2007 IEEE International Conference on
Robotics and Automation
Roma, Italy, 10-14 April 2007

Mowgli: A Bipedal Jumping and Landing Robot with an Artificial Musculoskeletal System

Ryuma Niiyama
Graduate School of Interdisciplinary Information Studies,
The University of Tokyo
Tokyo, Japan
niiyama@isi.imi.i.u-tokyo.ac.jp

Akihiko Nagakubo
Intelligent Systems Research Institute,
National Institute of Advanced Industrial Science and Technology,
Ibaraki, Japan
nagakubo.a@aist.go.jp

Yasuo Kuniyoshi
Department of Mechano-Informatics,
The University of Tokyo,
Tokyo, Japan
kuniyosh@isi.imi.i.u-tokyo.ac.jp

Abstract— **Jumping and landing movements are characterized by large instantaneous forces, short duration, and a high uncertainty concerning take off and landing points. Such characteristics make conventional types of control and robot design inadequate. Here we present an approach to realize motor control of jumping and landing which exploits the synergy between control and mechanical structure. Our experimental system is a pneumatically actuated bipedal robot called "Mowgli". Mowgli's artificial musculoskeletal system consists of six McKibben pneumatic muscle actuators including bi-articular muscle and two legs with hip, knee, and ankle joints. Mowgli can reach jump heights of more than 50% of its body height and can land softly. Our results show a proximo-distal sequence of joint extensions during jumping despite simultaneous motor activity. Extensions in the whole body motion are caused by the compliance and the natural dynamics of the legs. In addition to the experiments with the real robot, we also simulated two types of open loop controllers for vertical jumping with disturbance. We found that the model controlled by open loop motor command through a muscle-tendon mechanism could jump robustly. The simulation results demonstrate the contribution of the artificial musculoskeletal system as a physical feedback loop in explosive movements.**

I. INTRODUCTION

The ability to move actively in the real world is the essential base of embodied intelligence[1]. The issue of embodiment cannot be ignored, especially for dynamic motions in an uncertain real world. To improve understanding of embodied intelligence, insights from a synthetic approach using real robots are necessary.

The role of tendon elasticity and muscle function in locomotion is a much debated issue in biomechanics research[2]. It's argued that animals utilize physical properties of their bodies to control dynamic motion[3]. For simple, static tasks, many robot designs are possible. In dynamic whole body motions such as jumping, landing, and running, special problems arise which force the robot to have a lot in common with animals[4]. Thus biologically-inspired designs are particularly prevalent for robots which perform dynamic tasks.

The literature on jumping robots is extensive[5][6]. However, many jumping robots are designed as specialized machines, with little similarity to biological structures. There are few multiple-degrees-of-freedom jumping robots[7] .

In this research, we developed a bipedal robot for jumping and landing in order to understand the role of the body in explosive movements. We present an approach to realize motor control of jumping and landing which exploits the synergy between control and mechanical structure. We also discuss the design of an artificial musculoskeletal system using pneumatic actuators.

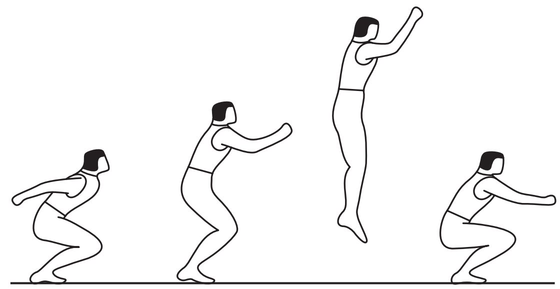

Fig. 1. Human vertical jumping.

II. ARTIFICIAL MUSCULOSKELETAL SYSTEM

The musculoskeletal system gives animals the ability to move in a huge variety of environments.

The artificial musculoskeletal system proposed here is based on the engineering concept of using biological structures as guidelines for robot architecture. In our work, pneumatic artificial muscles are used for the muscular system.

A. Explosive Movement

Explosive movements including jumping and landing are characterized by large instantaneous forces and short duration.

For example, execution times for vertical jumping (Fig.1) before take-off in humans is about 300ms. However, the biological neural feedback loop response takes about the same or longer than this[8]. For a conventional robot, it is difficult to control multiple degrees-of-freedom during such a short duration.

Especially in case of jumping and landing movements, it is necessary to account for the high uncertainty of the take off and landing points. Therefore, we consider the role of the body in explosive movements. Here we present an approach to motor control of jumping and landing which exploits the well-designed physical body as a peripheral controller.

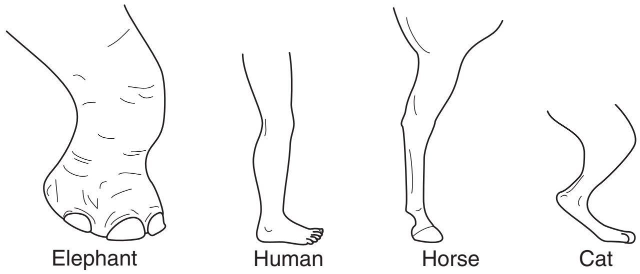

Fig. 2. Various limbs of mammals.

B. Biomechanics of Musculoskeletal System

Much of our knowledge about the rational form of legs comes from sports biomechanics. Two important functions of legs are supporting a trunk in the grounding phase, and stepping quickly in the swing phase. Animals which are good at jumping and running have tapered legs (Fig.2). A tapered leg has a small foot mass and a small moment of inertia, which is ideal for dynamic motion.

C. Bi-Articular Muscle

Biarticular muscles are muscles that work on two joints rather than just one. The human hamstring muscle is a primary example of bi-articular muscle[9]. The joint torque affects the movement of other joints throughout the mechanical linkage consists of skeleton and the bi-articular muscle. These effects can be applied to generate optimum force for jumping[10].

D. Pneumatic Artificial Muscle (McKibben Type)

Pneumatic muscles are the key element of the musculoskeletal system we propose. The McKibben pneumatic muscle is interesting for biologically inspired robots because of the similarity in length-load curves between the pneumatic muscle and biological muscle[11][12]. The compressibility and low-viscosity of air provide rich compliance and rapid contraction. The extremely high power/weight ratio is also good for dynamic motion. There are only a few previous examples of using pneumatic muscles for dynamic motion.

The contracting force as a function of pressure and muscle length without considering the detailed geometric structure, is theoretically estimated as follows[13][14]. The static characteristic of the McKibben Pneumatic Artificial Muscle is given by:

$$F = p\left\{A\,(1-\varepsilon)^2 - B\right\} \tag{1}$$

$$\text{where,}\quad A = \frac{3}{4}\pi D_0^2 \cot^2\theta_0,\quad B = \frac{1}{4}\pi D_0^2 \mathrm{cosec}^2\theta_0$$

The symbols have the following meaning: $F(t)$ [N]: contraction force, D_0 [m]: the initial diameter of the rubber tube, $p(t)$ [Pa]: the inner pressure, θ_0 [rad]: the initial angle between a braided thread and the axis along the rubber tube, $\varepsilon(t)$: the contracting ratio. The required energy for jumping and muscle parameters are derived from the above static characteristic.

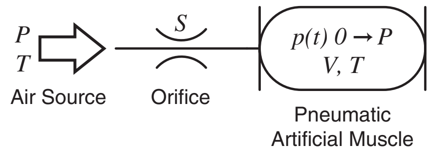

Fig. 3. Time constant of McKibben artificial muscle.

The response to air input is also a significant parameter for rapid motion. The time constant t_C [sec] of air system (Fig.3) is defined as "filling time of the tank of pressure $p(t)$ [MPa] and temperature T [K] by sonic speed air through effective cross-section area S [m^2] from the air source of pressure P [MPa] and temperature T [K] equal to". We applied this definition to pneumatic muscle.

The time constant of pneumatic muscle can be approximated as follows. In practice, the time constant t is longer than t_C because of the longer filling period for subsonic flows. The muscle also needs additional time to release air.

$$t = \left(1.285 - \frac{0.1013}{P}\right) t_C \tag{2}$$

$$\text{where,}\quad t_C = 5.216 \times 10^{-3}\frac{V}{S}\sqrt{\frac{273.16}{T}}$$

The above expression gives our estimate of the muscle parameter and its power.

III. JUMPING AND LANDING ROBOT MOWGLI

We developed a bipedal robot with an artificial musculoskeletal system. We use this robot for real world experiments. Experiments on real robots are essential to study explosive movements, including collisions, which are difficult to model.

A. Overview

Fig.4 shows a portrait of the bipedal jumping and landing robot Mowgli. The robot, weighs about 3[kg], is 0.9[m] body height with the legs extended, and has 6 pneumatic muscles for 6DOF legs. Mowgli can jump as high as 0.5[m], more than 50% of its body height, and can land softly.

Based on biomechanics of biological musculoskeletal structure, the robot has the tapered legs. In other words, the proximal (close to trunk) muscles are bigger than distal muscles. The size and mass of muscles proportional to their energy capacity.

B. Electro-Pneumatic System

We built a electro-pneumatic system to achieve fine pneumatic control (Fig.5). The solenoid valves to switch air and the electronic modules for measurement and control are mounted on the robot. An external PC running a real time OS is used to operate the robot. The electrical power and compressed air is supplied from external equipment. There is no essential technical difficulty in making the robot independent, though it is not currently.

The robot has a potentiometer on each joint, a pressure sensor on each muscle, and a touch switch on each foot.

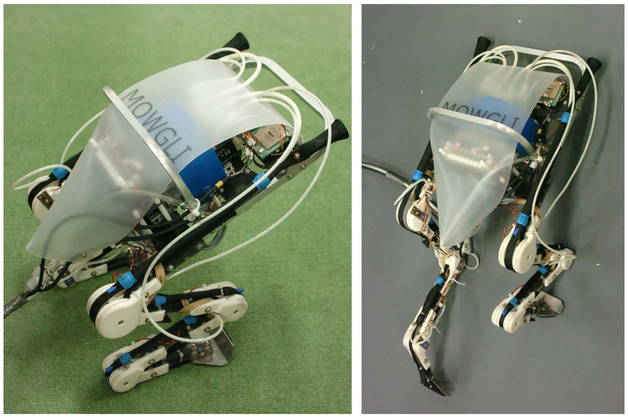

Fig. 4. Jumping and landing robot Mowgli.

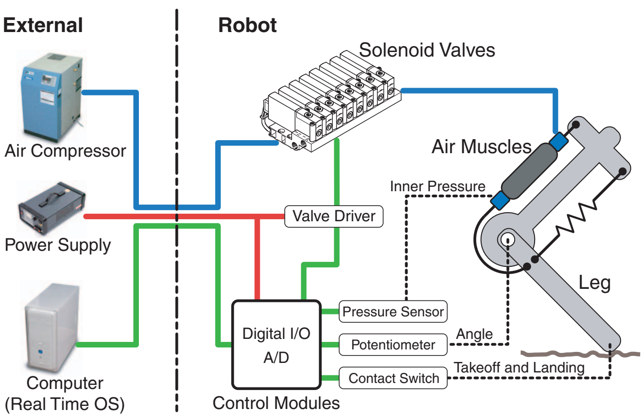

Fig. 5. Overview of electro-pneumatic control system.

C. Artificial Skeletal System

The skeletal frame consists mostly of polymer parts. The oilless polymer bearings, nylon joint parts, and carbon FRP bones contribute to lightweight and high-impact durable skeletal frame (Fig.6). A leg has 3 degrees of freedom, one for each joint (hip, knee, and ankle). The function of the skeletal frame is to support the muscles and transform muscle contraction forces into kicking motion.

Fig.7 shows the joint mechanism configuring an appropriate moment arm of the muscle-tendon system.

D. Artificial Muscular System

The allocation of muscles and the moment arm of each joint is shown in Fig.8. The main antigravity muscles are McKibben pneumatic muscles. To simplify the body, the muscles antagonistic to the main muscles are made of rubber tubes. The mono-articular muscles on the trunk have an inner diameter 0.010[m], and effective length 0.19[m]. The bi-articular muscles have an inner diameter 0.006[m], and effective length 0.09[m]. The initial angle of the braided thread for the muscle is 18[deg].

IV. SIMULATION EXPERIMENTS

We simulated a model of vertical jumping along with the development of the real robot. The design of the robot reflects the simulation results.

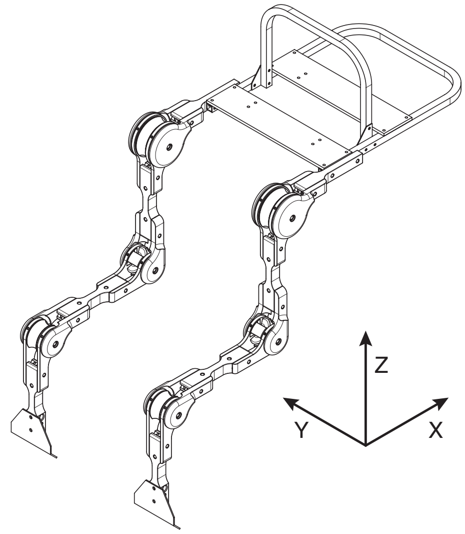

Fig. 6. Skeletal structure of the robot.

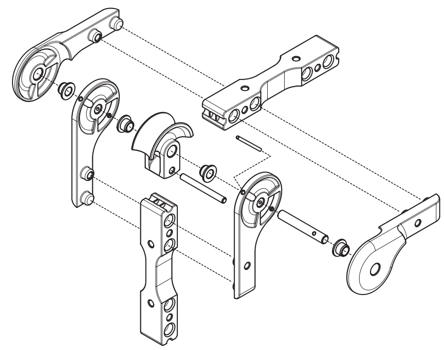

Fig. 7. Joint mechanism of the robot.

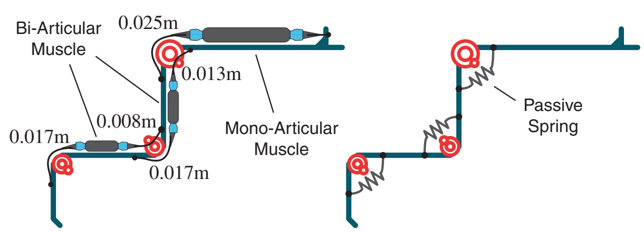

Fig. 8. Main antigravity muscles and antagonistic springs.

A. Skeletal Model and Control Block Diagram

We model the robot as a four-segment, sagittal, articulated linkage (Fig.9). At the toe, the skeletal model is connected to the ground by an unactuated joint. The parameters of the model are taken from physical properties of the robot Mowgli. The skeletal model starts in a static squatted position, with the heel off the ground.

As illustrated in Fig.10 the joint torques are calculated from motor commands and joint angles through a muscle-tendon model. The constant inner pressure applied to all muscles as motor command. The joint torques are simply described as follows.

$$T(t) = MF(t) \tag{3}$$

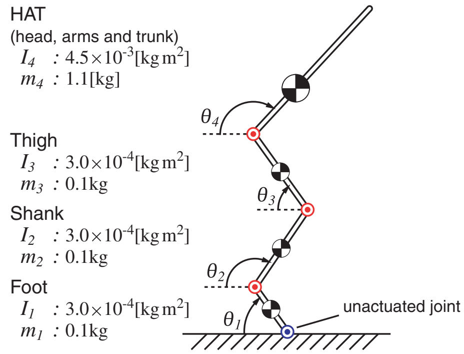

Fig. 9. Four-segment model for the vertical jumping. m_1, m_2, m_3, m_4 are the lumped masses of the segment. I_1, I_2, I_3, I_4 are the moments of inertia of the segment.

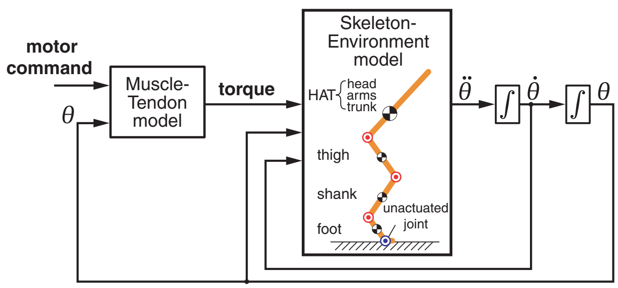

Fig. 10. Simulation model of musculoskeletal legged robot.

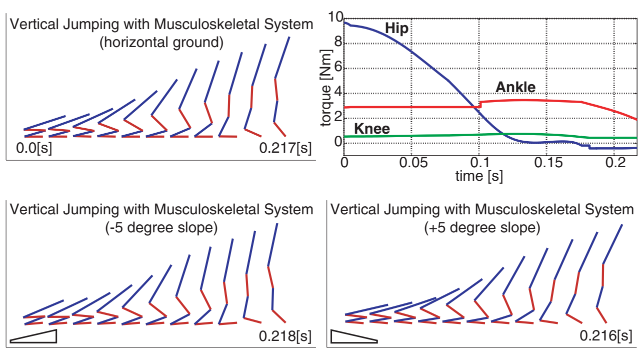

Fig. 11. Simulation of vertical jumping on level ground and slope.

The symbols have the following meaning :$T(t)$ [Nm]: joint torque, M [m]: moment arm, $F(t)$ [N]: contraction force calculated by eq.(1).

B. Simulation Results

The dynamic simulation results are shown in Fig.11. Vertical jumping can be performed on both level ground and sloped ground. The simulated motion agrees well with the real robot experiments described below. Further details are used in the comparative study in section VI-B.

V. REAL ROBOT EXPERIMENTS

We performed the experiments, vertical jumping and jumping onto the chair, with the real robot. Also, we considered the potential role of body in explosive movements. The joint angles, inner pressure of muscles, and ground contact are recorded in real time. We took movies to record whole body posture.

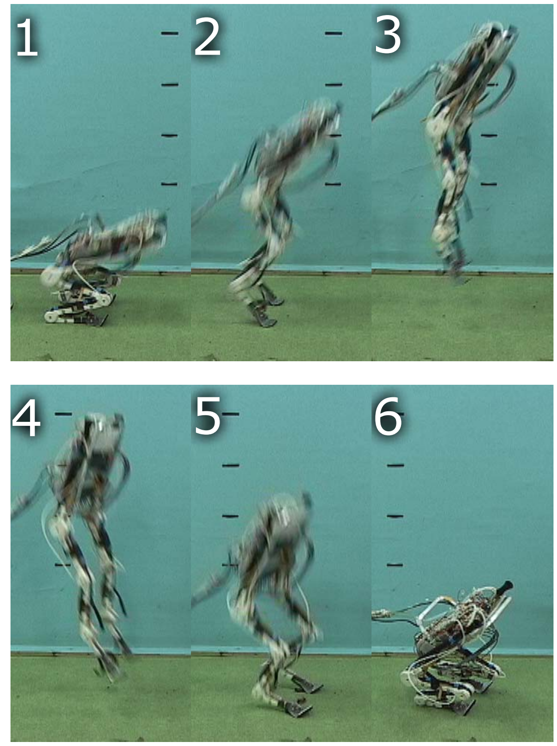

Fig. 12. Vertical jumping on the level ground.

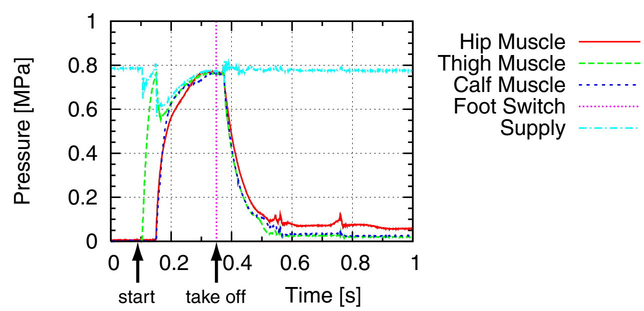

Fig. 13. Pressure (control input) at jumping onto chair.

A. Vertical Jumping

Fig.12 shows the robot executing a vertical jump on level ground. The jumping height between toe and ground is about 0.26[m]. The only applied control is the switching on and off of the valves, during both take off and landing.

B. Jumping onto chair

The robot is able to execute a jump of 0.4[m] onto a chair using a dynamic whole body motion. The measured inner pressure of muscles and joint angles shown in Fig.13, Fig.14. This performance is achieved in spite of the fact that Mowgli is a multiple-DOF legged robot which has hip, knee, and ankle joint. The natural dynamics of the body are such that the only required control is to switch on and off the valves.

VI. DISCUSSION

Our experiments confirmed that Mowgli can jump extremely high. The rich compliance of the legs ensures

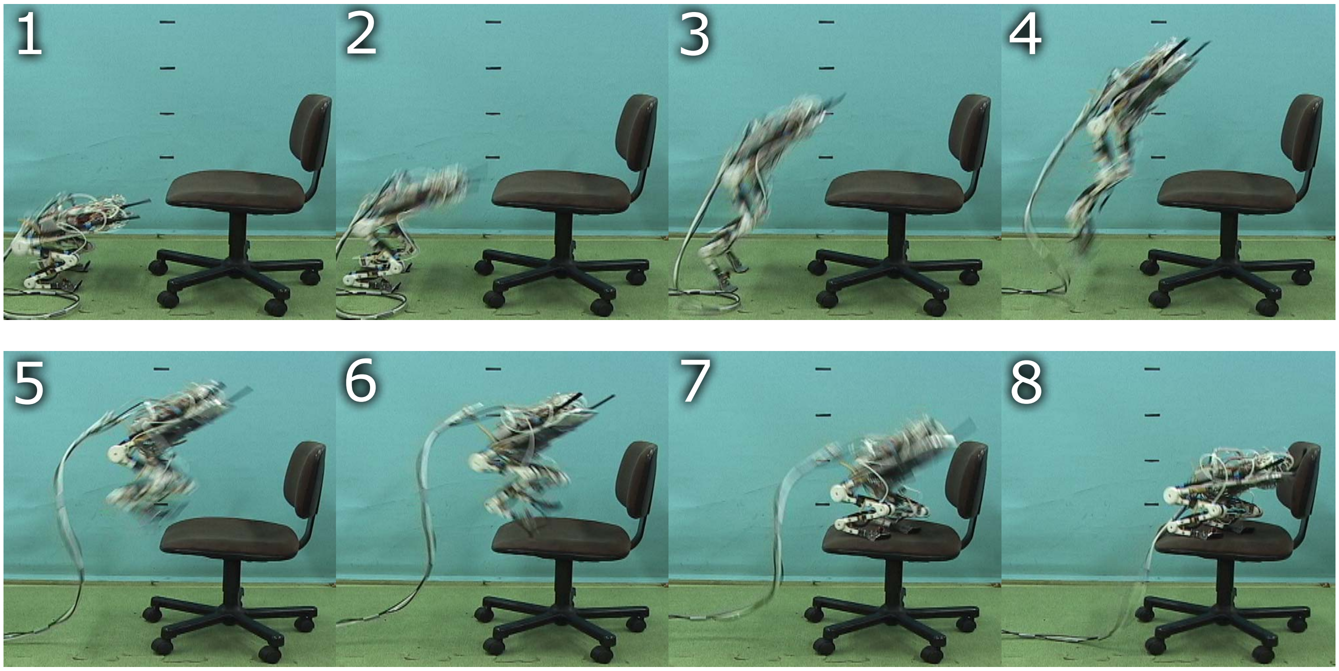

Fig. 15. Jumping onto a chair with a height of 0.4[m].

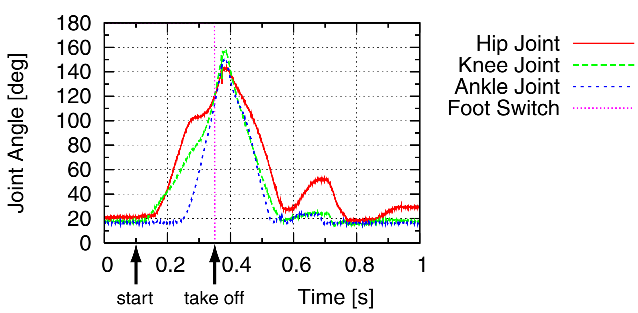

Fig. 14. Joint angle at jumping onto chair.

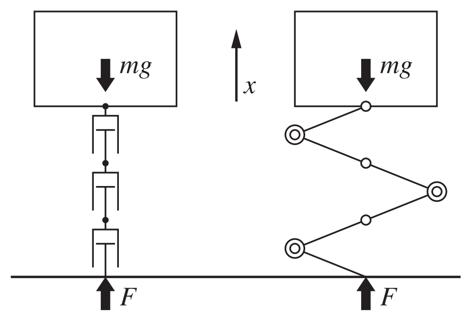

Fig. 16. Tandem actuator models of jumping.

that landing is soft and impact-proof. We now focus on the proximo-distal sequence of joint extension like humans[15][16], and consider the cause of this phenomenon.

A. Proximal to Distal Joint Extension

Our results show a proximo-distal sequence of joint extensions during jumping despite simultaneous motor activity. We assume a jumping model shown in Fig.16. The model is inverted pendulum with lumped mass and series actuated leg. Extensions in the whole body motion are caused by the compliance and the natural dynamics of the body.

B. Contribution of Physical Muscles to Rapid Motion

The skeletal muscle properties in human vertical jumping is studied in biomechanics by modeling approaches[8][16]. We investigate the contribution of the artificial musculoskeletal system in vertical jumping.

We compare two types of simulated open loop control for vertical jumping with disturbance. The first is motor command to the muscles. In this case, muscle-tendon model is included. The second is stored joint torque time series data. In this case, jumping is directly controlled by stored joint torque.

In order to compare the two kinds of controllers, first we make a reference movement using the motor command control model including the muscle-tendon effects. Then, based on the dynamics simulation, the joint torque time series data is obtained and stored. Thus, without disturbance, the two types of controllers perform the same reference movement. Then a initial angular velocity of the hip joint set to -1[rad/s] as a disturbance. The simulation results with disturbance are shown in Fig.17.

We found that the model controlled by open loop motor command sequences through a muscle-tendon mechanism can jump robustly (Fig.17a). In contrast, the vertical jumping directly controlled by stored joint torque sequences collapse under disturbance (Fig.17b). The simulation results demonstrate the contribution of the artificial musculoskeletal system as a physical feedback loop in explosive movements.

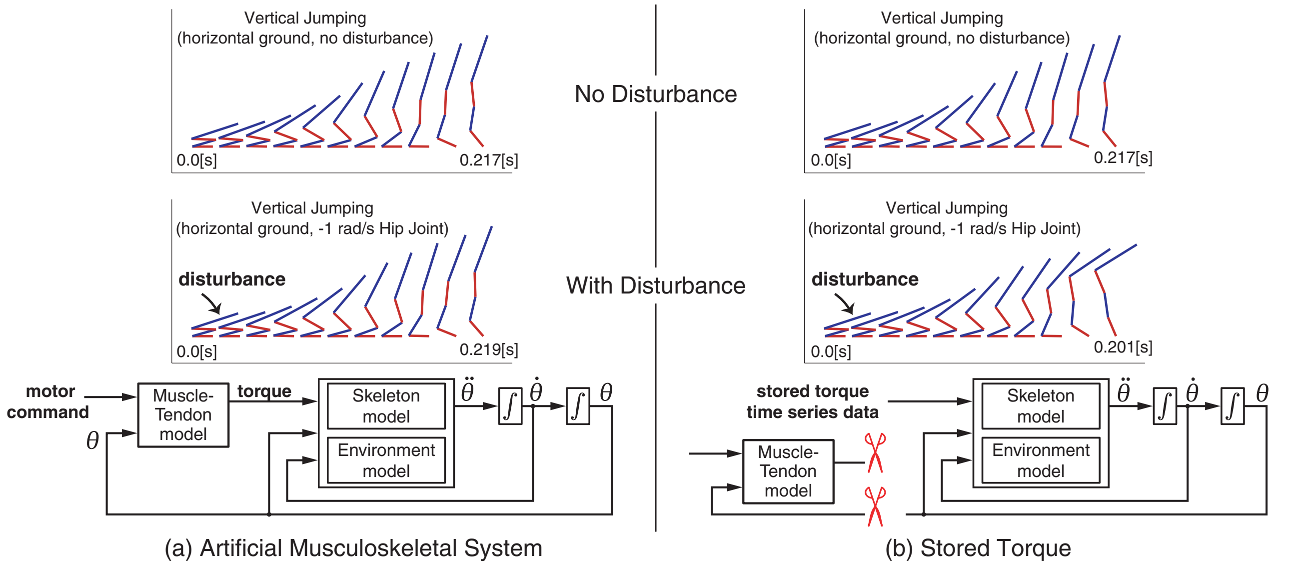

Fig. 17. Simulation of vertical jumping on level ground with disturbance.

VII. Conclusion and Future Work

A. Conclusion

In this research, we developed a bipedal robot with an artificial musculoskeletal system. Jumping and landing movements are characterized by short duration, and a high uncertainty concerning take off and landing points. Such characteristics make conventional types of control inadequate. The robot is also subject to strict restrictions of the mechanical design due to the large instantaneous forces.

Here we present an approach to realize motor control of jumping and landing which exploits the synergy between control and mechanical structure. Our experimental system is a bipedal robot called Mowgli. Mowgli's artificial musculoskeletal system consists of McKibben pneumatic artificial muscles and a skeletal frame composed mostly of polymer parts. Mowgli can reach jump heights of more than 50% of its body height and can land softly. As a multiple-DOF legged robot, this performance is extremely high.

Our results show a proximo-distal sequence of joint extensions during jumping despite simultaneous motor activity. To explain this, we present simple models of jumping and derive a hypothesis based on biologically well-designed structures. Extensions in the whole body motion are caused by the compliance and the natural dynamics of the legs.

In addition to the experiments with the robot, we also simulated two types of open loop controllers for vertical jumping with disturbance. We found that the model controlled by open loop motor command through a muscle-tendon mechanism could jump robustly. The simulation results demonstrate the contribution of the artificial musculoskeletal system as a physical feedback loop in explosive movements.

B. Future Work

We plan to analyze the dynamics of the artificial musculoskeletal system in greater detail. We will also perform experiments with various movements other than jumping.

References

[1] Rolf Pfeifer and Christian Scheier, *Understanding Intelligence*, The MIT Press, 1999.

[2] R. McNeill Alexander, "Tendon elasticity and muscle function", In Comparative Biochemistry and Physiology. Part A: Comparative Physiology, Vol. 133, Issue 4, pp. 1001–1011, 2002.

[3] Thomas A. McMahon, John Bonner, John Tyler Bonner, *On Size and Life*, Freeman Press, 1983.

[4] Yasuhiro Fukuoka, Hiroshi Kimura, Avis H. Cohen, "Adaptive Dynamic Walking of a Quadruped Robot on Irregular Terrain Based on Biological Concepts" International Journal of Robotics Research, Vol.22, No.3-4, pp.187-202, 2003.

[5] Marc H. Raibert, *Legged Robots That Balance*, The MIT Press, 1986.

[6] Sang-Ho Hyon, Tsutomu Mita "Development of a biologically inspired hopping robot –Kenken", Proc. of the IEEE Int. Conf. on Robotics and Automation 2005 (ICRA 2005), Vol.4, pp.3984–3991, 2002.

[7] Naoyuki Shiraishi, Yasuyuki Kawaida, Yuji Kitamura, Shigeki Nakaura, Mitsuji Sampei, "Vertical Jumping Control of an Acrobat Robot with Consideration of Input Timing", Proc. of the 41st SICE Annual Conference (SICE2002), Vol.4, pp.2531–2536, 2002.

[8] Arthur J. van Soest and Maarten F. Bobbert, "The Contribution of Muscle Properties in the Control of Explosive Movements", Biological Cybernetics, Vol.69, No.3, pp.195-204, 1993.

[9] Eric R. Kandel, James H. Schwartz, Thomas M. Jessell, *Principles of Neural Science*, 4th ed., Appleton & Lange, 2000.

[10] Marcus G. Pandy, Felix E. Zajac, Eunsup Sim, and William S. Levine, "An Optimal Control Model for Maximum-Height Human Jumping", Journal of Biomechanics Vol.23, No.12, pp.1185-1198, 1990.

[11] Björn Verrelst, Ronald Van Ham, Bram Vanderborght, Frank Daerden, Dirk Lefeber and Jimmy Vermeulen, "The Pneumatic Biped "Lucy" Actuated with Pleated Pneumatic Artificial Muscles", Autonomous Robots, Vol.18, No.2, pp.201–213, 2005.

[12] Takashi Takuma, Koh Hosoda, "Controlling the Walking Period of a Pneumatic Muscle Walker", International Journal of Robotics Research, Vol.25, No.9, pp.861–866, 2006.

[13] Glenn K. Klute, Joseh M. Czerniecki, Blake Hannaford, "Artificial Muscles: Actuators for Biorobotic Systems", International Journal of Robotics Research, Vol.21, No.4, pp.295–309, 2002.

[14] Ching-Ping Chou and Blake Hannaford, "Measurement and Modeling of McKibben Pneumatic Artificial Muscles", IEEE Transactions on Robotics and Automation, Vol.12, No.1, pp. 90–102, 1996.

[15] Gerrit Jan van Ingen Schenau, "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, 1989.

[16] R. McNeill Alexander, "Sequential Joint Extension in Jumping", Human Movement Science, Vol.8, Issue 4, pp.339-345, 1989.