Paper:

Effects of the Lower Leg Bi-Articular Muscle in Jumping

Toru Oshima*, **Kiyoshi Toriumi****, **Tomohiko Fujikawa*****, **and Noboru Momose***

* Department of Mechanical Systems Engineering, Faculty of Engineering, Toyama Prefectural University
Kurogawa 5180, Kosugi, Toyama 939-0398, Japan
E-mail: oshima@pu-toyama.ac.jp
** Faculty of Education, Toyama University
Gofuku 3190, Toyama 939-8555, Japan
*** Department of Electronic Control Engineering, Toyama National College of Maritime Technology
Ebieneriya 1-2, Shinminato, Toyama 939-0293, Japan

[Received July 7, 2004; accepted September 28, 2004]

We studied the effects of the lower leg bi-articular muscle in vertebrates in jumping. We used the proposed Jumping Jack model in computer simulation to analyze the impact of bi-articular muscle on postural jumping stability, energy transition caused by postural change, and the relationship between the ground reaction force and the center of gravity. We made a trial model and measured the jumping posture, ground reaction force, and jumping height to verify simulation results. The bi-articular muscle adjusted the ground reaction force so that the line of action invariably passed near the center of gravity and the conversion of elastic energy to rotational kinetic energy was suppressed, leading to a stable posture after takeoff.

Keywords: lower leg, jumping, bi-articular muscle, jumping posture, ground reaction force

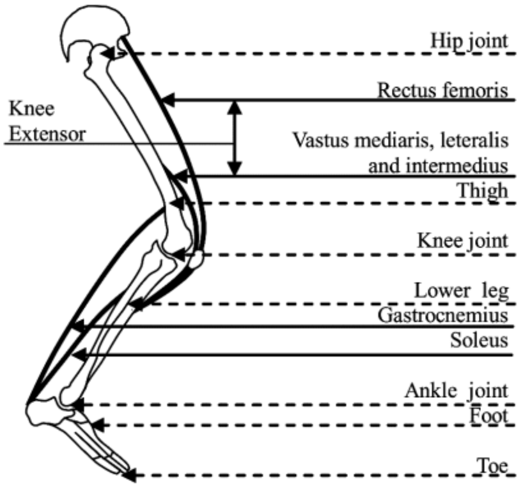


Fig. 1. Lower leg muscles necessary for jump.

1. Introduction

Many humanoid robots that walk bipedally, cannot overcome underfoot irregularities or obstacles, preventing them from moving quickly. On the other hand, human, an original of these robots, can move across various irregularities or obstacles at high speeds by running, which can be considered continuous jumping. Jumping is indispensable when a humanoid robot implements high-speed locomotion.

Most of conventional jumping robots has the slide joint mechanism [2–5] based on a legged robot [1]. However, the joints of vertebrates extremity use a rotary joint without the slide joint. The vertebrate actuator (muscle) of articulated motion by multiple rotary joints is the bi-articular muscle, which acts simultaneously on two joints. The gastrocnemius in the human lower leg (**Fig.1**) is a bi-articular muscle that acts on the knee and ankle simultaneously.

One jumping robot [6] with springs acting on two joints simulating elasticity by the bi-articular muscle tendon, but is considered only in energy transfer. Control function [7, 8] in cooperation mono-articular muscle is involved in the bi-articular muscle function. For the impact of the bi-articular muscle on jumping, a musculoskeletal model was made and the electromyography input for computer simulation clarifying the relationship between muscular activities and jumping [9, 10]. Experiments on jumping by used the Jumping Jack model [11] with springs on the knee as a drive source. The gastrocnemius, a bi-articular muscle, was replaced with a wire and the function of energy transfer proved to use the bi-articular muscle to transfer energy generated by the knee extensor from a difference between models with and without the wire. Since Jumping Jack was manufactured focused on energy transfer by the bi-articular muscle and jumping height, it was given a guide rail restricting the jumping direction. The Jumping Jack thus prevented us from considering other than energy transfer of the bi-articular muscle due to the guide rail.

We used the Jumping Jack without the guide rail to clarify the impact of the bi-articular muscle on the jumping.

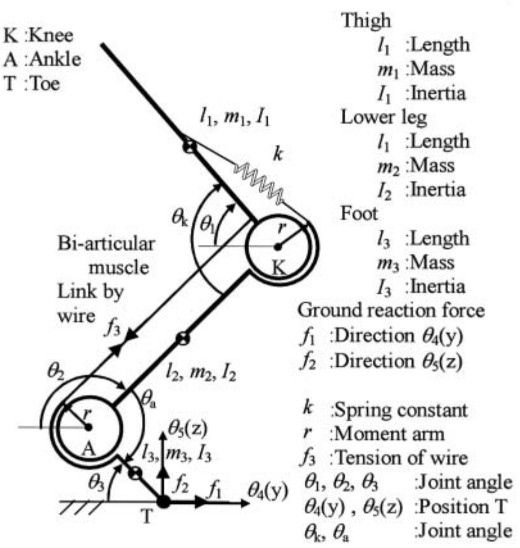


Fig. 2. Computer simulation model.

2. Analysis by Computer Simulation

We conducted computer simulation to analyze the impact of the bi-articular muscle on the jumping in stability of the jumping posture, energy transition caused by postural change, and the relationship between the ground reaction force and the center of gravity.

2.1. Computer Simulation Model

Figure 2 shows the Jumping Jack for computer simulation. This 3-link model consists of the link 1, i.e. the thigh (uniform rod of length $l_1 = 125$mm, mass $m_1 = 65$g), link 2, i.e. the lower leg (uniform rod of length $l_2 = 125$mm, mass $m_2 = 65$g), and link 3, i.e. the foot (uniform rod of length $l_3 = 25$mm, mass $m_3 = 20$g). A spring (spring constant $k = 5.3$N/mm, moment arm length $r = 14$mm, mass ignored) acts as an actuator equivalent to the knee extensor. Two models are used for comparison: one with a wire (moment arm length $r = 14$mm, mass ignored) that acts on the thigh and foot as the bi-articular muscle and the other without the wire. Since the wire function as the bi-articular muscle does not have a drive source, this muscle does not influence the generation of energy for jumping.

The posture ($\theta_k = \pi/2, \theta_a = \pi/2$) at the start of motion is assumed to be the initial posture (**Fig.3**) and three physical relationships between center of gravity G of the initial posture and toe T acting as the working point of the ground reaction force. These positions of the center of gravity are as follows:

Placed on the perpendicular passing through the working point of the ground reaction force (vertical position),

Placed $-\pi/6$ behind the perpendicular (posterior position),

Placed $\pi/6$ before the perpendicular (anterior position).

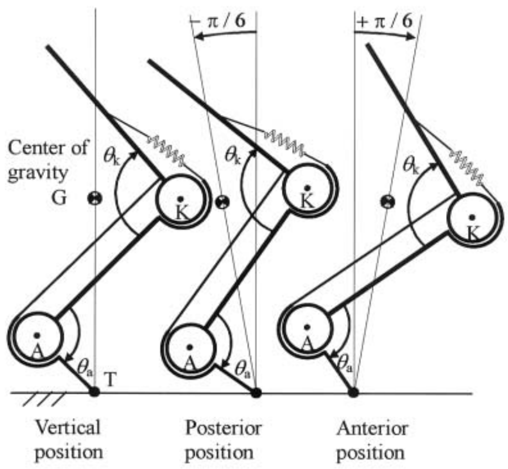


Fig. 3. Initial posture conditions.

The model without the bi-articular muscle has its leg joint fixed to retain these initial postures.

2.2. Computer Simulation

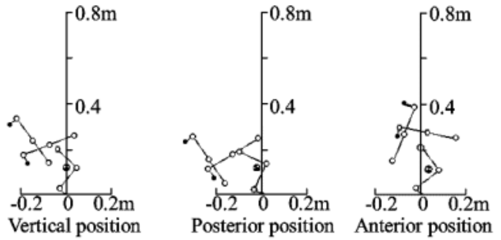
Simulation uses Mathematica, a mathematical expression software package developed by Wolfram Research, to solve the Lagrangian equation of motion. Assume a sum of U_g, a summation of gravitational potential energies at mass points of m_1 to m_3, and U_s, a spring elastic potential energy, to be total potential energy $U\ (= U_g + U_s)$, and a sum of T_v, a summation of translational kinetic energies, and T_w, a summation of rotational kinetic energies, to be the total kinetic energy $T\ (= T_v + T_w)$. From this assumption, build up the equation of motion with the Lagrangian as $L\ (= T - U)$ using the following expression:

$$\frac{d}{dt}\frac{\partial L}{\partial \dot{\theta}_i} - \frac{\partial L}{\partial \theta_i} = \sum_{j=1}^{3} A_{ij} f_j \qquad (i = 1, 2, \ldots, 5) \quad . \quad (1)$$

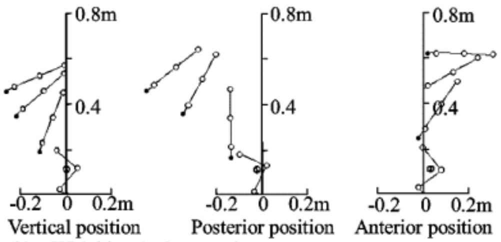
where θ_i is generalized coordinate, θ_1, θ_2, and θ_3 joint angles, θ_4, θ_5 positions of toe T, f_j Lagrange multiplier, f_1 and f_2 ground reaction force of toe T, f_3 wire tension, and A_{ij} is function of θ_i and found from initial conditions and constraints.

2.3. Stability of Jumping

Figure 4 shows model jumping with and without the bi-articular muscle. That without the bi-articular muscle jumps with a hard rotary motion with minimal height. The model with the bi-articular muscle jumps upwards with minimal rotary motion and considerable height. Without the bi-articular muscle, the center of gravity of the model jumps 0.20m heights in vertical as initial posture, 0.20 and 0.25m heights in posterior position and anterior position as the initial posture, respectively. With the bi-articular muscle, it has a jumping height of 0.55, 0.55 and 0.60m heights in the sequence of vertical, posterior position and anterior position as the initial posture.



(a) Without bi-articular muscle



(b) With bi-articular muscle

Fig. 4. Jumping posture in computer simulation.

The bi-articular muscle suppresses model rotation and stabilizes keeps it increasing jump height.

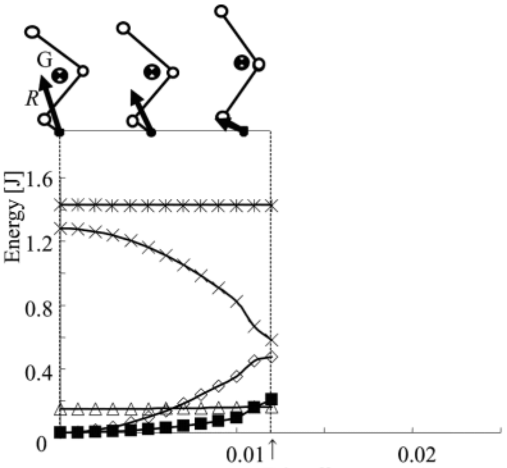
2.4. Relationship Between the Ground Reaction Force and the Center of Gravity

Figure 5 shows the posture until takeoff, changes in the ground reaction force *R* and center of gravity G, and transition of energy in case of initial posture condition is vertical. Time to takeoff is 0.01 second for the model without the bi-articular muscle and 0.02 second for that with the bi-articular muscle. Both have the same elastic energy generating a force, but the model with the bi-articular muscle has a longer time for ground reaction force *R* to work than without. For the model with the bi-articular muscle, the line of ground reaction force *R* moves near the center of gravity G even if the knee is extended. The model without the bi-articular muscle has line of ground reaction force *R* moves away from center of gravity G with extension in the knee. Posterior and anterior initial posture have a trend similar to the vertical posture.

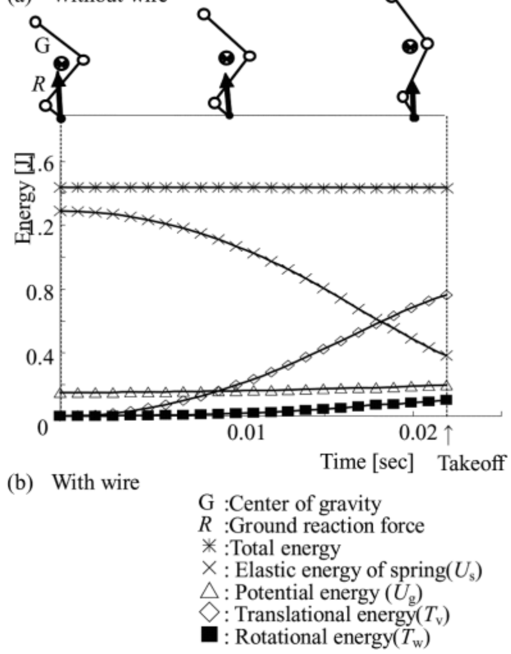
2.5. Energy Transition

Figure 5 also shows gravitational potential energy (U_g), elastic potential energy of the spring (U_s), translational kinetic energy (T_v), and rotational kinetic energy (T_w). The model without the bi-articular muscle has a translational kinetic energy (T_v) at takeoff about 0.6 times the model with the bi-articular muscle. The model without the wire has a rotational kinetic energy (T_w) at takeoff about 2.1 times the model with the wire. Posterior and anterior of the initial posture have a trend similar to the vertical posture.

The wire helps convert elastic potential energy of the spring (U_s) to a translational kinetic energy (T_v) and suppresses conversion to a rotational kinetic energy (T_w).



(a) Without wire



(b) With wire

Fig. 5. Energy transition during take off movement in computer simulation.

3. Experiments

The trial model was used to confirm the ground reaction force and the position of the center of gravity for the impact of the wire on its jumping.

3.1. Experiments Using the Trial Model

Figure 6 is the trial model that has embodied of the model used for computer simulation, whose specifications are almost the same as those for computer simulation. The model without the bi-articular muscle had its leg joint fixed to maintain the initial posture. In these experiments (**Fig.7**), the model is pushed and reduced on the force sensor until the initial posture is established (**Fig.3**) and the knee spring is stretched, accumulating elastic energy for jumping. The model jumps by release this restraint.

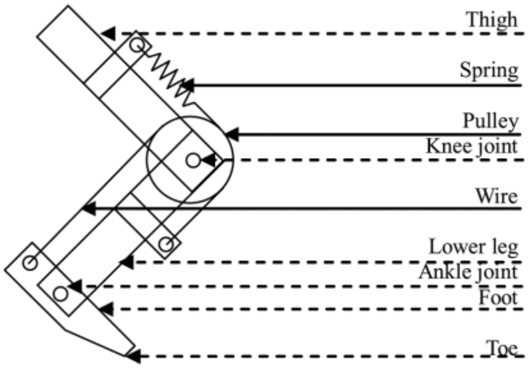


Fig. 6. Experimental model.

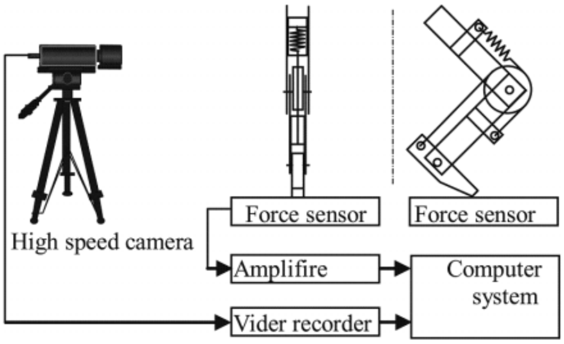


Fig. 7. Experimental schema.

A force sensor (9257-B Kistler Co.) measures the force acting on the ground until the model jumps. Simultaneously, the high-speed video camera (Fastcam-Rabbit mini 2 Photron Co.) records motion until jumping and posture in the air.

3.2. Stability of Jumping

Figure 8 shows aerial jumping posture for all initial posture conditions. The model without the bi-articular muscle jumps with a hard rotary motion, while the model with the bi-articular muscle jumps upward without a large rotary motion. Without the bi-articular muscle, the center of gravity of the model has a jumping height of 0.25, 0.20 and 0.30m in the sequence of horizontal, posterior tilting and anterior tilting as the initial posture, while the model with the bi-articular muscle has a jump height of 0.50, 0.40 and 0.50m in those posture and jumps higher.

These results agree with those for computer simulation. The bi-articular muscle enable a higher, stabler jump suppressing airborne model rotation.

3.3. Relationship Between the Ground Reaction Force and the Center of Gravity

Figure 9 shows postural change until takeoff in the vertical initial posture, for ground reaction force. The time until takeoff when ground reaction force *R* is 0.02 second for the model without the bi-articular muscle 0.03 second for that with the bi-articular muscle. The elastic energy of a spring that is the source of force is the same, but ground reaction force *R* operates longer for the model with the bi-articular muscle.

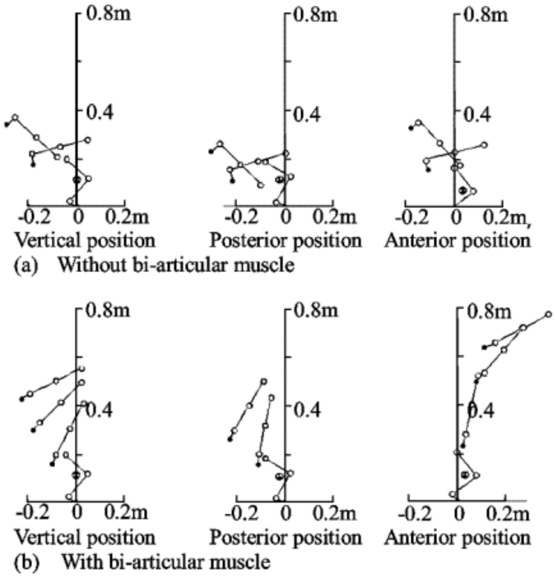


Fig. 8. Jumping posture in experiment.

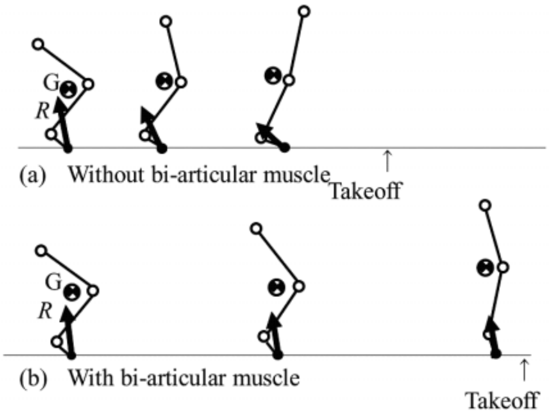


Fig. 9. Take off movement in experiments.

For the model without the bi-articular muscle, the action line of ground reaction force *R* moves away from center of gravity G and changes from the direction close to the horizontal to the vertical when the knee extends. For the model with the bi-articular muscle, the action line of ground reaction force *R* moves near center of gravity G and its direction remains almost constant even if the knee extends.

These results are the same as for computer simulation.

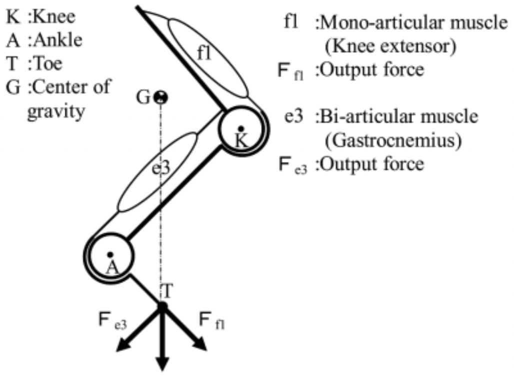


Fig. 10. Output force by each muscle.

4. Conclusions

We used the Jumping Jack without a guide rail to determine the impact of the bi-articular muscle on jumping. The bi-articular muscle enables the ground reaction force to adjust so its line of action invariably passes near the center of gravity, suppressing conversion from elastic energy to kinetic energy of rotation, stabilizing the posture after takeoff.

4.1. Energy Transfer by Bi-Articular Muscle

From an analysis of computer simulation and the trial model, the model with the bi-articular muscle jumps higher compared to the jump height of the center of gravity. It has a longer working time of the ground reaction force. This result agrees to the report by Bobbert et al. [11], who concluded that the difference in jump height is due to energy transfer by the bi-articular muscle. The model developed by Bobbert et al. has a guide rail that clears kinetic energy of rotation, resulting in only kinetic energy of translation. Energy changes in our paper, however, show the difference was due to conversion of elastic energy of the spring to kinetic energy of rotation or translation.

4.2. Direction Control by Bi-Articular Muscle

An analysis of the results of computer simulation and the trial model showed that the bi-articular muscle adjusted the direction of the ground reaction reducing the moment arm related to the center of gravity of the ground reaction force, suppressing conversion of elastic energy of the spring to kinetic energy of rotation and stabilizing the airborne posture after takeoff.

Figure 10 shows the output at toe T of the Jumping Jack for the output distribution of four limbs by functionally effective muscles reported by Oshima [8]. Output generated by knee extensor f_1 at toe T is F_{f_1} and its direction is the same as for the foot. Output generated by bi-articular muscle e_3 at toe T is F_{e_3} and its direction is the same as for the lower leg. When the center of gravity is added, it becomes the force applied to the ground by toe T and the reaction becomes the ground reaction force. If a wire is used as the bi-articular muscle, the size ratio is not clear between vectors F_{f_1} and F_{e_3}, but the ground reaction force with the wire is apparently more toward the center of gravity than for the model without the wire. The Jumping Jack assumes muscle e_3, a bi-articular muscle, to be a wire without energy, but if is made a controllable actuator with energy, size ratio can be changed intentionally between F_{f_1} and F_{e_3}, making it possible to control the direction of the ground reaction force.

Acknowledgements

We thank Dr. Minayori Kumamoto, Professor Emeritus of Kyoto University for his instruction on the bi-articular muscle enabling this study.

References:

[1] M. H. Raibert, "Legged Robot that Balance," The MIT Press, 1986.
[2] D. E. Koditscheck, and M. Buehler, "Analysis of a Simplified Hopping Robot," The International J. Robotics Research, Vol.10, No.6, pp. 587-605, 1991.
[3] A. F. Vakakis, J. W. Burdick, and T. K. Caughey, "An Interesting Strange Attractor in the Dynamics of a Hopping robot," The International J. Robotics Research, Vol.10, No.6, pp. 606-618, 1991.
[4] R. T. M'Closkey, and J. W. Burdick, "Periodic Motions of a Hopping Robot with Vertical and Forward Motion," The International J. of Robotics Research, Vol.12, No.3, pp. 197-218, 1993.
[5] C. Francois, and C. Samson, "A New Approach to the Control of the Planter One-legged Hopper," The International J. of Robotics Research, Vol.17, No.11, pp. 1150-1166, 1998.
[6] S. Hyon, S. Kamijo, and T. Mita, " 'Kenken' – A Biologically Inspired One-Legged Running Robot," J. Robot Society of Japan, Vol.20, No.4, pp. 103-112, 2002.
[7] M. Kumamoto, and T. Oshima, "Control Properties Induced by the Existence of Antagonistic Pair of Bi-articular Muscles (Mechanical Engineering Model Analyses)," Human Movement Science, Vol.13, No.5, pp. 611-634, 1994.
[8] T. Oshima, T. Fujikawa, and M. Kumamoto, "Coordination Control of Arm using Antagonistic Actuators," J. Robotics and Mechatronics, Vol.14, No.3, pp. 270-277, 2002.
[9] A. J. van Soest, A. L. Schwab, M. F. Bobbert, and G. J. van Ingen Schenau, "The Influence of the Biarticularity of the Gastrocnemius Muscle on Vertical-jumping Achievement," J. Biomechanics, Vol.26, No.1, pp. 1-8, 1993.
[10] M. G. Pandy, F. E. Zajac, E. U. Sim, and W. S. Levine, "An Optimal Control Model for Maximum-height Human Jumping," J. Biomechanics, Vol.23, No.12, pp. 1185-1198, 1990.
[11] M. F. Bobbert, E. Hoek, G. J. van Ingen Schenau, A. J. Sargeant, and A. W. Schreurs, "A Model to Demonstrate the Power Transporting Role of Biarticular Muscles," J. Physiology, Vol.387, p. 24, 1987.

Name:
Toru Oshima

Affiliation:
Associate Professor, Faculty of Engineering, Toyama Prefectural University

Address:
Kurogawa 5180, Kosugi, Toyama 939-0398, Japan

Brief Biographical History:
1986- Tokyo Metropolitan Prosthetic and Orthotic Research Institute
1990- Toyama Prefectural University

Main Works:
- "Effects of Link and Actuator Parameters on the Control Properties of the Two-joint Link Mechanism with the Bi-articular Actuators," Proc. of 6th Japan-France Congress & 4th Asia-Europe Congress on Mechatronics, pp. 530-534, 2003.

Membership in Learned Societies:
- The Japan Society of Mechanical Engineers (JSME)
- The Robotics Society of Japan (RSJ)
- The Japanese Society of Instrumentation and Control Engineers (SICE)

Name:
Tomohiko Fujikawa

Affiliation:
Assiatant Professor, Faculty of Education, Toyama National College of Maritime Technology

Address:
Ebieneriya 1-2, Shinminato, Toyama 939-0293, Japan

Brief Biographical History:
1999- Toyama National College of Maritime Technology

Main Works:
- "Effects of Link and Actuator Parameters on the Control Properties of the Two-joint Link Mechanism with the Bi-articular Actuators," Proc. of 6th Japan-France Congress & 4th Asia-Europe Congress on Mechatronics, pp. 530-534, 2003.

Membership in Learned Societies:
- The Japan Society of Mechanical Engineers (JSME)
- The Japan Society of Precision Engineering (JSPE)
- Society of Biomechanisms Japan (SOBIM)

Name:
Kiyoshi Toriumi

Affiliation:
Associate Professor, Faculty of Education, Toyama University

Address:
Gofuku 3190, Toyama 939-8555, Japan

Brief Biographical History:
1988- Chukyo University
1990- Toyama University

Main Works:
- "Functional Role of the Mono- and the Bi-articular Actuators Provided around the Ankle Joint of Jumping Robot," Proc. of 6th Japan-France Congress & 4th Asia-Europe Congress on Mechatronics, pp. 421-426, 2003.

Membership in Learned Societies:
- The Japan Society of Mechanical Engineers (JSME)
- The Robotics Society of Japan (RSJ)
- The Japanese Society of Physical Fitness and Sports Medicine (PFSM)

Name:
Noboru Momose

Affiliation:
Assistant Professor, Faculty of Engineering, Toyama Prefectural University

Address:
Kurogawa 5180, Kosugi, Toyama 939-0398, Japan

Brief Biographical History:
1991- Toyama Prefectural University

Main Works:
- "Control System for Human Stabilization of Electric Powered Wheelchair," Proc. of 6th Japan-France Congress & 4th Asia-Europe Congress on Mechatronics, pp. 56-60, 2003.

Membership in Learned Societies:
- The Japan Society of Mechanical Engineers (JSME)
- Heat Transfer Society of Japan (HTS)
- The Japanese Society of Instrumentation and Control Engineers (SICE)