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SWIMMING ANIMATS WITH MUSCULOSKELTAL STRUCTURE

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ABSTRACT

Animats are artificial creature studied in Alife. Musculo-skeltal structure is a skeleton control model usually used for humanoids. We apply the musculo-skeltal structure to simple swimming animats. The purpose of this study is to acquire proper locomotion of animats in a virtual water environment. The locomotion control is acquired by use of neuro-evolution. The evolved locomotion, swimming, is analyzed by comparing them with those of rigid-bodies and joints model. Results show that the musculo-skeltal structure becomes possible to swim by large oscillation.

KEYWORDS

Artificial fish, Animat, A-Life, Neuro-evolution, Artificial Neural Network, and Physics Modeling.

1. INTRODUCTION

Studies on A-life have attracted since the end of 1980. Reynolds [Reynold, C. W., 1987] proposed “bird-oid” objects generally called as “boid”, which is a model of “flock of flying birds”. He successfully made the short movie film on a flock of flying birds. However, the boid only consider the gravity, which is used to define the banking behavior. He did not take the air drag, buoyancy, and lifting force into consideration. The boid realized the flock but did not realized how it can fly, because such forces given by the environment (air or water) were not calculated. Sims et al. [Sims, K., 1994] exampled various artificial lives. They propose a mainframe work for the A-life to acquire its proper behavior. They adopted an artificial neural network (ANN) to control a virtual creature behavior, and an evolutionary computation method is utilized to give ANN output signals for the proper behavior. Their model is simulated based on physics modeling and its result is immediately animated as a movie. Although the creature behavior they showed seems to be real, it is not clear if they considered the environment forces. They proposed an important framework for A-life research, in which their creatures are activated by using physics modeling. His work has been still followed up [Chaumont, N., 2007]. Terzopoulos and et al. [Terzopoulos, D., 1994] made short movie films of the artificial fish, which seemed to be a real fish. Their fish is modeled by springs and sensors, and its motion is determined by a few rules and by solving the second order differential equation. Their work was so impressive at that time. However, their model does not include the water drag and buoyancy given as forces of the environment as well as C. Reynolds. Our work is closely related to their work.

We have studied to concisely implement fluid environments such as air and water for animats [Furukawa, M., 2011, 2010, Nakamura, K., 2011, Yamamoto, 2009, Ooe, R., 2011]. In these works fluid drags are modeled by use of an empirical equation because it is too time-consuming to precisely calculate them by use of analytical methods such as FEM, EDM, and the moving particle system method (MPS) [Premoze, S., 2003]. We have successfully realized many locomotion behaviors on animats in the air and water environments. However, those animats are modeled by rigid-bodies and joints.

This study proposes animats, especially living in the virtual water environment, which are modeled by a musculo-skeltal structure [Ogiwara, N. and Yamazaki, N., 2001]. The musculo-skeltal structure can be seen in human arms and legs. Because of this, most of studies to use the musculo-skeltal structure are directed to humanoid applications. We can find the musculo-skeltal structure in many kinds of animal, for instance legs of frog and lion. The purpose of this study is to embody animats' locomotion, which is modeled and controlled by the musculo-skeltal structure, in the water environment, and to examine locomotion difference from one modeled by the rigid bodies and joints model. There are many applications of this study in the field of Mechanical Engineering, Computer Graphics Animation, and Robotics.

The rest of this paper includes the followings: Section 2 describes how to construct the virtual water environment. Section 3 introduces the musculo-skeltal structure to the animat model. Section 4 describes neuro-evolution for acquiring animat locomotion control. In section 5, we show experimental results and discuss the acquired locomotion. In Section 6, this study is summarized as a conclusion.

2. BODY OF PAPER

A virtual water environment is realized as a physically modeled water environment by use of physics modeling. Animats are affected by physical forces such as buoyancy and water drag.

2.1 Virtual Forces in the Water Environment

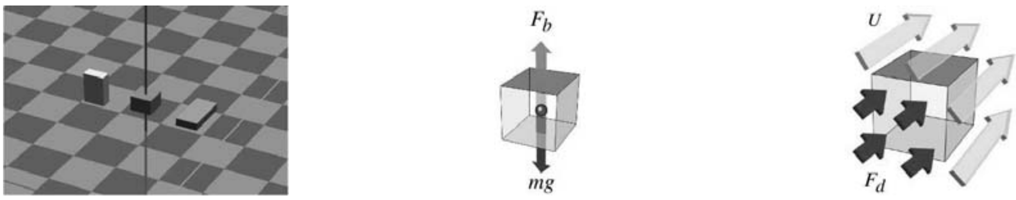
We implement two artificial forces given to an animat by the water environment. One is buoyancy and another is a water drag. We add the artificial force to the center of gravity of Animat as the buoyancy. The buoyancy is written by

$$F_b = -\rho V g \tag{1}$$

where F_b is the buoyancy, ρ_a is the density, V is the volume, and g is the gravity acceleration. An empirical equation has been used for estimating the water drag in the fluid engineering and it is expressed by (2),

$$F_d = \frac{1}{2}\rho C_w S U^2 \tag{2}$$

where F_d, S, U, and C_w are the water drag, the representing surface area of the body facing on the moving direction, the relative velocity, and the drag coefficient, respectively. In applying (2) to the rigid object, the water drag is calculated for only the representing surface. We divide the representing surface into *n*-pieces of surface (*n* sub-surfaces) to calculate the water drag more practically. Then, equation (3) is used to calculate the water drag F_{d_i} for the *i*-th sub-surface.



(a) Floating object by buoyancy (b) Buoyancy (c) Water drag

Figure 1. Buoyancy and water drag

$$F_{d_i} = \frac{1}{2}\rho C_w s_i u_i^2 \tag{3}$$

where s_i and u_i are the *i*-th sub-surface area and relative velocity, respectively. The artificial force F_{d_i} is added at the center of the *i*-th sub-surface as shown in Figure 1.

3. MUSCULOSKELETAL STRUCTURE

A musculoskeletal structure can be found in most of animals. An agonist-antagonist muscle pair connects skeletons in the musculosketal structure. It has mainly applied to humanoid robots and four legs' animats. We apply it to an artificial fish and frog to realize proper swimming behaviors.

3.1 Elastic Spring Model

A simple musculoskeletal Structure is shown in Figure 1-(a). It consists of an agonist-antagonist muscle pair, namely an active muscle, passive muscle, joint, and tendons. The muscle is modeled by an elastic-spring model that is represented by a Newtonian damper and Hookean elastic spring connecting two skeletons in parallel, as shown in Figure 1-(b). The force F_s of the muscle is written by

$$F_S = -k_S x_S(t) - b_S \frac{dx_S(t)}{dt} \tag{4}$$

where k_S, $x_S(t)$, and b_S are the coefficient of elasticity, displacement of spring, and damping factor. The displacement $x_S(t)$ is the difference between a natural length L_S and current length $l_S(t)$ of the spring, written by

$$x_S(t) = L_S - l_S(t)\,. \tag{5}$$

By treating L_S as a parameter, it becomes possible to control the displacement $x_S(t)$ and generate the force to the skeleton from the spring.
Muscles are paired by two kinds of muscle, an active muscle and passive muscle. By introducing the new parameter $z_S(t)$, two natural lengths of both muscles are simultaneously controlled by

$$L_{act}(t) = (1 + \sigma_{act} z_S(t)) L_{act}(0) \tag{6}$$

and

$$L_{pas}(t) = (1 - \sigma_{pas} z_S(t)) L_{pas}(0) \tag{7}$$

where $L_{act}(t)$, σ_{act}, and $L_{act}(0)$ are the current natural, the maximum and the initial length of the active spring, and $L_{pas}(t)$, σ_{pas}, and $L_{pas}(0)$ are those of the passive spring. It is possible to alternate the active spring with the passive spring. To control a pair of springs with ease, we set that $\sigma_{act} = \sigma_{pas}$, and $b_S = b_{act} = b_{pas}$.

3.2 Viscoelasticity Model

A viscoelasticity model is shown in Figure 2 (a). A muscle is stringed between two skeletons via a joint. Advantages of the viscoelasticity model are that the muscle does not traverse skeletons and it gives large motion to the skeleton. The muscle is modeled by the spring, damper, and contracting unit. The contracting unit generates the contracting force $u(t)$. Force $F_V(t)$ working to the muscle is written by

$$F_V(t) = u(t) - k_V u(t) x_V(t) - b_V u(t) \frac{dx(t)}{dt} \tag{8}$$

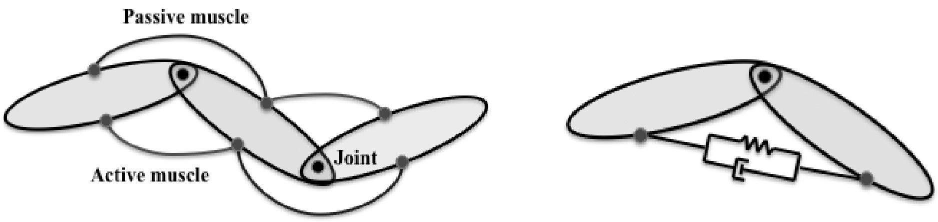
where k_V, $x_V(t)$, and b_V are the coefficient of elasticity, displacement of spring, and damping factor. The displacement $x_V(t)$ is the difference between a natural length L_V and current length $l_V(t)$ of the spring, written by

$$x_V(t) = L_V - l_V(t). \tag{9}$$

The contracting force of the viscoelasticity model is controlled by use of the parameter $z_V(t)$

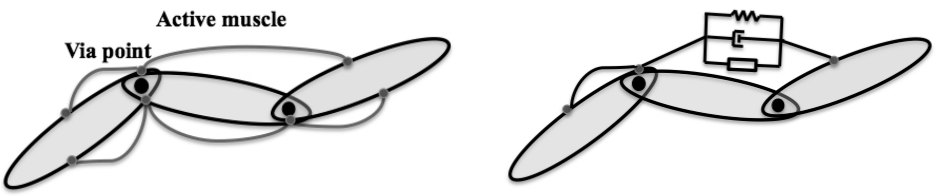
$$u(t) = U z_V(t) \tag{10}$$

where U is the maximum contracting force and $z_V(t) \in [0,1]$.



(a) A simple musculoskeletal structure (b) An elastic spring model

Figure 2. The musculoskeletal structure and its kinematic muscle model



(a) A viscoelasticity model (b) A spring, damper, and contracting unit model

Figure 3. The musculoskeletal viscoelasticity structure and its kinematic muscle model

3.3 Viscoelasticity Model

A viscoelasticity model is shown in Figure 3 (a). A muscle is stringed between two skeletons via a joint. Advantages of the viscoelasticity model are that the muscle does not traverse skeletons and it gives large motion to the skeleton. The muscle is modeled by the spring, damper, and contracting unit. The contracting unit generates the contracting force $u(t)$. Force $F_V(t)$ working to the muscle is written by

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4. MODELING ANIMATS WITH MUSCULOSKELETAL STRUCTURE

We apply two musculoskeletal models to animat for examining whether it generates swimming behavior by adopting neuro-evolution. The elastic spring structure is applied to a simply connected plate fish model, which mimics a cephalochordate. The viscoelasticity model is applied to hind legs of frog.

4.1 A Plate Fish Model

A plate fish model consists of six rigid plates with five joints. Plates are jointed in series connection as shown in Figure 3. A pair of muscles using the elastic spring model is assigned to the second and third, the third and forth, and the forth and sixth plates. Joints connecting two rigid plates have one degree of freedom like a hinge. A dimension of this model in three views drawing is shown in Figure 4, in which broken lines mean muscles. Two virtual photo sensors are attached to the first plate like eyes shown by solid circles in Figure 4. PhysX offered by NVIDIA is used for geometric modeling. Density of each plate equals to one of water.

4.2 Frog Hind Legs’ Model

A frog without fore legs is modeled. This model consists of a body, thighs, shins, feet, and fins as shown in Figure 6. The body, thighs, shins, and feet are geometrically defined by the ellipse approximated by polyhedrons as shown in Figure 7. Fins are defined by the plate. We arrange muscles represented by viscoelasticity structure to hind legs as shown in Figure 8. Red, blue, and yellow lines in Figure 8 correspond to flexion, extension, and biceps muscles. Movable angles of joints set in hind legs are shown in Figure 9. In Figure 9, the upper leg shows the maximum movable angle of each joint when the leg is fold, and the lower leg shows the maximum movable angle of each joint when the leg is stretched.

5. CONTROLLING MUSCLES BY NUERO-EVOLUTION

We use neuro-evolution (NE) to control muscles. NE evolves artificial neural networks (ANNs) using evolutionary computation. ANNs are assigned to controllers and actuators.

Figure 4. A plate fish model

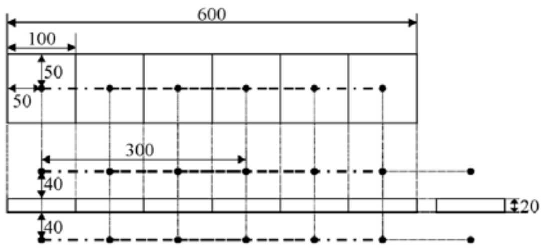


Figure 5. Three views drawing of a plate fish

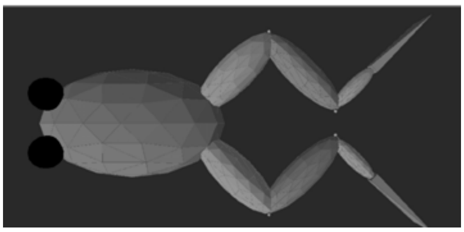


Figure 6. A frog model without fore legs

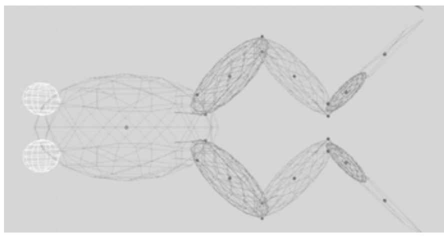


Figure 7. A frog model using polyhedron

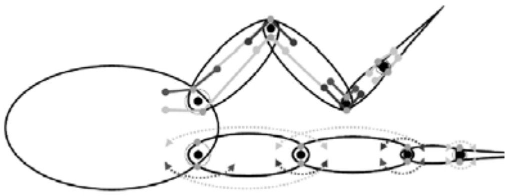


Figure 8. Assignment of muscles

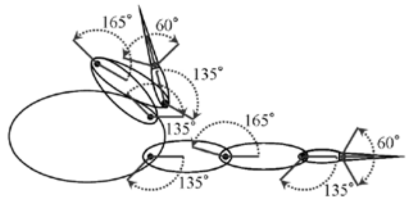


Figure 9. Movable angles of joints

5.1 ANN as Controller

A recurrent type of ANN is implemented as a controller. It outputs signals to an actuator that runs muscles. It consists of three layers as shown in Figure 9. An output of hidden layer unit (neuron) *j* is calculated by equation (11) and so is one of output layer unit *k* by equation (12).

$$y_j(t) = Sig(\sum_{i=1} u_{ij} x_i(t) + \sum_{j'=1} v_{j'j} y_{j'}(t-1) - \theta_j) \quad (11)$$

$$z_k(t) = Sig(\sum_{j=1} w_{jk} y_j(t) - \phi_k) \quad (12)$$

In equations (11), $x_i(t)$, u_{ij}, $y_j(t)$, θ_j, w_{jk}, $z_k(t)$, and ϕ_k are an input of the input layer unit *i,* a synapsis weight from input layer unit *i* to hidden layer unit *j*, an output of hidden layer unit *j*, a threshold value of hidden layer unit *j*, a synapsis weight from input layer unit *j* to hidden layer unit *k*, an output of output layer unit *k*, the threshold value of the output layer unit *k*. $Sig(\cdot)$ is a sigmoid function in equation (12).

5.2 Evolutionary Computation

Enforced Sub-population (ESP) [Gomez, F and Miikkulainen R, 1997, 1998] is applied to neuro-evolution to learn swimming behavior. In the ESP, neuron *j* has sub-population. A chromosome of neuron *j* consists of a set of input synapses, a set of output synapses, and a set of recurrent synapses as shown in Figure 10. ANN is formed by randomly selecting one chromosome from each sub-population. Genetic operations are executed within the sub-population. Furthermore, once the neuron sub-populations have reached minimal diversity, the best network is saved and Delta-Coding [Gomez, F and Miikkulainen R, 1997, 1998] is performed.

6. EXPERIMENTS TO ACQUIRE SWIMMING BEHAVIOR

6.1 Virtual Forces in the Water Environment

By applying neuro-evolution to tow models described in Section 4, it is examined what behavior is acquired to swim. All simulation is done by use of the physics modeling software Physx [Physx] offered by NVIDIA.

6.2 Swimming of Simple Plate Fish

A light source is located in front of a simple plate fish with two photo sensors (eyes) as shown in Figure 11. Then experiments for the plate fish to obtain swimming behavior are conducted.

Experimental Setting Parameters k_V, $b_S = b_{act} = b_{pas}$, and $\sigma_{act} = \sigma_{pas}$ in the elastic spring model are set to 20.0, 0.1, 0.5, respectively. Three layers recurrent network is used to control muscles. The number of inputs, the number of hidden units and the number of outputs are 9, 9, and 3. A set of inputs consists of two angles measured from right and left eyes and angles of six joints connecting plates. A set of outputs consists of three $z_S(t)$ in equations (6) and (7). $z_S(t)$ Controls a pair of muscles simultaneously. The number of individuals is 10, and the number of average selection from the sub-population in ESP is 10. In ESP, if no updated solution appears during 10 generations, Delta-Coding is executed. The terminated condition is when the number generations reaches 50. The fitness function for ESP is defined by

$$Fitness = \sum_{t=1}^{T} D(t) \qquad (13)$$

where *D*(*t*) is the distance between the light source and the fish position at time step *t*.

We compare swimming behavior of the plate fish with that of another type of plate fish, which is directly controlled by five joints connecting six plates. For this fish we use the three layer recurrent neural network as well, but the number of outputs are five. A set of outputs is five joints' angles for use of followed step joints' angles.

Resulting in Behavior Snapshots of the obtained behavior is shown in Figure 12. Six plates' angles measured from the line, which is drawn between the starting location and the light source, are recorded during swimming. Figure 13 (a) shows the chart on an elastic spring control model. Figure (b) shows the chart on a directly joint control model. It is observed that the plate fish using the elastic spring control model makes lager oscillation of the fish body than one using the directly joint control model.

6.3 Swimming of Frog Hind Legs' Model

A light source is located in front of a frog with two photo sensors (eyes) as shown in Figure 14. Then experiments for the frog to obtain swimming behavior are conducted as well as the plate fish.

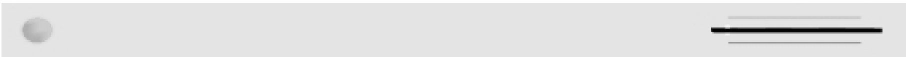


Figure 11. A light source and an initial position of a plate fish

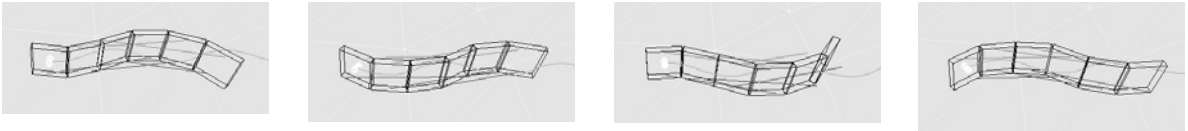
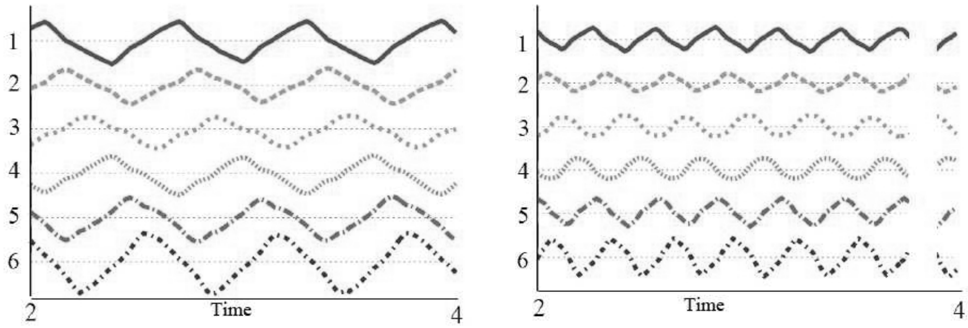


Figure 12. Swimming of a plate fish



(a) An elastic spring control

(b) Directly joint control

Figure 13. Transition of six joint angles

6.4 Swimming of Frog Hind Legs' Model

A light source is located in front of a frog with two photo sensors (eyes) as shown in Figure 14. Then experiments for the frog to obtain swimming behavior are conducted as well as the plate fish.

Experimental Setting Parameters k_v, b_v, and b_v in the viscoelasticity model are searched in [0, 0.005], [2.0, l_v, ∞], and [0, 0.000005], respectively. The three layers recurrent network is used to control muscles. Because the number muscles implemented with legs as shown in Figure 7 is 9, the number of inputs, the number of hidden units and the number of outputs are 6, 14, and 9. A set of inputs consists of angles measured from right and left eyes and angles of four joints set in legs. A set of outputs consists of nine $z_V(t+1)$ in equation (10). The number of individuals and the number of average selection from the sub-population in ESP are set to 500 and 10. In ESP, if no updated solution appears during 10 generations, Delta-Coding is executed. The search is terminated when the number generations reaches 500. The fitness function for ESP is defined by equation (13) as well.

Resulting in Behavior Snapshots of obtained behavior is shown in Figure 15. Transition of four angles is shown in Figure 16. From Figures 15 and 16, obtained swimming is that the frog pull its legs to body as close as possible and then it kicks the legs till its thigh, shin, foot and fin are aligned. This large motion behavior can only be obtained by use of the viscoelasticity model.

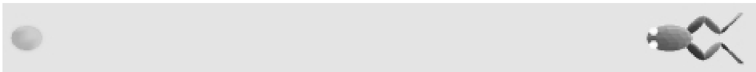


Figure 14. A light source and an initial position of a plate fish

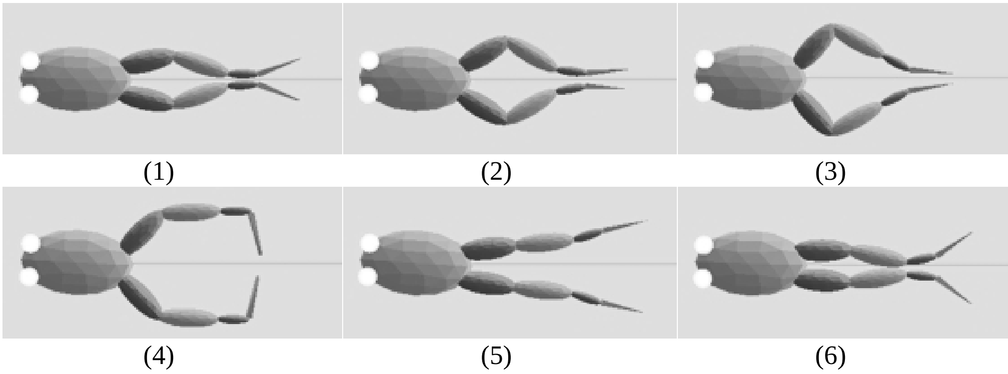


Figure 15. Snapshots of obtained swimming behavior

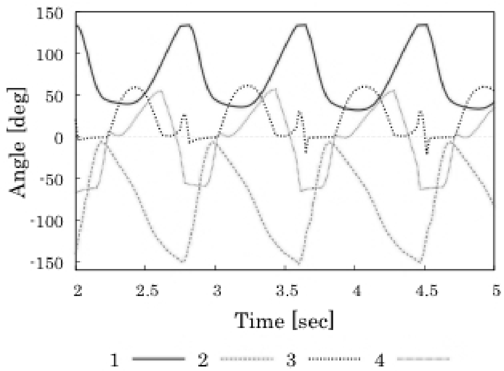


Figure 16. Transition of four joint angles

7. CONCLUSION

The musculoskeletal structure model is well known because it is observed in human muscle system. Because of this, it has applied to do research for humanoids and mammals. There have been few researches to explore animats living in an underwater environment. This is because it is necessary to implement the underwater environment accurately. To do so, time consuming methods such as a finite difference method and a moving particle method must be implemented. We introduced an empirical method concisely to implement the underwater environment for realization of swimming animats.

Two kinds of musculoskeletal structure model are introduced into fish muscles. The one is an elastic spring structure model and the other is a viscoelasticity model. The elastic spring structure model is implemented with a simple plate fish. Acquired swimming behavior of the plate fish, whose muscles are controlled by the elastic spring model, using neuro-evolution has larger oscillation than one of the plate fish, whose joints are directly controlled. The viscoelasticity model is implemented with a frog hind leg. Acquired swimming behavior of the frog is mostly like a real frog swimming behavior.

It is proved through our experiments that introducing the musculoskeletal structure model is useful for studying A-life behavior.

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