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Brainless Running: A Quasi-quadruped Robot with Decentralized Spinal Reflexes by Solely Mechanical Devices

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***Abstract*— As a strategy to address the difficulties encountered when modeling and controlling a musculoskeletal system, we present a straightforward implementation of an autonomous decentralized motion control system in this paper; the system is inspired by the spinal reflex system of animals. We developed an artificial receptor, a muscle, and a neuron to mechanically implement the reflex mechanisms of animals. Among the reflex mechanisms, this paper presents a reflex system with reciprocal innervation for a musculoskeletal quasi-quadruped robot, including antagonist muscles. In the experiments, the robot autonomously generated a leg trajectory and a gait pattern with smooth alternating motions of the antagonist muscles through the interaction between the body, the ground, and the artificial reflex systems. To evaluate the reciprocal innervation, we compared the developed robot with one that does not include antagonist muscles. The reciprocal innervation allows for twice as many muscle implementations as those offered by the robot without antagonist muscles. Moreover, it improves the running speed by 5% on average and the flexion and extension velocities of all joints by 28% on average at around touchdowns and liftoffs of the foot. This successful result lead to implement more advanced nervous systems by solely mechanical devices.**

I. INTRODUCTION

Most robots consisting of rigid bodies require precise sensors and powerful microprocessors to adapt to an unpredictable environment. Conversely, musculoskeletal robots with large-DoF and compliant bodies can solve various tasks without precise control. For instance, grasping [1] and door opening [2] tasks, thanks to the adaptability of the body shape to the environment. However, the musculoskeletal body has some nonlinearity caused by its complex body geometry, slack muscles, and nonlinear elastic components such as tendons. Due to the nonlinearities, modeling and control of the musculoskeletal system in an unstructured environment are difficult.

One strategy to solve the problem is to use autonomous decentralized control, which is employed by animals to survive in an unstructured environment. Except for a few creatures, all animals have a large number of local sensory feedback, which consists of sensory receptors, neurons, and muscles. Moreover, animals exploit the interaction between the body dynamics, the environment, and the sensory feedback, to coordinate each body part [3]. Several studies have proposed various autonomous decentralized controllers to understand such excellent control principles inherent to animals, to apply these principles for developing robot controllers. [4], [5], [6], [7].

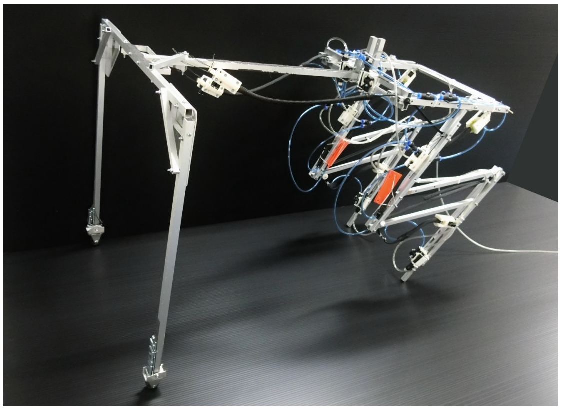

Fig. 1. Musculoskeletal quasi-quadruped robot with mechanically implemented artificial receptors, muscles, and neurons.

As it is challenging to implement several control modules directly on the robot, most robots execute the decentralized controllers on a central computer. Although a few robots with several decentralized control modules [8], [9], [10] have been developed, microprocessors and peripheral circuits, batteries, and communication devices are required for each decentralized module. Therefore, a problem arises concerning the fabrication time and cost of autonomous decentralized robots, which are enormous compared with a robot having just one central controller. Thus, the application of musculoskeletal robots with a decentralized controller is limited.

To address the problem mentioned above, we presented an extremely simple implementation approach for an autonomous decentralized controller called the brainless control approach [11]. In this regard, we embed decentralized actuator devices, responding reflexively to external stimuli, in distal robot body parts. A remarkable point of this approach is that the actuator devices consist of purely mechanical components; hence, each control module is developed without microprocessors or software-based controllers. Typically, a robot requires a computer for the controller, which can be seen as the animal brain. As the actuator devices are developed without microprocessor, we call this method a brainless control approach. In a brainless robot, each de-

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centralized device adjusts its motion through the mechanical interaction between the body, the environment, and the intrinsic dynamics of each actuator. Therefore, the actuator entrains the coupled dynamics of the body–environment and coordinated motor patterns arise.

This paper describes an implementation method of an autonomous decentralized motion control system without electronics, which can be seen as the first step toward easy-to-implement autonomous decentralized controllers for musculoskeletal robots. In a previous study [11], we developed a pneumatic actuator device to embed simple reflexive rules in distal robot parts. The device consists of a mechanical artificial receptor and an artificial muscle. When a force-sensitive valve in the artificial receptor receives a muscular force, the valve turns on. Subsequently, air pressure enters into the artificial muscle, which makes the muscle contract reflexively. In the study [11], based on a walking cat experiment in biology, an artificial reflex pathway was constructed. The study showed that a musculoskeletal quasi-quadruped robot (Fig. 1) autonomously develops a running motion (a leg trajectory and a gait pattern) through the interaction between the body, the ground, and the artificial reflexes. However, the actuator device can only achieve an excitatory reflex mechanism. Thus, significant limitations exist regarding the types of reflex functions and the number of muscles that can be embedded. Animals have roughly two types of neurons, excitatory and inhibitory. Moreover, inhibitory neurons are the ones contributing to most of the motor functions, including the reciprocal innervation, which produces smooth alternating motion of the antagonist muscles. Therefore, in this study, in addition to the conventional artificial receptor and muscle, we develop an artificial inhibitory neuron that inhibits muscle activity in response to a pneumatic input. Moreover, we construct an artificial reflex pathway with a reciprocal innervation consisting of artificial inhibitory neurons. For evaluating the reciprocal innervation consisting of artificial neurons, we compared the proposed robot and the previous one without the antagonist muscles. The reciprocal innervation enables implementing twice as many muscles as in those in the previous method and provides faster running motion compared to the previous method.

II. SPINAL REFLEX SYSTEM WITHOUT ELECTRONICS

This section describes the artificial reflex system that is inspired by the spinal reflex mechanisms of animals.

A. Spinal Reflexes in Animals

Animals, in particular vertebrates, have some reflexes in their neuronal system[1]. Fig. 2 (a) illustrates a typical spinal reflex loops in animals, which consists of a sensory receptor, a muscle, and one or two neurons. If a sensory receptor in the muscles receives muscle tension or an elongation, subsequently, the receptor sends some impulsive signals to the spinal cord according to the sensory values. Roughly two types of neurons exist in animals; excitatory and inhibitory. If an excitatory neuron in the spinal cord receives a signal from a receptor or another neuron, the neuron activates the next nerves or muscles. Conversely, if an inhibitory neuron in the spinal cord receives a signal, the neuron inhibits the activity of the next nerves or muscles. The inhibitory neuron plays a crucial role in rhythmic and smooth motion control in animals [12]. Therefore, in this paper, we develop an artificial inhibitory neuron and implement a fundamental inhibitory reflex mechanism called the reciprocal innervation, which provides a smooth alternating motion of antagonist muscles.

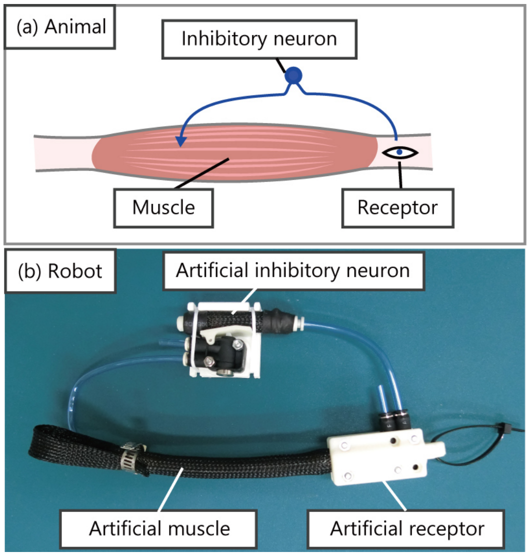

Fig. 2. (a) Spinal reflex pathway in animal body. (b) The artificial reflex system without electronics.

B. Artificial Receptor, Muscle, and Nerves

Fig. 2 (b) shows the reflex pathway we developed. The reflex pathway consists of artificial receptors, muscles, and inhibitory neurons. The remarkable point of this work is that all the artificial devices consist of purely mechanical pneumatic elements without any electronic devices[2]. Note that the reflex pathway in Fig. 2 (b) is only an example, and various other pathways can be constructed by combining each artificial device.

The artificial receptor consists of a force-sensitive normally closed valve [3] and a slider mechanism. If the artificial receptor receives a muscular tensile force, subsequently, the valve is opened. Therefore, the valve sends air pressure to the next neuron. For more detail, see [11].

Fig. 3 shows the structure of the artificial inhibitory neuron. The artificial neuron consists of a normally opened valve [4] and a small pneumatic actuator. The actuator is

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[1] Although typical reflexes have been known as the stretch reflex, the crossed extension reflex, the tendon reflex, and the reciprocal inhibition, in addition to these typical examples, several diverse reflex pathways have been discovered [12].

[2] The real receptors and neurons send impulsive signals to the next neurons or muscles. In this study, we consider the firing rate of the impulsive signal transmitted by the neuron as the air pressure in the pneumatic circuit.

[3] A valve that opens when the switch is pressed and closed when the switch is released

[4] A valve that closes when the switch is pressed and opened when the switch is released

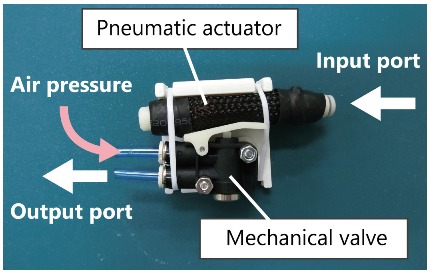

Fig. 3. Structure of the artificial inhibitory neuron.

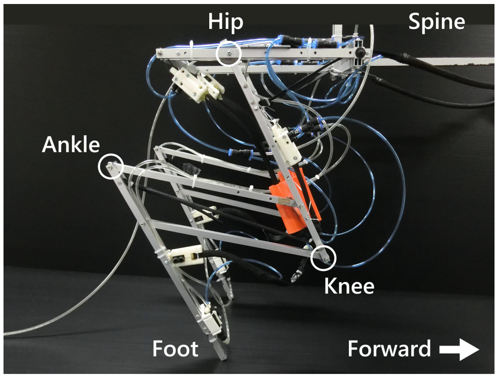

Fig. 4. Structure of a hind-limb of the musculoskeletal quasi-quadruped robot.

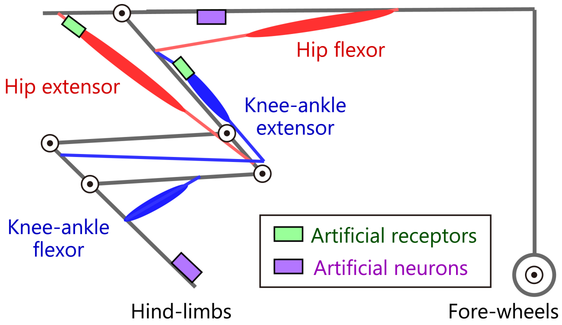

Fig. 5. Layout of the pneumatic muscles.

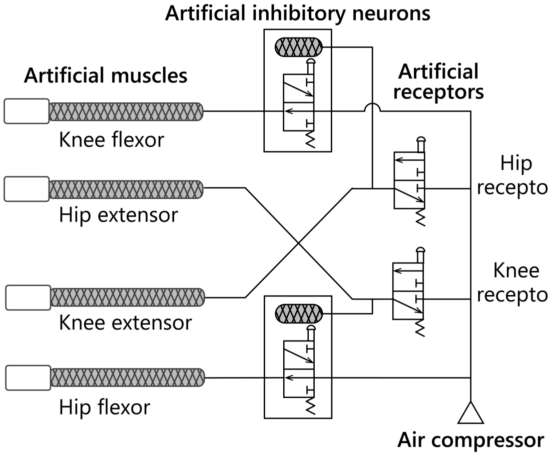

Fig. 6. Schematic diagram of the artificial reflex pathway with the reciprocal innervation.

developed in the same way as the pneumatic muscles. If the artificial neuron received an air pressure from an artificial receptor or another valve into the input port, then the air pressure inflates the small actuator, and the actuator presses the push switches on the valve. Therefore, the valve closes and inhibits the airflow from the input to the output port, conected to the next neuron or muscles.

III. QUASI-QUADRUPED ROBOT WITH ARTIFICIAL REFLEXES

We developed a musculoskeletal quasi-quadruped robot that autonomously develops a running motion (a leg trajectory and a gait pattern) through the interaction between the ground, the body, and a mechanically embedded reflex pathway. This robot is driven only by constant air pressure supplied from an external compressor and does not have any electric controller.

A. Body Structure

Fig. 4 shows the structure of a hind-limb of the musculoskeletal quasi-quadruped robot. The robot consists of fore-wheels and hind-limbs. Each limb consists of three links and three joints, and the knee and ankle joints are constrained by a pantograph mechanism, as with the previous robot [11].

Fig. 5 shows the layout of the artificial muscles, receptors, and neurons in one leg. Each limb has four pneumatic muscles, thus the robot has eight muscles in total (twice the number of muscle of the previous robot [11]). The layout of the muscles relies on the layout of the hip and knee–ankle muscles in typical quadrupeds (hip extensor and flexor, knee–ankle extensor and flexor). Table I shows the link length and the length of the muscles.

TABLE I

THE LINK LENGTH AND THE LENGTH OF MUSCLES.

Property	Value
Length × Width × Height	780 × 520 × 560 mm
Hip-to-knee length	300 mm
Knee-to-ankle length	350 mm
Ankle-to-foot length	360 mm
Total weight	4.3 kg
Length of hip extensor	shrink from 260 to 190 mm
Length of hip flexor	shrink from 260 to 190 mm
Length of knee–ankle extensor	shrink from 120 to 85 mm
Length of knee–ankle flexor	shrink from 120 to 85 mm

B. Reflex Pathways Based on Walking Experiments with Cats

We designed an artificial reflex pathway with the reciprocal innervation that relies on the reflex mechanisms observed in two previous experiments with walking cats [13], [14]. The first experiment [13] shows that the electrical stimulation of a neuronal pathway from a knee–ankle muscle receptor (*Golgi*

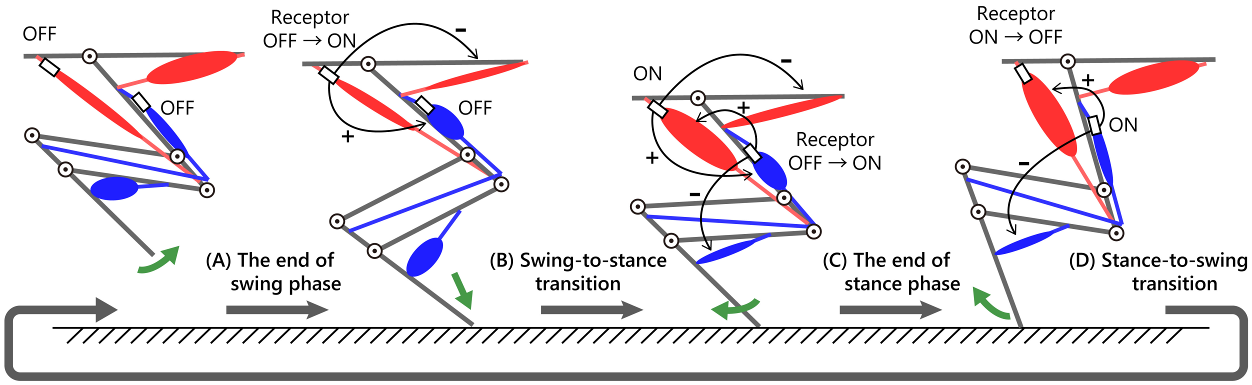

Fig. 7. Sequence of reflex actions in each phase during running.

tendon organ) prolongs the stance phase and delays the beginning of the swing phase. The second experiment [14] shows that stretching of the hip flexor muscles during the stance phase activates the hip flexor muscles and deactivates the ankle extensor muscles. This observation suggests the existence of two reflex mechanisms in the body of cats during walking. The first mechanism is the inhibition of the flexor muscles by the receptor of the knee–ankle extensor muscles. Furthermore, the second is a triggering mechanism of the stance-to-swing transition according to the hip angle. Note that this pathway also functions as the mechanism of the swing-to-stance transition activated by stretching of the hip extensor [15]. Fig. 6 illustrates the schematic diagram of the artificial reflex pathway based on the two reflex mechanisms. A remarkable aspect of this novel implementation is that the pneumatic circuit between the left and right limb is independent, except for the supply line of constant air pressure. Nevertheless, later chapter will show the phases of the left and right limbs of the robot converges to a reciprocal gait pattern through a physical interaction.

Fig. 7 shows the sequence of reflex actions in each phase during running. At the end of the swing phase (A), as the inertia of the limb stretches the hip extensor muscle, the hip receptor is turned on and sends air to the knee–ankle extensor [15]. Simultaneously, the hip receptor inhibits the hip flexor through the inhibitory neuron. If the extended limb touches the ground (B), subsequently, the knee–ankle receptor is turned on, and the swing-to-stance transition occurs due to the activation of the hip extensor. At the end of the stance phase (C), the hip joint is extended as the body moves forward. Thus, the slacking of the hip extensor turned off the hip receptor, and the knee–ankle extensor is deactivated. Therefore, the hip and knee–ankle flexor is released from inhibition simultaneously, and the stance-to-swing transition occurs (D), as with the second mechanism [14]. Here, if the ground reaction force continues to be applied to the knee–ankle extensor, the loading of the knee–ankle extensor continues to activate the hip extensor. Hence, the stance-to-swing transition is delayed, and the stance phase is prolonged, as with the first mechanism [13].

IV. Running Experiments

We perform running experiments on the robot to verify the artificial reflex pathway with the reciprocal innervation. In this section, we show that the robot with the reciprocal innervation autonomously develops a leg trajectory and a gait pattern. Moreover, the antagonist muscles with reciprocal innervation provide fast joint extension and flexion motion.

A. Experimental Setup

We set the robot with the feet together as the initial position. Subsequently, the robot starts running in a 6-meter section by receiving constant air pressure from the external air compressor; the air pressure was kept between 0.75 and 0.8 MPa. For comparison purposes, we conducted five running experiments with the developed robot and two experiments with the previous robot without the reciprocal innervation. In all experimental data, increasing joint angles corresponds to a joint extension.

B. Emergence of Running Motion

Fig. 8 shows the joint angles of the left limb in the running experiment. The figure shows that all joints flex at the beginning of the swing phase, whereas at the end of the swing phase, the joints extend due to reflex action. After the touchdown, the extended knee and ankle joints flex again by receiving a ground reaction force. At the end of the stance phase, the joints extend, and liftoff of the foot occurs. Fig. 9 shows the snapshot of the running. Analyzing the average speed from 2.5 seconds to 4 seconds after the start of the running in each trial, the average speeds ranged from 6.54 to 7.34 km/h. The average speed of the five trials was 6.94 km/h, and the momentary maximum speed reached was 9.11 km/h. Compared to the speed of the previous robot without the reciprocal innervation (6.59 km/h), the running speed improved by 5% on average.

Fig. 10 shows a gait diagram of the running. The black regions represent the stance phase. Despite the pneumatic circuit between the left and right limb is independent, except for the supply line of constant air pressure, the phases of the left and right limbs quickly converge to a reciprocal (anti-phase) gait pattern in all trials. The result shows that

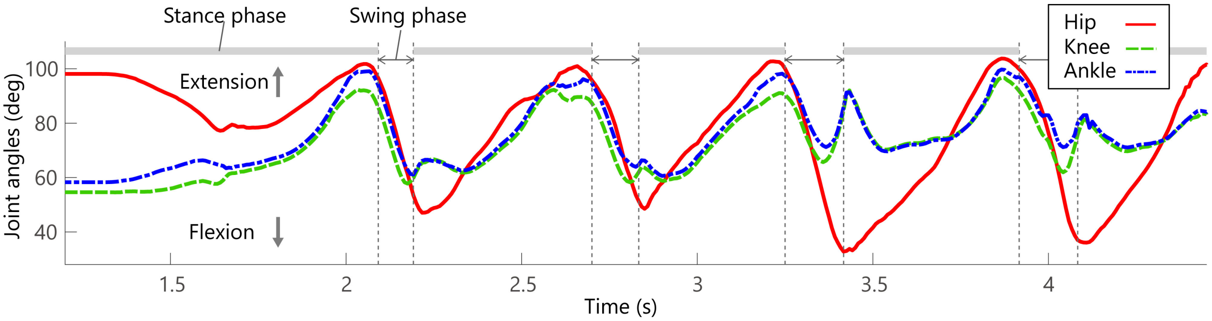

Fig. 8. Joint angles of the left limb in the running experiment. Increasing joint angles corresponds to a joint extension

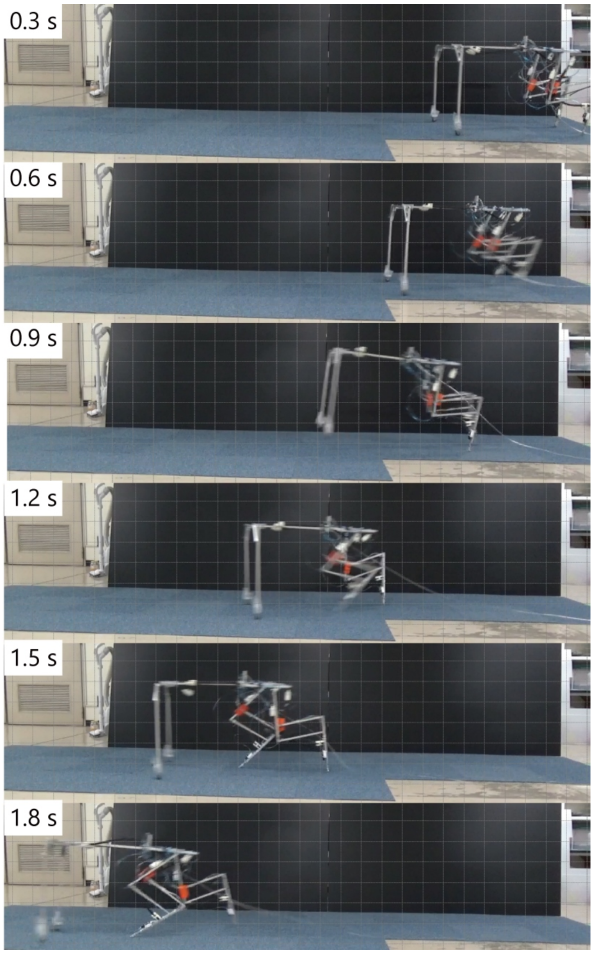

Fig. 9. Snapshots of the running experiment.

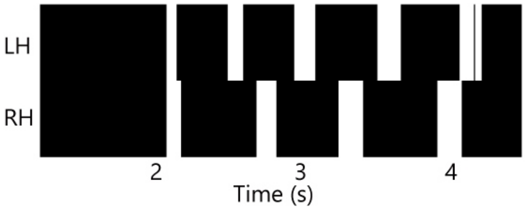

Fig. 10. Gait diagram of the developed running motion.

the robot autonomously generated a reciprocal limb motion through the interaction between the body, the ground, and the artificial reflexes, despite having no electrical controller such as a microprocessor.

C. *Fast and Smooth Actuation of Antagonist Muscles*

In the above experiment, we observed that the running speed improved by implementing the reciprocal innervation to the robot. Therefore, to identify the cause of the performance improvement, we evaluate the actuation speed of each robot joints.

Fig. 11 and Fig. 12 show the average of the maximum and minimum angular velocity of the hip and knee joints before and after foot touchdowns. The blue data indicates the angular velocity of the robot with the reciprocal innervation, and the red is without the system. As the knee and ankle joints move almost simultaneously by the link mechanism, the data of the ankle is omitted. From the result, the antagonist muscles with the reciprocal innervation improve the flexion and extension velocity of all joints. The angular velocity increased by 28% on average, 86% at maximum, and 4% at the minimum. Although the improvements of the flexion velocity are simply due to the effect of the flexor muscles, interestingly, the extension velocity also improved. It is considered that the joint velocity of the previous robot [11] has decreased due to the robot used the spring instead of the flexor muscle when flexing each joint. On the other hand, thanks to the reciprocal innervation, the robot in this study can actuate the antagonist muscles alternately and smoothly. Thus, the joint velocity increased as no need for wasted energy to extend the spring, which was required in the previous robot.

V. CONCLUSION

We proposed an extremely simple implementation for an autonomous decentralized motion control system without electronics. We developed a quasi-quadruped robot with an artificial receptor, muscle, and neuron to implement the spinal reflex system of animals only with purely mechanical elements. The design of the artificial reflex pathway with the reciprocal innervation relied on the reflex mechanisms, which are found in the walking of a cat. The experiments showed that the robot can autonomously generate a reciprocal limb motion, despite having no electrical controller and no mutual coupling between the limbs except for the supply line of

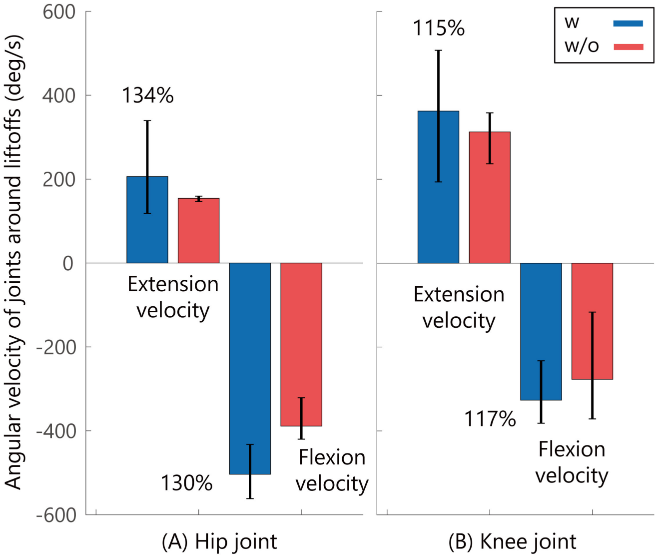

Fig. 11. Average of maximum and minimum angular velocity of the hip and knee joints before and after liftoffs of the foot.

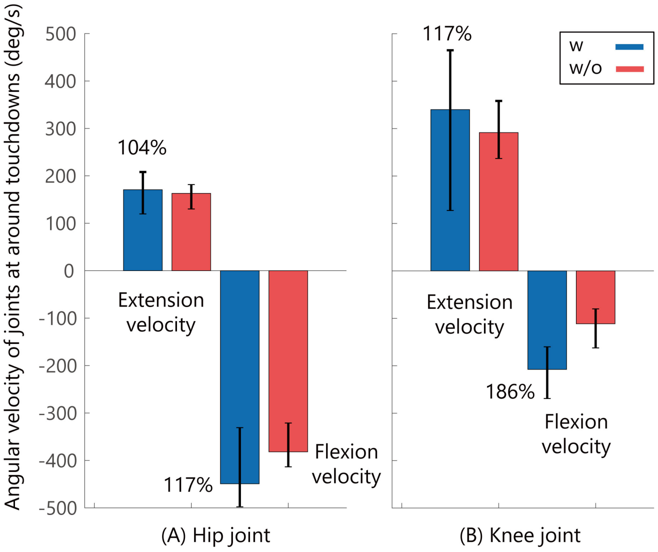

Fig. 12. Average of maximum and minimum angular velocity of the hip and knee joints before and after touchdowns of the foot.

the air pressure. Moreover, the contribution of reciprocal innervation for fast actuation was evaluated.

Although it is not clear why the gait converged to a reciprocal pattern without a neural interaction between the limbs, an observation [16] suggests that it is because of the force–length and force–velocity relationship of the actuators. We observed that the pneumatic muscle delays the limb motion according to the reaction forces from the ground. In other words, the reflex device has a function to delay the phase of the limb while receiving a large reaction force from the environment. The emergence of gait patterns from physical interaction of limbs and the force–velocity relationship of electric motors is reported in [17]. Thus, understanding the principle of the actuator synchronization phenomena, and the comparison with other researches of autonomous gait generation from physical interaction [18] are future works.

Moreover, we plan to develop a control method that is a hybrid of a centralized control and the decentralized spinal reflex. In the plan, a central controller leaves most of the motion control of each body part with the artificial reflex system and switches the various motion by slightly adjusting the parameters of the reflex system.

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