Development of a Monopedal Robot with a Biarticular Muscle and Its Hopping Motion

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Abstract: An electromagnetic linear actuator which we developed can emulate the spring-damper characteristics of a human muscle by quick control of the output force (i.e. impedance control) and it is expected to be used as an artificial muscle. We have been developing the electromagnetic linear actuator which has long stroke, quick response and large thrust by effective use of interior permanent magnets. In this paper, we develop a monopedal robot possessing bi- and mono-articular muscles implemented by the linear actuators. Thanks to the biarticular muscle, the bouncing direction of the robot can be controlled by changing the stiffness ellipse at the endpoint (i.e. foot) of the robot. We confirm that the bouncing direction of the robot and realize hopping by changing the stiffness ellipse.

Keywords: Compliance control, Electromagnetic linear actuator, Hopping, Monopedal robot, Stiffness ellipse.

1. INTRODUCTION

Animals perform dynamic whole body motions such as running and hopping in various environments. To realize these motions, compliance of muscles against external force and structural stability contributed by biarticular muscles are crucial. [1].

Biarticular muscles improve the stability of their body motion by changing the direction of the force output and the compliance characteristics at the endpoint. The latter property can be represented by the stiffness ellipse [1]. We focus on a control of a monopedal robot with a biarticular muscle to realize the hopping motion, as a first step for dynamic motions.

An electromagnetic linear actuator which we developed is advantageous in its response compared to pneumatic actuator which is widely used for various robots [2, 3]. Pneumatic actuator has compliance due to its physical property. A legged robot "Athlete Robot" driven by pneumatic actuators [2] can change the direction of the long axis of the stiffness ellipse. Though a control of the bouncing direction can be achieved by presetting the stiffness ellipse, a quick change of stiffness during the robot moving is difficult due to the slow response of the pneumatic actuator.

For compliance control, direct drive rotary electric motor is suitable thanks to its quick response. However, linear actuator is advantageous for adopting biarticular muscle since rotary motor requires complex wire drive system for it.

In this research, we develop a monopedal robot which has bi- and mono-articular muscles implemented by electromagnetic linear actuators [3]. The stiffness ellipse at the endpoint (i.e. foot) of the robot is easily controllable thanks to the biarticular muscle. The robot can control its bouncing direction when it touches down to the ground. We confirm the bouncing direction and realize hopping by changing the stiffness ellipse.

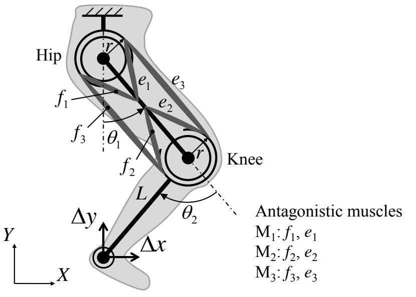

Fig. 1 Simple model of human leg

2. STIFFNESS ELLIPSE

The model of human leg is shown in Fig. 1. f_n and e_n are the flexor and extensor muscles respectively. M_n is antagonistic pair of muscles. M_1 and M_2 are the monoarticular muscles at the hip and knee joint respectively. M_3 is the biarticular muscles which can constrain the motion of two joints. The compliance characteristic at the foot is expressed as an ellipse (stiffness ellipse) defined by three parameters; the length of the long axis, short axis and the direction of the long axis. They are determined uniquely according to elastic coefficients of M_1, M_2 and M_3

3. MONOPEDAL ROBOT AND RESULTS

The monopedal robot which we developed is shown in Fig. 2. The height from the foot to the hip is about 210mm (θ_1=20° and θ_2=40°). Three antagonistic pairs of muscles (i.e. six) are replaced by three actuators.

Since the current actuator cannot output sufficient thrust for the robot to jump under the environment with the gravity acceleration, a counter weight is used in the experiment. The movement of the trunk is restricted to the translation (i.e. no rotation) in horizontal and

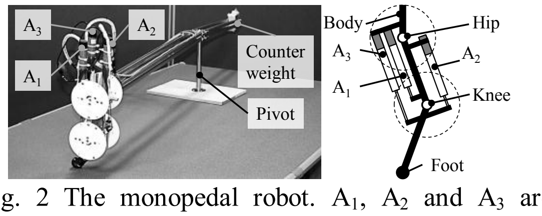

Fig. 2 The monopedal robot. A_1, A_2 and A_3 are actuators correspond to M_1, M_2 and M_3 respectively.

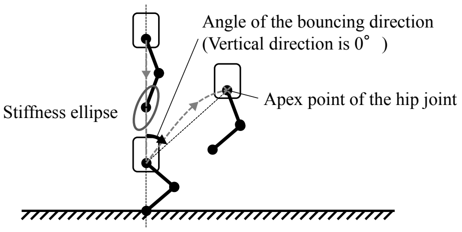

Fig. 3 Bouncing direction

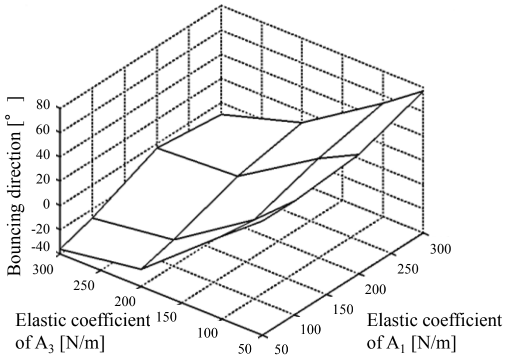

Fig. 4 Relationship between the elastic coefficients and the bouncing direction. A_1 and A_3 are actuators as mono- and bi-articualr muscles respectively.

vertical directions (sagittal plain).

The bouncing direction defined by the angle between the vertical direction and the moving direction is shown in Fig. 3. The bouncing direction can be controlled by changing the elastic coefficients of the linear actuators; i.e. stiffness ellipse. Fig. 4 shows the relationships between these parameters and the bouncing direction. The bouncing direction becomes larger as the elastic coefficient of A_1 increases and vice versa.

The above discussion on the stiffness ellipse is about the passive behavior of the robot. During each hopping cycle, energy loss occurs for each unloading. In order to continue the hopping, we employ a new control method for the knee joint; i.e. the monoarticular muscle A_2. Since this actuator does not affect to the direction of the stiffness ellipse, it is able to change the output force of the actuator at the knee joint without changing hopping direction. Therefore, bouncing direction and thrust force can be controlled independently. In the landing duration, the elastic coefficient is set to be small. In the unloading duration, on the other hand the elastic coefficient is set to be large. Fig. 5 shows motion sequences of hopping of the monopedal robot. The robot jumped twice.

It is important to note that use of biarticular muscle reduces computational cost. Even if there is no biarticular muscle, the stiffness ellipse can be controlled by calculating output force depending on posture of the robot with rapid control cycle. However, in our robot, it can be controlled by making each actuator emulate a spring, i.e. each actuator is controlled by a simple P control with fixed target. The robot only changes stiffness of actuators around hip joint (A_1, A_3) in each cycle and does not consider the motion on the ground. As the result, the robot with compliant actuator and biarticular muscle can realize stable hopping by using simple controller.

4. CONCLUSIONS

In this research, we developed a monopedal robot with the electromagnetic linear actuators. To realizing hopping of the monopedal robot, the monoarticular muscle around the hip joint and biarticular muscle are used to determine the bouncing direction of the robot. The monoarticular muscle around the knee joint is used to provide energy loss during each step. As the result, the hopping of the robot is achieved.

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REFERENCES

[1] M. Kumamoto, T. Oshima and T. Yamamoto, “Control properties induced by the existence of antagonistic pairs of bi-articular muscles — Mechanical engineering model analyses”, *Human Movement Science*, Vol.13, No.5, pp.611-634, 1994.
[2] R. Niiyama and Y. Kuniyoshi, “Design principle based on maximum output force profile for a musculoskeletal robot”, *Industrial Robot: An International Journal*, Vol.37, No.3, pp.250-255, 2010.
[3] Y. Nakata, H. Ishiguro, K. Hirata, “Dynamic Analysis Method for Electromagnetic Artificial Muscle Actuator under PID Control”, *IEEJ Transactions on Industry Applications*, Vol.131, No.2, pp.166-170, 2011.

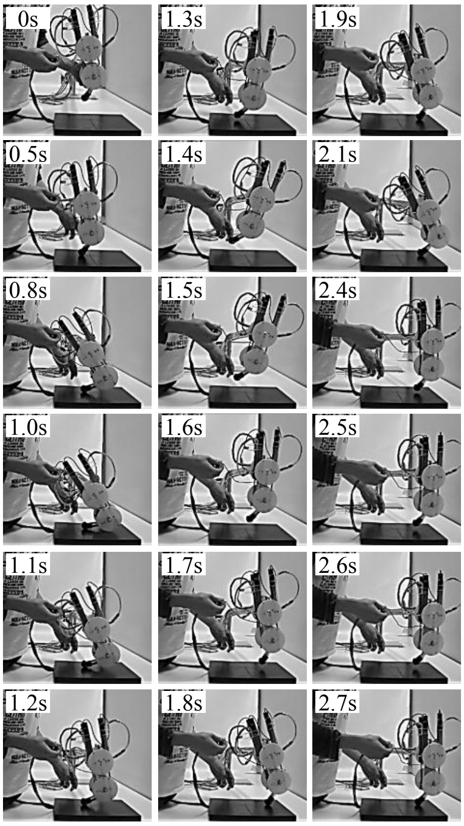

Fig. 5 Hopping of the monopedal robot. The black board under it is hard rubber board as slip-proof mat.