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ESA ESTEC
Noordwijk, The Netherlands

Bionics and
Space System Design

Landing and Planetary
Exploration

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D'APPOLONIA

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Landing and Planetary Exploration

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1 BACKGROUND

Biomimicry is a multi-disciplinary science involving a wide diversity of other domains like electronics, informatics, medicine, biology, chemistry, physics, mathematics, and many others. However, it is quite unusual to find key people or expertise centres that have cognition and expertise in all these disciplines as a whole. Therefore, there is a need for the establishment of a capillary network of contacts through Europe and elsewhere that will enable to reach also those academic centres, which are not much visible due to their reduced dimension or recent origin. Additionally, although some peculiar conditions characterizing space environments can be similarly encountered on earth (e.g. desert zones) and specific solutions found within these terrestrial contexts can be adapted to space conditions, there is a majority of cases, which are subject to conditions which are broadly different from those encountered on earth (e.g. gravity absence). Therefore, the biomimetic approach in the space sector results more complex and has to be considered in a multidisciplinary and cross-sectorial framework to overcome barriers. The problems to be addressed to exploit the potential of the biomimicry approach in the space domain can be summarized as follows:

- biomimicry has become a real science only in recent years and therefore there is no consolidated co-operation environment with space engineers;
- research in biomimicry across Europe and Canada and more generally at world wide level is scattered and fragmented, it is not easy to locate the proper academic experts for a given space application;
- biomimicry is a multi-disciplinary science and it requires several expertise which is difficult to locate in the same organization;

- some databases with information about possible natural phenomena, biomimetic products, ongoing biomimetic research, biomimetic researchers, published articles exist, but they lack a systematic and a large-scale exploration of the potential of nature in view of applications in engineering, especially as far as the space domain is concerned;
- in current knowledge-basis the abstraction of the biological functionality is missing, therefore solutions inspired by nature are sporadic and random-governed;
- space conditions are completely different from life forms habitats and space engineers are so far not fully aware of applications of biomimetics.

Therefore, the overall objectives of the study consists in the development of a co-operation platform between space and biomimicry experts in order to bridge current gaps that exist for an effective application of natural mechanisms and phenomena in space system design and to foster the development of a new generation of space systems. This has been achieved by:

- performing a comprehensive collection and review of information concerning attempts made since today in Europe and elsewhere in finding solutions through a biomimic approach, including an insight into planned research activities and trends;
- developing a detailed biomimicry knowledge map that allows to identify expertise and competencies in ESA member states and elsewhere;
- providing an overview of the unique characteristics and properties of various life forms found in nature (e.g. animals, plants, etc) and to ascertain whether these characteristics could be an inspiration to create innovative space systems;
- conceptualising several innovative space systems and components which incorporate the design, features and mechanisms of nature's life forms.

All the gathered information have been implemented into a database which is available online at www.bionics2space.org. The added value of the database is in the deep analysis made on each biological system described, supported by literature and reference articles, patents, etc.

The project group has then been focusing on the analysis of the information collected and on whether any of these biological principles might hold potential for application to the design of space systems or provide solutions to space-related technical challenges.

Therefore, the project group has identified twelve different cases in which the application of biological principles could bring a real added value to the solution of technical constraints within the space field. The identified case studies are reported below:

- deployable digging mechanism for sampling below planetary surfaces;
- energy storage structures for deployable systems;
- rigidisation of deployable structures;
- smart swarm on mars;
- robust biologically inspired navigation techniques;
- planetary exploration with free energy (based on sun flowers);
- adaptive and versatile biologically inspired locomotion control;
- balance between adaptability and stability;
- automatic self-assembly in space;
- landing and planetary exploration;
- energy storage structures for deployable systems;
- planetary exploration with free energy (based on dandelion seeds).

Such work has set the base from which a more detailed analysis has been performed: for each of the topics, a responsible among the Bionics Expert Team has been identified; such expert has been in charge of providing to the partners the assessment of the idea of application.

The results of such detailed analysis have been presented in the framework of the Bionics workshop held in ESTEC on November 2004. The output of such event has been the selection of four case studies which have been further assessed by proposing first attempts of engineering solutions inspired by nature. Such case studies are the following:

- energy storage structures for deployable systems;
- case study on adaptability versus stability;
- deployable digging mechanism for sampling below planetary surfaces;
- landing and planetary exploration.

In this report the work undertaken for the "Landing and planetary exploration" case study is described.

2 LANDING AND PLANETARY EXPLORATION

2.1 INTRODUCTION

A typical problem in planetary exploration is landing on a planet and then start its exploration often in unpredictable environment with variable sized obstacles. On Earth, one group of animals is efficient in locomotion in such environments and has flexible bearing capacities: the birds. They are designed for flying, for landing, and many birds are efficient walkers, exploring their environment searching for food on the ground. Birds are bipeds, like humans and in our mind bipedy seams an instable mean of locomotion, requiring fine balance adjustments. This is a projection of our bipedal structure features. Birds are bipeds but their structure is different compared to human and seems much more stable, as suggested by this two examples:

- most of the birds sleep standing on only one limb, keeping balance with attenuated vigilance;
- contrary to humans, they never fall down.

In this case study, we will discuss the features of bird structure and how it performs. Our aim is to illustrate some properties of bird limb structure that could give us inspiration for technological innovations.

Birds live everywhere on earth and are able to walk on many substrata: ground, tree branches or trunk, snow, even floating vegetation. Bird’s legs are not only used for landing and taking-off, but also for walking, hopping, running. Despite this functional diversity, birds have the most homogenous morphology among the vertebrates (Alexander, 2003), even if there sizes are scaled from some grams, like Humming-birds, up to hundred kilograms, like Ostriches. Bird’s limbs structure is rather simple and so its kinematics and mechanics that it could be easily transpose to engineering applications.

This report is not exhaustive because it does not detail the biological structures but rather presents some relations between animal behaviours and limb osteological structure, being more a biological review than a fully detailed engineering proposition.

2.2 STRUCTURE

The skeleton structure of all the birds is basically the same, whatever their dimension and habitat. As shown in Figure 1 the Quail (A), ground dwelling bird, the Penguin (B) swimming bird, the Kiwi (C) which does not flight, and the kite (D) Prey bird share the same features, highlighted here on the quail skeleton (A). Their trunk is rigid and compact, their neck is long and flexible, the fore limbs are transformed into wings, the bony tail is short and the hind limbs have three long segments (Abourachid, in press). Animal behaviour or locomotion slightly marks this basic common structure: compared to ground dwelling birds, diving birds like penguins have a longer pelvis; non flying birds like Kiwi, or like Ostriches, have only vestigial wings and a flat sternum, whereas the Kite, as all Prey birds, have a posterior down curved pelvis.

2.2.1 Birds limb structure

The bird limb is composed of three long segments:

- the Femur, surrounded by the thigh, from the hip to the knee;
- the Tibiotarsus, surrounded by the leg, from the knee to the ankle;
- the Tarsometatarsus, surrounde by the fibula and the tarsus, from the ankle to the toes.

All birds walk on their toes only. On Figure 2 it is possible to compare the bird limb structure with the human one. The three joints and three long segments of the bird limb are defined on the quail skeleton. The colour code is the same on the bird and human schema. It is important to notice that in bird the centre of mass is under the hip, between the knee, but it is above the hip in human. As well in bird the trunk is horizontal and vertical in human. The tarsus is long in birds and short, included in the foot, in human. The limb is shaped in a flexed Z-like in birds but vertical and strait in human.

In birds, the femur is oriented cranially and brings the more distal segments and the feet at the body centre of mass level. The Tibiotarsus and the Tarsometatarsus, the two other long segments are more mobiles.

The proportions of the three main segments are variable (Gatesy, 1997): the Femur corresponds to 12% to 37 % of the total leg length; the Tarsometatarsus corresponds to 13% to 45 % of the total leg length; the Tibiotarsus varies much less, usually corresponding between 40% to 50 %. of the total leg length. Those proportions are related to diverse adaptation for live-style of birds family. The feet of birds are very diversified, in the number of toes (from two to four), in their shape, but mainly in their spatial arrangement, in relation to their behaviour. Terrestrial birds usually have four toes, the thumb oriented backward and the three other oriented forward.

Figure 3 shows a ternary diagram where each side of the triangle represents the proportion of one long segment. The coloured area represent a morphospace including the proportion of large sample of birds: Tarsometatarsus's axis is the longer, indicating a high variability of this segment length. Tibiotarsus's axis is more stable, and its proportion is usually around 45 %. Femur length often decreases when Tarsometatarsus portion increases.

From the joint structure point of view, the major leg's join is composed by the femur head as this join can articulate with three degrees of freedom with the pelvis. The two other joints, knee and ankle, have one degree of freedom each.

2.2.2 Lightness of bones

Limb bones are more or less cylindrical hollow beams which are able to resist to different loading modes (compression, tension, bending or torsion) during locomotion. Aside cross-sectional shape optimisation (e.g. circularity and thickness of the bone walls), microscopical adaptations within bone tissue create a biological composite material that increases the strength and stiffness of the beam. Also the orientations of the collagen fibers and the vascular network (small cavities traversing the tissue) have an important role in the resistance of the whole bone shaft. In birds, pressure on mass-saving (for increased flight performance) places a special demand on material strength, in order to maintain sufficient resistance with less bone tissue (i.e. less mass). Their bones are known to be lightened, with pneumatization, of the proximal limbs bones (Casinos, 2001; Cubo, 1999; Cubo, 2000). The minute structure of long bones in birds, in a biomechanical perspective, is currently investigated (de Margerie 2004; de Margerie, in press). Comparisons of cross-sectional morphometrical parameters (geometry of the section, fibers and canals orientations) between long bones of a same skeleton and between species with different locomotor habits show that loading mode has indeed an important influence on bone microstructure. For instance, some long bones have a structure optimised to resist torsional loads, with relatively thin and circular bone walls, containing oblique and transverse fibres and canals. These features are preferentially found in the femur, on which torsion forces are applied during locomotion (Hutchinson, 2000). Other bones of the skeleton show thicker and less circular walls, containing longitudinal fibres and canals, and are optimal to resist other loading mode as compression, tension and bending (Casinos, 2001).

2.3 BIRDS LEGS FUNCTIONING

2.3.1 Landing

Birds are able to land on many kinds of surface, including flat expanses of ground or water, vertical tree trunks and perches such as ledges or branches. Landing may be also performed in turbulent air. Before landing, birds stretch their limb forward using the limbs as damping structures. Two strategies are proposed by (Green, 1998) for landing :

- a hovering mean of landing, when the bird descends slowly and adjusts its trajectory so that the risk of damage is reduced. This strategy must is energetically expensive and possible only for small birds;

- landing by following a shallow descent trajectory, either gliding or in powered flight. Once close enough to the ground, birds can increase the angle of attack to slow the forward speed and stall the flow of air over the wings. This strategy is energetically cheaper and, when landing on suitable ground surface, requires a relatively simple control of speed and trajectory. But when the approach velocity is higher, the risk of damage is higher than in the hovering strategy.

These two strategies must represent the two extremes of a continuum of landing strategies. Normally birds operate in different parts of this range depending on the species size and behavior but also depending on the landing circumstances (type of landing surface, speed, motion of the surrounding air). On Figure 4 the force components of a landing on perch event of a Startling are recorded (Bonser, 1996): after an initial foot-to-perch contact, the vertical force initially raises a plateau, while there is no change in horizontal force; after approximately 0.05 seconds the horizontal and vertical forces both increase rapidly to a peak of about twice the body mass, then the force decrease until the bird is at rest. In this case the angle of landing was comprised between 50 and 90°. The same force profiles (maximum force about twice body mass, and direction of approach approximately 80°) were found in Pigeon landing for the first time on a novel perch (Green, 1998) but when the pigeons were familiar with the perch, Pigeons changed for a fast and straight approach and the bird strikes the perch with a maximum force of eight times its body mass at an angle of approximately 50° below horizontal. That means that bird limbs are able to support at least eight time their body mass when landing. This suggests that the limbs have damping mechanical properties which can be related to the structure of the limb. This structure, with three joints, have a redundant functioning, that is known to be efficient in shock absorption (Gertz , 1991).

2.3.2 Swimming

Relatively few animals swim on the water surface for extended periods (Vogel, 1998). This may be due to avoid predation and reduce energy of locomotion (Aigeldinger, 1995) but among vertebrates only birds show adaptation for floating on water like ships. For example birds are able to increase their buoyancy trapping the air so that the body density in reduced

(0.6 for a Mallard). Then the body density can be increased by expulsing the trapped air by plastering feathers down on the body: on this way Grebe is able to change its body density from 0.6 to 0.8 before diving (Veselosky, 1996). For propulsion in water birds adduct their limbs and use them as paddles and the three DoF of the hip joint is used to bring the thigh toward horizontal. The propulsion is exerted by the leg moving backward, the web of the foot increasing the thrust. Depending on the species and the speed, birds can use alternated or in phase limb movements. The body shape is also important for water surface swimming: as for ships, the body hull-shape is important because it determines the effective speed limit (hull speed). Large water birds, like Swans, have long and narrow body that increase the waterline length. Smaller water birds have different body design to allow an easy escape: Duckling body can become a planning type of hull and to skim on the water surface. It can therefore increase four time its maximum burst speed compared to the hull speed. Thanks to this behavior, the paddling motion of the webbed feet are used to generate both thrust and lift (Aigeldinger, 1995).

2.3.3 Walking

Cursorial birds are able to fast run : 90km/h for Ostriches and 25km/h for the smaller Road-runners. The last one are also able to make 3 meters hopping, representing twelve times their body length (Veselosky, 1996). Beside these extreme adaptations, many birds are good walkers (Gatesy, 1991; Abourachid, 2001; Clark, 1975; Cracraft, 1971). The three limb segments allow large steps and the birds are able to walk fast, without running, for very long time. Bird are also able to walk in very different posture, with the body more or less erected, depending on the circumstances: they can walk more crouched if they need to be hided by the vegetation or more erected if they need to look around. There is not consistent differences in energy-cost between all terrestrial vertebrates, including human: generally the cost of transport decreasing with animal mass in the same way for bipeds and quadrupeds (Fedak, 1979).

Figure 5 shows the kinematics of Quail walking, in lateral view and from below: lateral view shows that the femur excursion have low amplitude; the knee have a simple flexion-extension movement, stretching during the stance and flexing during the swing; the movement of ankle is more complex with two flexion-extension movements, one during the stance and one larger during the swing; the view from below shows that these movements are made in an oblique limb plane, passing by the hip, knee and foot; this limb plane moves 35° and around vertical, 20° around horizontal during a locomotor cycle, allowing to keep the foot under the vertebral axe during all the stance, and in a vertical plane under the knee during the swing.

2.3.4 Unstable substrate

Terrestrial birds have often large feet relatively to their size and their flexible toes allow stability even on cluttered environment. An extreme adaptation for unstable substrate is found in Jacanas as these birds spend all their life on floating vegetation. Jacanas have long limbs, with proportionally long Tarsometatarsus representing 34% of the 190 mm total limb length. Instead Femur represents 18% and Tibiotarsus represents 48% of the limb length. Their very elongated toes increase the bearing area, that is up to 87 cm². Thanks to their specific structure, floating vegetation does not have to bear more than 1.4g per cm² even with a 120g Jacana standing on one foot. The increase in the length of the toes is a very efficient way to reduce the force exerted on the substrate. Lengthening of the toes results from an increase in both the phalangeal part and the claw length. The very long thumb claw is curved upward. This shape allows the bird to slip on the substrate at the end of the stance phase, when the foot begins to move upward. This movement keeps the claw in continuous contact with the substrate, giving a large bearing surface even when the foot begins to move up. Figure 6 shows the kinematics of a Jacana locomotor cycle.

A large vertical excursion of the foot during the swing phase permits it to move the toes without touching the substrate even if the kinematics of each leg joint during walking is not outside the normal ranges found in other species. The large amplitude involved from the adjustment of the segment length and of the synchronisation of the joints movements (Abourachid, in press).

2.4 APPLICATION FOR LANDING AND PLANETARY EXPLORATION

The bird limb structure is the result of million years evolution improvement. It presents mechanical properties in shock absorption and in adaptability. The interest of bird limb structure for landing and planetary exploration comes from the simplicity of the structure, its damping properties during landing, its stability even on unstable surface (see Jacana), and its adaptability (same structure for landing, walking, swimming, etc). As well bird bones are of interest because of the optimisation of a material strength and lightness.

Bird limb models could give ideas for solving problem in landing and exploration and can inspire engineers on designing new robotic structures for planet exploration.

A first attempt of developing such robot has been started with the RoboCoq project aiming to design a prototype of autonomous biped based on the avian model, as summarized below.

2.4.1 RoboCoq project

The adaptability of the bird walking system seemed of interest for autonomous robot and RoboCoq project, aimed to design a robot moving like a bird, demonstrate that interesting results can be achieved. During this project, as no 3D data were available on birds walking kinematics, a precise 3D kinematics analysis of the Quail walking was realized and the data are used for the design of the robot. Biological data were obtained using a high-speed video-radiography, successively in lateral and in dorsal views, recording the Quail skeleton movements when the animal walks in a X-Ray field. The RoboCoq project can be seen as the necessary step to design a kinematic and dynamic model for a bird-like robot that could be used to build a biped prototype of increased locomotive and crossing capabilities. The section below reports the results achieved so far by Robocoq and introduces some issues that will have to be taken into account in the design of the bird-like robot.

2.5 FIRST ATTEMPT FOR AN ENGINEERING SOLUTION

Contrary to humans that walk with feet 8 cm apart, birds walk with both feet on a strait line, below the vertebral column. The limbs don't move in a vertical para-sagittal plane but in an oblique plane. This limb plane passes by the hip, knee and bottom of the foot. During the stance phase, it rocks inward, allowing the foot to be under the trunk. It rocks outward for the swing phase, allowing not bumping the other limb during recovery. The knee, the ankle and the foot move in a vertical plane during the swing, suggesting an use of pendulum effect for the recovery. The head-bobbing movement, a gaze stabilization reflex, is coordinate with locomotion, and has a light effect on centre of mass position during walking. Quails are able to walk without head-bobbing, when walking on a treadmill with a fixed visual environment.

Kinematic investigation

The data used are the coordinates of the different joints in top and sideways views obtained thanks to the cineradiography system device of the National Museum of Natural History. In addition to the usual plotting of joint angles as a function of time to get the variation profiles, it has been useful to plot the 2D Cartesian trajectories with respect to a reference frame linked to the body of the animal. This gave an idea of the shape of the trajectory. It was also interesting to change the origin of the reference frame by taking the knee, the ankle, or the foot instead of the hip joint. This enabled to investigate the possible synchronizing of motion between the different leg segments.

Since it was not possible to capture simultaneously top and sideways views, it has been necessary to perform a 3D synchronizing and mapping of the separate 2D coordinates. A special technique has been designed for getting the 3D coordinates of the leg joints along the cycle.

All those techniques have lead to determine the 3D motion of the bird leg in a qualitative way, and to identifying specific configurations along the cycle (landing, mid-stance, take-off start, end of take-off, mid-swing, see Figure 7). These configurations can be used to decompose the motion into several steps.

Kinematic model

RoboCoq proposed a kinematics design for a bird like limb as shown in Figure 8: compared to the human model, the bird leg has one additional segment. The limb is made of three segments having the same proportions as the quail limb : the first represents 34% of the total length, the second 42 % and the third 24 %. Two rotation axes move the limb plane at the hip: one around the vertical axe, the other around the first segment longitudinal axe. This result comes from observations drawn by biologists and calculations carried out by roboticians from the 3D coordinates.

The hip joint features 3 rotary degrees of freedom (d.o.f.). The knee joint has one rotary d.o.f.. The ankle joint has also one rotary d.o.f.. There is no joint at the foot that links the last segment to the foot. Instead the foot is modelled with 3 phalanges. Each phalange has two rotary degrees of freedom, the rotation whose axis is horizontal is active, the other one whose axis is vertical can be let passive (see Figure 9).

Kinematic simulation

The kinematics simulation consists of using the 3D coordinates of the different leg joints as inputs and calculating the actuator angles related to the degrees of freedom of the model. The simulation interface (see Figure 10) has been designed using OpenGL and permits to change the position and orientation of the rotation joints. The algorithm designed in this framework can be utilized to tabulate the different motions captured. The trajectories can also be parameterised to adapt the stride length or the hip height among other parameters. In addition to the generic trajectories of forward motion, turns can be captured and parameterised in the same way.

Kinematic control

If only the trajectory of the leg foot is given in the reference frame of the body, it is possible to calculate the joint angles of the robot model that will reproduce the 3D movement of the bird leg.

From the kinematics investigation it comes that the movement of the leg can be decomposed into a movement of the leg plane and a movement of the leg segments inside this plane. The movement of the leg plane has been described with precision and can be reproduced easily according to the temporal profiles of the orientation angles of the leg plane. Because the leg is redundant, the movement inside the plane must result from an optimisation criterion. The criterion used is different for each phase of the leg motion cycle, namely stance, take-off, swing and landing phases.

The definition of the role of toes has yet to be solved, but exact data on birds are not yet available. Experiments are still needed to study the displacement of the centre of pressure under the toes during the stance. Nevertheless, we think that the foot could be designed with three toes with two rotations for each.

RoboCoq project highlights the interest of mimicking bird limb structure for robots and the feasibility of such a structure. A low centre of mass, hanged between the limbs, large flexible feet forming large bearing areas, allowing a large support polygon even during one foot support, assure a good stability. The three segmental limb structure with damping properties seems to bee also usefully for stability, and indeed, birds are able to walk on extremely unstable substrate, like floating vegetation.

Bipedal locomotion is one of the more challenging control problems in robotics. While it is possible to construct a platform that is statically stable, such platforms tend to be limited in their speed and flexibility. One such example is the Machine Intelligence Lab’s “Orb”(Thakker, 1997), a successful biped robot that achieved balance primarily by the use of very large feet in which the bulk of the robot’s weight was concentrated. While Orb was able to walk forward and to turn away from obstacles by means of a shuffling gait, its speed and agility were limited. Agility can be achieved by application of dynamic balancing, in which the robot is constantly falling and catching itself on the next forward stride. The control problem is therefore significantly more complicated than that encountered in static balance. Application of a neural network to handle the control problem is therefore quite appropriate, given that the issue is to model appropriate compensatory reactions to perturbations in the robot's balance, based on weighted sensory input.

In order to actuate the joints a possible solution could be represented by the use of shape memory alloy pistons (Shape Memory Pistons, Mondo-tronics Inc.) for flexion and extension of the knee and ankle. This could significantly reduce the weight and the complexity of the control problem. Shape-memory alloys (SMAs) are ordinarily found in either wire or strip form, which can then be formed into springs, coils, and other shapes. When cool, the SMAs can be stretched, compressed, or otherwise deformed, but will return to their original dimensions with the application of heat (usually via the application of electric current). Nevertheless, this kind of solution brings several technical issues: the shape-memory alloy pistons have a certain recovery time to return to their fully extended position. It can be imagined that a fast response is vital in order for the robot to respond adequately to overbalancing: so in adopting and developing such kind of solution, the design of the actuators and the selection of the alloys itself should be aimed at the optimisation of time response. Further, while SMA are excellent for contractive motion, it could be difficult to design them in order to provide the necessary thrust required for forward locomotion. Springs can be used to return them to the start position, but the propulsive thrust will still be lacking.

3 CONCLUSIONS

The work performed in the framework of the Bionics and Space System Design has lead to the identification of four case studies which have been analyzed and described in the previous chapters. Based on the different and complementary expertise of the Biomimicry Expert Group, D'Appolonia has assigned each of the case studies selected by ESA to a different working team. In order to facilitate the management activities, a responsible has then been selected within each working group. The work has lead to a better understanding of the biological principle, together with a first attempt of an engineering solution.

In this framework, the case study related to landing and planetary exploration has provided with interesting new ideas of exploiting mechanisms inspired by birds landing to space applications.

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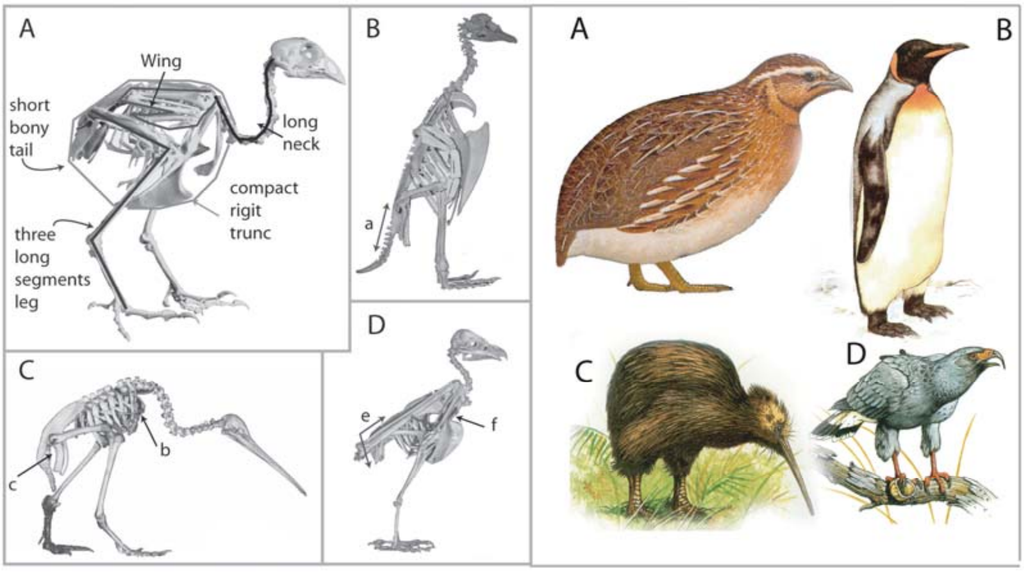

A) quail (Coturnix coturnix);
B) Penguin (Spheniscus magelanicus),
C) Kiwi (Apteryx australis)
D) Kite (Milvus gorinda).

FIGURE 1

BIRDS SKELETON AND ENTIRE ANIMAL

PREPARED FOR

ESA, ESTEC
Noordwijk, The Netherlands

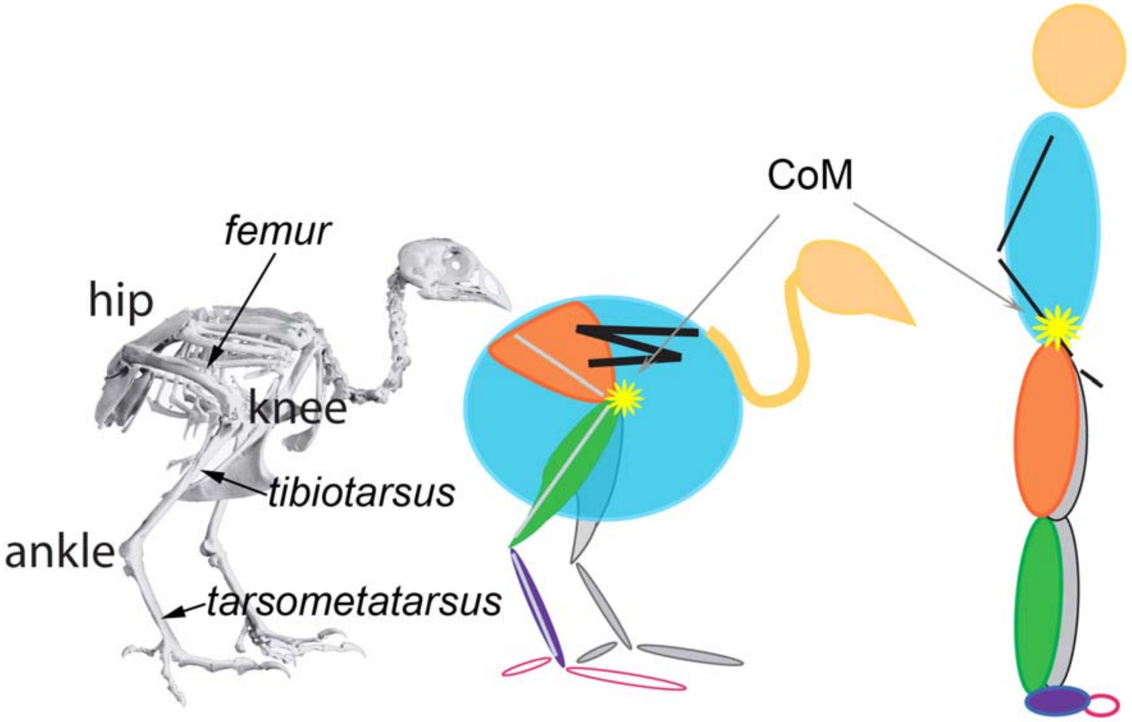

FIGURE 2

BIRD LIMB STRUCTURE COMPARED TO HUMAN STRUCTURE

PREPARED FOR

ESA, ESTEC
Noordwijk, The Netherlands

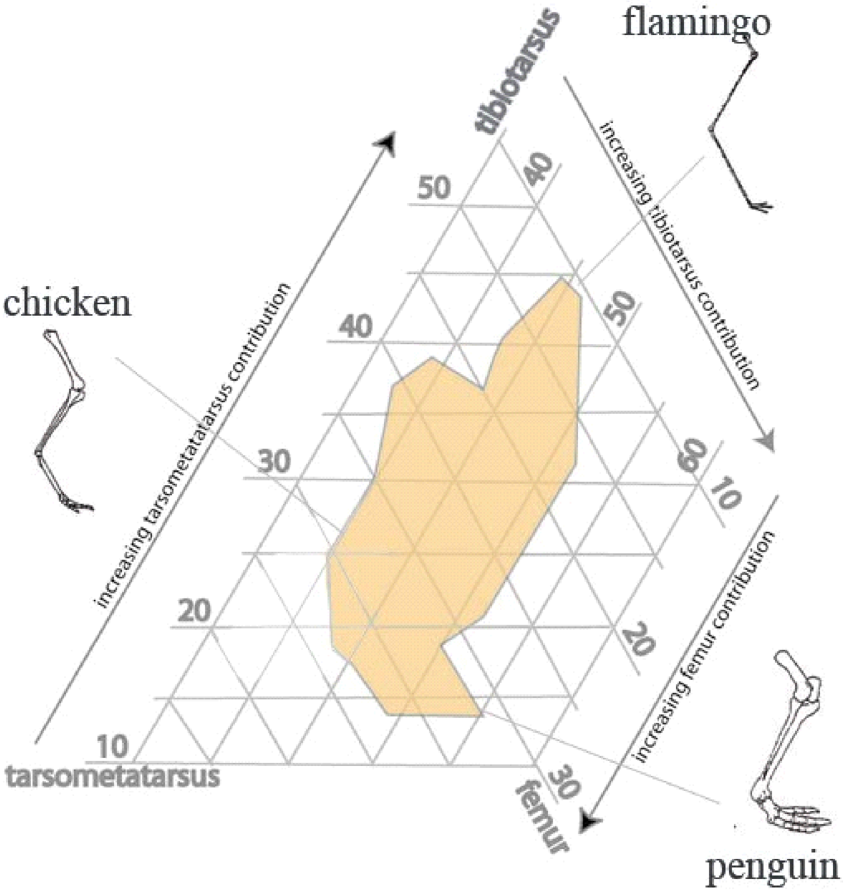

FIGURE 3

SEGMENT PROPORTIONS IN BIRD LIMBS

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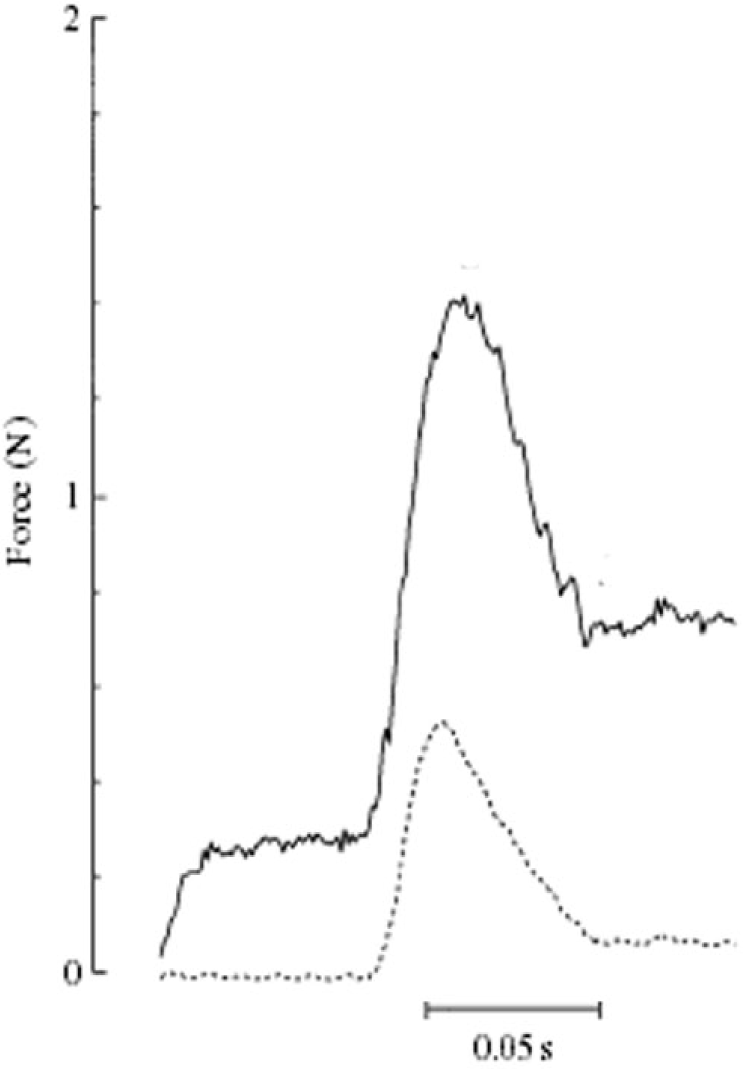

FIGURE 4

LANDING IMPACT

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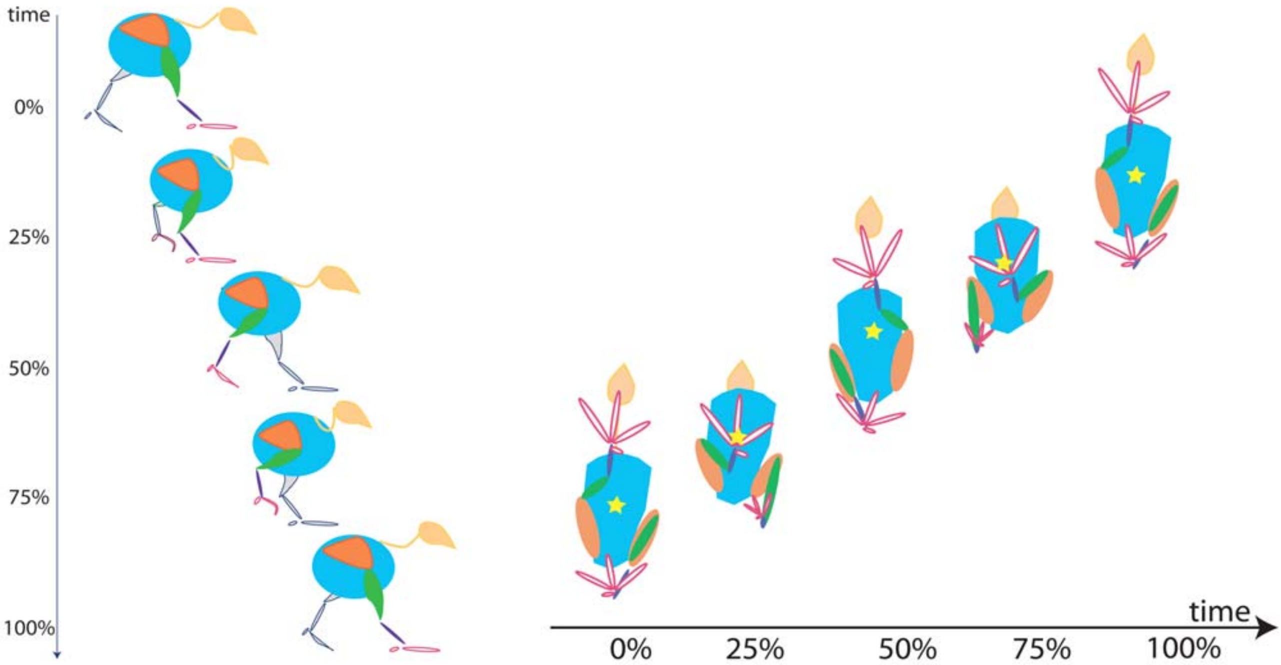

FIGURE 5

KINEMATICS OF QUAIL WALKING, IN
LATERAL VIEW AND FROM BELOW

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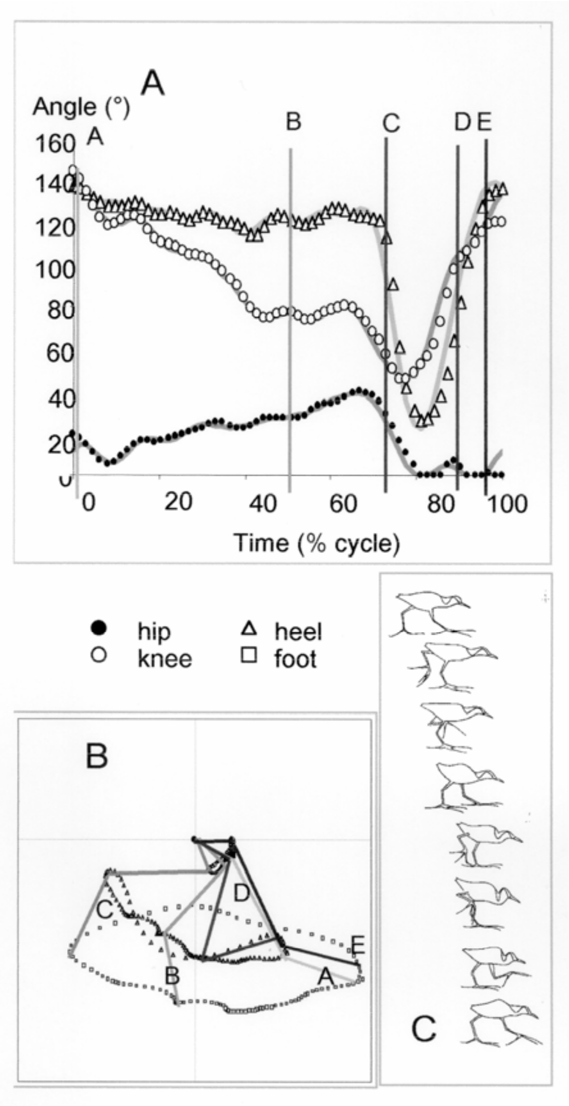

A: angular movements of the hip, knee and ankle joint plotted versus time

B : joint trajectory during the cycle. The hip is fixed. The position of the leg and body are presented at touch down (A), beginning of the pre-take of, (B) and when the foot is the higher.

C: drawing of the jacana during the cycle.

FIGURE 6

KINEMATICS OF A JACANA LOCOMOTOR CYCLE.

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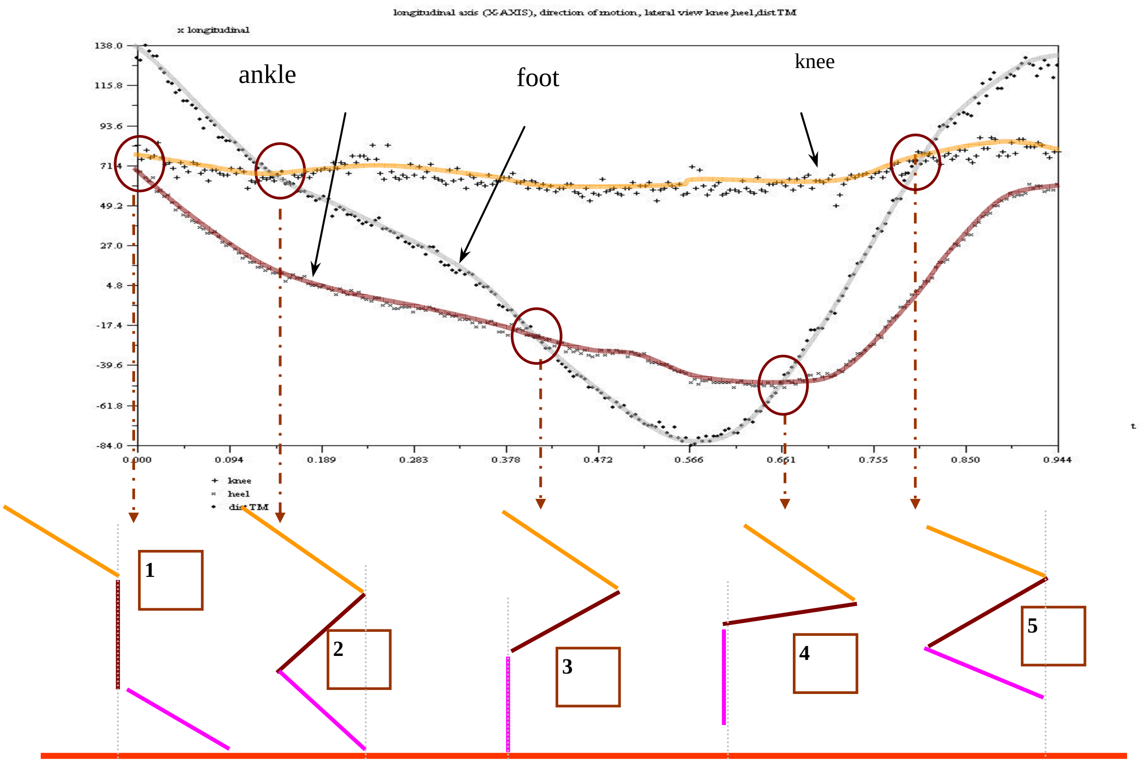

FIGURE 7

LEG CONFIGURATION ALONG THE CYCLE. PROJECTIONS OF KNEE, ANKLE, AND FOOT JOINTS ONTO THE LONGITUDINAL AXIS OF MOTION DIRECTION

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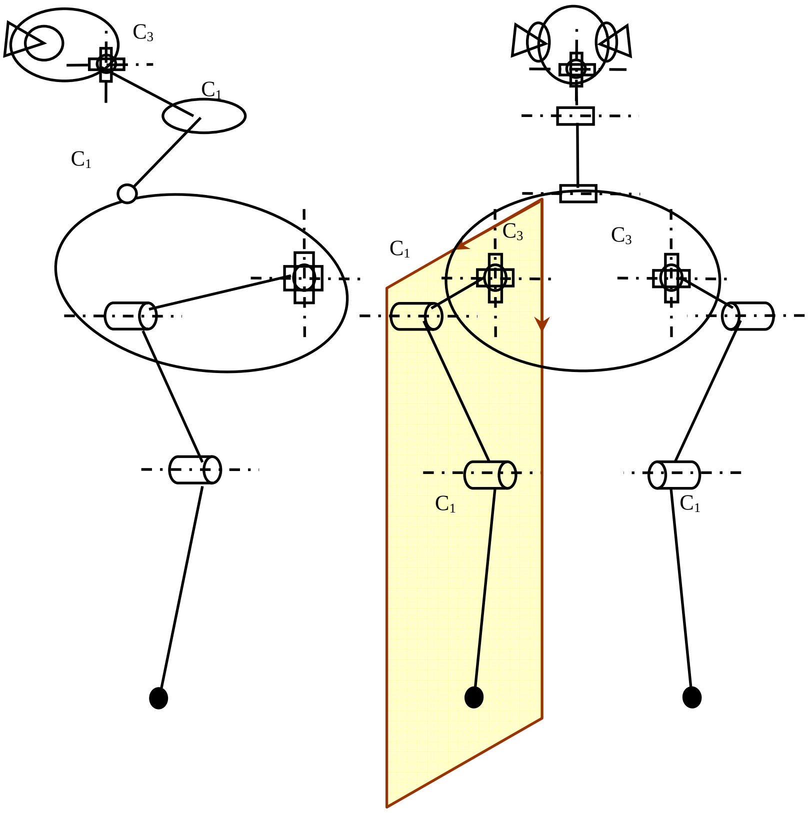

FIGURE 8

KINEMATICS MODEL

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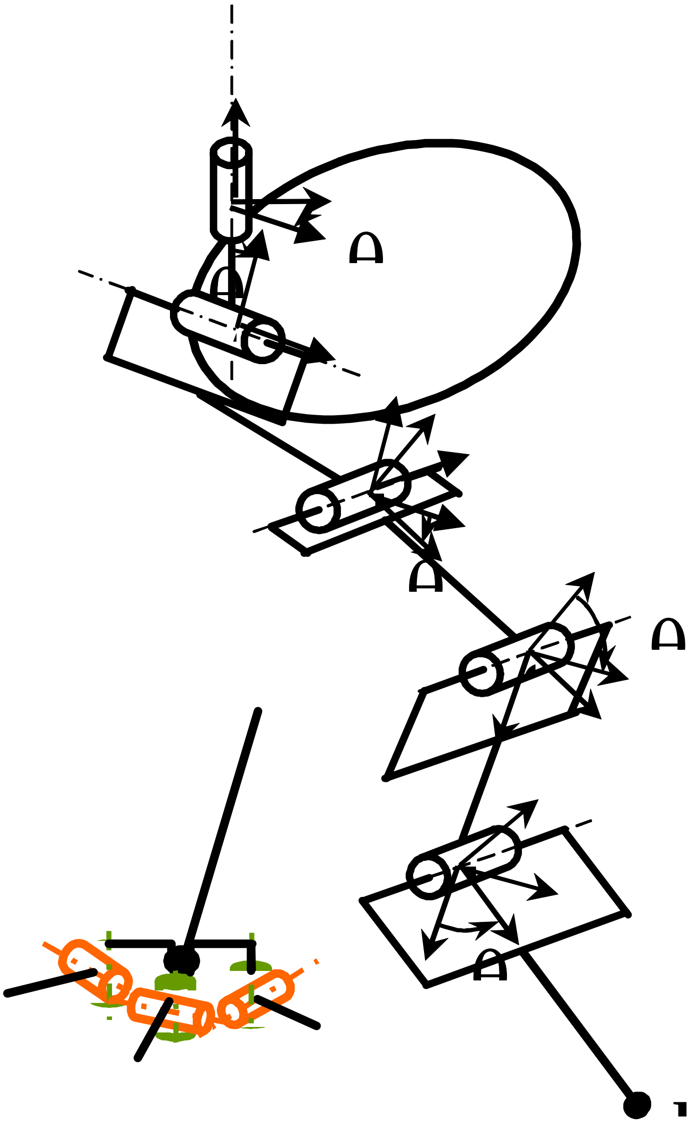

FIGURE 9

DESIGN OF ROBOCOQ LIMB

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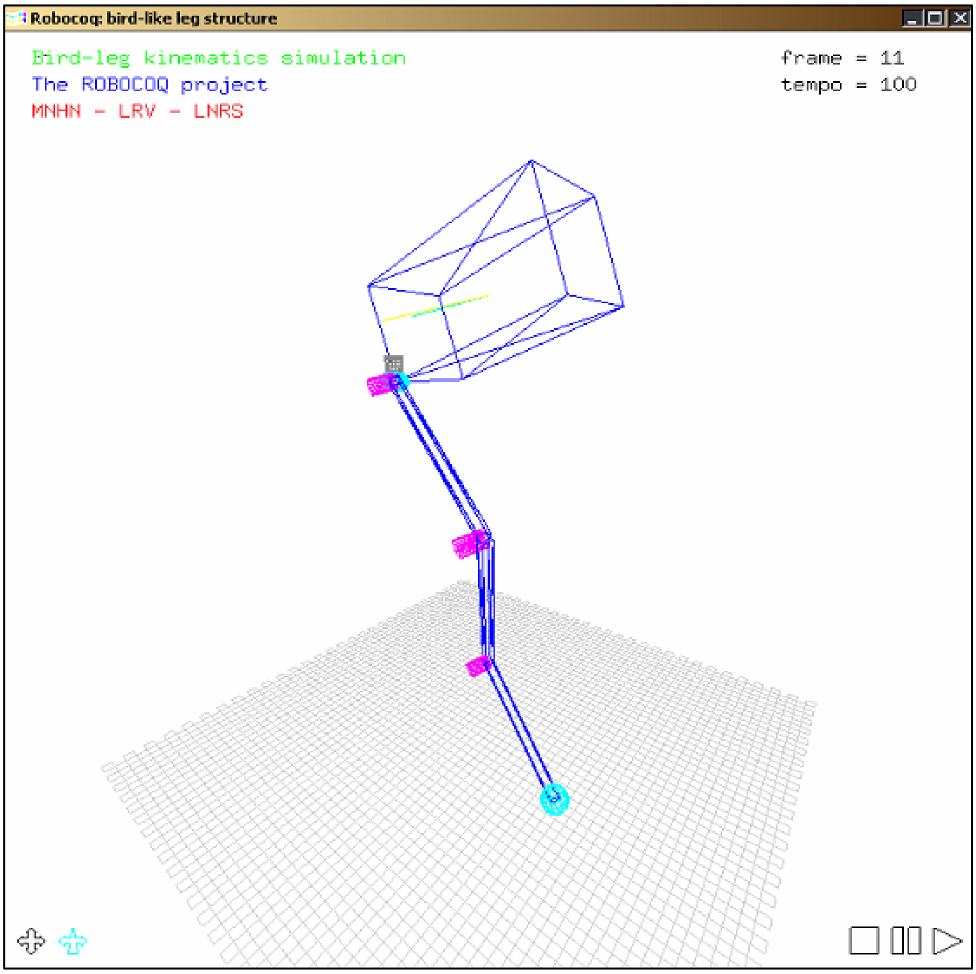

```
Bird-leg kinematics simulation
The ROBOCOQ project
MNHN - LRV - LNRS
```

```
frame = 11
tempo = 100
```

FIGURE 10

KINEMATICS SIMULATION USING OPENGL

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