Design of a Musculoskeletal Athlete Robot: A Biomechanical Approach

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In this research, we propose an "Athlete Robot" which is compatible with a biomechanical structure of a human. In our work, pneumatic muscle is used for the actuator. We also provide a method to describe the properties of musculoskeletal leg with "Convex Polygon of Forces". In the experiment, we observed sway of the center of gravity similar to a human during bipedal stance. Our results show that the robot which has well-designed leg can land softly from one meter drop by exploiting the anti-gravity muscles and its compliance. In addition, by using preset stiffness of the musculoskeletal leg, we can control the direction of the bouncing predictively. The musculoskeletal robot helps to illuminate design principles of the robot which can move quickly and skillfully in the real world.

Keywords: Musculoskeletal System, Legged Robot, Biomechanics, Explosive Movements

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.[1,2] 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.[3] A lot of bio-inspired legged robot had been proposed. For example, researchers have developed a bipedal walker driven by pneumatic muscle,[4] mono-leg hopping robots,[5,6] and humanoid robots driven by wire.[7] However, there are a few robots which have a biologically-correct musculoskeletal structure.[8,9]

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 postural control, soft landing and passive control of a bouncing.

2. Design of a musculoskeletal leg

2.1. *Forces and stiffness of a leg*

To analyze the characteristics of the musculoskeletal system, we employ the method based on statics and kinematics of the serial-link structures[10] . Note that the model include the actuators and the transmissions, and one actuator can affect multiple joints as shown in Fig.1.

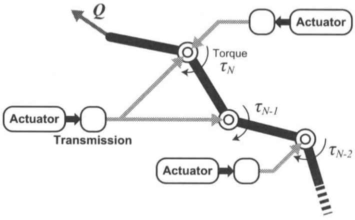

Fig. 1. Statics and kinematics of the link-actuator model.

Here a matrix $\boldsymbol{J}(\boldsymbol{\theta})$ is a Jacobian matrix which associate velocity of joint angle with velocity of link end. And a matrix $\boldsymbol{G}(\boldsymbol{\theta})$ is a Jacobian matrix which associate velocity of joint angle with velocity of actuator output. Then, inconsideration of duality between differential kinematics and statics, the equilibrium of joint torque τ, force applied to link end $\boldsymbol{Q}$ and torque or force of actuator $\boldsymbol{F}$ are described as eq.(1).

$$\tau = \boldsymbol{J}^T \boldsymbol{Q}, \qquad \tau = \boldsymbol{G}^T \boldsymbol{F} \tag{1}$$

In addition, using stiffness of link end $\boldsymbol{K_e}$, joiint $\boldsymbol{K_j}$ and actuator $\boldsymbol{K_a}$, relation among these stiffness are described as follows.

$$\boldsymbol{K_j} = \boldsymbol{J}^T \boldsymbol{K_e} \boldsymbol{J}, \qquad \boldsymbol{K_j} = \boldsymbol{G}^T \boldsymbol{K_a} \boldsymbol{G} \tag{2}$$

Based on the above discussion, the control of the musculoskeletal system is a inverse problem which compute stiffness $\boldsymbol{K_a}$ and output force $\boldsymbol{F}$ of actuators from desired stiffness $\boldsymbol{K_e}$ and output force $\boldsymbol{Q}$ of link end.

2.2. *Convex polygon of forces*

To represent the characteristics of the musculoskeletal leg, we propose a "Convex Polygon of Forces". From eq.(1) we can compute a force vector of the leg caused by actuators. Here, the matrix $\boldsymbol{G(\theta)}$ include muscle moment arm on each joint. The "Convex Polygon of Forces" is a polygon which encompasses force vectors produced by all combination of actuator ourput. The polygon can represent a distribution of maximum force vectors of the musculoskeletal leg.

Fig.2 shows the polygon of the 3 DoF leg with uniform muscles including bi-articular muscles. Its shape depends on the muscle configuration and the orientation of the leg. Previously, only the characteristics of two-joint arm based on graphical method has been known.[11]

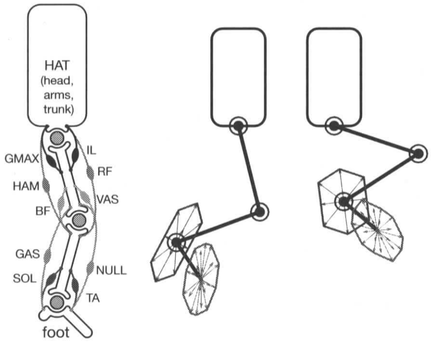

Fig. 2. Convex polygon of forces on ankle and toe of the musculoskeletal leg with uniform muscles.

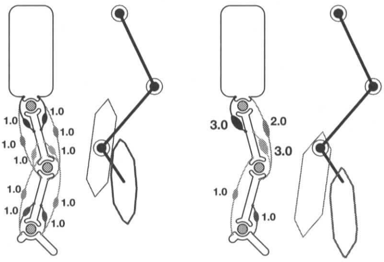

Fig. 3. Optimization to the gravity field. The total amount of muscles is constant.

Fig.3 represent the manually derived muscle configuration under the constraint of constant total amount of muscles. The leg with uniform muscles has unprofitable convex polygon of forces. Flexibility of design is limited in the system which has neither antagonistic mechanism nor multi-articular actuator.[12,13]

3. Athlete Robot with an Artificial Musculoskeletal System

3.1. *overview*

We developed a bipedal Athlete Robot with an artificial musculoskeletal system (Fig.4). The robot, weighs about 10 kg and is 1.25 meters tall with the legs extended. We apply proportional valves, which transform an analogue input signal into a corresponding air flow, to the electro-pneumatic system instead of conventional on-off valves 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.

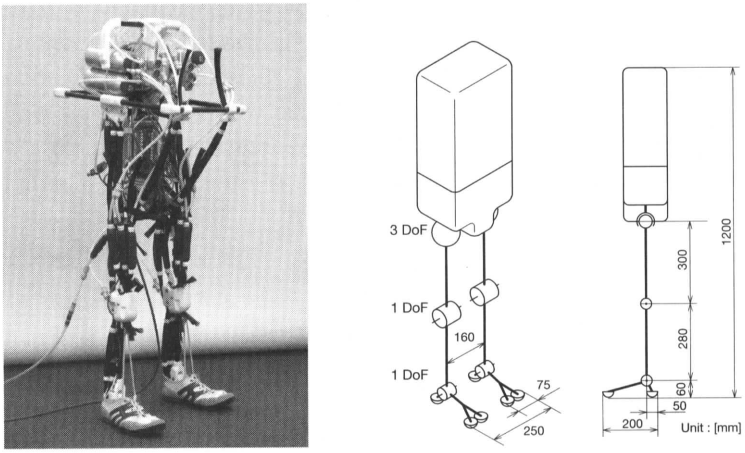

Fig. 4. Athlete Robot with artificial musculoskeletal system.

3.2. *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.[14] As a full-scale humanoid robot, the physical ability of the Athelet Robot is extremely high (Fig.6).

The musculoskeletal system of the robot corresponding to the anatomical structure of the human is shown in Fig.5 and Table 1. The configuration of the muscles, range of motion (RoM), maximum force of muscles and moment arms on each joint are compatible with a human.

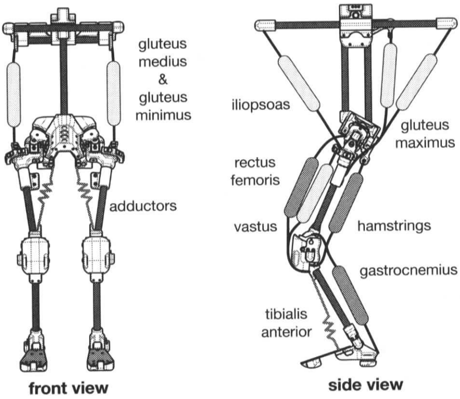

Fig. 5. Musculo-skeletal system of the Athlete Robot.

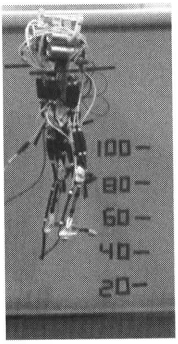

Fig. 6. Physical ability of the Athlete Robot.

Table 1. Maximum force of muscles and moment arms on each joint.

	F_{max} (N)	D_{hip} (m)	D_{knee} (m)	D_{ankle} (m)
adductors	200	0.060	-	-
gluteus medius & 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. *Postural control in bipedal stance*

We performed the balance control during bipedal stance by the PID control of each joint (Fig.7, Fig.8). The joint angles and inner pressure of muscles are recorded. Although the movement of the center of gravity is relatively greater than for a stiff robot, the observed sway is similar to human movement reported in biomechanics research.[15]

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, feedforward controls become considerably important in explosive movements. The musculoskeletal leg can use preset stiff-

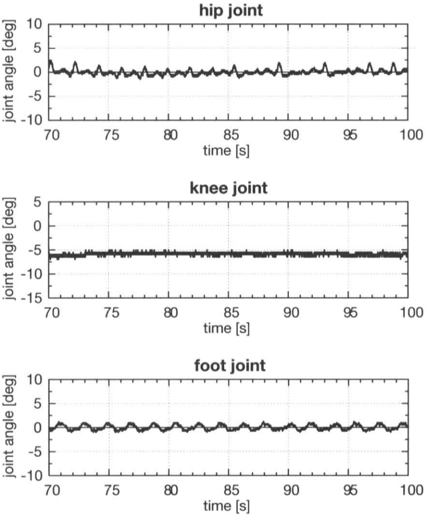

Fig. 7. Joint angles during standing with ankle strategy.

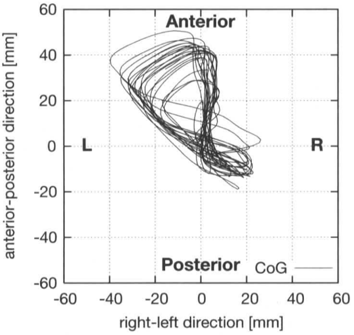

Fig. 8. Trajectory of the CoG in standing posture.

ness to control posture predictively.

As shown in Fig.9, the robot can land softly from one meter drop by exploiting the anti-gravity muscles and its compliance. These tasks are particularly difficult for the robot which is driven by the geared motors because of the large instantaneous forces and short duration.

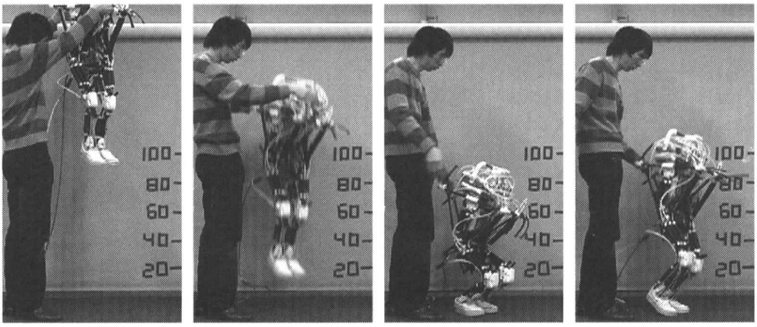

Fig. 9. Soft landing from height 1.0 m.

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 (Fig.10) and fall backward (Fig.11).

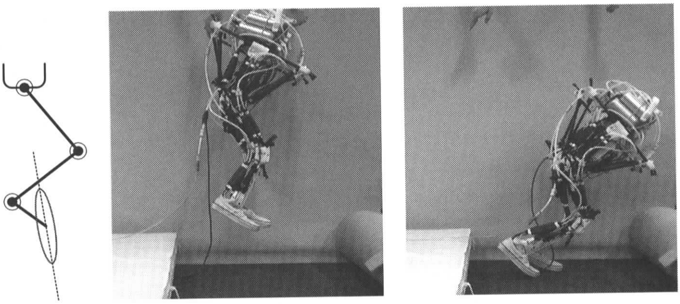

Fig. 10. Passive control of bouncing by the preset stiffness (fall forward).

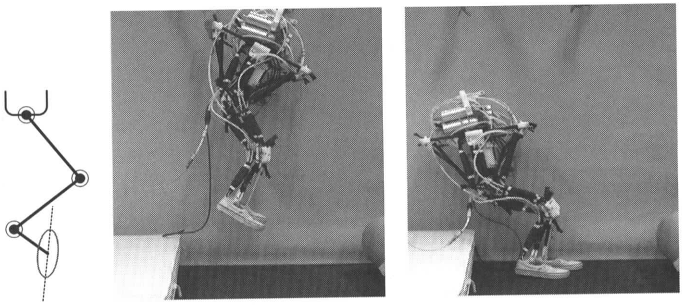

Fig. 11. Passive control of bouncing by the preset stiffness (fall backward).

5. Conclusion

In this research, we propose the Athlete Robot with an artificial musculoskeletal system which is compatible to human musculoskeletal system. We also propose the "Convex Polygon of Forces" to visualize and design the properties of the musculoskeletal leg. The method, which is based on the kinematics and statics of link-actuator model, is able to describe output force and stiffness of the musculoskeletal leg.

The Athlete Robot has the biomechanical properties such as range of motion, muscle configuration, muscle strength and muscle moment arm which is similar to the human. In the results of the postural control, the observed sway of center of gravity is similar to human movement reported in biomechanics.

The well-designed leg has the asymmetry antagonistic muscles optimized for the gravity field. The results shows that the robot can 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 feedforward control play big role especially in the explosive movements with large instantaneous forces and short duration time.

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