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SURVEY PAPER

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ABSTRACT
The effects of mechanical system dynamics are often disregarded in the design process of humanoid robots. Sophisticated control methods may compensate for some limitations of the mechanical structure, however, principal limitations of the system performance can arise from poor mechanical architecture. Therefore, it is important to develop robot hardware that behaves close to an ideal model and that is easy to be modeled from the viewpoint of mechanics. This paper surveys the mechanics of humanoid robots from the viewpoint of joint mechanism, kinematic structure of the leg joints, and foot mechanisms. Firstly, the actuators and power transmission mechanisms for driving the joints are summarized. For the kinematic structure of leg joints, the characteristics of serial and parallel mechanisms are explained, and the specific configuration of the hip, knee and ankle joints are introduced. In order to make a robot move as close to the ideal movement as possible, we need to design the robot to reduce backlash at each joint. Various foot mechanisms are also introduced in the paper.

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1. Introduction

When verifying walking control of a humanoid robot, even if its effectiveness is confirmed through simulation, the controller often doesn't work with an actual robot. This is mainly due to model errors such as deflection of the actual robot, servo stiffness, and errors of various sensors. Of course, such model errors should be considered in the simulation, but it is difficult to model all of them exactly. It is important to develop balance control that can compensate for the model errors, but it is also important to develop robot hardware that behaves close to an ideal model and that is easy to be modeled from the viewpoint of mechanics.

The legs of a humanoid robot are generally designed with attention to the following points:

(1) Reduce the model error
(2) Reduce the leg inertia

In order to realize (1), each link is designed to have high stiffness against bending and torsion, and a mechanism with small backlash is often adopted for each joint. For (2), the end link is designed to have a low mass. Since the moment of inertia is proportional to the fifth power of the dimension, we must pay attention not to increase the moment of inertia especially for a life-size robot.

It is also important to maximize the height of the robot's center of mass (CoM). The dominant dynamics of a bipedal robot can be described by an inverted pendulum during single support phase [1]. The reduced model assumes that the mass of the robot can be lumped into the CoM. The CoM motion in the frontal direction is independent of the motion in the lateral direction. When the CoM height is held constant, the lateral CoM motion gives a particularly simple solution as follows:

$$\ddot{y} = \frac{g}{z} y \tag{1}$$

where y is the lateral CoM motion, z is the vertical CoM position, g is gravitational acceleration. Given the above dynamics, the lateral CoM motion during walking with an initial condition of $(y(0), \dot{y}(0))$ is described by the following pieces of hyperbolic curves.

$$y(t) = y(0)\cosh\left(\sqrt{\frac{g}{z}}T_S\right) + \sqrt{\frac{z}{g}}\dot{y}(0)\sinh\left(\sqrt{\frac{g}{z}}T_S\right) \tag{2}$$

$$\dot{y}(t) = \sqrt{\frac{g}{z}}y(0)\sinh\left(\sqrt{\frac{g}{z}}T_S\right) + \dot{y}(0)\cosh\left(\sqrt{\frac{g}{z}}T_S\right) \tag{3}$$

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where T_s is a duration of a single support phase. According this model, the higher the CoM, the smaller the lateral swing of the CoM for a given single support period. Therefore, maximizing the CoM height can contribute to reduce the angular momentum about the fore-aft axis especially at higher walking speeds.

This paper surveys the mechanics of humanoid robots, referring to development examples of humanoid robots.

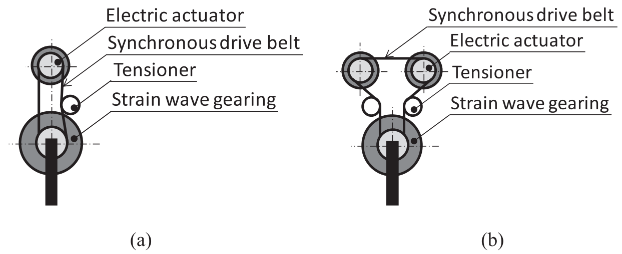

Figure 1. Multi-motor drive system: (a) single motor drive system, (b) double motor drive system.

2. Joint mechanism

2.1. Actuator

Actuators used for humanoid robots can be roughly divided into three types: pneumatic actuators, hydraulic actuators, and electric actuators.

It is difficult to control the position and speed of the pneumatic actuator due to the compressibility of air, however, there are research examples that utilize compliance based on air compressibility to achieve dynamic movements such as jumping [2,3].

Hydraulic actuators have higher power density than pneumatic actuators. Raibert [4] developed a 3D one-leg hopper using a hydraulic actuator for the hip joint and a pneumatic actuator for the prismatic joint leg, and achieved jumping motion with a monopod robot in the 1980s. At present, Boston Dynamics [5] has developed a legged robot using a hydraulic actuator, and Atlas has realized backflips. Although hydraulic actuators are very attractive, if we try to develop a humanoid robot using only commercially available components such as power units and other systems, the robot system tends to be complex and bulky. On the other hand, there is an example of applying hydrostatic transmission (HST) or electro-hydrostatic actuators (EHA) to humanoid robots because of its high backdrivability. The early works applying HST or EHA to robot joints include the work by Bobrow and Desai [6] and Habibi and Goldenberg [7]. Kaminaga et al. [8] firstly focused on their possibility of high backdrivability and experimentally showed that superior backdrivability can be realized than a gear driven joint with a proper low friction design. Furthermore, Kaminaga et al. [9] developed a whole-body electro-hydrostatic actuator driven humanoid robot Hydra.

The actuator used in many humanoid robots is an electric actuator. Each joint of a life-size humanoid robot requires a large output, so a single electric motor that can be mounted on an independent robot may not have enough output. In such a case, a multi-motor drive system, in which one joint is driven by double or triple motors as shown in Figure 1, is often adopted as used in HRP-2Kai [10], JAXON [11], DRC-HUBO + [12], and HRP-5P [13]. However, the multi-motor drive system is more disadvantageous in volume than driving one joint with one motor. In recent years, we can find some humanoid robots that realize a flexible design using a high-output frameless motor, such as WALK-MAN [14], CHIMP [15], and ARMAR-6 [16]. The authors also developed a high-power actuator unit with a hollow structure using a frameless motor for WAREC-1 [17], which is a four-limbed robot having advanced locomotion capabilities with versatile locomotion styles, including bipedal walking, quadrupedal walking, vertical ladder climbing, and crawling on its stomach. It is possible to pass the wiring inside the joints of WAREC-1 due to the hollow structure. When using a frameless motor, advanced design technology is required so that the motor must be glued to the frame and shaft, and the frame and shaft must have high machining accuracy. However, since the frame for the motor and the speed reducer can be shared, the total size and weight can be reduced. Furthermore, a design with a high degree of freedom can be achieved, such as having a hollow structure and various built-in sensors.

Here, the CHIMP's actuator unit equipped with various mechanisms and sensors is introduced by depicting schematic diagrams [15] (Figure 2). A torque tube is incorporated as a mechanical elastic element to protect the joint from a large impact received when the robot falls. An incremental encoder is mounted on the motor axis to detect the rotation angle of the motor rotor, and an absolute encoder is mounted on the joint axis to detect the rotation angle of the torque tube after deceleration. Torque sensing is also possible by measuring the deflection of the torque compliant tube. In order to protect the strain wave gear reducer from overload, a mechanical clutch is installed between the strain wave gear reducer and the torque tube. The mechanical clutch here is a friction clutch that connects the drive side and the driven side by frictional force. In addition, an electromagnetic brake is installed so that the posture of the robot doesn't change even when the power is turned off. Since the electromagnetic brake is installed before deceleration, a small

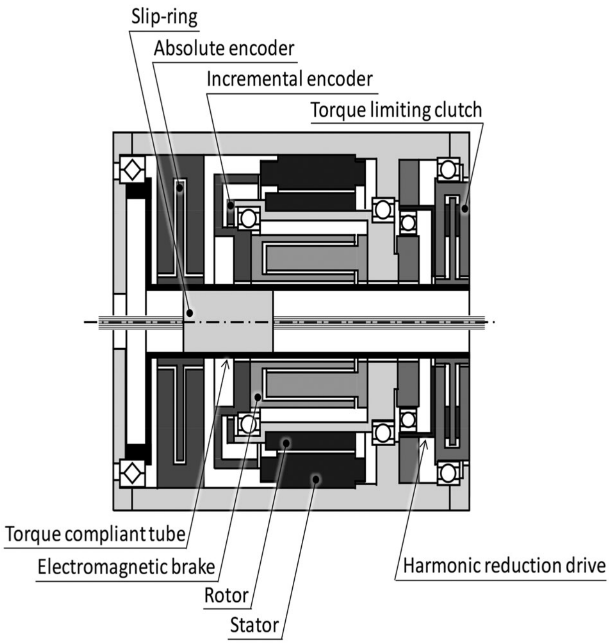

Figure 2. Schematic diagram of the actuator unit of CHIMP [15].

brake with small holding torque can be adopted. Furthermore, a slip-ring is incorporated to realize infinite rotation of the joint.

2.2. Drive mechanisms

It is simple and efficient to drive the joints of a humanoid robot directly with the actuators without using reduction gears, however, it is not realistic to mount a direct-drive motor on a humanoid robot because the actuator itself is heavy and large in size. Electric actuators are good at high-speed rotation but are not good at producing high torque, so electric actuators are often used together with reduction gears. Also, when incorporating an electric actuator into a joint of a humanoid robot, the direction of motion may be converted from rotary motion to linear motion.

The most commonly used reducer for humanoid robots is the strain wave gearing such as Harmonic Drive® [18]. Harmonic Drive® strain wave gearing utilizes a unique operating principle which is based upon the elastic mechanics of metals. The unique operating principle allows extremely high reduction ratio in a very compact and lightweight package. The high performance attributes of this gearing technology including zero backlash, high torque, compact size, excellent positional accuracy and repeatability are all a direct result of the unique operating principle. Although planetary gears and cycloidal gears are also the candidates, there are few applications to humanoid robots due to their weight and space-consuming compared to the strain wave gearing.

When transmitting the power of an electric actuator to a place distant from the actuator, synchronous drive belts, or timing belts, are often used. If belt drives are used with a strain wave gearing, a timing belt should be installed between an actuator and the input of a reduction gear because this can reduce the elongation of a timing belt itself and the backlash between the actuator and the input of the reduction gear by the reduction ratio. Cable drives are also used for auxiliary transmissions, however, we must pay attention to the elongation of the wires themselves. If the wire is wound so that the wires overlap each other, the diameter of the wound portion changes, and deformation due to the overlapping wire occurs. Therefore, the winding position must be devised so that the wires do not overlap.

Ball screws and planetary roller screws can convert the rotational motion of an electric actuator into linear motion. Planetary roller screws are characterized by higher load ratings and better tolerance against shock loading because the number of contact points between the screw shaft and nut is significantly higher than ball screws. When a ball screw or planetary roller screw is used for the leg of a humanoid robot, it is advisable to rotate the lead screw shaft and move the nut in the axial direction to reduce the effect of inertia.

In addition to the mechanisms introduced above, link mechanisms such as a four-bar link mechanism are often used as drive mechanisms.

3. Kinematic structure of leg joints

3.1. Single-DoF revolute joint

Revolute joints with single degree-of-freedom (DoF) can be actuated by either rotary or linear drives.

Regarding rotary drives, a strain wave gearing such as Harmonic Drive® that is coaxial with the joint axis interfaces the actuator to the robot link. Spatial separation between the actuator and reduction gear is simply realized by using auxiliary transmissions such as synchronous drive belts. Rotary drives based on a strain wave gearing are simple in design and control due to the linear relationship of input and output. If strain wave gearings are arranged coaxially with the articulated joints, the movable part such as the ankle joint becomes heavy and the leg inertia becomes large, which may limit the dynamic performance of the walking robot.

Linear drives are alternative to actuate a single-DoF revolute joint by using a four-bar linkage, a ball screw, a planetary roller screw, and so on. Since this approach also enables the spatial separation between the entire drive and the joint, there is the advantage that the movable parts can be lightened. However, the relationship of input and output of such mechanisms is nonlinear which makes joint control more difficult since the nonlinearities must be taken into account. The stiffness of the joint and surrounding structure increases because the leg link and the linear actuator form a closed kinematic chain. However, such mechanisms are more complex in design and manufacturing, and the several bearings may introduce backlash.

3.2. Multi-DoF joint

Multi-DoF joints such as the hip and ankle joints are roughly divided into two types: serial actuation and parallel actuation. Table 1 summarizes the features of each mechanism.

The serial configuration has the advantage that the movable range is large and kinematic control is easy if the serial mechanism has no redundant degree of freedom. However, the position error of the robot foot becomes large because the angle error at each joint is accumulated.

Parallel mechanisms have smaller workspace than serial mechanisms due to self-collisions and kinematic singularities, but the accuracy in positioning and orientating the end-effector is better because positioning errors are averaged. The stiffness and output of parallel structures are usually high thanks to coupled drive. Moreover, the leg inertia can be reduced since heavy objects such as actuators and reduction gears can be mounted separately from the moving parts. However, although parallel mechanisms can theoretically achieve high positioning accuracy, its structure tends to be more complex than that of serial mechanisms. In addition, it should be noted that high positioning accuracy cannot be achieved unless the backlash in the bearings is suppressed.

3.3. Hip joint actuation

Most humanoid robots have 3-DoFs in the hip joint. The hip joint must be designed to withstand large loads because the swing leg receives high moment loadings when landing on the ground. Since the hip joint requires large movable angles during locomotion, it is difficult to realize 3-DoFs by simply using a parallel mechanism.

Large workspace can be achieved to some extent if the 2-DoFs such as the roll and pitch axes are designed with parallel mechanisms and the other DoF such as the yaw axis is actuated by an independent rotary joint. However, serial mechanisms are often adopted to the hip joints because the structure can be simplified and it doesn't matter if the hip joint, which is the base of the leg, becomes slightly heavy in terms of the leg inertia.

Very few robots have introduced parallel mechanisms into the hip joints. ROBIAN [19] has a 3-DoFs parallel-actuated mechanism for the hip joint. LISA [20] employs a 3-DoFs spherical parallel mechanism for the hip joint. The hip joint of RHP2 [21] consists of 2-DoFs closed linkage mechanism for the roll and pitch axes and 1-DoF rotary joint for the yaw axis. The robot developed by Morisawa & Ohnishi [22] and WL-16 [23] adopt a parallel mechanism for the entire leg.

Table 1. Characteristics of serial and parallel mechanisms.

	Serial	Parallel
Workspace	Large	Small
Position error	Accumulates	Averages
Stiffness	Low	High
Inertia	Large	Small
Payload	Low	High
Forward kinematics	Easy	Difficult
Inverse kinematics	Difficult	Easy
Modelling and solving dynamics	Relatively simple	Complex

3.4. Knee joint actuation

Human knee joints are not simple revolute joints, but the knee joints of humanoid robots are often composed of 1-DoF revolute joints. The most common structure is to transmit the actuator power to the strain wave gearing of the knee joint by means of a synchronous drive belt as described in Section 3.1 (Figure 3(a)). This structure has the advantage of reducing backlash and is widely used, however, the leg inertia increases because a heavy wave gear reducer is mounted on the knee joint. The leg inertia can be reduced by applying the crank mechanism to the knee joint as shown in Figure 3(b) since the actuator and the speed reducer can be arranged on the thigh. Another solution is to convert the rotary motion of the actuator into a linear motion with a ball screw and drive the knee joint (Figure 3(c)). This also has the advantage that a heavy object such as an actuator can be installed near the hip joint. The structure in Figure 3(c) is adopted in LOLA [24].

Tomishiro et al. [25] apply a variable reduction ratio crossed four-bar linkage mechanism to the knee joint, which mimics the cruciate ligament of animals. The non-uniform transmission ratio is utilized advantageously by adjusting the mechanism to the torque-speed characteristics of typical movements of the robot. The four-bar linkage mechanism contribute to improve the vertical jumping height of a legged robot.

3.5. Ankle joint actuation

Many humanoid robots have 2-DoFs at the ankle joint connecting the lower leg and the foot. The conventional

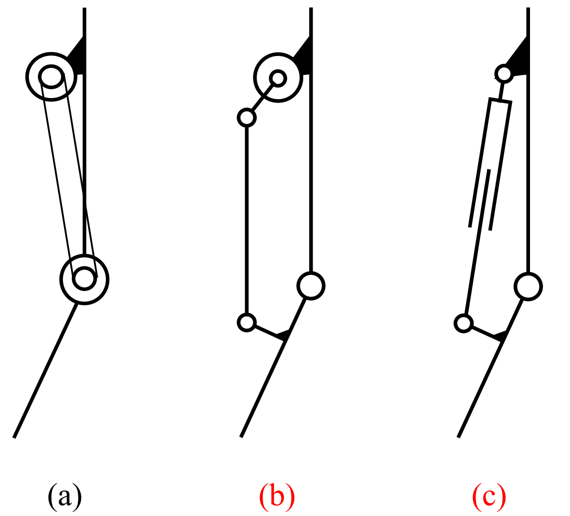

Figure 3. Configuration example of knee joint: (a) knee joint using a synchronous drive belt and a strain wave gearing, (b) knee joint using a crank mechanism, (c) knee joint using a linear motion mechanism.

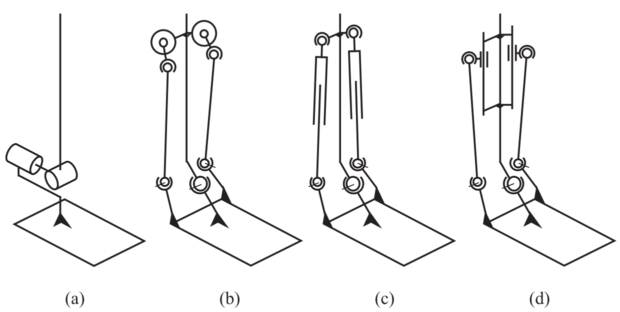

Figure 4. Configuration example of ankle joint: (a) ankle joint using a serial-link mechanism, (b) ankle joint using a parallel-crank mechanism, (c) ankle joint using a linear motion mechanism where linear actuators act as length-variable couplers, (d) ankle joint using a linear motion mechanism where linear actuators are housed on the shank.

structure of the ankle joint is to use a strain wave gearing and to make pitch and roll axes orthogonal by a serial arrangement (Figure 4(a)). However, it is more effective to adopt a parallel mechanism for the ankle joint to reduce the leg inertia. Since the ankle joint requires greater torque and angular velocity for the plantarflexion/dorsiflexion axis than for the adduction/abduction axis, distributing forces by mounting two actuators in parallel is of great advantage.

One example of realizing an ankle joint by the parallel structure is to use a parallel-crank mechanism (Figure 4(b)). The robot developed by Kamioka et al. [26] seems to adopt the parallel-crank mechanism as far as seeing the figures and videos in the paper. A patent application by Honda describes an ankle joint using a parallel-crank mechanism [27].

Figure 4(c) shows another solution using linear actuators. The lightweight design of all components is possible with this structure by designing so that only tension and compression loads act on the coupler links. This has been discussed in the design phase of LOLA [28], and the authors have adopted this structure in WABIAN-2RIII [29]. However, since the linear motion mechanism tends to be slightly bigger, the ankle joint must be designed not to limit the workspace by self-collisions.

The structure as shown in Figure 4(d) is also proposed in which a spherical joint is mounted between on the nut of a ball screw or planetary roller screw and the coupler link, and the coupler link is connected to the foot via the spherical joint. With this solution, it is easier to protect the screws housed on the shank from collisions. Moreover, the movable angles of the ankle joint can be larger than in the previous solution as depicted in Figure 4(c) because collisions with the shank are reduced by the slender design of the coupler links. A similar structure is adopted to the robot Johnnie [30]. The actuators are placed on the lower leg in Johnnie, but in LOLA [24], the actuators for driving the ankle joints are placed on the thigh by skillfully arranging the timing belts and bevel gears. The leg inertia has been successfully reduced by concentrating heavy objects such as actuators and reduction gears around the hip joint. However, each component must be carefully designed, paying attention to the deterioration of transmission efficiency due to the increase in the number of power transmission mechanisms and backlash with bevel gears.

4. Foot mechanism

The feet are key components in the mechanical structure of the humanoid robot. The feet are the only parts which are subjected to external loads during normal locomotion, and they greatly affect the stability and controllability of the robot. Although humanoid robots have been studied at many research institutions, there are surprisingly few detailed literatures on the foot mechanism. This section introduces some characteristic foot mechanisms.

4.1. Foot with toe joint

Some humanoid robots have the toe joints like human feet [31]. Several functions of the human toe mechanism have been reported in the field of clinical gait analysis [32]. One of the principal findings is that the toe joint doesn't play a role as propulsion during steady walking, but generates body propulsion with long-stride walking.

Another finding is that the toe joint also contributes to walking stability.

Based on the former finding, WABIAN-2 [33,34] has a passive toe joint and realizes knee-stretched walking with heel-contact and toe-off motion. HRP-2LT [35] has a spring-loaded, passive toe joint and realizes jumping using the kinetic energy of the spring. H6 [36], LOLA [24], Toyota's running robot [37], and HRP-4C [38] have active toe joints. These robots realize walking with larger step lengths and climbing higher steps by utilizing the actuated toe joints. Moreover, quick turning is realized by using slipping motion between the feet and the ground by switching ground contact conditions such as heel contact, sole contact and toe contact [39,40].

The feet with active toe joints mentioned above must contact the ground with only the toe link when a humanoid robot lifts heel up. A disadvantage of this configuration is that the total weight of the robot is supported only by the toe joint. On the other hand, humans share the total weight with the ball of the toe and the fingertip, and the toe joint doesn't require a large actuator. Focusing on this point, a novel toe joint mechanism using a parallel four-bar linkage is proposed [41]. This mechanism enables a humanoid robot to contact with the floor at points of a multilink, namely the toe pad and toe tips, similar to human motion.

4.2. Characteristic foot mechanism

Yamaguchi et al. [42] develop a novel foot mechanism with a shock absorbing material for acquisition of landing surface position information. A biped robot with the proposed foot mechanism can detect the landing surface and adapt to unknown uneven terrain. Pajon et al. [43] propose a closed-loop controller stabilizing humanoid robots when walking with soft soles which can absorb impacts and cast ground unevenness during locomotion on rough terrains.

Other distinctive foot mechanisms have been patented by companies. Honda proposes a number of foot mechanisms to reduce the landing impact [44,45]. Sony and Yamaguchi also file many patent applications such as a foot mechanism equipped with a sensor to measure the relative movement, or slippage, between the robot foot and the ground [46]. In addition, they propose a foot mechanism aiming to secure the posture stability of a biped robot by passively adapting to various road surfaces [47].

Other patent applications by Toyota describe a foot system that can measure the distance between the foot and the ground [48], and a foot structure making a biped robot fall inside [49].

5. Summary

This paper introduces the joint mechanism, kinematic structure of the leg joint, and foot mechanisms of a humanoid robot. In this paper, the author focuses on the lower limbs, but the design of the upper limbs is also important. The upper limb of a humanoid robot must be well designed when moving with the robot's hands on the wall or handrails, however, the technique introduced in this paper will be useful for upper limb design too.

This paper mainly dealt with robots with stiff joints, but it is also important to utilize passive compliance in robotic systems, which has the potential to improve their performance during locomotion and interactions. Finally, it should be noted that humanoid robots with compliant joints have been widely studied [50].

From the viewpoint of mechanics, wiring must be considered when designing a humanoid robot. A humanoid robot that reduces wiring by utilizing optical communication technology also appears [51]. The author hopes that the technology introduced in this paper will help researchers developing humanoid robots in the future.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Notes on contributor

Kenji Hashimoto received the B.E. and M.E. degrees in mechanical engineering in 2004 and 2006, respectively, and the Ph.D. degree in integrative bioscience and biomedical engineering in 2009, all from Waseda University, Japan. While a Ph.D. candidate, he was funded by the Japan Society for the Promotion Science as a Research Fellow. He was a Postdoctoral Researcher at the Laboratoire de Physiologie de la Perception et de l'Action in UMR 7152 Collège de France-CNRS, France from 2012 to 2013. From 2015 to 2018, he was an Assistant Professor and an Associate Professor at the Waseda Institute for Advanced Study, Waseda University. In the April of 2018, he joined the faculty of the Department of Mechanical Engineering Informatics, Meiji University, where he is currently an Associate Professor. His research interests include legged robots, and humanoid robots. He is a member of robotics related academic societies such as IEEE, RSJ, JSME, Japan Council of IFToMM, etc. He received the IEEE Robotics and Automation Society Japan Chapter Young Award in 2006, the JSME Fellow Award for Outstanding Young Engineers in 2008, the RSJ Young Investigation Excellence Award in 2015, and the Kisoi Motohiro Award for Academic Achievement in 2018.

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