Research article

Design Principle Based on Maximum Output Force Profile for a Musculoskeletal Robot

Ryuma Niiyama
Graduate School of Interdisciplinary Information Studies,
The University of Tokyo, Japan, and

Yasuo Kuniyoshi
Graduate School of Information Science and Technology, Department of Mechano-Informatics,
The University of Tokyo, Japan

Abstract

Purpose – This paper focuses on an engineering application of the vertebrate musculoskeletal system. The musculoskeletal system has unique mechanisms such as bi-articular muscle, antagonistic muscle pairs and muscle-tendon elasticity. The "Artificial Musculoskeletal System" is achieved through the use of the pneumatic artificial muscles. The study provides a novel method to describe the force property of the articulated mechanism driven by muscle actuator and a transmission.

Design / methodology / approach – A musculoskeletal system consists of multiple bodies connected together with rotational joints and driven by mono- and bi-articular actuators. We analyze properties of the musculoskeletal system with statically calculated omni-directional output forces. A set of experiments has been performed to demonstrate the physical ability of the musculoskeletal robot.

Findings – We propose a method to design a musculoskeletal system based on an analysis of the profile of convex polygon of maximum output forces. The result shows that the well-designed musculoskeletal system enables the legged robot to jump 0.6m high and land softly from 1.0m drop off.

Originality / value – The paper provides a design principle for a musculoskeletal robot. The musculoskeletal system is the bio-inspired mechanism for all multi-degrees-of-freedom articulated devices, and has the advantages of optimized actuator configuration and force control.

Keywords Biomechanics, Legged Robot, Pneumatic Artificial Muscle, Bio-Inspired Machine

Paper type Research paper

1. Introduction

The musculoskeletal system gives animals the ability to move in a huge variety of environments. The mechanical properties of the muscle-tendon and its function in dynamic motion are much debated issue in biomechanics research (Alexander *et al.,* 2002; van Soest and Bobbert*,* 1993; van Ingen Schenau, 1989). The athletic motions involve collision and contact with the ground which are difficult to model and simulate. Thus we propose biomechanical approach using a musculoskeletal "Athlete Robot'" to investigate the role of the musculoskeletal structure of the animals.

The dynamic motion (such as jumping, landing and running) is characterized by large instantaneous forces and short duration. In such motion, strict design limitations force the robot to have a lot in common with animals (Niiyama *et al.,* 2007). A lot of bio-inspired legged robot had been proposed. For example, researchers have developed a bipedal walker driven by pneumatic muscle (Verrelst *et al.*, 2005), mono-leg hopping robots (Hyon *et al.*, 2002; Hosoda *et al.*, 2008), and humanoid robots driven by wire (Mizuuchi *et al.,* 2002). However, there are a few robots which have a biologically-correct musculoskeletal structure (Niiyama *et al*., 2008; Takuma *et al*., 2008).

In this research, we propose a method to design the properties of the musculoskeletal robot. Our experimental system is a bipedal "Athlete Robot'" with an artificial musculoskeletal system. We demonstrate the physical ability of the well-designed musculoskeletal robot through the experiments of vertical jumping, soft landing and passive control of a bouncing.

Industrial Robot: An International Journal
37/3 (2010) ???–???
Emerald Group Publishing Limited [ISSN 0143-991X]

2. Force Properties of Musculoskeletal System

2.1 Modeling of Musculoskeletal Structure

To analyze the characteristics of the musculoskeletal system, we employ the method based on statics and kinematics of the serial-link structures (Ito *et al.,* 1988). Note that the model includes the actuators and the

Figure 1 Mono- and bi- articular actuator.

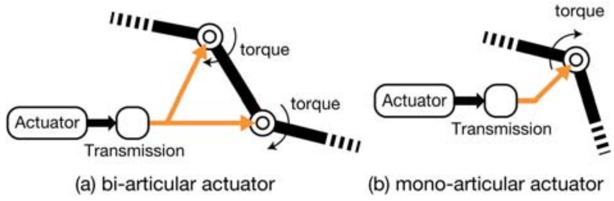
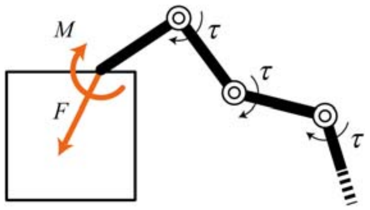


Figure 2 Statics of the serial-link structure.



transmissions, and one actuator can affect multiple joints as shown in Figure 1.

Let $\boldsymbol{Q}$ be the generalized force consist of force $\boldsymbol{F}$ and moment $\boldsymbol{M}$ at the contact between link and environment (Figure 2).

$$\boldsymbol{Q} = \begin{bmatrix} \boldsymbol{F} \\ \boldsymbol{M} \end{bmatrix} \qquad \text{eq.(1)}$$

The equilibrium of joint torque $\boldsymbol{\tau}$ with generalized force $\boldsymbol{Q}$ is described by the well known equation due to the duality between differential kinematics and statics as

$$\boldsymbol{\tau} = \boldsymbol{J}^T(\boldsymbol{\theta})\boldsymbol{Q} \qquad \text{eq.(2)}$$

Here a matrix $\boldsymbol{J}(\boldsymbol{\theta})$ is the Jacobian matrix represents the differential relationship between the joint motion and the resulting end-effecter motion at the contact point. We can also consider the equilibrium of joint torque $\boldsymbol{\tau}$ with force and moment $\boldsymbol{f}$ generated by the actuators as follows.

$$\boldsymbol{\tau} = \boldsymbol{G}^T(\boldsymbol{\theta})\boldsymbol{f} \qquad \text{eq.(3)}$$

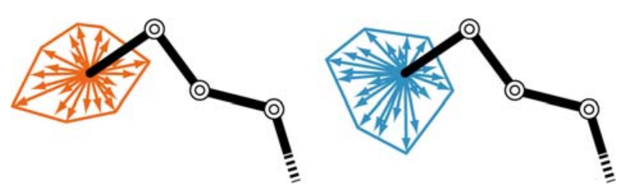
The matrix $\boldsymbol{G}(\boldsymbol{\theta})$ is the Jacobian matrix represents the differential relationship between joint motion and the displacement of the actuator output. The each element of the matrix $\boldsymbol{G}(\boldsymbol{\theta})$ represents transmission ratio depends on the moment arm of the joint for muscle or the gear reduction ratio for electric motor. In addition, the stiffness of the system at the contact point and stiffness of the actuators are also described using Jacobian matrix $\boldsymbol{J}(\boldsymbol{\theta})$ and $\boldsymbol{G}(\boldsymbol{\theta})$.

Based on the above discussion, the design of the musculoskeletal system is an inverse problem which computes output force $\boldsymbol{f}$ and stiffness of the actuators from desired stiffness and output force $\boldsymbol{Q}$ of the system at the contact point.

2.2 Maximum output force profile

The measures of dexterity and force properties of robotic mechanisms are discussed (Yoshikawa, 1985; Siciliano, 1990). In previous study, only the force properties of two-joint musculoskeletal arm based on the geometric method was described (Oshima *et al*., 2000; Kumamoto *et al*., 1994). We propose a "Maximum output force profile" to describe the force properties of the musculoskeletal system. The method is applicable for the musculoskeletal system with more than two joints and which takes into account the limited range of actuator output.

Figure 3 Concept of maximum output force profile.



The "Maximum output force profile" defined as a convex polygon which encompasses force vectors produced by all combination of actuator output (Figure 3). The polygon can represent a distribution of maximum output force vectors of the musculoskeletal system. The convex polygon could be naturally extended to three-dimensional convex polytope.

We can rewrite the eq.(1) using norm $\| \boldsymbol{F} \|$ and unit direction vector $\boldsymbol{n}$ as follows to derive a maximum force vector in a particular direction.

$$\boldsymbol{Q} = \begin{bmatrix} \boldsymbol{F} \\ \boldsymbol{M} \end{bmatrix} = \begin{bmatrix} \| \boldsymbol{F} \| \boldsymbol{n} \\ \boldsymbol{M} \end{bmatrix} \qquad \text{eq.(4)}$$

From the eq.(2) and eq.(3) we get

$$\boldsymbol{G}^T(\boldsymbol{\theta})\boldsymbol{f} - \boldsymbol{J}^T(\boldsymbol{\theta})\boldsymbol{Q} = \boldsymbol{O} \qquad \text{eq.(5)}$$

Thus the norm of output force vector is derived using eq.(4) and (5) as follows.

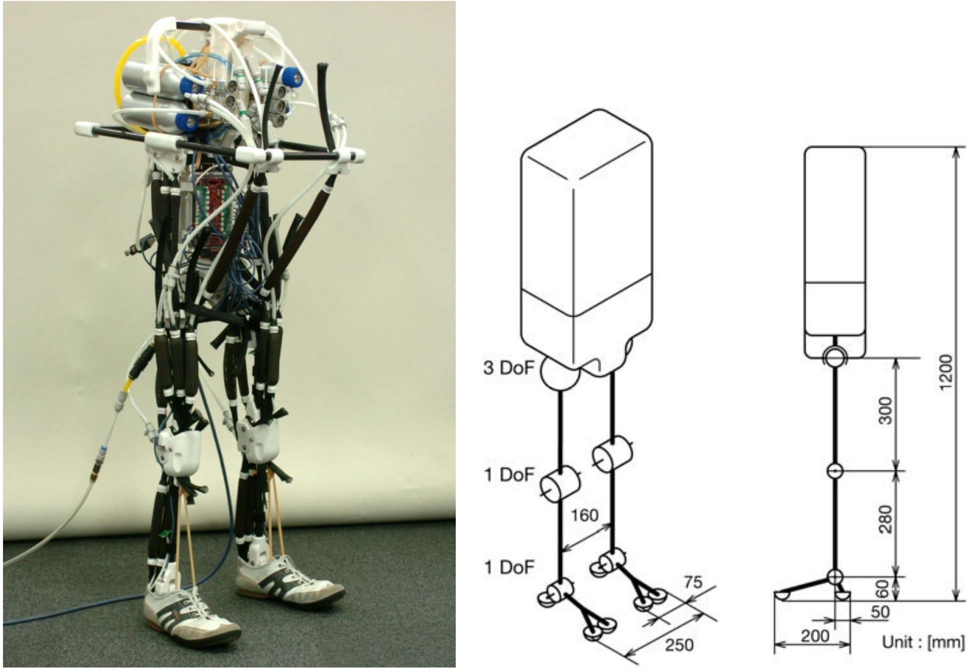
$$\begin{aligned} \| \boldsymbol{F} \| &= \frac{\boldsymbol{a}(\boldsymbol{\theta})^T}{\boldsymbol{a}(\boldsymbol{\theta})^T \boldsymbol{a}(\boldsymbol{\theta})} \left(\boldsymbol{G}^T(\boldsymbol{\theta})\boldsymbol{f} - \boldsymbol{b}(\boldsymbol{\theta}) \right) \\ \boldsymbol{a}(\boldsymbol{\theta}) &= \boldsymbol{J}^T(\boldsymbol{\theta}) \begin{bmatrix} \boldsymbol{n} \\ \boldsymbol{O} \end{bmatrix}, \quad \boldsymbol{b}(\boldsymbol{\theta}) = \boldsymbol{J}^T(\boldsymbol{\theta}) \begin{bmatrix} \boldsymbol{O} \\ \boldsymbol{M} \end{bmatrix} \end{aligned} \qquad \text{eq.(6)}$$

An optimization problem to find the $\boldsymbol{f}$ and $\boldsymbol{M}$ which maximize the scholar function eq.(6) from given direction vector n, is specified by eq.(7). The actuator output $\boldsymbol{f} = [f_1, f_2, \dots, f_n]^T$ must be set within a range of lower boundary $\boldsymbol{f}_{lb} = [f_{lb\ 1}, f_{lb\ 2}, \dots, f_{lb\ n}]^T$ to upper boundary $\boldsymbol{f}_{ub} = [f_{ub\ 1}, f_{ub\ 2}, \dots, f_{ub\ n}]^T$.

$$\begin{aligned} &\max_{\boldsymbol{f}, \boldsymbol{M}} N_F = \frac{\boldsymbol{a}(\boldsymbol{\theta})^T}{\boldsymbol{a}(\boldsymbol{\theta})^T \boldsymbol{a}(\boldsymbol{\theta})} \left(\boldsymbol{G}^T(\boldsymbol{\theta})\boldsymbol{f} - \boldsymbol{b}(\boldsymbol{\theta}) \right) \\ &\quad \boldsymbol{a}(\boldsymbol{\theta}) = \boldsymbol{J}^T(\boldsymbol{\theta}) \begin{bmatrix} \boldsymbol{n} \\ \boldsymbol{O} \end{bmatrix}, \quad \boldsymbol{b}(\boldsymbol{\theta}) = \boldsymbol{J}^T(\boldsymbol{\theta}) \begin{bmatrix} \boldsymbol{O} \\ \boldsymbol{M} \end{bmatrix} \\ &\text{s.t.} \quad \boldsymbol{G}^T(\boldsymbol{\theta})\boldsymbol{f} - N_F \boldsymbol{a}(\boldsymbol{\theta}) - \boldsymbol{b}(\boldsymbol{\theta}) = 0 \\ &\qquad f_{lb\ i} \le f_i \le f_{ub\ i} \quad i = 1, 2, \dots, n \end{aligned} \qquad \text{eq.(7)}$$

In the case of legged robot, it cannot be obtained sufficient

Figure 4 Athlete Robot with an artificial musculoskeletal system.



torque (moment of force) at the contact point. Hence we can transcribe the eq.(7) with the zero moment condition as eq.(8).

$$
\begin{aligned}
&\max_{\boldsymbol{f}} N_F = \frac{\boldsymbol{a}(\boldsymbol{\theta})^T}{\boldsymbol{a}(\boldsymbol{\theta})^T \boldsymbol{a}(\boldsymbol{\theta})} \boldsymbol{G}^T(\boldsymbol{\theta}) \boldsymbol{f} \\
&\boldsymbol{a}(\boldsymbol{\theta}) = \boldsymbol{J}^T(\boldsymbol{\theta}) \begin{bmatrix} \boldsymbol{n} \\ \boldsymbol{O} \end{bmatrix} \\
&\text{s.t.} \quad \boldsymbol{G}^T(\theta)\boldsymbol{f} - N_F \boldsymbol{a}(\boldsymbol{\theta}) = 0 \\
&\qquad f_{lb\ i} \le f_i \le f_{ub\ i} \quad i = 1, 2, \ldots, n
\end{aligned}
\qquad \text{eq.(8)}
$$

The outline of the maximum output force profile is plotted with the series of end points of the maximum output forces in all direction calculated by above equations.

3. Musculoskeletal Athlete Robot

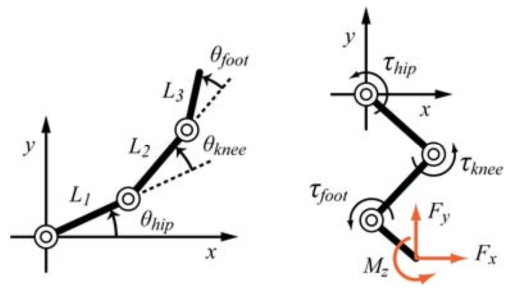
3.1 Overview

We apply the method to a bipedal "Athlete Robot" with an artificial musculoskeletal system (Figure 4). The artificial musculoskeletal system is the novel robot architecture based on biomechanics of the biological structure of vertebrate animals. In our work, pneumatic artificial muscles are used for the actuator. The robot, weighs about 10 kg and is 1.25 meters tall with the legs extended. We apply proportional valves to the electro-pneumatic system instead of conventional on-off valves. The proportional valve can transform an analogue electric signal into a corresponding air flow. The valves and a CPU board are mounted on the robot. The electrical power and compressed air is supplied from external equipment. The robot has a rotary position sensor on each joint, and a pressure sensor on each muscle.

3.2 Force Profile of planar 3-DoF musculoskeletal leg

We calculate the maximum output force profile of planar musculoskeletal legs with various muscle configurations as the pilot study. The joint angle, joint torque and output force at the contact point are defined as follows.

Figure 5 Parameters of the planar 3 DoF leg.



$$
\begin{aligned}
\boldsymbol{\theta} &= [\theta_{hip}, \theta_{knee}, \theta_{foot}]^T \\
\boldsymbol{\tau} &= [\tau_{hip}, \tau_{knee}, \tau_{foot}]^T \\
\boldsymbol{Q} &= [F_x, F_y, M_z]^T
\end{aligned}
\qquad (3)
$$

The following is the column vector of actuator output consists of tension forces generated by muscles. The symbols in subscripts are, GMAX: gluteus maximus muscle, IL: iliopsoas muscle, HAM: hamstrings, RF: rectus femoris, BF: short head of biceps femoris muscle, VAS: 3-component vastus muscles, GAS: gastrocnemius muscle, NULL: a muscle not exist in human, SOL: soleus, TA: tibialis anterior.

$$
\begin{aligned}
\boldsymbol{f} = [\ & f_{GMAX} \quad f_{IL} \quad f_{HAM} \quad f_{RF} \quad f_{BF} \\
& f_{VAS} \quad f_{GAS} \quad f_{NULL} \quad f_{SOL} \quad f_{TA}\ ]^T
\end{aligned}
\qquad (4)
$$

We use simplified parameters to investigate the brief force profile of the musculoskeletal leg. The maximum

Industrial Robot: An International Journal
Volume 37 ・ Number 3 ・ 2010 ・ ???–???

Figure 6 Maximum output force profile of the musculoskeletal leg with uniform muscle configuration. There are two types of conditions at the contact point: zero moment and unlimited moment (L_1 = 0.3m, L_2=0.3m, L_3=0.15m, θ_{hip}=-π/3, θ_{knee}=-π/2, θ_{foot}=π*2/3)

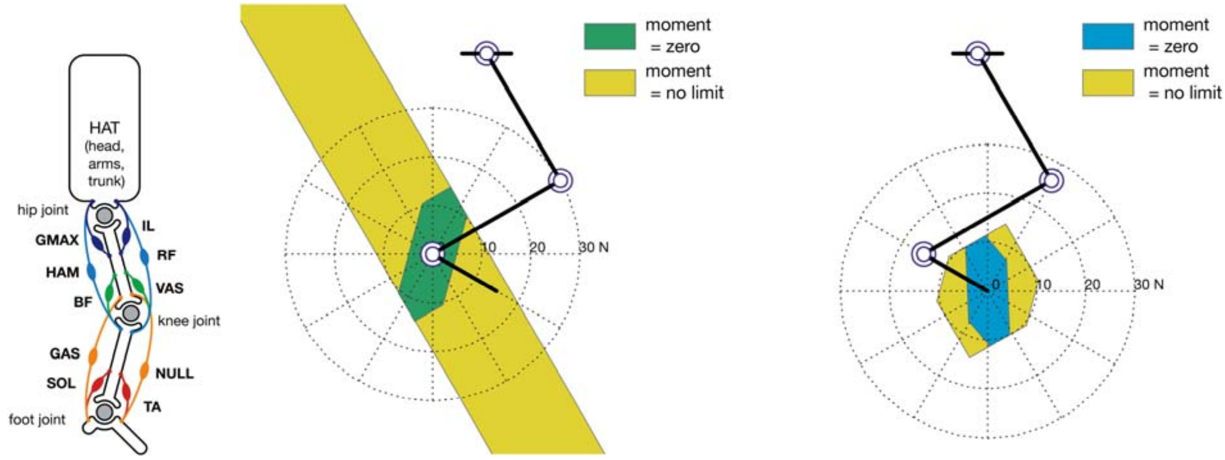
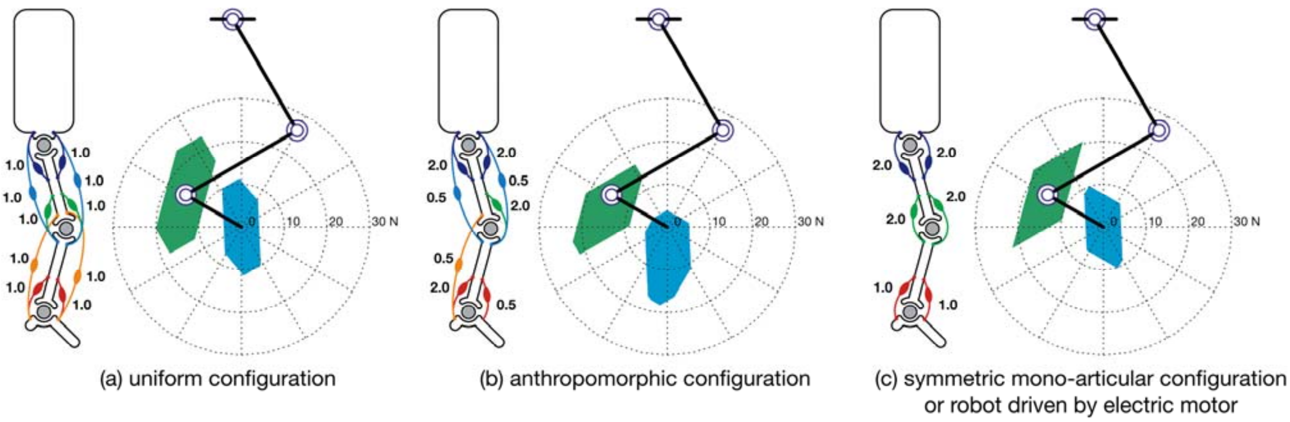


Figure 7 Force profiles of the various muscle configurations.



tensions of the muscles are constant in any length. The moment arms of the joints are also constant and set to unit value 1.0 or -1.0 as follows. The bi-articular muscles have multiple moment arm values in matrix $\boldsymbol{G}(\boldsymbol{\theta})$.

$$\boldsymbol{G} = \begin{bmatrix} -1 & 1 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 1 & -1 & 1 & -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 & -1 & 1 \end{bmatrix}^T \quad (5)$$

Figure 6 shows the basic property of the maximum output force profile at the heel and the toe of the musculoskeletal leg with the uniform muscle configuration.

Figure 7 shows the various muscle configurations under the constraint of constant total amount of muscles. The leg with uniform muscles has isotropic force profile in all directions. The leg with human-like muscle configuration has the force profile with large downward forces which is optimized for movements under the force of gravity. The leg with symmetric mono-articular muscles, which is compatible with the joint mechanism with an electric motor, has isotropic but angular shaped force profile. Flexibility of design is limited in the system which has neither antagonistic mechanism nor multi-articular actuator (Hogan, 1998; Kumamoto *et al*., 1994).

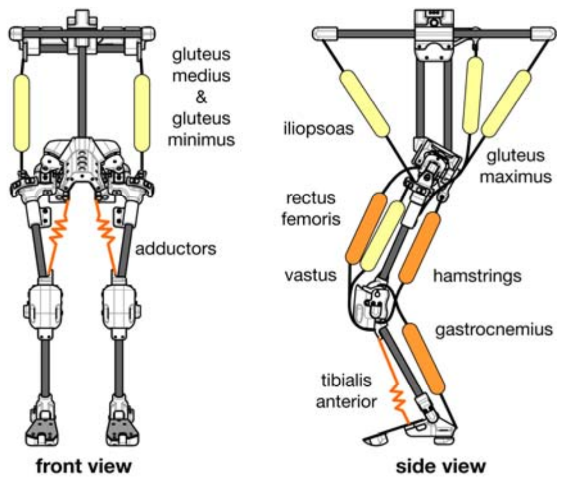
3.3 Muscular System and Skeletal System

The McKibben type pneumatic artificial muscle is used for the practical implementation of the artificial musculoskeletal system we propose. The pneumatic muscle has extremely high power/weight ratio and similar characteristics in length-load curves with biological muscle (Schulte *et al*., 1961).

The skeletal frame consists mostly of polymer parts. The polymer bearings, nylon joint parts, and FRP bones contribute to lightweight and high-impact durable skeletal frame.

The musculoskeletal system of the robot corresponding to the anatomical structure of the human is shown in (Figure 8). The range of motion (RoM) and moment arms on each joint are designed to be compatible with a human. Then, configuration of the muscles and upper limits of muscle forces are designed base on the matching of the maximum

Figure 8 Layout of muscles of the Athlete Robot.



output force profiles of the musculoskeletal robot and human. The parameters of the musculoskeletal system of the robot are shown in Table 1.

Table 1 Muscle tensions and moment arms on each joint.

muscle	F_{max} (N)	D_{hip} (m)	D_{knee} (m)	D_{foot} (m)
adductors	200	0.060	-	-
gluteus medius, gluteus minimus	1600	0.048	-	-
gluteus maximus	3200	0.050		
iliopsoas	1600	0.050	-	-
hamstrings	1600	0.060	0.020	-
rectus femoris	800	0.024	0.024	-
vastus	2400		0.024	-
gastrocnemius	1600	-	0.020	0.050
tibialis anterior	200	-	-	0.035

4. Experiments and Results

4.1 Vertical jumping and soft landing

The vertical jumping is a simple movement which widely used to evaluate power, skills, and characteristics of the musculo-tendon complex. Our experiments confirmed that the robot can reach jump heights of 0.5 m, as shown in Figure 9. As a full-scale humanoid robot, the physical ability of the Athlete Robot is extremely high.

The robot can land softly from one meter drop by exploiting the enhanced anti-gravity muscles, compliance of the actuators, and back-drivability of the joint mechanism (Figure 10). These tasks are particularly difficult for the robot when driven by the geared motors because of the large instantaneous forces and short duration.

4.2 Passive control of landing and bouncing

The sensor feedback control is a dominant component in the task to maintain posture against disturbance. In contrast, feed-forward controls become considerably important in explosive movements. The musculoskeletal leg can use preset stiffness to control posture predictively.

The direction control of the bouncing appears in running for example. Here, we achieve passive control of the bouncing by preset stiffness. The stiffness of the leg is expressed as ellipsoid and its gradient of long axis. The results shows that we can control the direction of the bouncing both fall forward (Figure 11) and fall backward (Figure 12).

5. Conclusion

In this research, we propose the “Maximum output force profile” to visualize and design the properties of the musculoskeletal system. The method, which is based on the kinematics and statics of serial-link structure, is able to describe force properties of the musculoskeletal system as a convex polygon or a convex polytope.

We use bipedal “Athlete Robot” with an artificial musculoskeletal system to demonstrate the physical ability of the musculoskeletal robot designed by the method of maximum output force profile.

The well-designed leg has the bi-articular muscles and the asymmetry antagonistic muscle pairs optimized for the gravity field. The result shows that the robot can reach jump heights of 0.5 m and endure the large ground reaction force involved in landing. In the experiments of the passive control of bouncing, we can control the direction of the bouncing by preset stiffness of the musculoskeletal leg. Such feed-forward control play big role especially in the explosive movements with large instantaneous forces and short duration time.

References

Alexander, R.M. (2002), “Tendon elasticity and muscle function”, *Comparative Biochemistry and Physiology. Part A: Comparative Physiology*, Vol. 133, Issue 4, pp. 1001–1011.

Hogan, N. (1985), “The Mechanics of Multi-Joint Posture and Movement Control”, *Biological Cybernetics*, Vol.52, No.5, pp.315-331.

Hosoda, K., Takayama, H., and Takuma, T. (2008), “Bouncing monopod with bio-mimetic muscular-skeleton system, *Proceedings of the 2008 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2008)*, pp.3083–3088.

Hyon, S. and Mita, T. (2002), “Development of a Biologically Inspired Hopping Robot –Kenken”, *Proceedings of the IEEE International Conference on Robotics and Automation 2005 (ICRA 2005)*, Vol.4, pp.3984–3991.

van Ingen Schenau, G.J. (1989), “From Rotation to Translation: Constraints on Multi-Joint Movements and the Unique Action of Bi-Articular Muscles”, *Human Movement Science*, Vol.8, Issue 4, pp.301–337.

Ito, K., Tsuji, T., and Nagamachi, M. (1988), “Motor impedance and inverse kinematics in musculoskeletal systems”, *Proceedings of the IEEE Engineering in Medicine & Biology Society 10th Annual International Conference*, pp. 624–625.

Industrial Robot: An International Journal
Volume 37 · Number 3 · 2010 · ???–???

Figure 9 Vertical jumping from squatting position.

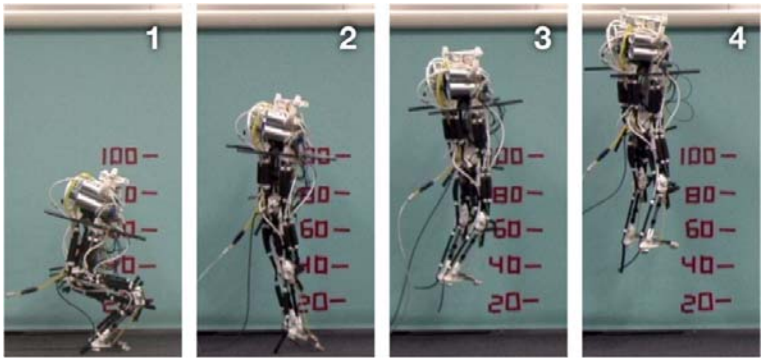


Figure 10 Soft landing from drop off height of 1.0 meter.

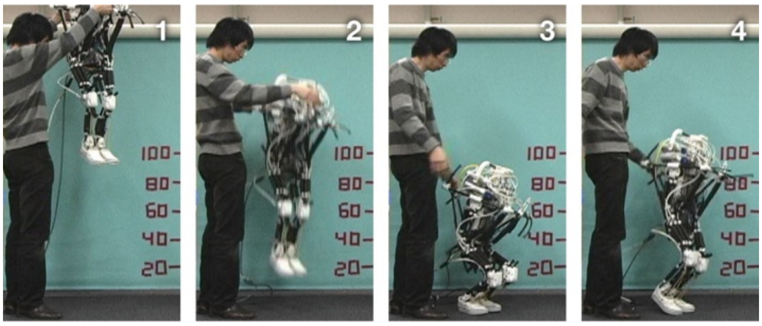


Figure 11 Passive control of bouncing by the preset stiffness (fall forward).

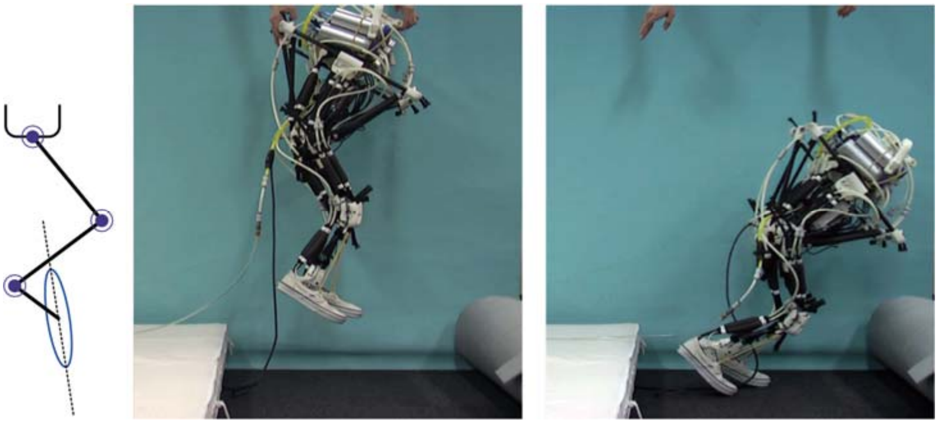
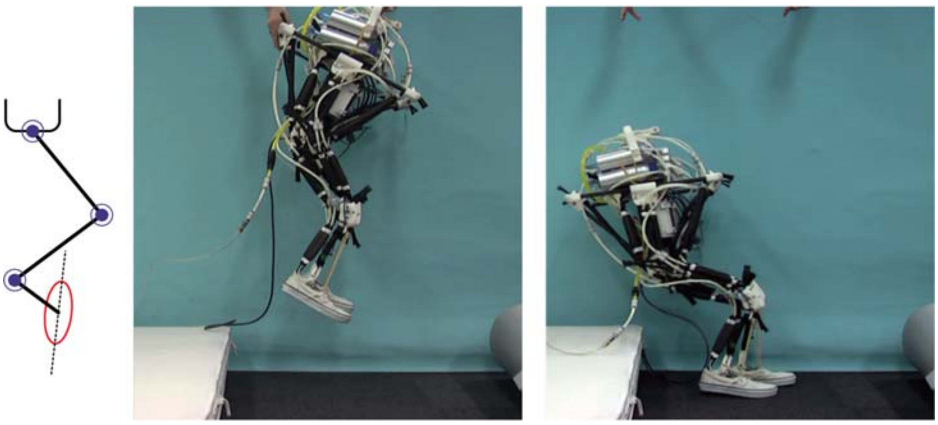


Figure 12 Passive control of bouncing by the preset stiffness (fall backward).



Industrial Robot: An International Journal
Volume 37 · Number 3 · 2010 · ???–???

Klute, G. K., Czerniecki, J. M. and Hannaford, B. (2002), “Artificial Muscles: Actuators for Biorobotic Systems”, *The International Journal of Robotics Research*, Vol. 21, No. 4, pp.295–309.

Kumamoto, M., Oshima, T., and Yamamoto, T. (1994), “Control Properties Induce by the Existence of Antagonistic Pairs of Bi-Articular Muscles –Mechanical Engineering Model Analyses”, *Human Movement Science*, Vol.13, No.5, pp.611–634.

Mizuuchi, I., Tajima, R., Yoshikai, T., Sato, D., Nagashima, K., Inaba, M., Kuniyoshi, Y., and Inoue, H. (2002), “The Design and Control of the Flexible Spine of a Fully Tendon-Driven Humanoid Kenta”, *Proceedings of the2002 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS2002)*, pp. 2527–2532.

Niiyama, R., Nagakubo, A. and Kuniyoshi, Y. (2007), “Mowgli: A Bipedal Jumping and Landing Robot with an Artificial Musculoskeletal System, *Proceedings of the 2007 IEEE Int. Conf. on Robotics and Automation (ICRA 2007)*, pp. 2546–2551 (ThC5.2).

Niiyama, R., Kuniyoshi, Y. (2008), “A Pneumatic Biped with an Artificial Musculoskeletal System”, *Proceedings of the 4th International Symposium on Adaptive Motion of Animals and Machines (AMAM2008)*, pp.80–81.

Takuma, T., Hayashi, S., and Hosoda, K. (2008), “3D bipedal robot with tunable leg compliance mechanism for multi-modal locomotion”, *Proceedings of the 2008 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2008)*, pp.1097–1102.

Oshima, T., Fujikawa, T., Kameyama, O., and Kumamoto, M. (2000), “Robotic Analyses of Output Force Distribution Developed by Human Limbs”, *Proceedings of the 2000 IEEE International Workshop on Robot and Human Interactive Communication*, pp. 229–234.

Schulte, H. F., Adamski, D. F. and Pearson, J. R. (1961), “Characteristics of the Braided Fluid Actuator”, *The University of Michigan Medical School Department of Physical Medicine and Rehabilitation Orthetics Research Project*, Technical Report No.5.

Siciliano, B. (1990), “Kinematic control of redundant robot manipulators: A tutorial”, *Journal of Intelligent and Robotic Systems*, Vol.3, No.3, pp.201–212.

van Soest, A. J. and Bobbert, M. F. (1993), “The Contribution of Muscle Properties in the Control of Explosive Movements”, *Biological Cybernetics*, Vol. 69, No. 3, pp.195–204.

Verrelst, B., Ham, R. V., Vanderborght, B., Daerden, F., Lefeber, D. and Vermeulen, J. (2005), “The Pneumatic Biped “Lucy” Actuated with Pleated Pneumatic Artificial Muscles”, *Autonomous Robots*, Vol. 18, No. 2, pp.201–213.

Yoshikawa, T. (1985), “Manipulability of Robotic Mechanisms”, *The International Journal of Robotics Research*, Vol.4, No.2, pp.3–9.