単･二関節筋同時駆動を模擬したマルチリンクロボットレッグの外力のある環境での歩行制御

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Walking Control of Multiple Link Robotic Leg under External Forces by Emulating Functionality of Combined Mono and Bi-Articular Muscles

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Conventional humanoid robots and biological subjects differ in their mechanisms and control strategy. Biological subjects have musculoskeletal systems that can drive two joints at the same time while conventional robots use one joint drive mechanisms. In this research, a dynamic model of a multiple-link robotic leg that mimics biological subjects is presented and walking scheme is designed and analyzed. Details of the mathematical modeling for the proposed method will be explained and simulation results will be presented.

キーワード：二関節筋、ロボット、歩行制御
(biarticular Muscle, robot, walking control)

1. Research Background

Technologies related to humanoid robots are advancing in the last years. Some researchers concentrate on control of robotic arms and some concentrate on robotic leg control. ASIMO from HONDA, QRIO from Sony, and KONDO VHR series walking robots can be given as examples of the most well-known walking robots. The similarity between these robots is that all of them are controlled with the actuators placed on their joints, which is generally called conventional type. Besides these models, emulation of life mechanisms has also attracted many researchers' attentions since the late years of 20th century. In order to develop biologically inspired robot manipulators, observation of human and animal characteristics are essential. Some researchers are focusing on to gather living mechanism's dynamic gaits like [1][2] while others try to use those features to apply on their robotic systems like [3][4]. By analyzing the musculoskeletal systems of human and animals, robot arms[6][10] and legs[5][7][8] that mimic their behaviors, are modeled and controlled. Moreover, some power assisted devices are also designed to support elderly and disabled people or to increase the performance of workers or soldiers who perform difficult tasks and are carrying heavy loads. In this research, the main objective is the modeling and walking control of such biologically inspired robotic leg with combined monoarticular and biarticular muscles in the existence of external forces acting on the body and to achieve safer and more human-like motion of a robotic leg against external forces.

1.1 Biarticular and monoarticular muscle model explanation

In conventional robot manipulators, actuators are placed on the joints and each joint is activated by only one actuator which is generally a servomotor. On the other hand, human and animals have more complex musculoskeletal structure based on monoarticular and biarticular muscles. Monoarticular muscles connect one joint and one link and can generate force for only one joint; but biarticular muscles connect two adjacent joints and generate the same contractive force on two joints at the same time. A basic model of conventional model and muscle model is shown on the Figure 1 below.

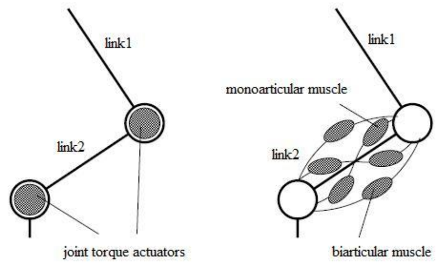

Figure 1. Conventional Model vs. Muscle Model

In conventional robot systems, the number of actuators is equal to the number of joints. Contrary, in musculoskeletal systems, the number of pairs of antagonistic muscles is larger than the number of joints, which means that there is actuator redundancy; but this redundancy can be used in such a way to maximize the total torque at the joints as well as the total force in the end effector. A simple model of human leg and also the model which is used in this research is shown in the Figure 2.

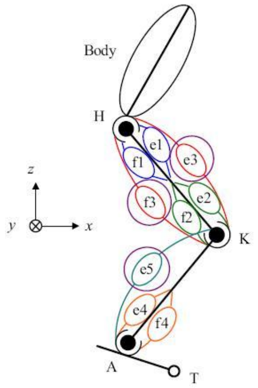

Figure 2. Robotic Leg Model with monoarticular and biarticular muscles.

In this model; e1,e2,e3 and e4 denote extensors and f1,f2,f3,f4 denote flexors. The pairs of e1-f1, e2-f2 and e4-f4 generate torques around hip, knee and ankle joints respectively. The couple e3-f3 and the extensor e5 generate torques around both hip and knee joints, and knee and ankle joints respectively. 5 torques generated by these pairs can be shown as;

$$\begin{aligned} T_1 &= (e_1 - f_1).r \\ T_2 &= (e_2 - f_2).r \\ T_3 &= (e_3 - f_3).r \\ T_4 &= (e_4 - f_4).r \\ T_5 &= e_5.r \end{aligned} \quad \cdots\cdots(1)$$

where r is the radius of both hip, knee and ankle joints.

1.2 Graph of force directions according to each muscle activation

Force directions are calculated by using EMG(electromiogram) on static conditions. Amplitudes and directions of the end effector force in conventional model and the proposed method differs as it is seen on the Figure 3.[6] The black parallelogram shows the force directions in conventional model while the shape D1～D6 shows the directions in the proposed method. For instance, activation of the muscle f3 will result in a force towards to D3, and activation of e3 will result a force in opposite direction. That is to say, the pairs e3-f3 works oppositely. It is also possible to achieve stiffness control by adjusting the individual muscle forces e3 and f3 without changing the difference between them to keep the joint torque same.

In the proposed method, maximum output force at the end effector is larger and the distribution of force directions are more homogenous than conventionally driven robotic manipulators. Since the force is distributed to more actuators, maximum torque that can be produced is also large in robotic manipulators with mono and biarticular muscles. Another advantage is that,

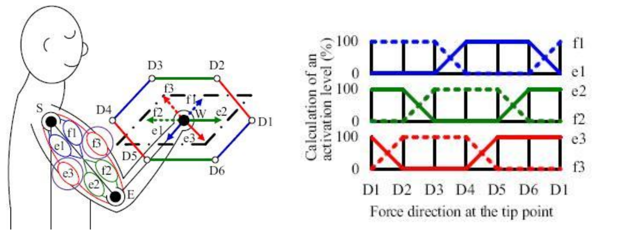

Figure 3. Graph of Force Direction according to each muscle activation

feedforward control can be implemented by using the advantage of viscoelasticity of biarticular muscles for disturbance suppression and trajectory tracking.

2. Mathematical Modeling for Proposal

In this section, the mathematical equations and their explanations will be presented in detail. Parameters that are used in this section, their explanations and units are shown in the Table1

Table 1. Parameter Explanation

Parameters	Explanation	Units
T_1, T_2, T_4	Monoarticular muscle torques	Nm
T_3, T_5	Biarticular muscle torques	Nm
τ_1	Hip joint torque	Nm
τ_2	Knee joint torque	Nm
τ_3	Ankle joint torque	Nm
m_1, m_2	Mass of links	kg
ℓ_1, ℓ_2	Length of links	m
ℓ_{c1}, ℓ_{c2}	Center of masses of links	m
r	Radius of links	m
I_1, I_2	Inertia of links	$kg.m^2$
g	gravity	m/s^2

Mathematical modeling is prepared for both legs. The notation 'legon' will be used for the leg which contacts with the ground while walking and the notation 'legoff' will be used for the leg which does not contact with the ground and taking one step forward.

2.1 Trajectory Planning

The trajectory of hip position for legon state, is planned in such a way that angle of the ankle is between 75 and 95 degrees. The trajectory of the ankle position for legoff state is planned in such a way that its velocity in x-direction is 2 times of hip velocity. Z positions of both legs are calculated according to the designed x positions.

Figure 4. Representation of Legon and Legoff States

For leg on state;

$$\begin{bmatrix}\tau_3\\ \tau_2\end{bmatrix}=\begin{bmatrix}T_4+T_5\\ T_2+T_5\end{bmatrix} \quad \text{..........................(3)}$$

For leg off state;

$$\begin{bmatrix}\tau_2\\ \tau_1\end{bmatrix}=\begin{bmatrix}T_2+T_3\\ T_1+T_3\end{bmatrix} \quad \text{..........................(4)}$$

The angle of knee and ankle for the legon state, and the angle of knee and hip for the legoff state are calculated by inverse kinematics as follows:

2.2 Calculation of Torques

Position of hip for the legon state can be represented as:

$$\begin{bmatrix}x\\ z\end{bmatrix}=\begin{bmatrix}\ell_1.\cos(\theta_2+\theta_3)+\ell_2.\cos\theta_3\\ \ell_1.\sin(\theta_2+\theta_3)+\ell_2.\sin\theta_3\end{bmatrix} \quad \text{.....................(5)}$$

And Jacobian of the robotic leg can be derived as follows:

$$J=\begin{bmatrix}-\ell_1.\sin(\theta_2+\theta_3)-\ell_2.\sin(\theta_3) & -\ell_1.\sin(\theta_2+\theta_3)\\ \ell_1.\cos(\theta_2+\theta_3)+\ell_2.\cos(\theta_3) & \ell_1.\cos(\theta_2+\theta_3)\end{bmatrix} \quad \text{.........(6)}$$

The general torque equation is given as:

$$\tau=D(\theta).\ddot{\theta}+C(\theta,\dot{\theta}).\dot{\theta}+g(\theta) \quad \text{.................(7)}$$

where D matrix is the inertia matrix, C matrix is the Coriolis and Centrifugal matrix and g is the gravity factor. Representation of D matrix is given as;

$$D(\theta)=\begin{bmatrix}d_{11} & d_{12}\\ d_{21} & d_{22}\end{bmatrix}$$

where;

$$\begin{aligned}d_{11}&=m_2.\ell_{c2}^{\ 2}+m_1.(\ell_2^{\ 2}+\ell_{c1}^{\ 2}+2.\ell_2.\ell_{c1}.\cos\theta_2)+I_1+I_2\\ d_{12}&=d_{21}=m_1.(\ell_{c1}^{\ 2}+\ell_2.\ell_{c1}.\cos\theta_2)+I_1\\ d_{22}&=m_1.\ell_{c1}^{\ 2}+I_1\end{aligned} \quad \text{..........(8)}$$

Coriolis matrix is the matrix which includes Coriolis and centrifugal forces. It is dependent on the angular velocities of the links. Coriolis matrix is derived from Inertia matrix D as;

$$C(\theta,\dot{\theta})=\begin{bmatrix}-(m_1.\ell_2.\ell_{c1}.\sin\theta_2).\dot{\theta}_2 & -(m_1.\ell_2.\ell_{c1}.\sin\theta_2).(\dot{\theta}_2+\dot{\theta}_3)\\ (m_1.\ell_2.\ell_{c1}.\sin\theta_2).\dot{\theta}_3 & 0\end{bmatrix} \quad \text{.......(9)}$$

Since modeling is done in x-z plane, it is also required to include the effect of gravity into our system. Gravity factor can be written as;

$$g(\theta)=\begin{bmatrix}(m_2.\ell_{c2}+m_1.\ell_2).g.\cos\theta_3+m_1.\ell_{c1}.g.\cos(\theta_2+\theta_3)\\ m_1.\ell_{c1}.g.\cos(\theta_2+\theta_3)\end{bmatrix} \quad \text{.........(10)}$$

In the simulations, the gravity factor is taken positive for legon state, and negative for the legoff state. For the legon state, torques of ankle and knee is calculated as;

$$\begin{bmatrix}\tau_3\\ \tau_2\end{bmatrix}=\begin{bmatrix}d_{11} & d_{12}\\ d_{21} & d_{22}\end{bmatrix}.\begin{bmatrix}\ddot{\theta}_3\\ \ddot{\theta}_2\end{bmatrix}+\begin{bmatrix}c_{11} & c_{12}\\ c_{21} & c_{22}\end{bmatrix}.\begin{bmatrix}\dot{\theta}_3\\ \dot{\theta}_2\end{bmatrix}+\begin{bmatrix}g_1\\ g_2\end{bmatrix} \quad \text{.........(11)}$$

In addition to calculated joint torques, there might be some external force acting on the body and the effect of those torques on the joint torques should also be required to be calculated and these effect can be represented with the following equation.

$$T=-J^TF \quad \text{....................................(12)}$$

For our leg model the equation becomes;

$$\begin{bmatrix}\tau_3\\ \tau_2\end{bmatrix}=\begin{bmatrix}\ell_1.\sin(\theta_2+\theta_3)+\ell_2.\sin(\theta_3) & -\ell_1.\cos(\theta_2+\theta_3)-\ell_2.\cos(\theta_3)\\ \ell_1.\sin(\theta_2+\theta_3) & -\ell_1.\cos(\theta_2+\theta_3)\end{bmatrix}\begin{bmatrix}F_x\\ F_z\end{bmatrix} \quad \text{.........(13)}$$

The torque resulted from external forces should be added to previously calculated joint torques before individual muscle torques are calculated.

2.3. Calculation of Individual Muscle Torques

The calculation of each muscle torque is done by minimizing the square root of sum of squares.

minimize $\Longrightarrow$ $\sqrt{T_1^{\ 2}+T_2^{\ 2}+T_3^{\ 2}}$

The solution for $\begin{bmatrix}\tau_2\\ \tau_1\end{bmatrix}=\begin{bmatrix}T_2+T_3\\ T_1+T_3\end{bmatrix}$ will be;

$$T_1 = \frac{2}{3}\tau_1 - \frac{1}{3}\tau_2$$
$$T_2 = -\frac{1}{3}\tau_1 + \frac{2}{3}\tau_2 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (14)$$
$$T_3 = \frac{1}{3}\tau_1 + \frac{1}{3}\tau_2$$

After individual muscle torques are calculated next step will be to find the necessary displacements of the muscles. The model that we used in this process is shown in the figure 10 below.

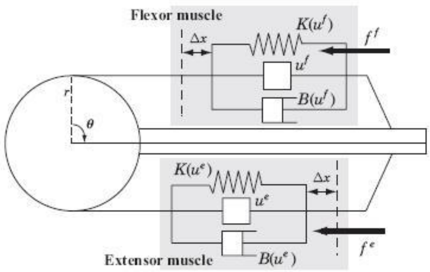

Figure 4. Muscle Model

A spring and damper system is used for the transmission of muscle force. The relation between displacement of muscle and the force generated by the muscle is given in the equation below.

$$f = m\Delta\ddot{x} + K\Delta x + B\Delta\dot{x}$$
$$f_{monoarticular} = m(\ddot{x} - r\ddot{\theta}) + K(x - r.\theta) + B(\dot{x} - r.\dot{\theta})$$
$$f_{biarticular} = m(\ddot{x} - r(\ddot{\theta}_1 - \ddot{\theta}_2)) + K(x - r(\theta_1 - \theta_2)) + B(\dot{x} - r(\dot{\theta}_1 - \dot{\theta}_2)) \quad \ldots\ldots\ldots (15)$$

where K is the spring constant and B is the damping coefficient. The displacement which results from the change in the joint angle is $x = r\theta$ for monoarticular muscle since it is connected to only one joint, and $x = r(\theta_1 - \theta_2)$ for biarticular muscle since it is connected to adjacent joints.

For the control of individual muscle forces, a DC motor is used to tighten the muscle length. Parameters used in the representation of DC motor are shown in the Table 2.

Table 2. DC Motor Parameters

Parameters	Explanation	Units
J	inertia	Kg-m²/rad
b	damping coefficient	N-m/(rad/s)
K_e	back-emf constant	Volt/(rad/s)
K_t	torque constant	N-m/A
L	inductance	H
R	resistance	Ohm

$$J\ddot{\theta} + b\dot{\theta} = K_t i(t)$$
$$L\frac{di(t)}{dt} + Ri(t) = V - K_e\dot{\theta} \quad \ldots\ldots\ldots\ldots\ldots (16)$$

Laplace transformation and the transfer function can be calculated as follows:

$$\frac{\theta(s)}{V} = \frac{K_t}{JLs^3 + (JR + bL)s^2 + (K_e K_t + bR)s} \quad \ldots\ldots\ldots (17)$$

3. Simulation Results

Table 3. Table of Given Values

m_1, m_2	2 kg
ℓ_1, ℓ_2	0.2 m
θ_2	10^0
r	0.03 m

Since external forces is needed to be rejected in the legon state, simulations are done for the leg that is in contact with the ground.

Joint torques for ankle and knee is calculated for legon state and the results are shown in Figure 5 The resulted individual muscle torques are shown on Figure 6.

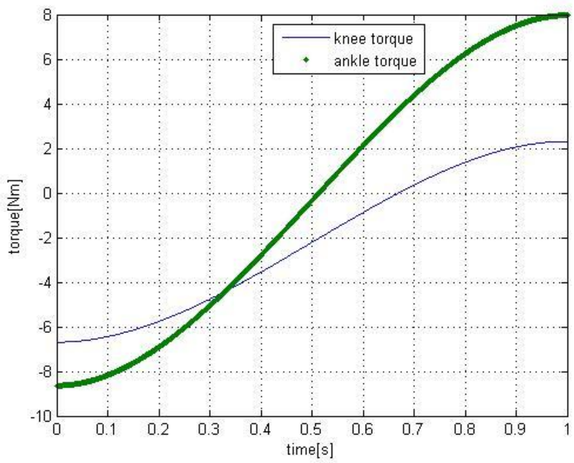

Figure 5. Knee and Ankle Joint Torques

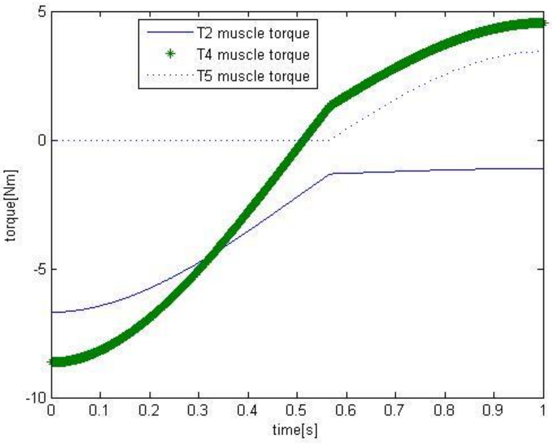

Figure 6. Individual Muscle Torques (T2,T4,T5)

The effect of external force on individual muscle torques are simulated and the results are represented in figure 7. Since T5 can exert force in only one direction, it will start to tighten around t=0.57s

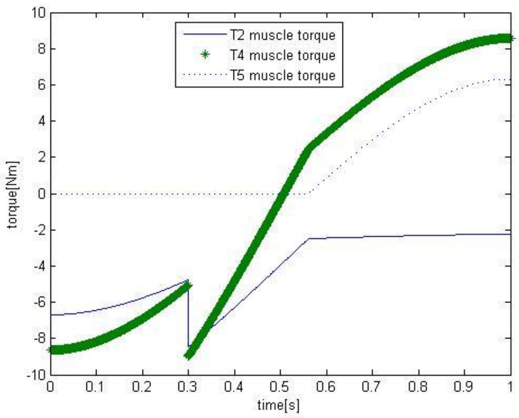

Figure 7. Individual Muscle Torques (F_{ex}=100N)

For the selection of spring constant, the displacement of muscle e4-f4 pair is calculated for different spring constants since muscle torque T4 is the highest. Spring constant is decided to be 3000 since the displacement of the muscle cannot exceed the length of the muscle.

All of displacements of muscles are calculated and these values are used in the position control of DC motor that is used to tighten the muscle. The external force is applied to system at t=0.3s. The resulted control outputs for the displacement of 3 individual muscles are shown in figures 8-9-10.

The response of the system when external force is applied at t=0.3s seems to be good enough; and can be improved by applying a different method.

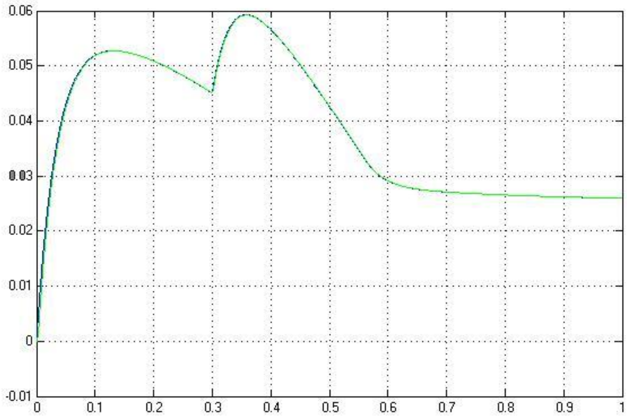

Figure8. Control Output of Monoarticular Muscle #2 (Kp=50,Kd=1)

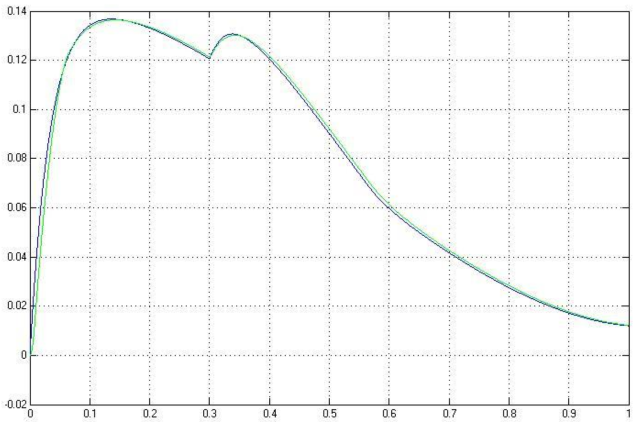

Figure 9. Control Output of Monoarticular Muscle #4 (Kp=5,Kd=0.1)

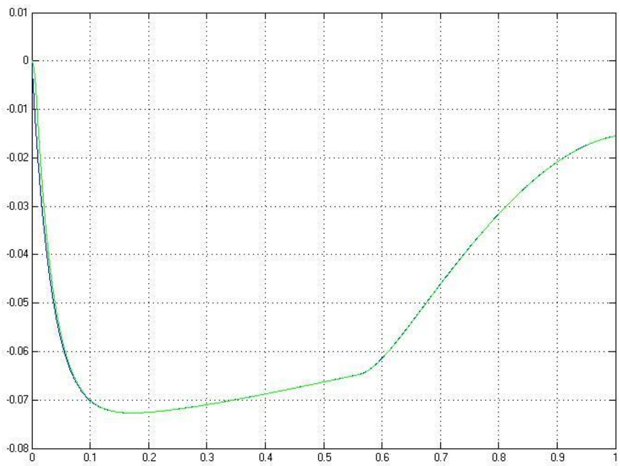

Figure 10. Control Output of Biarticular Muscle #5 (Kp=60,Kd=1)

4. Conclusion and Discussion

After giving a brief review of previous and on-going researches, the strategy to use monoarticular and biarticular muscles for simultaneous drive of two joints is proposed. Then, the difference between conventional robot control method and proposed method is clarified. Human walking model and humanoid robot leg with such muscle system are explained and forces which results from activation of those mono and biarticular muscles are shown on a graph. Characteristics of biological musculoskeletal mechanism and cooperation control of monoarticular drives and biarticular simultaneous drives have been mathematically described on dynamic condition. Mathematical modeling and calculations are presented in detail in the second section and simulation results for individual muscle torques, their displacements and position control of actuators are shown in the third section. As it can be seen from simulation results, total torque that is required on the joints is shared by mono and biarticular muscles and muscles are controlled successfully by a DC motor with a spring-damper system.

Although it is difficult to achieve simultaneous control of such muscles, it can be relied on muscles' viscoelasticity in the very early response against external forces in control algorithms. Stiffness control is expected to be easier compared to conventional method.

5. Future Work

Optimization of individual muscle torque calculation should be analyzed more and the tracking control should be improved. Further study should be done to improve the numerical analysis, In addition, a system model is required to be built to get joint angles from joint torques to verify the position of the hip point in legon state in the simulations. In addition, stiffness control can be implemented to achieve better external force rejection. In the existence of large external force, the stiffness can be increased for faster and more precise motion. Finally, it is needed to verify the usability of this system in real experimental setup.

- References

[1] Endo K., Herr H.: "*Human Walking Model Predicts Joint Mechanics, Electromyography and Mechanical Economy*", IEEE/RSJ International Conference on Intelligent Robots and Systems, St. Louis, USA(2009-10)

[2] Huang Y., et al: "*Energetic efficiency and stability of dynamic bipedal walking gaits with different step lengths*", IEEE/RSJ International Conference on Intelligent Robots and Systems, Taipei, Taiwan (2010-10)

[3]Zang Y. ,Yasuno T., Nogami R., Suzuki H.: *"Adaptive Walking Control Using CPG Network for Quadruped Robot with Bi-articular Muscles Model"*, SICE Annual Conference, The Grand Hotel, Taipei, Taiwan, (2010-9)

[4] Babic J.: "Biarticular Legged Robot: Design and Experiments", Proceedings of IEEE International Conference on Robotics and Biomimetics, Bangkok, Thailand(2009-2)

[5] Iida F., Rummel J., Seyfarth A.: "Bipedal walking and running with spring-like biarticular muscles", Journal of Biomechanics 41, pp.656-667,(2008)

[6]Fukusho H. , Koseki T.: "*Control of a Straight Line Motion for a Two-Link Robot Arm Using Coordinate Transform of Bi-articular Simultaneous Drive*", 11th IEEE International Workshop on Advanced Motion Control, Nagaoka, Japan,(2010-3)

[7] Babic J., Lim B., Omrcen D., Lenarcic J., Park F.C.: "*A Biarticulated Robotic Leg for Jumping Movements: Theory and Experiments*", Journal of Mechanisms and Robotics, Vol 1/011013,(2009-2)

[8] Rummel J. et al: "*Stable and Robust Walking with Compliant Legs*", IEEE International Conference on Robotics and Automation, Anchorage, Alaska, USA,(2010-5)

[9] Endo K., Herr H.: "*A Model of Muscle-Tendon Function in Human Walking*", IEEE International Conference on Robotics and Automation, Kobe International Conference Center Kobe, Japan,(2009-5)

[10] Yoshida K, Hata N., Oh S., Hori Y.: "Extended Manipulability Measure and Application for Robot Arm Equipped with Bi-articular Driving Mechanism", IECON 35th Annual Conference of IEEE, pp.3083 - 3088 Porto, Portugal, (2009)