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HUMANOID AND BIPEDAL ROBOTICS (E YOSHIDA, SECTION EDITOR)

Soft Actuation and Compliant Mechanisms in Humanoid Robots

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Abstract

Purpose of Review We aimed to reveal the impact of soft robotics, which has developed in the last decade, on humanoid robotics research. Although humanoid robots are usually classified as hard robotics, softness should be integrated because soft materials and mechanisms are used extensively in the human body.

Recent Findings In recent years, new soft actuators based on hybrid approaches, such as the combination of electricity and fluid, have emerged. Physically compliant robotic systems that are safe and robust are needed to take on higher-risk tasks and to tolerate large numbers of trials in the process of machine learning.

Summary Emerging soft actuators are enabling humanoid robots to achieve rapid movements with physical impacts. Efforts to integrate soft robotics and humanoid robots are still on their way. A potential direction for humanoid robots is their application to physical human-robot interaction, where further exploitation of softness is expected.

Keywords Soft robotics · Artificial muscles · Soft actuators · Motor learning

Introduction

Soft robotics is an emerging field that focuses on transforming robotics by leveraging the properties of soft materials. It was around 2008 that soft robotics was coined and discussed in the context used today [1]. Research on soft-bodied robots, soft grippers, soft actuators, and soft sensors has rapidly emerged and has been actively studied since around 2010 as shown in Fig. 1. On the other hand, the history of bipedal humanoid robot research dates back to the 1970s and became particularly active after the 2000s. As a recent trend, the publication record on humanoid robots seems to have declined after a peak around 2015, the year the DARPA Robotics Challenge was held. Since around 2019, publication records show that there are more soft robotics-related papers than humanoid robots. Research topics linked to industrial applications such as unmanned aerial vehicle (UAV) and autonomous vehicles are growing differently. Although humanoid robots and soft robotics have different histories and publication trends, they should be able to collaborate in a new direction to be called "soft humanoid robots." This paper was written to explore this possibility.

The contribution of soft robotics to the hardware of the bipedal humanoid robot appears to be minor [2]. This is because the physical phenomenon of bipedal walking is well explained by rigid links known as passive walking machines [3]. Incorporating softness into the humanoid robot's feet can help cushion the peaks of impact forces and assist the robot in stepping over bumps [4]. Soft robotics is more closely related to the locomotion of aquatic organisms. In the underwater environment, the effects of gravity can be canceled by buoyancy, and thrust can be obtained from the water through undulating motion and flapping of the fins. To investigate softness in humanoid robots, we need to focus on topics beyond locomotion.

Softness is demanded at the interface with the unknown objects/environment. Flexible skin would also be useful if contact is expected throughout the robot's body [5, 6]. Soft grippers are one of the largest categories in soft robotics, including many examples of multi-fingered robotic hands. They are often combined with industrial robot arms as end-effectors and are not an issue unique to humanoid robots; thus, they are not discussed here.

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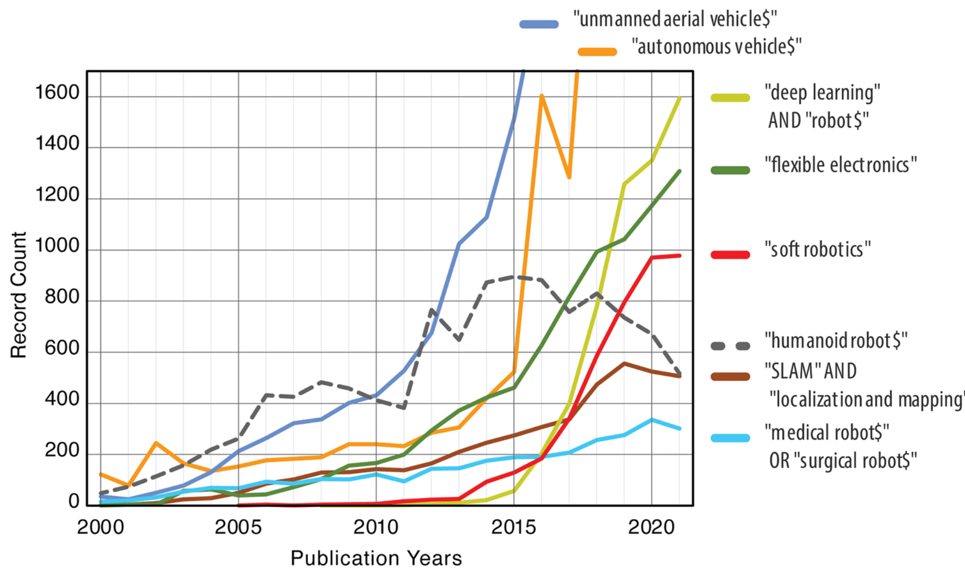

Fig. 1 Number of publications per research topic based on keyword searches on the Web of Science database

Another application of humanoid robots is as a human phantom that evaluates devices on behalf of humans. The form of humanoid robots is not suitable for wearing human clothing or wearable devices, requiring a soft shell to cover the hard body and joint gaps [7]. Human dummies with structures that mimic abdominal shapes around the pelvis have been developed [8].

A key topic at the interface between humanoid robots and soft robotics will be the trend in the development of soft actuators for use in human-sized multi-articulated robots. As a historical background, pneumatic rubber artificial muscles, a type of soft actuator, were used for limbs in the early days of humanoid robots. Researchers were interested in their application to prosthetic limbs and in neural muscle control. Later, hydraulic rotary motors were tried for dynamic bipedal walking [9], and electric motors with improved performance are the current mainstream. The approach of driving a humanoid robot with a large number of artificial muscles still has many challenges. A recent highlight is the achievement of Kengoro, a humanoid robot with 116 muscle modules, employing a wire-winding mechanism with an electric motor [10].

Soft humanoid robots will evolve in contexts where physical and psychological interactions with the environment, objects, and humans are required. One of the unique human activities that take advantage of the deformation of soft materials is facial expression. Face robots are probably one of the ancestors of soft robotics [11], along with robots that mimic soft-bodied animals. The face is an organ that can take on a continuous state through deformation of soft materials. Recent advances in digital fabrication technology have led to studies that attempt to develop a soft face with multi-material 3D printer [12]. Faces are intended for communication, not physical force exchange, and are essential to social intelligence as an interface with others. Facial expressions are visually recognized and, in some cases, can be substituted by graphics on a two-dimensional display.

Soft deformations are essential in tasks that involves contact. Shapeshifting humanoid robots were developed as active mannequins for fitting garments [13, 14]. Soft contact is also important in nonverbal communication. Major examples are handshakes, high-fives, hugs, and kisses. These intimate interactions with humanoid robots based on current hard robotics would be difficult from both a functional and psychological safety perspectives. This paper also discusses the advances of humanoid robots into a field called physical human–robot interaction (pHRI) in a later section.

Hybrid Approach for Soft Actuation

A trend in actuator technology that deserves attention is the hybrid approach. Actuator performance is strongly constrained by the physical laws, and novel principles are unlikely to be discovered in a short time. Most of the artificial muscle actuators reported in recent years show apparently excellent performance at the laboratory level, which often lacks their practical utility in terms of speed, displacement, portability, and scalability. Therefore, electric actuators and hydraulic/pneumatic actuators are the primary focuses in medium-sized robot systems such as humanoid robots. Humanoid robots are difficult to apply new actuators because the system requires an integrated energy source and a large number of actuators. An example using a new type of pneumatic actuator is a humanoid robot that performs an agile and risky movement, jumping followed by hitting a ball [15]. This simple humanoid robot has two 3-DoF legs and two 1-DoF arms and is dedicated to sagittal plane movements. The actuator used in the robot is a pneumatic cable cylinder: an actuator that replaces the heavy piston rod of a pneumatic cylinder with a wire cable to reduce weight and enable direct wire drive. Taking advantage of the large power/weight ratio of the pneumatic actuators, the robot predicts the trajectory of the launched ball and can hit the ball with the arm end.

The approach to improving actuator performance has been mainly to optimization of structure and materials. Actuators with unique properties are now being explored by combining known principles. For example, a hybrid approach that combines the quietness and portability of electric actuators with the high power and robustness of fluidic actuators can be seen in TaeMu [16], Hydra [17], and Atlas [18]. They are humanoid robots with combined electric pump and hydraulic cylinder systems.

Another form of hybrid approach is the electro-pneumatic hybrid system, which combines electromagnetic force and air pressure. Pneumatic actuators offer a large output with a simple structure; however, their working pressure is lower than that of hydraulic actuators. In addition, due to the compressibility of air, feedback control is difficult unlike electric motors and hydraulic actuators. Pneumatic-electromagnetic hybrid linear actuators have been proposed to address these issues [19]. The pneumatic-electromagnetic hybrid linear actuators have coils around the pneumatic cylinder and permanent magnets embedded in the piston, forming a combined structure of a pneumatic cylinder and an electromagnetic linear actuator. This mechanism does not spoil the back drivability. Recently, an example of a 7-DoF humanoid robot arm driven by pneumatic-electric hybrid linear actuators was reported [20]. The main hybrid actuator used in this robot arm has a mass of 391 g, the pneumatic force is 343 N at a pressure of 0.7 MPa, and the electromagnetic force is 32.0 N at a current of 25A. The force split ratio between pneumatic and electromagnetic forces is roughly 10:1. By using pneumatic feed-forward control to obtain a large output while adding electric feedback control, the accuracy of badminton's fast swing motion was improved. There is an idea that attempts to solve the gas source problem inherent in pneumatic actuators by vaporizing a liquid [21]. The liquid pouch motor is a hybrid actuator in which the gas source is replaced by a low boiling point liquid and an electric heater.

The hydraulically amplified self-healing electrostatic (HASEL) actuators are hybrid actuators of electrostatic and hydraulic actuators [22••, 23]. The previously known dielectric elastomer actuator (DEA) is an electrostatic soft actuator with large output and fast response; however, it has the disadvantage of being easily damaged by insulation breakdown due to the use of high voltages. By using insulating oil as the dielectric material, HASEL actuator is expected to have self-healing capability against dielectric breakdown. Maxwell stresses were converted to elastomer deformation in DEA, but in the HASEL actuator they are taken out as dielectric liquid pressure. Currently, HASEL actuators have only been applied to a simple robotic arm.

Figure 2 presents examples of new types of hybrid actuators. Humanoid robots are multi-degree-of-freedom systems, and there is a scalability challenge when applying new forms of actuators. A single hybrid actuator is already overcoming the issues of speed, power, and controllability. We expect to witness the development of scalable artificial muscles and their application to humanoid robots.

Proprioceptive Actuation Paradigm

The essence of muscle actuation does not seem to be linear drive or viscoelasticity itself. Hydraulic and pneumatic cylinders are linear actuators but are not called artificial muscles. Mechanisms that insert elastic elements in series with the actuator are well known, although they could degrade control performance and cause vibration in feedback control. The elasticity found in the human leg is relatively stiff and localized at the ends, like the Achilles tendon, and is not springy in all places. Also, passive elasticity seems to be effective only in vigorous exercise, such as running and hopping. Viscoelastic joint behavior can be simulated by force control. Torque-controllable robot manipulators for each axis are becoming the standard, and their widespread use in cooperative robots is encouraged. Recent examples of advanced manipulators and bipedal machines demonstrate the importance of force control as the foundation of skillful motion [24]. The nature of muscle actuation may also be related to intelligent force control. Bi-articular muscles, a unique mechanism found in the musculoskeletal system, have been shown to contribute to force directional control [25]. Softness in muscle actuation means that intrinsic force control is provided and passive dynamics of the body are accessible.

In recent years, these considerations have led to an idea called the proprioceptive actuation paradigm [26]. Dexterous motor skill is the ability to respond to external forces responsively. Direct drive (DD) or quasi-direct drive that uses low gear reduction ratio contributes to proprioceptive actuation. The quasi-DD concept also contributes to the realization of agile movement [27, 28]. The expected feature of future soft actuators is also to enable sensory-motor coupling through direct-drive mechanisms.

Safety and Robustness

A humanoid robot in the narrow sense of the term is not a torso on a moving platform, but a bipedal robot. Due to concerns about the falling down, a life-sized humanoid robot

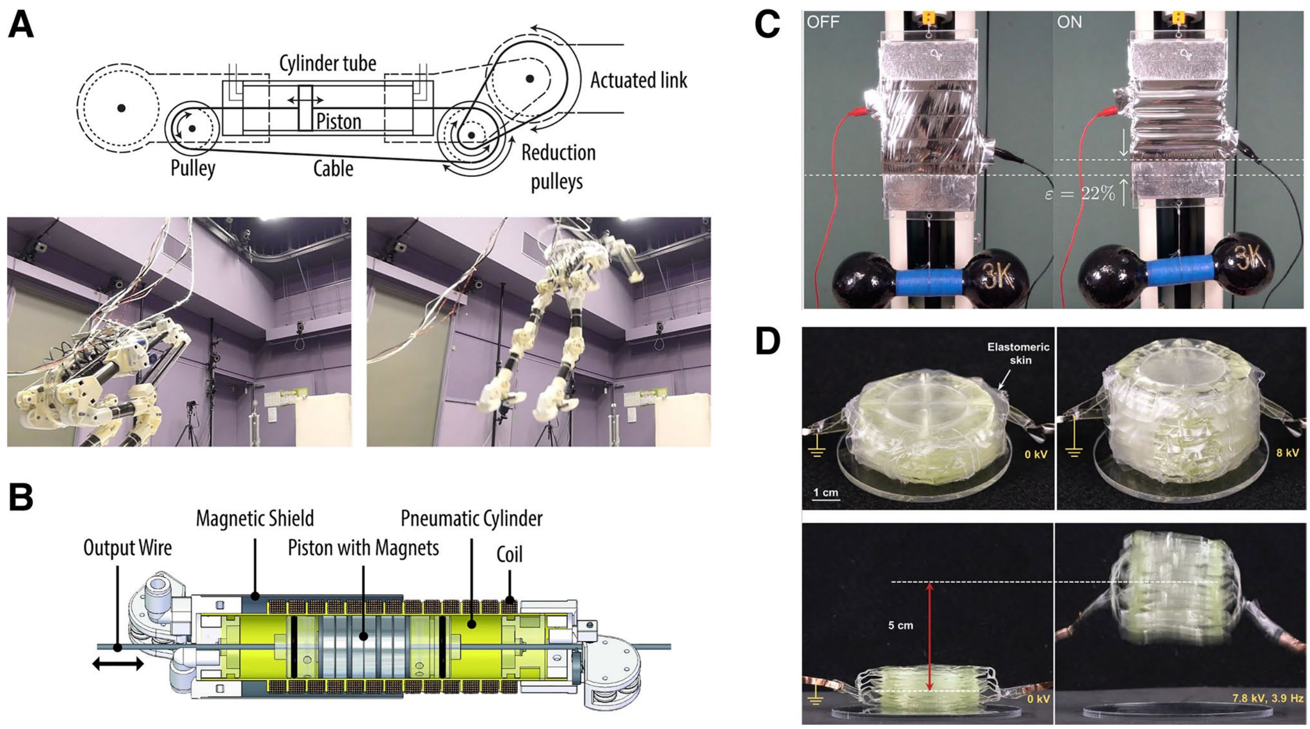

Fig. 2 New types of actuators. **A** Pneumatic cable cylinder for jump-and-hit motions of humanoid robot (CC BY license, Copyright 2021 by the authors) [15]. **B** Pneumatic-electric hybrid linear actuators for badminton swing (CC BY license, Copyright 2019 by the authors) [20]. **C** Liquid pouch motor based on liquid–gas phase change (© [2021] IEEE. Reprinted, with permission, from [21]). **D** Stack of quadrant donut HASEL actuators (CC BY license, Copyright 2019 by the authors) [23]

is unlikely to cohabitate with humans. Even quadruped robots, which are relatively stable compared to bipeds, face the risk of injuring humans due to falls from cliffs or stairs. Falls of humanoid robots also cause serious failures of the robots themselves. Small humanoid robots are not only less expensive, but also less damaging in the event of a fall due to the scale effect. Although rarely mentioned in papers, the robustness of robot hardware is critical to the success of research. If the robot is fragile, the number of experiments will be constrained, and researchers will not be able to perform bold movements. Traveling over rough terrain is a major challenge, and rope support from the ceiling is widely used [29]. Airbags for humanoid robots have been developed to deal with falls [30]. In addition to the overload resistance of the aforementioned direct-drive mechanism, the softness of the exterior will be an advantage.

A significant advance in recent years has been the motor learning of humanoid robots using deep reinforcement learning [31, 32]. In these cases, robot simulator is essential because a very large number of trials and unexpected motion patterns are assumed. When a computer autonomously explores a wide range of motions, it is difficult to secure the operation on a real robot. Emergent locomotion is feasible only in the simulator and does not seem feasible on a real robot given friction, torque, and other constraints [33, 34]. Conducting motor learning from scratch on real robots through reinforcement learning is a challenging task from the perspective of sampling efficiency. The number of trials required for the convergence of learning is usually not feasible in real time. The development of "machine learning-ready" humanoid robots is greatly anticipated.

Communication and Physical HRI

Humanoid robots may be attractive to humankind because of their human shape, among other animal-like machines. In the context of social and affective robotics, physical human–robot interaction (pHRI) is an area for future development. The application of soft robotics to collaborative robots for caregiving is often mentioned as a future direction for soft robotics [35]. Soft-bodied robots need to consider the affective effects in addition to physical safety [36]. Nonverbal communication between humans and robots through gestures, facial expressions, and physical contacts should be developed as a science that approaches human cognition and emotion.

Building and maintaining a self-contained, bipedal robot with a large number of actuators are expensive. Some of the difficulties inherent in humanoid robots are mitigated if dynamic stability and the task of carrying heavy objects are not imposed. This suggests that the design methodology for humanoid robots for pHRI may be significantly different from that for existing task-oriented humanoid robots. If gesture expression is the primary function, it is even possible to place all actuators outside, like a puppet [37].

At the level of mechanism and appearance, soft robots have different characteristics from rigid robots [38•]. Commonly used in soft-bodied robots, silicone rubber suffers from problems of deformability and increased weight as its volume increases. Therefore, foam materials and inflatables are used for soft collaborative robots [39]. There is an instance of an upper body robot that combines a rigid skeleton with a 3D printed soft skin [40]. The inflatable robot named King Louie, manufactured by Pneubotics, has two 5-DOF arms, grippers, and a torso joint [41]. A prototype legged robot with an inflatable sleeve that provides the functions of a tactile sensing has been developed [42•]. Inflatable robots are promising from the safety aspect in case of contact or falling over, as they can produce large yet lightweight robots. The inflatable structure also has a feature not found in conventional robots: it can be stored compactly when deflated and occupies minimal space. Recent progress has shown examples of the realization of an articulated humanoid upper body robot and physical interaction with a human through wire actuation [43•]. This huggable inflatable upper body robot fits in a few kilograms, including actuators and blowers. Figure 3 shows hard humanoid robots with soft mechanisms and soft humanoid robots. Humanoid robots for R&D are expensive custom-made products, and mass production of human-sized robots in particular has been difficult. Inflatable humanoid robots could be used in the HRI field as an inexpensive platform that can be customized in function and appearance for each application.

Future Directions

Currently, humanoid robotics research seems to have taken two separate paths. One is the realization of human work skills by machines; technology once integrated into the human form is being broken down into hands, dual-arm systems, vision, etc. The other direction is to utilize the cognitive significance of the human form itself in human–robot interaction. In other words, the ultimate goal of humanoid robots used to be a combination of indistinguishable human appearance and human-like skills, which are now being separated. Soft actuation is important in the context of human science, such as sports biomechanics, while from a practical standpoint the use of force-controlled quasi-direct-drive motors would be preferred for both legs and manipulators. Compliant mechanisms for humanoid robots are expected to achieve great strides in the context of physical human–robot interaction. In typical humanoid robot experiments, humans only poke the robot with a stick; it is hard to imagine robots and humans hugging or playing soccer together. What the author would personally like to see is a natural cohabitation of the human factor in humanoid robotics research.

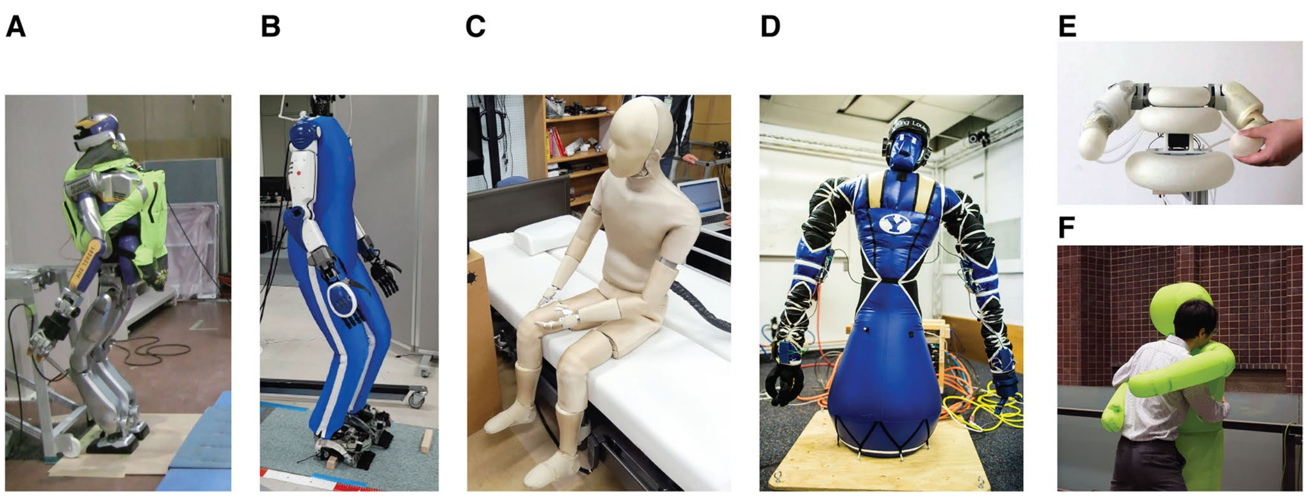

Fig. 3 Humanoid robots with soft mechanisms. **A** HRP-2Kai with an airbag jacket (© [2016] IEEE. Reprinted, with permission, from [30]). **B** HRP-4 with a soft fabric suit and soft feet) (© [2021] IEEE. Reprinted, with permission, from [4]). **C** An active dummy robot (© [2018] IEEE. Reprinted, with permission, from [8]). **D** King Louie robot with 5-DoF arms (© [2015] IEEE. Reprinted, with permission, from [41]). **E** Upper body robot with 3D printed soft skin (© [2015] IEEE. Reprinted, with permission, from [40]). **F** Blower-inflated upper body robot for physical human–robot interaction (CC BY license, Copyright 2021 by the authors) [43•]

Conclusion

Humanoid robots are a type of bio-inspired robot based on Homo sapiens and should be closely related to soft materials by their nature. On the other hand, there seems to be little connection between humanoid robots as work machines and soft robotics at the present time. This paper reviews recent efforts to realize soft-bodied humanoid robots. Soft actuation for humanoid robots has moved from the naive stage of simply using serial elastic elements to a stage of redesign from the perspective of whole-body motion in response to physical input, referred as the proprioceptive actuation approach. As a new trend in soft actuation, we found hybrid approaches, for example, combining electromagnetic forces and fluid pressure. Passive or actively controlled softness would allow for large numbers of experiments with real robots and would also contribute to the robustness required for the direct application of reinforcement learning today. A promising application for soft humanoid robots is physical HRI. Humanoid robots with completely different forms and functions, such as inflatable humanoid robots, will be the seeds of a new robot species.

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Declarations

Conflict of Interest The authors declare no competing interests.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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- •• Of major importance

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