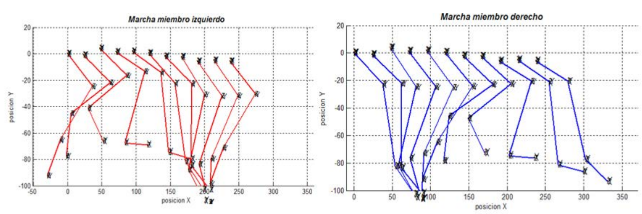

Figure 10. Moderate Locomotion (a) walk left limb (b) walk right.

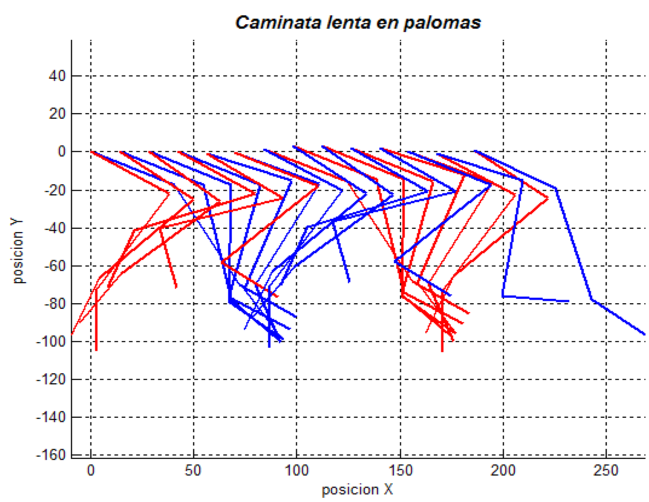

Figure 11. Both dove feet-slow locomotion.

4.3 Energetic Analysis

In this section, we use the parameters shown in Table 9 in order to calculate kinematic energy, potential energy and the variation of the total energy.

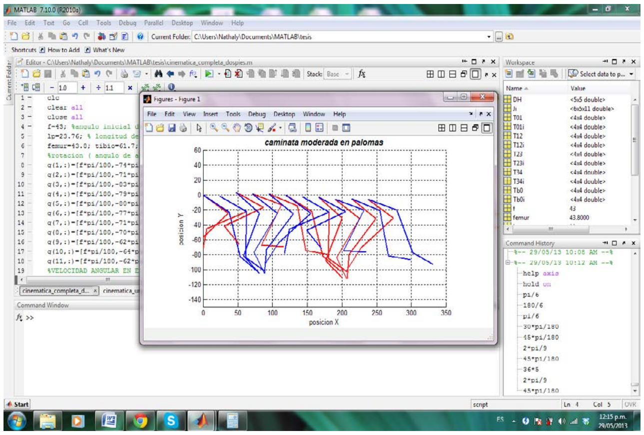

Figure 12. Both dove feet-moderate locomotion.

According to (4), the kinetic energy calculation requires the angular and lineal velocities for each step sample. These are calculated using respectively the expressions

$$w_{i+1}^{i+1} = {}^{i+1}_{i}R w_i^i + \dot{\theta}_{i+1}' \, {}^{i+1}Z_{i+1} \tag{7}$$

and

$$V_{i+1}^{i+1} = {}^{i+1}_{i}R\left(v_i^i + w_i^i x P_{i+1}^i\right) \tag{8}$$,

where, ***i={1,…,5}*** represents the joint variables, **R** is the rotation matrix and **P** the mass center position for each bone. Additionally, the calculation of this energy requires the inertial tensor shown in the fifth column of Table 9. On the other hand, the potential energy calculation requires the bird mass, the gravitational constant and the height of each link in relation to the ground, which in this case is given by the third column of Table 9.Once the energies are obtained, we use the Lagrange-Euler equation given in (6) to develop a Matlab algorithm in order to describe through simulations the energy consumption of the system. The results are shown in Figures 13 and 14 to contrast the kinetic energy and the system energy consumption on each link (femur, tibia-tarsus and tarsus-metatarsus) and the hip both for slow and moderate locomotions, respectively. The feet kinematic energy is calculated having into account each step sample on the full step, which results in 89mJ for slow locomotion and 129.5mJ for moderate locomotion. Taking the duration time for slow and moderate locomotion's, we calculate the power for each case differentiating the energy over these periods of time. In this sense, the power for slow locomotion is 232mW and for moderate locomotion is 295mW.

4.4 Efficiency Analysis

The efficiency analysis is performed through a comparison between the results shown in (27) and the results of

Table 9. Selected parameters for dynamic model

Link	Mass (g)	Length (mm)	Mass center (mm)	Inertia tensor (gr x cm^2)
Trunk	295.5	98.3	43,8	$\begin{bmatrix} 2.73e3 & 0 & 0 \\ 0 & 2.64e3 & 0 \\ 0 & 0 & 2.64e3 \end{bmatrix}$
Femur	8.94	43.8	18.42	$\begin{bmatrix} 4.76 & 0 & 0 \\ 0 & 16.86 & 0 \\ 0 & 0 & 16.86 \end{bmatrix}$
Tibiotarsus	4.35	61.7	25.25	$\begin{bmatrix} 0.83 & 0 & 0 \\ 0 & 15.30 & 0 \\ 0 & 0 & 15.30 \end{bmatrix}$
Tarsome-tatarsus	0.29	32.9	15.24	$\begin{bmatrix} 6.15e^{-3} & 0 & 0 \\ 0 & 31.24e^{-2} & 0 \\ 0 & 0 & 31.24e^{-2} \end{bmatrix}$

this work, which are described in Section 5. The metabolic energy consumption in Roberts is estimated through the body weight and the time that a foot is in contact with the ground, in other words, the energetic cost for each gram of active muscle in a walker animal is inversely proportional to the time that the foot and the ground are in contact, as is given in the expression 9

$$\dot{E}_{metab} = \frac{cW_b}{t_c} \tag{9}$$

where, $\dot{E}_{metab}$ is the energy consumption rate, W_b the body weight in Newtons, t_c the foot support time in seconds, and **c** a cost coefficient that represents the proportionality between the body weight, the specific energy cost and the force generation rate.

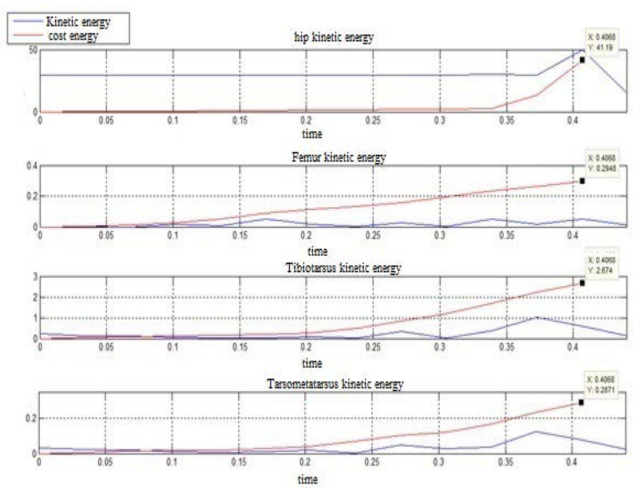

Figure 13. Kinetic energy for slow walking.

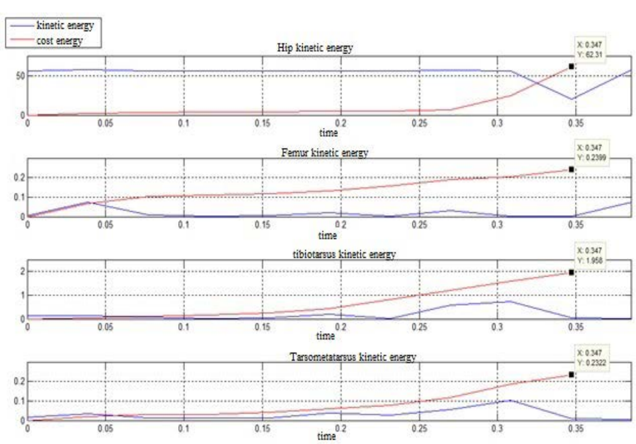

Figure 14. Kinetic energy for moderate walking.

In our approach, $\dot{E}_{metab}$ we calculate for slow and moderate locomotion using the cost coefficient 0.225 J, which corresponds to Quails, a bird with similar characteristics to the *Columba livia*. For slow locomotion we have from Table 7 that t_c is equal to the 65% of the full step, i.e., 0.287 s. Then, the limb power during a step is 2.34 W. For moderate locomotion, is the 60% of the full step, i.e., 0.231 s. This means that the limb power during a step is 2.92 W. In this sense, a comparison between our results and results shown in Roberts reflect an efficiency of 9.9% and 10.10% for slow and moderate locomotion, respectively.

5. Conclusions

In this work we propose a kinematic model inspired in the dove *Columba livia*. This model expects to expand the knowledge about the bio-mechanical patterns in birds that can be implemented in biped robots in order to address the drawbacks of locomotion over irregular terrains where wheel-locomotive solutions are inadequate. The selected dove offers a general locomotive pattern and allows us to make comparative analysis since it is a common bird in the environment where this study was performed.

The mathematical description used in this approach uses the matrices and the Craig nomenclature. The results and comparative analysis demonstrate that these mathematical tools produce good and consistent results and low complexity when they are computationally implemented. However, a more exact model could be developed if successive screw analysis is included in order to obtain results closer to reality.

We compare the results of this model and the other obtaining efficiency values of 9.9% and 10.10% for slow a moderate locomotion. These efficiency values could be improved if head and torso analysis are included in this model.

6. References

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