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Pneumatic-driven jumping robot with anthropomorphic muscular skeleton structure

Koh Hosoda · Yuki Sakaguchi · Hitoshi Takayama · Takashi Takuma

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Abstract Human muscular skeleton structure plays an important role for adaptive locomotion. Understanding of its mechanism is expected to be used for realizing adaptive locomotion of a humanoid robot as well. In this paper, a jumping robot driven by pneumatic artificial muscles is designed to duplicate human leg structure and function. It has three joints and nine muscles, three of them are biarticular muscles. For controlling such a redundant robot, we take biomechanical findings into account: biarticular muscles mainly contribute to joint coordination whereas monoarticular muscles contribute to provide power. Through experiments, we find (1) the biarticular muscles realize coordinated movement of joints when knee and/or hip is extended, (2) the extension of the ankle does not lead to coordinated movement, and (3) we can superpose extension of the knee with that of the hip without losing the joint coordination. The obtained knowledge can be used not only for robots, but may also contribute to understanding of adaptive human mechanism.

Keywords Muscular skeleton system · Pneumatic artificial muscles · Humanoid robot · Jumping · Biarticular muscles

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K. Hosoda (✉) · Y. Sakaguchi · H. Takayama
Dept. of Adaptive Machine Systems, Graduate School of Engineering, Osaka University, Suita, Japan
e-mail: hosoda@ams.eng.osaka-u.ac.jp

T. Takuma
Dept. of Electrical and Electronic Systems Engineering, Osaka Institute of Technology, Osaka, Japan
e-mail: takuma@ee.oit.ac.jp

1 Introduction

A human has complicated muscular skeleton structure consisting of bones, joints, ligaments, and muscles. The structure has essential redundancy that plays an important role for adaptive locomotion, which is advantageous for survival. Understanding of its mechanism is expected to be useful for realizing robots' adaptive locomotion as well. In turn, by constructing a robot with anthropomorphic structure, we may understand mechanism of a human for realizing adaptive behavior.

This paper focuses on contribution of muscular skeleton structure to jumping. We develop a monopod robot with anthropomorphic structure consisting of bones, ligaments, and muscles. We conduct experiments to investigate roles of muscles by changing control parameters. In the field of biomechanics, they have intensively investigated the muscle roles by measuring EMG and/or kinematics. However, it is relatively difficult to identify function of each muscle since they cannot control the muscles individually. If we can use a robot, we can investigate them from constructivist's viewpoint (e.g. we can *switch off* one of muscles so that we can confirm its function), in which large contribution is expected to the field.

There have been many studies on animal and robot jumping so far. Blickhan's simple spring/mass model is one of the milestones for studying dynamic locomotion of animals (Blickhan 1989). As the model was so simple and easy to describe storing and releasing energy during running, many researchers adopted it and analyzed running (e.g., Koditscheck and Buehler 1991; Ahmadi and Buehler 1997, and Seyfarth et al. 2002). Based on a similar dynamic model, Raibert carried out pioneering research and developed a biped robot that had a springy prismatic joint that could run, jump and perform somersaults (Raibert 1986). However, the structure of the robot is too simple and it may not realize adaptability of animals.

There are several studies to realize simple but animal-like structure for adaptive locomotion. Hyon et al. developed a running robot imitating the structure of a hind leg of a dog (Hyon and Mita 2002). Iida et al. developed a human-like robot with several springs as muscles and investigated emergence of walking and running (Iida et al. 2007). In these studies, springs are fixed whereas tunable springs are essential for adaptive locomotion of biological system. Hurst et al. developed a monopod with tunable springs to realize wider range of dynamic locomotion (Hurst et al. 2007). Since they adopted huge fiberglass springs, realized structure was relatively simple. In Vanderborght et al. (2008), they performed a study how the stiffness has to be changed according to a desired trajectory to minimize energy consumption and experimentally validated this. Wisse et al. made a great effort to realize bipedal walking utilizing pneumatic artificial muscles (Wisse et al. 2004, 2005; Collins et al. 2005). They started from adding artificial muscles to a planar passive dynamic walker and finally built a 3D biped robot with a torso and flat feet. In the existing work, two artificial muscles are used antagonistically to drive one joint.

There is, however, still a large gap between realized robots that have simple structure and the animals that have really complicated muscular skeleton system. Simple structure is advantageous for analysis, but the realized mechanism lacks robustness and adaptability. The biological structure consists of many bones connected with muscles and ligaments that work antagonistically and/or synergistically. Biarticular muscles that drive not only one joint but also multi joints provide redundancy and play an important role for realizing coordinated motion of the body. Redundancy provided from such complicated mechanism may also contribute to design of the controller. In short, such complexity obviously contributes to robustness and adaptability of animal's behavior.

We utilize the redundancy provided by the structure for simplifying the control scheme. If the robot does not have any biarticular muscles, joints should be coordinated explicitly by the controller (Hosoda et al. 2008), which makes it hard to find appropriate control parameters. If the robot is equipped with biarticular muscles, they can be utilized for joint coordination, which is also observed in a human (Jacobs et al. 1996). Complicated body structure simplifies the control scheme. We investigate the contribution of biarticular muscles to robot's behavior by changing their control parameters of a real robot. To the best of authors' knowledge, the only work trying to duplicate the human leg structure is done by Niiyama and Kuniyoshi (2008). They built a biped robot with complicated muscular skeleton system. However, they did not investigate the roles of muscles in detail.

Existing humanoid robots can jump with the help of fast feedback control (e.g. Nagasaka et al. 2004 and Kajita et al. 2005). But, animals realize dynamic locomotion with relatively slow nerve system and muscles that have large time-delay. There must be essential difference inbetween. This paper suggests that we can realize stable jumping without high-bandwidth control if we utilize the compliance and joint coordination of the muscluar-skeletal system.

In the following, we firstly introduce the monopod design imitating human's muscular skeleton system, which has three features; pneumatic compliant muscles with ligaments including biarticular muscles, anthropomorphic open joints, and pressure sensors to sense extension of muscles. Secondly, we investigate coordinated movement of joints by biarticular muscles. We assign basic roles to the muscles and investigate the effect by actuating them one by one. We suppose that this is the constructivist approach for understanding the human locomotion. Finally, we superpose extension of the knee with that of the hip without losing the joint coordination.

2 Design of an anthropomorphic monopod

2.1 Overview of the monopod

In Fig. 1, we show a picture of a developed monopod. It has 4 links: body, thigh, shank, and foot. These links are attached with each other by an anthropomorphic open joint and driven by pneumatic artificial muscles. It has totally 9

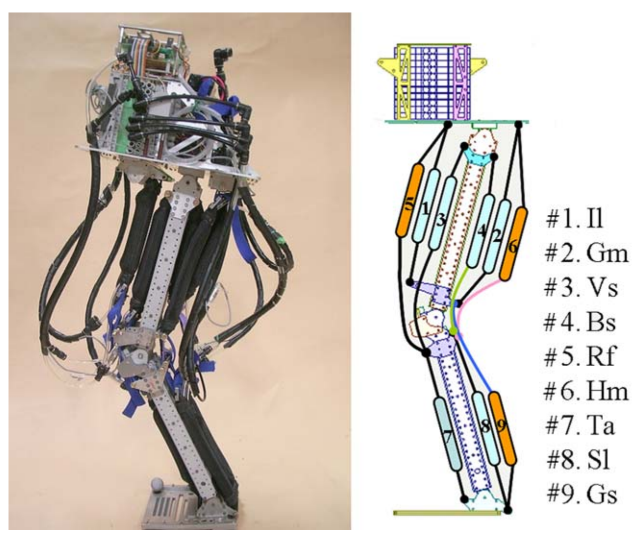


Fig. 1 A jumping robot with anthropomorphic muscular skeleton structure. Muscles #1 (iliacus) and #2 (gluteus maximus) are monoarticular muscles driving the hip joint. Muscles #3 (vastus lateralis) and #4 (popliteus) drive the knee and muscles #7 (tibialis anterior) and #8 (soleus) drive the ankle joint, respectively. Muscles #5 (rectus fomoris), #6 (hamstring muscles) and #9 (gastrocnemius) are biarticular muscles that drive not only one but also two joints

muscles, 3 of them are biarticular muscles. Its height and weight are 730 mm and 6.5 kg (torso 4.7 kg, thigh 0.7 kg, shank 0.7 kg, and foot 0.4 kg), respectively.

2.2 Pneumatic artificial muscles

The robot is driven by McKibben pneumatic artificial muscles (van der Linde 1999). The muscular skeleton system of the robot is also shown in Fig. 1. Muscles #1 (iliacus) and #2 (gluteus maximus) are monoarticular muscles driving the hip joint. Muscles #3 (vastus lateralis) and #4 (popliteus) drive the knee and muscles #7 (tibialis anterior) and #8 (soleus) drive the ankle joint, respectively. Muscles #5 (rectus fomoris), #6 (hamstring muscles) and #9 (gastrocnemius) are biarticular muscles that drive not only one but also two joints.

Muscles #3 and #8 are what they call anti-gravity muscles that are supporting the body against the gravitational force. Since these muscles are important to generate force for jumping up, we put two parallel muscles to double the force.

We used off-the-shelf McKibben pneumatic actuators produced by Kanda Tsushin Kogyo Co., ltd. The radius of the actuator is 20 mm (when it contracts). The length of the actuator is 200 mm. They generate approximately 800 N when the pressure in the inner tube is 0.7 MPa. The time delay to fill the muscle is approximately 0.4 [s], which is experimentally examined in Hosoda et al. (2008).

There are several other types of artificial muscles such as EPA (Electro-Active Polymer) and SMA (Shape Memory alloy), but in this paper, we adopted McKibben pneumatic muscles because they are more robust and powerful.

2.3 Anthropomorphic open joints

The previous version of the jumping robot (Hosoda et al. 2008) had conventional joints consisting of an axis and ball bearings. The impact against the ground was so hard that we experienced the axis was bended and the balls broke so often. Therefore, some improvement is required to make the robot robust.

Since the joint of the monopod is driven antagonistically, that is, the joint is pulled with two muscles, we can adopt an open joint that is similar to the one used for prosthetics. Since the structure supports impact force with a surface, the joint is stronger against impact than conventional ball bearings. We use friction-free polyamide (see Fig. 2) for the joint.

2.4 Pressure sensors to sense the displacement of the muscles

Since the anthropomorphic joint is disjointed, it is relatively hard to install an angle sensor such as a potentiometer or an optical encoder. Instead, we install pressure sensors to sense the state of the artificial muscles.

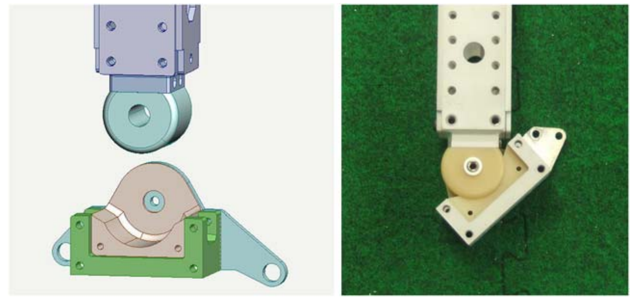


Fig. 2 An anthropomorphic open joint. The joint is made from polyamide and is not tightly connected (although you can see a hole and an axis in the joint, it does not support the external force: it only avoids disjoint when the muscles are totally powerless). The structure is robust against impact, since the joint is supported by a surface not by ball bearings

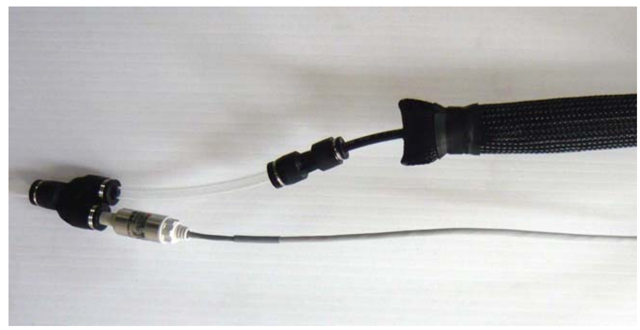


Fig. 3 A pressure sensor PSE 530 installed in the artificial muscle

We adopted a pressure sensor PSE530 produced by SMC Corp (shown in Fig. 3). By a preliminary quasi-static experiment, we found consistent relation between extension of the muscle and pressure change even though the initial pressure changed (see Fig. 4). Therefore, at least in the quasi-static case, we can use the pressure sensor to measure the extension of the muscle.

In the following experiments, however, the pressure sensor is used only for sensing time when the gravity center of the robot is the lowest. We installed a pressure sensor in the muscle #3, the knee extensor. When the robot lands on the ground, the muscle is tensed, and by measuring the peak of the pressure, we can estimate when the gravity center of the robot is lowest. From Fig. 3, we assume that we can estimate the time when the muscle is most extended whatever the initial pressure of the muscle is.

2.5 Hardware configuration for the monopod

In Fig. 5, we show hardware configuration of the robot. 0.7 MPa pressured air is supplied from an air compressor (with a 25 l buffer) through 8 mm tube. The monopod is self-contained except this compressor. The robot is equipped

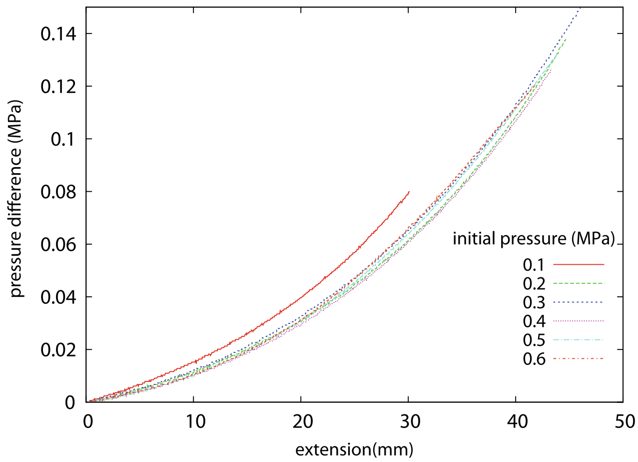


Fig. 4 Relation between extension of the muscle and difference in pressure in quasi-static experiments. Even though the initial pressure is different, the relation is almost the same. This means that the pressure sensor can sense the extension of the muscle

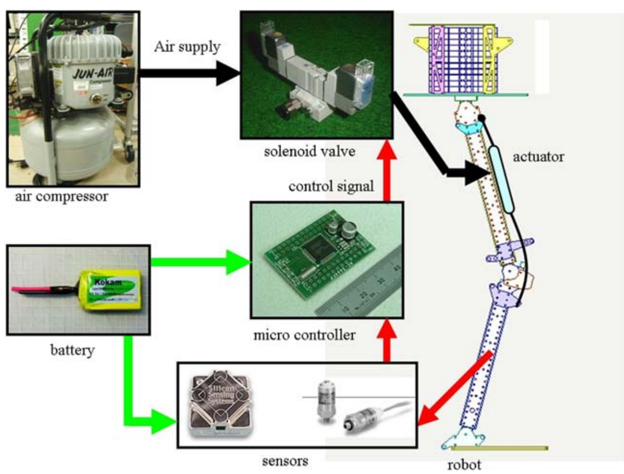


Fig. 5 The hardware configuration for the monopod. The robot is equipped with a gyro sensor and pressure sensors. The signal from these sensors is sent to the microcontroller. The micro controller outputs the control command to the 3-position solenoid valves. Through the valves, compressed air is supplied to the pneumatic actuators. If we put appropriate amount of air to the muscles, for example, the robot does not need any control for landing. Therefore, amount of required control is small. As a result, everything except the compressor can be mounted on the monopod

with gyro sensor and pressure sensors. The sensed data is sent to a micro controller H8-3664N (clock: 16 MHz, Renesas Technology Co.) through an on-board A/D converter. The gyro sensor is, however, not used in the following experiments, but for future use.

To reduce size and weight of the controller, we used three-position solenoid valves produced by SMC Corp instead of using huge proportional valves. Therefore, they can only take three states: supplying with the air, exhausting the air, and closed. However, in the experiments, we show that the robot can dynamically jump with these simple valves.

3 Joint coordination by biarticular muscles

3.1 Constructivist approach to investigate muscle roles

In the field of biomechanics, they observed human behavior and measure physiological values such as EMG so that they investigated the roles of the muscles. They supposed that the biarticular muscles contributed to energy transfer (Jacobs et al. 1996; Voronov 2004) and to direction of external force (Doorenbosch et al. 1996; Fukashiro et al. 2005). However, since we cannot intentionally control each muscle, only we can observe is its role in the context of whole body synergy. Furthermore, there may be effect originated from neural coordination, which is also difficult to distinguish. On the other hand, if we construct a robot model, we can control condition whatever we want to.

3.2 Valve operation for jumping experiments

The robot is constructed to imitate the human leg structure: we installed major muscles to contribute planar locomotion. All the joints are driven by antagonistic pairs of monoarticular muscles. In addition, it has three biarticular muscles. Therefore, the robot is essentially redundant, and the control scheme would be complicated if we try to utilize all possibilities provided by the mechanism.

Following observation in biomechanics, we assume that biarticular muscles mainly contributes to transfer force/power whereas monoarticular ones contribute to generate power (Voronov 2004). Therefore, we do not actively control the biarticular muscles during movement, that is, the valves for the muscles are closed during experiment after initial supply. Monoarticular ones are driven for generating jumping power.

Figure 6 shows the valve operation adopted for jumping experiments. On the very left in the figure, we show initial supply for several muscles. At the beginning of each experimental trial, the biarticular muscles are supplied with certain amount of air (the amount is controlled by changing the opening time of the supply valves). During jumping, these valves are closed so that the biarticular muscles maintain compliance to translate power but not to generate driving force.

We change the duration to supply/close/expel to modify the behavior. By observing the pressure sensor installed to the knee extensor, we initiate the jumping operation. The landing operation is initiated after fixed time from it.

In the following experiments, we observe two quantities: body rotation and apex ratio (Fig. 7). The apex is

$$\alpha = \frac{h_{highest} - h_{lowest}}{h_{initial} - h_{lowest}}. \quad (1)$$

We used motion capture system to observe these quantities.

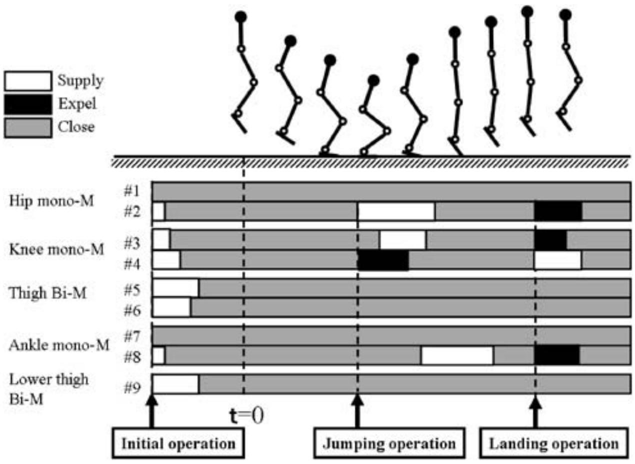


Fig. 6 Valve operation for jumping: On the very left, we show initial operation for the muscles. In jumping and landing operation, we just control monoarticular muscles following observation of real humans

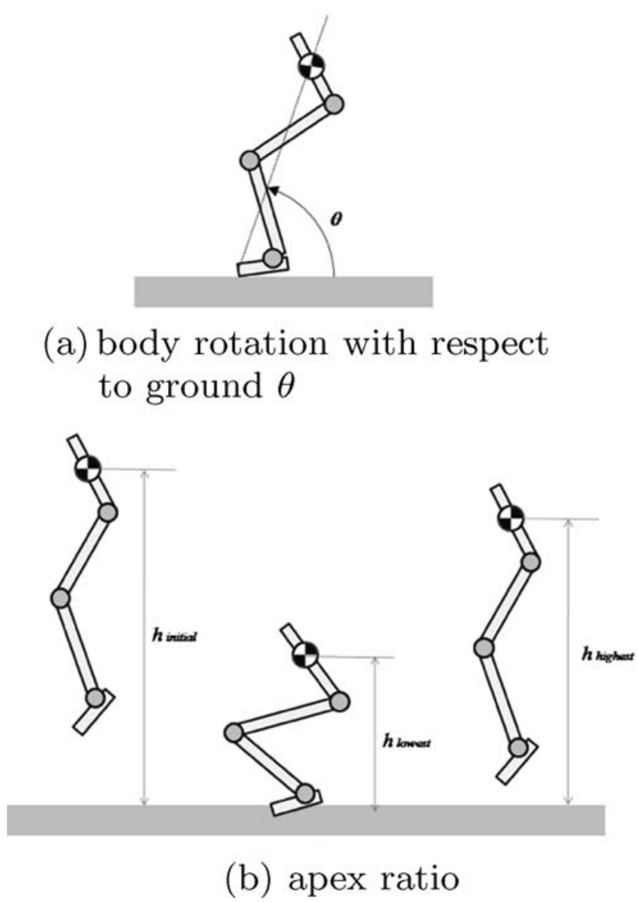


Fig. 7 Observed quantities for estimating jumping performance: (**a**) body rotation with respect to ground and (**b**) apex ratio

3.3 Joint coordination driven by knee extensor #3

First, we investigated the coordination driven by the knee extensor #3 (Fig. 8). When the muscle #3 contracts, the knee is extended. If the biarticular muscles #6 and #9 are tensed, they transfer force to hip and ankle joints respectively. As a result, the whole leg is extended. If the biarticular muscles are not tensed, this coordination is not facilitated.

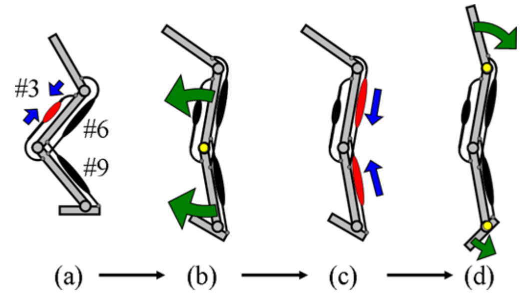


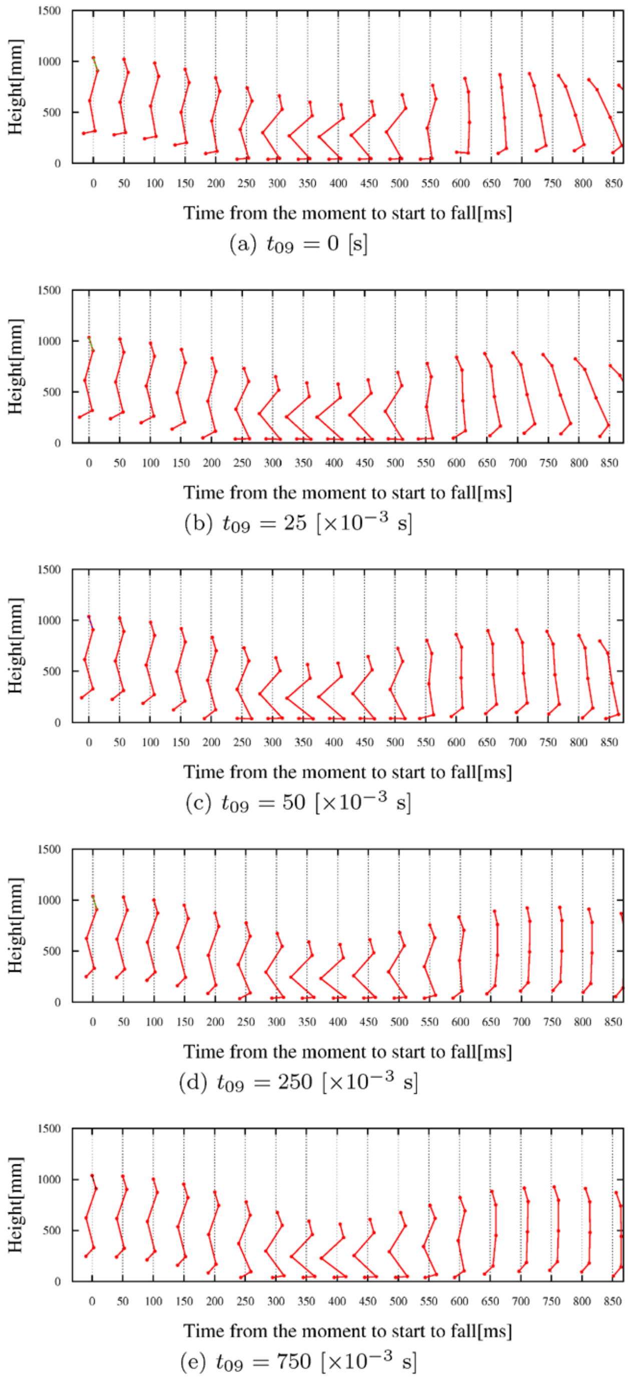
Fig. 8 Joint coordination driven by the knee extensor #3: (**a**) When extensor #3 contracts, (**b**) the knee is extended, (**c**) biarticular muscles #6 and #9 transfer force to hip and ankle joints, respectively, and (**d**) the whole leg is extended

We changed tension of #9 by changing initial air-supply duration t_{09} and observed behavior. Captured motion of the robot is shown in Fig. 9. The muscle #9 drives knee and ankle joints. Therefore, when it is tensed, power generated by the muscle #3 in the knee is translated to the ankle through it. As a result, we find in Fig. 9 that the more it is tensed, the more ankle extension becomes.

In Fig. 10, we plot (a) relation between the body angles when the robot is at the apex $\theta_{highest}$ and the one when the robot is about to take off $\theta_{takeoff}$ and (b) apex ratio. We also draw the line $\theta_{highest} = \theta_{takeoff}$ in the figure. When the biarticular muscle #9 is tensed (t_{09} increases), it translate power from the knee to the ankle, which suppresses body rotation. As a result, the points gather along the line $\theta_{highest} = \theta_{takeoff}$ (Fig. 10(a)). Jumping height increases when the biarticular muscle is tensed (Fig. 10(b)). We could find strange turning point around 50 ms. Maybe supplying time less than 50 ms is not enough for inflating the muscle, and therefore, it cannot transfer any power. In conclusion, rotation and Jumping height are modulated by tension of the biarticular muscle #9. We conducted similar experiments using the biarticular muscle #6, which is another coordination between knee and hip joints, and obtained similar results (Fig. 11) although it is not so significant as the case of #9.

3.4 Joint coordination driven by hip extensor #2

Second, we investigated the coordination driven by the hip extensor #2 (Fig. 12). When the muscle #2 contracts, the hip is extended. If the biarticular muscle #5 is tensed, it transfers force to the knee joint. The knee is extended and the biarticular muscle #9 transfers force to the ankle. As a result, also in this case, the whole leg is extended. If the biarticular



(a) $t_{09} = 0$ [s]

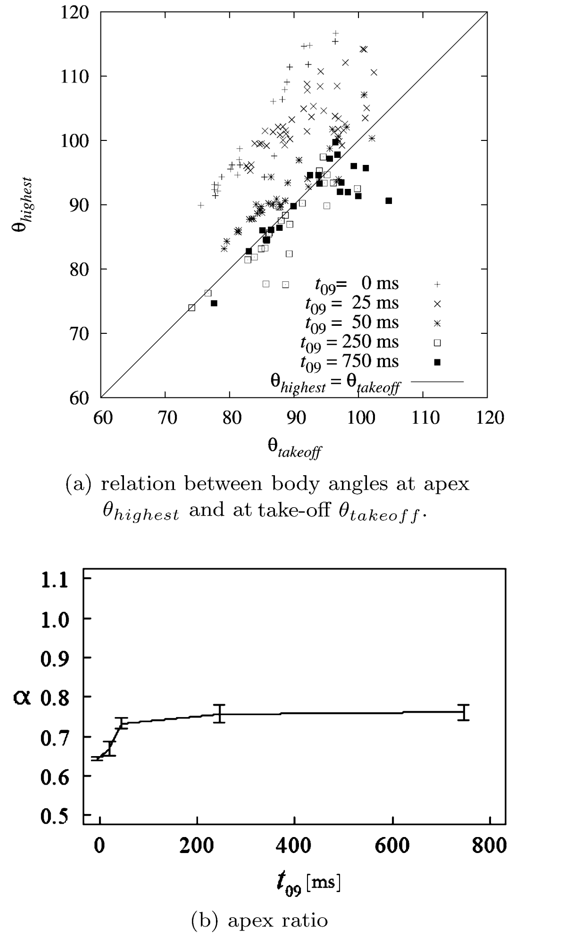
(b) $t_{09} = 25$ [$\times 10^{-3}$ s]

(c) $t_{09} = 50$ [$\times 10^{-3}$ s]

(d) $t_{09} = 250$ [$\times 10^{-3}$ s]

(e) $t_{09} = 750$ [$\times 10^{-3}$ s]

Fig. 9 Jumping behavior driven by knee extensor #3. We changed initial duration to supply air to #9: t_{09}



(a) relation between body angles at apex $\theta_{highest}$ and at take-off $\theta_{takeoff}$.

(b) apex ratio

Fig. 10 Body rotation and apex ratio: Power is provided by the monoarticular muscle #3. Rotation and Jumping height are modulated by tension of the biarticular muscle #9. t_{09} is duration to supply air to the muscle #9 (Gs). When it is tensed, it translate power from the knee to the ankle. (**a**) As a result, the more tensed it is, the less body rotation becomes, which results in the points gathering along the line $\theta_{highest} = \theta_{takeoff}$. (**b**) Jumping height increases when the biarticular muscle is tensed

muscles are not tensed, this coordination is not facilitated as well.

We changed tension of #5 by changing initial air-supply duration t_{05} and observed behavior. Captured motion of the robot is shown in Fig. 13. The muscle #5 drives hip and knee joints. Therefore, when it is not tensed, power generated by the muscle #2 cannot be translated to the knee joint. As a result, we find in Fig. 13 that when #5 is not tensed, only the hip joint is extended, but not the whole leg.

As we can see from Fig. 13, the robot cannot jump up when only the muscle #2 contracts. Therefore, we only show the apex ratio with respect to the tense of the biarticular muscle #5 in Fig. 14. When we increase the air amount, the power provided in the hip is translated to the knee, and the height increases to some extent.

3.5 The case the ankle extensor #8 is contracted

Third, we investigated the case when only the ankle extensor #8 is contracted (Fig. 15). In this case, because human structure does not have antagonistic biarticular muscle against #9, there is no joint coordination.

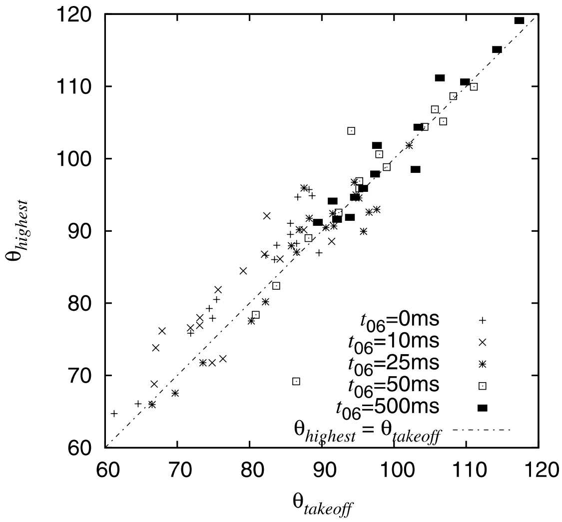


Fig. 11 Experimental results: relation between body angles at apex $\theta_{highest}$ and at take-off $\theta_{takeoff}$. t_{06} is duration to supply air to the muscle #6 (Hm). Rotation and Jumping height are modulated by tension of the biarticular muscle #6

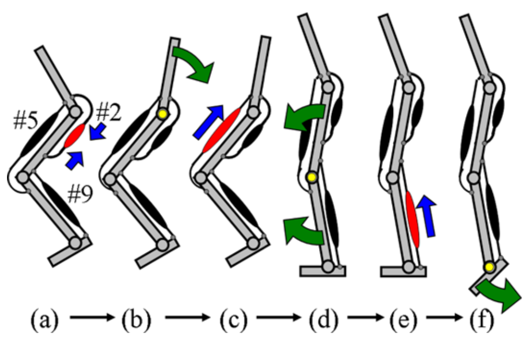


Fig. 12 Joint coordination driven by the hip extensor #2: (**a**) When extensor #2 contracts, (**b**) the hip is extended, (**c**) the biarticular muscle #5 transfers force to the knee, (**d**) the knee is extended, (**e**) the biarticular muscle #9 transfers force to the ankle, and (**f**) it is extended

We confirm it by experiments (Fig. 16). In these cases, we changed the tension of the biarticular muscle #9, but there is no significant change in the behavior.

4 Jumping experiments

According to the investigation on the role of each muscle in the last section, we superpose the activation to realize a controller for jumping.

4.1 Jumping driven by #2 and #3

When the biarticular muscles are tensed, the robot can jump up straight driven by #2 and by #3 as well. Therefore, we suppose that we can superposed these controllers. By taking the biomechanical inference into account (Jacobs et al.

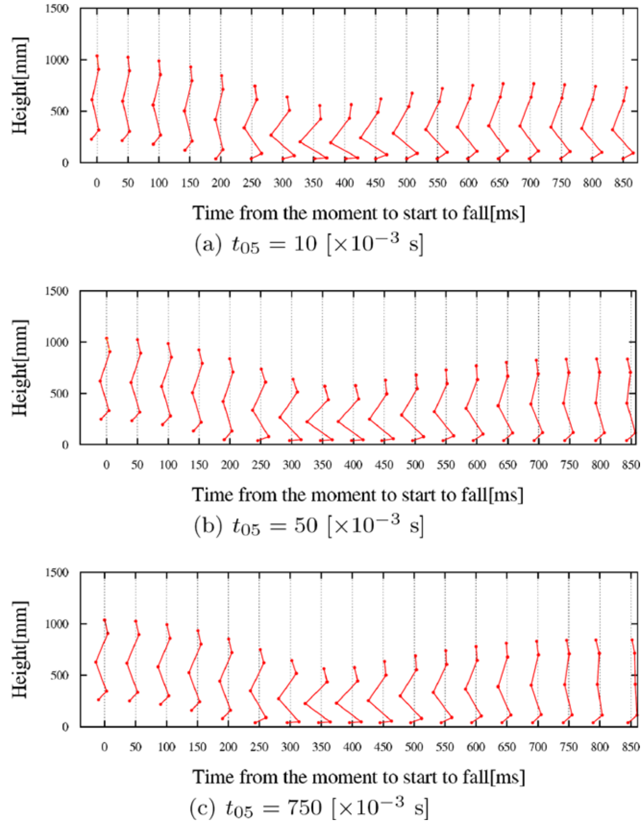


Fig. 13 Jumping behavior driven by hip extensor #2. We changed initial duration to supply air to #5: t_{05}

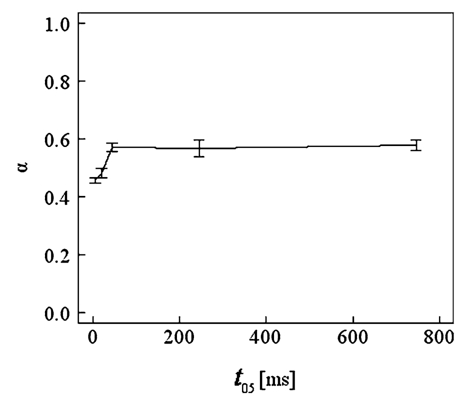


Fig. 14 Experimental results: Power is provided by the monoarticular muscle #2. Jumping height is modulated by tension of the biarticular muscle #5. When it is tensed, it translate power from the hip to the knee. As a result, jumping height increases

1996), we activate the proximal joint #2 and after Gt_{03} [s] activate the distal one #3. The results are shown in Fig. 17. As we expected, the robot does not rotate so much even we change time-gap Gt_{03}. However, the jumping height is maximum when it is 0 [s]. This somewhat contradicts the biological inference (Jacobs et al. 1996), but we have to investigate more precisely since there are so many uncertainty such as non-linearity and delay of the muscles.

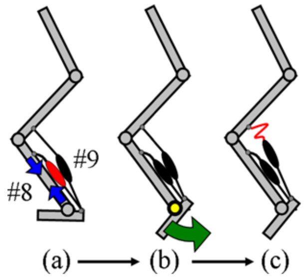
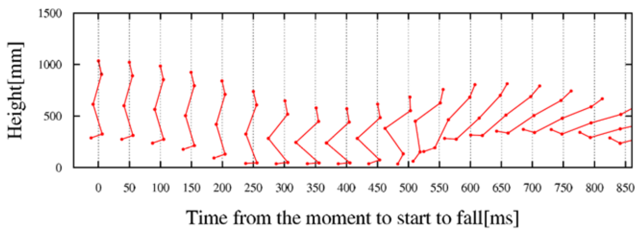
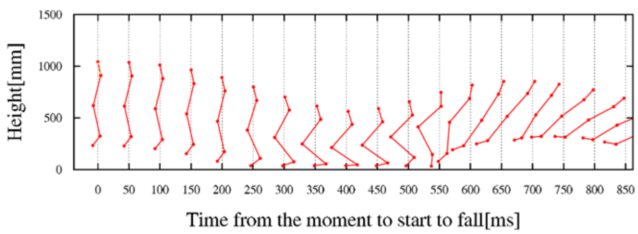


Fig. 15 The robot motion by the ankle extensor #8: Even though extensor #8 contracts, there is no biarticular muscle to translate power to the knee. The muscle #9 is just loosened

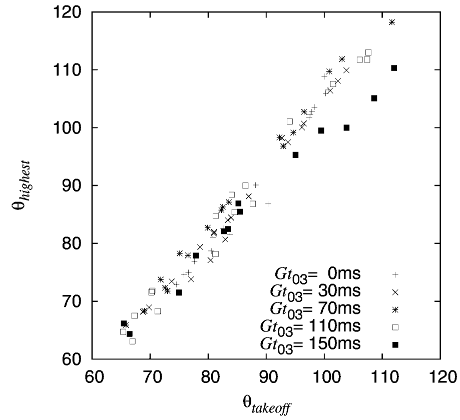


(a) $t_{09} = 0$ $[\times 10^{-3}$ s]

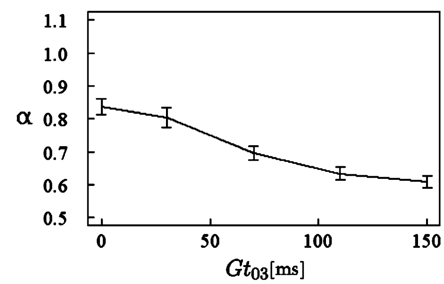


(b) $t_{09} = 750$ $[\times 10^{-3}$ s]

Fig. 16 Behavior driven by ankle extensor #8: We changed initial duration to supply air to #9: t_{09}. Regardless of the tension, the whole body extension is not realized, and the robot just rotates backward



(a) relation between body angles at apex $\theta_{highest}$ and at take-off $\theta_{takeoff}$.



(b) apex ratio

Fig. 17 Body rotation and apex ratio: Gt_{03} is the time gap between activation of #2 and that of #3. The robot does not rotate so much even we change time-gap Gt_{03}. The jumping height is maximum when it is 0 [s]

4.2 Jumping driven by #2, #3, and #8

Finally, we superpose activation of the ankle. From the last experiment, we set $Gt_{03} = 0$. The muscle #8 is extended after Gt_{08}. The results are shown in Fig. 18. As we expected, the robot rotates in this case. The robot starts to jump just after muscles #2 and #3 are activated. Therefore, when the time gap Gt_{08} is large, the movement of ankle does not have large effect on the behavior. As a result, the rotation decreases when Gt_{08} is large. In this case, the jumping height is maximum when Gt_{08} is 0 [s] as well.

Following these results, by activating the muscles #2 and #3 simultaneously, we could realize several jumping steps without any attitude feedback (Fig. 19). Therefore, we suppose that the system is somewhat stable with the anthropomorphic structure, but it remains to be proved in the future.

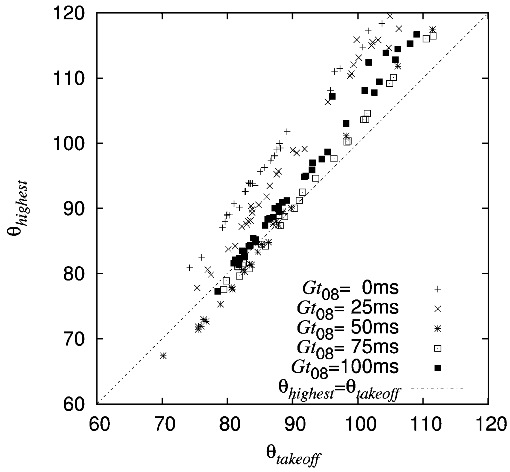
5 Conclusions

In this paper, we developed a jumping robot with anthropomorphic structure driven by pneumatic artificial muscles. Based on biomechanical findings, we investigated roles of the muscles. We used biarticular muscles as coordinators of joints, and monoarticular ones for providing power for jumping.

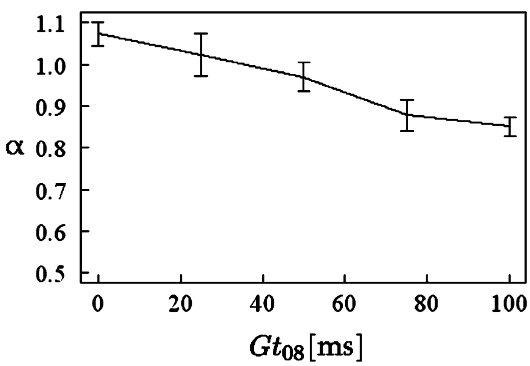
Through experiments, we found (1) the biarticular muscles realized coordinated movement of joints when knee and/or hip is extended, (2) the extension of the ankle did not lead to coordinated movement, and (3) we could superpose extension of the knee with that of the hip without losing the joint coordination. The obtained knowledge can be used not only for robots, but may also contribute to understanding of adaptive human mechanism.

We devoted ourselves to investigate the function/role of each muscle. Therefore, we did not apply any feedback based on the gyro sensor or on other sensors. Since we can modulate the coordination between joints by changing tension of biarticular muscles, obviously, we can improve stability of jumping by applying feedback (Raibert 1986), but it remains as a future issue.

The robot is a planar monopod that can move in the sagittal plane. To build a humanoid, we have to deal with the motion in the frontal plane also, but in such a case, balancing problem becomes important.



(a) relation between body angles at apex $\theta_{highest}$ and at take-off $\theta_{takeoff}$.



(b) apex ratio

Fig. 18 Body rotation and apex ratio: Gt_{03} is the time gap between activation of #2 and that of #3. the robot does not rotate so much even we change time-gap Gt_{03}. The jumping height is maximum when it is 0 [s]

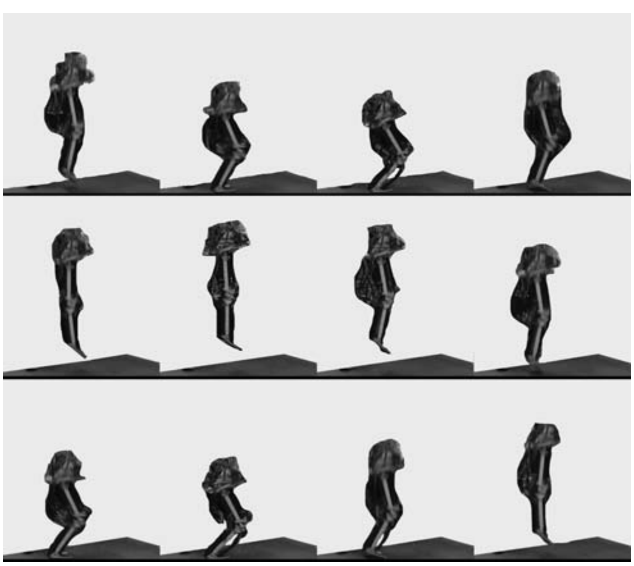


Fig. 19 Sequential Jumping experiment. By applying a fixed sequence of valve operation shown in Fig. 6, the robot can jump continuously and stably without any attitude feedback

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Koh Hosoda received his Ph.D. degree in mechanical engineering from Kyoto University, Japan in 1993. From 1993 to 1997, he was a Research Associate of Mechanical Engineering for Computer-Controlled Machinery, Osaka University. Since Feb. 1997, he has been an Associate Professor of the Department of Adaptive Machine Systems, Osaka University. In 1998, he was a guest professor in Artificial Intelligence Laboratory, University of Zurich. Since Nov. 2005, he serves concurrently as a group leader of the JST Asada ERATO Project.

Yuki Sakaguchi received his M.Sc. degree in department of Adaptive Machine Systems, Osaka University, Japan in 2009. He studied dynamic locomotion of muscular-skeleton robots. Since April 2009, he has been working for TERUMO Corporation, Japan.

Hitoshi Takayama received his M.Sc. degree in department of Adaptive Machine Systems, Osaka University, Japan in 2008. He studied dynamic locomotion of muscular-skeleton robots. Since April 2008, he has been working for Honda Motor Co., Ltd.

Takashi Takuma received his B.E. degree and M.E. degree in Engineering from Osaka University in 1999 and in Informatics from Kyoto University in 2001, respectively. He received his Ph.D. degree in Adaptive Machine Systems, Osaka University, Osaka, Japan in 2007. Since 2008, he has been a Lecturer in the Department of Electrical and Electronic Systems Engineering, Osaka Institute of Technology.