

HUMANOIDS

Design principles of a human mimetic humanoid: Humanoid platform to study human intelligence and internal body system

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Many systems and mechanisms in the human body are not fully understood, such as the principles of muscle control, the sensory nervous system that connects the brain and the body, learning in the brain, and the human walking motion. To address this knowledge deficit, we propose a human mimetic humanoid with an unprecedented degree of anatomical fidelity to the human musculoskeletal structure. The fundamental concept underlying our design is to consider the human mechanism, which contrasts with the conventional engineering approach used in the design of existing humanoids. We believe that the proposed human mimetic humanoid can be used to provide new opportunities in science, for instance, to quantitatively analyze the internal data of a human body in movement. We describe the principles and development of human mimetic humanoids, Kenshiro and Kengoro, and compare their anatomical fidelity with humans in terms of body proportions, skeletal structures, muscle arrangement, and joint performance. To demonstrate the potential of human mimetic humanoids, Kenshiro and Kengoro performed several typical human motions.

INTRODUCTION

For at least the last two millennia, human beings have endeavored to understand the systems and mechanisms that make up the human body, such as the principles of muscle control, the sensory nervous system that connects the brain and the body, the mechanisms of learning in the brain, and the accomplishment of the simple act of walking. In recent years, technology has developed to the point where humanoid robots that mimic human body structures are now being constructed, and these enable us to study the systems in the human body by making humanoids or through experimental trials in the real world. However, a limitation of conventional humanoids is that they have been designed on the basis of the theories of conventional engineering, mechanics, electronics, and informatics. They are also primarily intended for engineering-oriented applications, such as task achievement in daily life, personal assistance, or disaster response. By contrast, our intent is to design a humanoid based on human systems—including the musculoskeletal structure, sensory nervous system, and methods of information processing in the brain—to support science-oriented goals, such as gaining a deeper understanding of the internal mechanisms of humans.

Our research team has successfully developed musculoskeletal robots (1–5), and it seems possible to use these to our stated purpose because they imitate the human musculoskeletal structure, support the flexible body and behaviors of humans, and support human-style muscle actuation using tendon-driven actuators. However, those musculoskeletal robots are not accurate enough for our purpose from an anatomical point of view, such as body proportions, muscle arrangements, and joint structures, although their actuation does mimic human muscle contraction. Other research teams have also successfully developed musculoskeletal robots from an anthropometric point of view (6–12). The body structures and shapes of their robots were inspired from humans, and they provided effective

schemes for controlling and modeling those kinds of robots. However, their robots were not capable of performing whole-body motions because they did not have tendon-driven legs for supporting their weight.

Therefore, we propose a human mimetic humanoid that provides a high degree of anatomical fidelity to the human structure and is capable of whole-body motions. We believe that such a human mimetic humanoid can provide new opportunities to advance science, such as in the field of musculoskeletal physical simulation, to capture and quantitatively analyze the internal data of a moving human body using the sensors of a human mimetic humanoid. Here, we detail the design principles of an anatomically correct human mimetic humanoid in the following areas: (i) body proportions, (ii) skeletal structures, (iii) muscle arrangement, and (iv) joint performance.

We also describe the development of the Kenshiro and Kengoro humanoids as examples. The human mimetic design concept is the common concept for each humanoid. Kenshiro is the first humanoid developed based on the concept, and then Kengoro was developed with a lot of improvements for a higher degree of fidelity to humans. These humanoids have anatomically correct musculoskeletal structures in their bodies, so that we can evaluate the fidelity of the musculoskeletal structures relative to that of a human. A design overview of the proposed human mimetic humanoid is shown in Fig. 1.

RESULTS

In this section, we describe the anatomical fidelity of Kenshiro and Kengoro and evaluate how accurately their musculoskeletal structure mimics that of a human in the four specific areas of interest.

Body proportion fidelity

The body proportions of Kenshiro and Kengoro were designed by using human statistical data (13–16) as the design target, so that the humanoids would have more human-like body proportions, and the link lengths of Kenshiro and Kengoro were designed on the basis of the corresponding lengths in a human body. To evaluate

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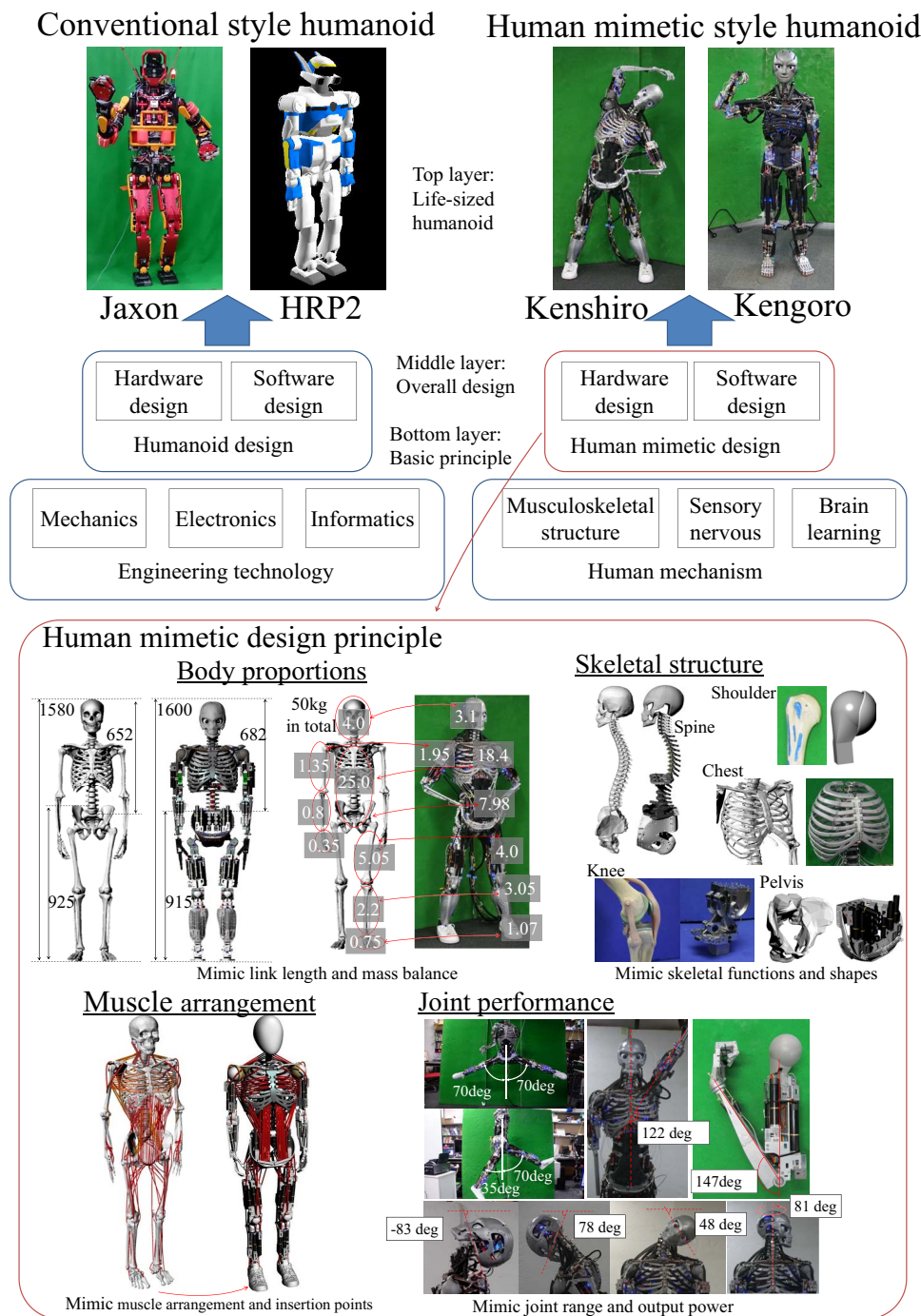


Fig. 1. Basic design concept of human mimetic humanoid. Human mimetic humanoids were designed on the basis of the mechanisms in the human body, in contrast to conventional humanoids designed based on the theory of engineering. In the design of a human mimetic humanoid, the same body proportions and musculoskeletal structures as those of an average human were used as design specifications.

their human mimetic body proportions, we conducted a link length comparison between Kenshiro, Kengoro, and an average human using the body segments shown in Table 1. Note that the ratio of the human link length and weight has been reported in several studies. The results indicated that the average link lengths in Kenshiro and Kengoro versus a human were 101 and 99.3%, respectively.

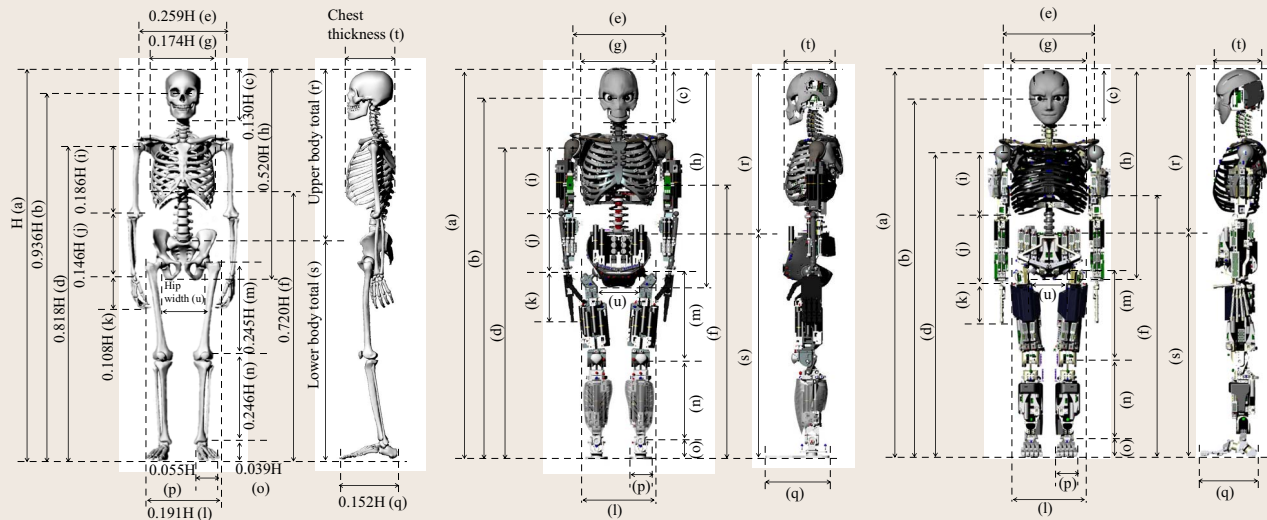
A comparison of the mass distribution properties between Kenshiro, Kengoro, and an average human was also conducted. The results of this comparison are presented in Table 2, where it can be seen that Kenshiro and Kengoro exhibited an average of 115 and 116% of the mass of an average human, respectively. Thus, we confirmed that the assembled humanoids exhibited high fidelity from the mass distribution point of view.

Skeletal structure fidelity

In terms of the skeletal structure evaluation, we compared the number of degrees of freedom (DOFs) between a human and several humanoids, including Kenshiro and Kengoro. In a human, 548 joint DOFs have been identified; when excluding the face and hands, there are 419 DOFs based on the number of bone connections according to their functional classification (17). Each joint may include one, two, or three DOFs. The comparison of joint DOFs, excluding those of the face and hands based on the data of Kenshiro, Kengoro, or other life-sized humanoids (3, 4, 18–25), is shown in Fig. 2. These humanoids can be largely separated into two groups. The first group (that is, the axial-driven group) is composed of ordinary humanoids with actuators at each joint to move their structural links, and the number of joint DOFs is 27 to 35. Examples of this group include the HRP2 or ASIMO humanoids. The second group (that is, the tendon-driven group) is composed of tendon-driven humanoids with human-inspired musculoskeletal structures that have a relatively large number of joint DOFs (55 to 114). The use of multiple spine joints is one of the most important factors required to approach the flexibility of a human, and the number of DOFs of current humanoids is limited by whether the humanoid has spinal flexibility. Kenshiro has 64 DOFs, which is just 15% of the 419 DOFs possessed by a human. Multiple spine joints and a yaw rotational DOF in the knee joint are the reason for the relatively larger number of whole-body DOFs compared with other humanoids. Kengoro has 114 DOFs, which

is 27% of the number possessed by humans and is the largest number of DOFs among life-sized humanoids. When hand DOFs are included, Kengoro is equipped with 174 DOFs. Multiple DOFs in its end effectors are considered the reason for the increased number of DOFs. End effectors are a challenging topic in humanoid robotics, and a large gap remains in this area between humanoids and humans.

Table 1. Link length comparison between Kenshiro, Kengoro, and an average human. The body segments of each are indicated for comparison purposes. Human anthropometry data were obtained from (47) based on (48). The human length proportions were calculated, assuming the same body height as Kenshiro and Kengoro. The proportional values for *r-u* were not provided, whereas those of Kenshiro and Kengoro are described in the referenced information. Dash entries indicate excluded data.



Sign	Part	Length (mm)			Length (mm)		
		Human	Kenshiro*	Ratio (%)	Human	Kengoro*	Ratio (%)
a	Body height	1600	1600	100	1670	1670	100
b	Eye height	1500	1470	98.5	1560	1540	98.8
c	Head	208	227	109	217	237	109
d	Shoulder height	1310	1270	97.3	1370	1310	95.8
e	Shoulder width	414	372	89.9	432	395	91.4
f	Chest height	1150	1130	98.6	1200	1140	94.6
g	Chest width	278	306	110	291	328	113
h	Trunk with head	831	897	108	868	901	104
i	Upper arm	297	270	90.9	311	270	86.9
j	Forearm	233	236	101	244	292	120
k	Hand	173	-†	-	180	161	89.4
l	Hip width(trochanter)	305	309	101	319	293	91.8
m	Thigh	391	348	89.0	409	384	93.8
n	Shank	393	343	87.4	411	348	84.7
o	Foot	62.3	74.3	119	65.1	79.2	122
p	Foot width	87.9	90.0	102	91.8	90.1	99.0
q	Foot length	243	260	107	254	241	94.9
r	Upper body total	-	682	-	-	745	-
s	Lower body total	-	915	-	-	924	-
t	Chest thickness	-	211	-	-	203	-
u	Hip width (joint)	-	168	-	-	151	-
		Average(b-q)		101	Average(b-q)		99.3

* The distances between the parts were measured on geometrical 3D models. † The hand was excluded from the list because Kenshiro does not have hands.

Table 2. Link weight comparison between Kenshiro, Kengoro, and an average human. The human data used in this comparison were reported in (49) based on the data of (27) and (50). Each human link weight was calculated assuming the same body weight as Kenshiro and Kengoro.

Name	Ratio of segment weight (%)	Weight (kg)			Weight (kg)		
		Human	Kenshiro	Ratio (%)	Human	Kengoro	Ratio (%)
Body weight	100	51.9	51.9	100	56.5	56.5	100
Head*	8.0	4.15	3.10	74.7	4.52	2.6	57.5
Trunk†	50.0	26.0	26.3	102	28.3	26.0	91.9
Upper trunk‡	-	-	18.4	-	-	17.3	-
Pelvis	-	-	7.98	-	-	8.64	-
Upper arm	2.70	1.40	1.95	139	1.53	2.19	144
Forearm	1.60	0.830	1.16	140	0.904	1.54	170
Hand	0.70	0.363	- [§]	-	0.396	0.3	75.9
Thigh	10.1	5.24	4.0	76.3	5.71	5.07	88.8
Shank	4.4	2.28	3.05	134	2.49	3.53	142
Foot	1.5	0.779	1.07	137	0.85	1.34	158
		Average			Average		
		115			116		

*The heads of Kenshiro and Kengoro include their necks. †Trunk includes upper trunk and pelvis. ‡Upper trunk includes spine, chest, and shoulder blade. §Kenshiro does not possess a hand.

Body part	The number of joint DOFs					
	Human	HRP2	Kenshiro			Kengoro
Spine	73	4	24	lumber 11, neck 13		40
Arms	26	12	26	collar 3, blade 3, shoulder 3, elbow 1, radioulnar 1 (passive), wrist 2 (passive)		26
Hands	126	2	0			60
Legs	12	12	14	hip 3, knee 2, ankle 2		16
Feet	140	0	0			32
Others	171	0	0			0
Total	548	30	64			174

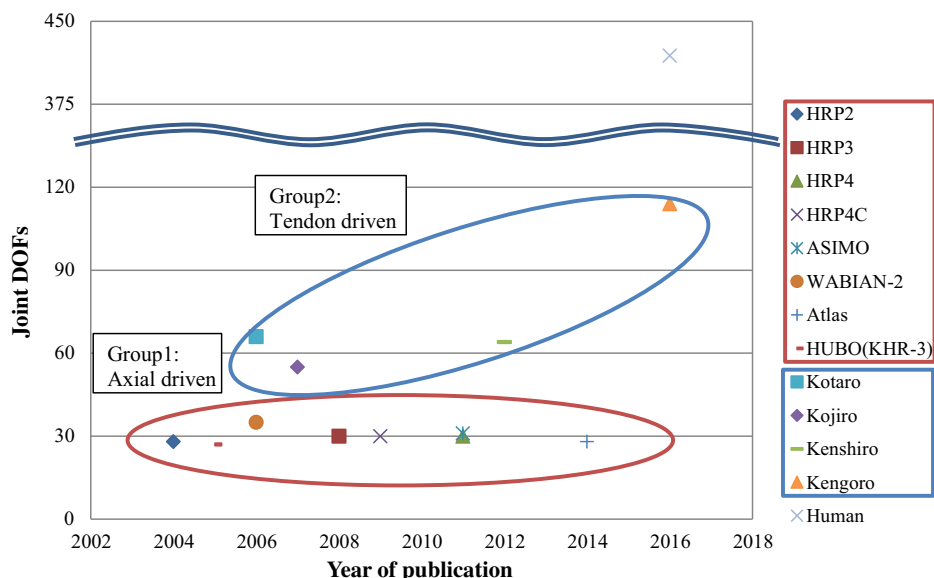


Fig. 2. Joint DOF comparison between several humanoids and an average human.

Muscle arrangement fidelity

A human mimetic muscle arrangement means that muscle actuators are placed and arranged so that they replicate muscle origin and insertion points based on human anatomy. This arrangement enables the naming of muscle actuators in a musculoskeletal humanoid to match that in humans, which, in turn, increasing the plausibility of the muscle data obtained from the movement of the human mimetic humanoid. A comparison of the number of synonymous muscles between humans and several musculoskeletal robots, including Kenshiro and Kengoro, is presented in Table 3. Human muscles important for whole-body motions and joint movements were counted. The muscles for face or organs are eliminated from the number. In the table, the count is not based on the muscle (actuator) number but the name of the muscle, because there are cases where Kenshiro and Kengoro are equipped with multiple muscle actuators that represent a single muscle. For example, Kenshiro is equipped with two muscle actuators that represent the gastrocnemius muscle to ensure enough muscle output. In the spine, Kenshiro and Kengoro have a higher number of muscle relationships than other robots. In the arm, excluding the inner muscles of

Table 3. Muscle fidelity evaluation. The number of muscles was counted based on the muscle names corresponding to those of the human. The numbers of muscles in the musculoskeletal robots developed by (12, 51, 52) are described in the comparison.

	Number of muscles/Ratio to human					
	Human	Athlete robot*	Pneumat-BS	Anthrob [†]	Kenshiro	Kengoro
Spine	34	–	2	–	10	10
Ratio (%)	100	–	5.88	–	29.4	29.4
Arm (without hand)	37	–	3	9	10	19
Ratio (%)	100	–	8.10	24.3	27.0	51.4
Leg (without foot)	42	7	16	–	21	24
Ratio (%)	100	16.7	38.0	–	50.0	57.1
Whole body (without hand and foot)	106	–	22	–	40	52
Ratio (%)	100	–	20.8	–	37.7	49.1
Whole body (with hand and foot)	133	–	22	–	40	53
Ratio (%)	100	–	16.5	–	30.1	39.1

*Legged robot †One-armed robot

the hand, Kenshiro and Kengoro are equipped with 27.0 and 51.4%, respectively, of the muscles of humans. Kengoro has a larger number of muscles than Kenshiro, because the muscles for its forearm and wrist contribute to increasing the number of muscles. In the leg, excluding the inner muscles of the foot, Kenshiro and Kengoro are equipped with 50.0 and 57.1% of the muscles of humans. In the entire body comparison, excluding the inner muscles of the hand and the foot, the muscle fidelity of Kenshiro and Kengoro are 37.7 and 49.1%, respectively, in that of humans. On the basis of these results, we confirmed that the human mimetic humanoids Kenshiro and Kengoro have the largest rate of muscle fidelity with respect to humans when compared to the other humanoids. Nevertheless, when the muscles of the hands and feet are included, the fidelity decreases to 30.1% for Kenshiro and 39.1% for Kengoro. These results are due to the muscles for the end effectors being a large part of the entire muscle ratio of humans. Thus, end effectors are quite important for humans in their daily lives. This suggests that it is essential to develop human mimetic end effectors to move humanoid robotics forward.

Joint performance fidelity

A joint range comparison between Kenshiro, Kengoro, and an average human was conducted. Note that the joint range of a human has been reported in (17, 26, 27). The mechanical joint range of Kenshiro and Kengoro were examined using geometrical computer-aided design models or actual movement of the real robot, and the neck, spine, shoulder, elbow, hip, knee, and ankle joint ranges were compared. The results are shown in Fig. 3. We confirmed that almost all the joint ranges of Kenshiro and Kengoro are similar to those of humans, indicating that these humanoids can achieve flexible human-like postures. In particular, the spherical joints in the shoulder and hip enable joint movements over a wide range. A multijointed spine is a human mimetic joint that enables human-like flexible poses. In the humanoid, a human-like wide range of motion can be achieved because of the human mimetic muscle arrangement. A redundant muscle arrangement

ensures sufficient joint torque near the joint limit, where the stability of the joint tends to decrease because of insufficient constraint force.

DISCUSSION

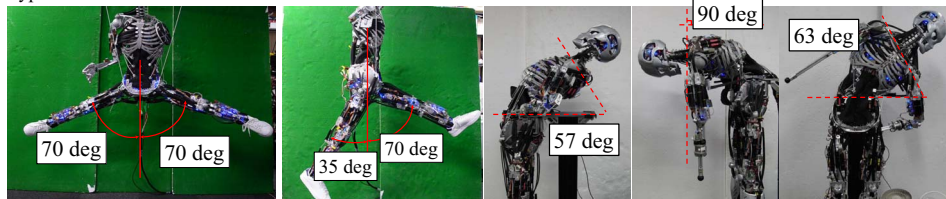
Summary

Here, we described our work on human mimetic humanoids, whose musculoskeletal systems are as close as possible to that of a human. We proceeded with the study based on the idea that the features crucial for improving humanoids are hidden behind the structure and motion processes of humans. Hence, we incorporated elements that facilitate fidelity with the human musculoskeletal system. To realize these humanoid systems, we mimicked human musculoskeletal structures based on our knowledge of anatomy. In terms of the design principles of the human mimetic humanoid, our design centered around four key areas—body proportion, skeletal structure, muscle arrangement, and joint performance—and the humanoids Kenshiro and Kengoro were developed on this basis. We conducted an evaluation of their design by comparing them with humans or existing humanoids and confirmed that the two humanoids have great anatomical fidelity to humans.

Flexibility or rigidity

A conventional design approach is based on the improvement of rigidity that makes a humanoid rigid and structurally strong. It is better for controlling of humanoids in accurate positions; however, with those approaches, humanoids tend to be bulky. On the other hand, a flexible part in the body, such as the spine, is helpful for producing human-like flexible motions, but it tends to be structurally weak. We think that there is a trade-off between flexibility (weakness) and rigidity (strength). We believe that incorporating flexibility inspired from living things is more important than rigidity to make humanoids more human-like. Therefore, we incorporated flexibility of humans into the structure of our humanoids.

Typical motions of Kenshiro



Typical motions of Kengoro

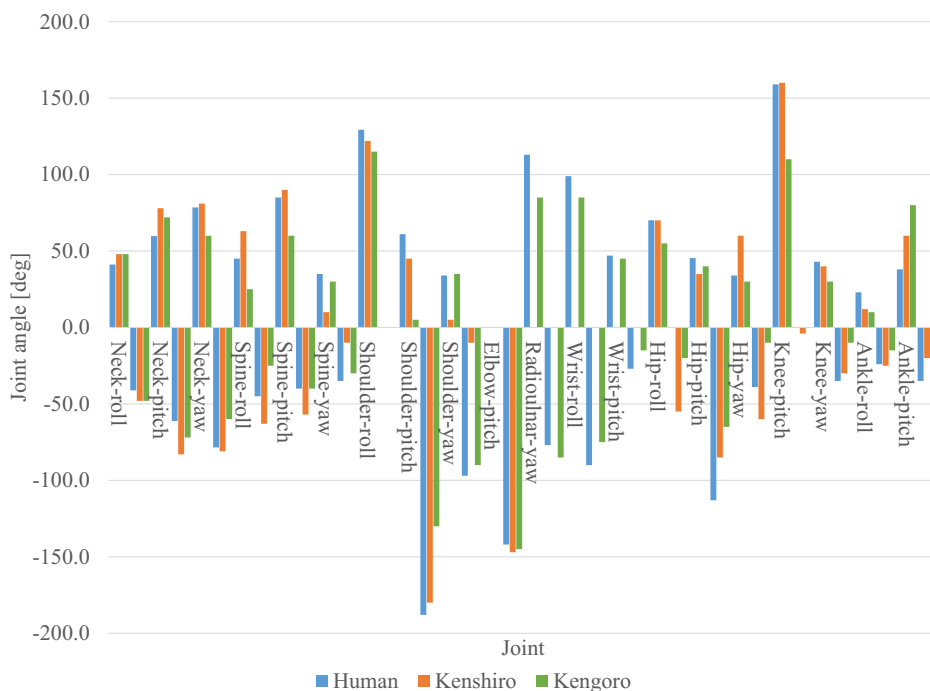
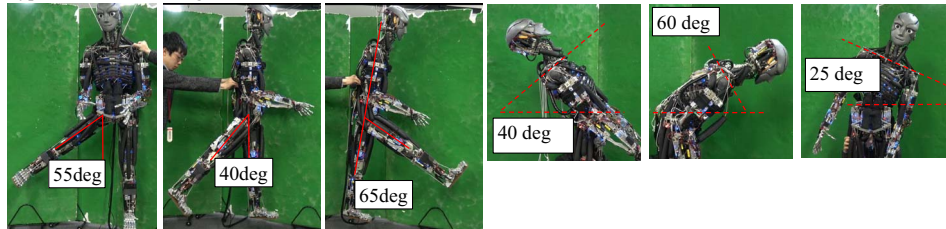


Fig. 3. Joint range comparison of Kenshiro, Kengoro, and an average human.

Future applications

We believe that human mimetic humanoids have the potential to be used in several new applications that have not been considered previously. For example, human body musculoskeletal simulators can be used to obtain information related to the invisible internal body of humans by evaluating sensory data received from human mimetic humanoids in the real world. This type of simulator can also be used to verify hypotheses regarding human control by applying control programs artificially implemented from the human system, because human mimetic humanoids have structures quite close to those of humans. These tools can be used to provide a deeper understanding of the human mechanism. In addition, other practical applications are also possible. An interesting application is active crash test dummies used during car crash testing, because current dummies can only measure passive behavior. A human mimetic humanoid enables the replication of human reflective behavior by muscle actuation.

One research group has suggested the possibility that a musculoskeletal humanoid can be used in medicine, such as to grow tissue grafts (28). If a humanoid can replicate human movements, then the resulting muscle contribution analysis or sensory data obtained during motion will benefit athletes or sports trainers. In addition, human-shaped robotic limbs are also expected to be used in other fields, such as for artificial limbs or tele-operated human agents.

MATERIALS AND METHODS

Four design principles

We are concentrating on the capability of whole-body motions by our human mimetic humanoids to achieve our goals (for example, a physical musculoskeletal simulator in the real world for motion analysis of humans). To satisfy the requirement and emulate human, similarity of kinematics and dynamics between a human and the humanoid are quite important. We considered comprehensively following factors for developing human mimetic humanoids and decided that the four principles should be our focus.

Similar link lengths and mass distributions (in other words, body proportions) to humans provide similar kinematics and dynamics. Sensory data obtained from those humanoid movements have high correlations to those of humans. In addition, strong similarity also enables these humanoids to fit in the environment for humans, such as using tools, wearing clothes for humans, or getting in a car.

A high degree of anatomical fidelity in skeletal structures is effective for emulating human body characteristics. Human joints are not only single-axis rotation joints, but also are rolling-sliding joints that are composed of a combination of rotation and sliding movement between the bones (for example, knee joint). Spine joints with multiple vertebrae are effective to make various human-like postures and flexible upper body movement. Human-like multiple DOFs in the entire body are effective for adaptive environmental contact or movement under environmental constraint.

On the basis of the basic equations for tendon-driven robots $\tau = {}^tGT$ and $\tau = {}^tJF$ (where τ is joint torque, T is muscle tension, F is end-effector force, G is muscle Jacobian, and J is Jacobian), muscle-joint-operational state mappings are necessary to control musculo-skeletal robots. Muscle arrangements are important for deciding those mapping characteristics. Anatomically correct muscle arrangements can provide muscle contribution in correct tendency during the whole-body motions.

Joint performances are related to the above-mentioned three properties and decide humanoid performance in terms of whole-body

motion. Joint range and output power were determined by skeletal structures and by a combination of joint moment arm and muscle output power, respectively. Similar joint range and joint output power are essential for useful analyses of human motions by the humanoid.

How to design a human mimetic humanoid

To develop a humanoid with human body proportions, the use of statistical data is important. Similar studies were conducted for the development of the HRP4 (20) and HRP4-C (21) humanoids. In our case, the design priority was to achieve bone lengths and limb shapes similar to those of humans. With this priority in mind, the components, muscle actuators, skeletal structure, and electrical components were designed and placed by trial and error.

The skeletal structure of the human mimetic humanoid was designed to imitate the skeletal shape, joint structure, and joint DOFs of humans. During the design process, we first studied human skeletal structures and extracted essential human skeletal mechanisms and functions that were considered useful for humanoids. Then, we simplified the biologically complex human joint structures into mechanical humanoid structures by extracting and focusing on certain functions. In addition, we considered mechanical designs or elements that enabled us to realize the important functions.

To develop a human mimetic humanoid with a human mimetic muscle arrangement, the humanoid should be equipped with as many muscle actuators as possible; however, trade-offs must be considered between the number of muscle actuators and the available design space. To overcome this challenge, we adopted a dense arrangement of muscle actuators. By modularizing the muscle actuators, we were able to effectively implement many muscles in the entire body. Muscle insertion points of the humanoids are decided according to those of humans. However, a muscle expressed by a wire can only emulate just a point insertion, not regional attachment. Planar muscle is adopted to emulate regional attachment or multiple points to more correct emulation of the human.

Development of Kenshiro

Kenshiro incorporated human mimetic musculoskeletal structures based on the knowledge of human anatomy that we obtained (1, 29–31). Figure 4 shows the body specification of Kenshiro. For Kenshiro development, the target body parameters were those of an around average 13-year-old Japanese male, which is 158 cm and 50 kg. It was important that the body have the multi-DOFs structure of a human because this provides flexibility and adaptability to the environment. Kenshiro was equipped with several unique joints inspired by those of humans, such as multiple spine joints (32), screw-home mechanisms (33), and open-sphere joints (34). The spine joints provide a wide range of motion to the upper body. The screw-home mechanism in the knee provides not only the pitch DOF, but also the yaw DOF that enables the movement of the toe while the femur is under constraint in the sitting posture. The open-sphere joint in the shoulder enables the joint to have a wide range of motion by adhesion of muscle and bones. These structures allowed the robot to achieve human-like behavior and contribute to increased flexibility. The skeletal structure of Kenshiro is mainly made of machined aluminum alloy (A5052). For several parts that require three-dimensional (3D) complex form, we made those parts by 3D printing. For example, covers and blade bone are made of acrylonitrile butadiene styrene (ABS) plastic and stainless steel [420SS, bronze (40%)] respectively. The ribs are made by lost wax casting process with aluminum (AC4C) material.

A muscle actuator is composed of an electrical motor, mechanical parts, a wire, and sensors, which are mechanically assembled and modularized for easy use. We arranged these over the entire body of Kenshiro to achieve muscle arrangements similar to those of humans. Motors are brush-less dc (BLDC), and the output of those is 100 W for almost all muscles and 40 W for narrow parts of the body. Muscle length, tension, and temperature can be obtained from the sensors. The wire in the muscle actuator is wound by a motor to replicate muscle contraction. It is a chemical wire named Dyneema, which is strong against friction. Planar muscles that replicate the planar surface of human muscles were used in the spine and neck joints. In terms of muscle control, the behavior of muscle actuators can be made similar to human muscle behavior by implementing artificial motor controls inspired by the characteristics of human muscles. We also implemented muscle-tendon complex control to provide muscle flexibility (35) and muscle cooperation for sharing load over redundant muscles (36).

Balance control was implemented by using distributed force sensors and human-like joint structures on the body. We implemented a balancing strategy for the musculoskeletal humanoid that relied on muscle tension and the spine (37). To control the musculoskeletal humanoid, a muscle Jacobian that expresses the relationship between muscle length and joint angle is necessary. A machine learning-based approach to obtain the muscle Jacobian was proposed, and it enabled bidirectional conversion between the muscle length and joint angle (38). To overcome large robot-model errors, learning using real sensor data, but not simulation data, is preferable.

Development of Kengoro

In the design process of Kengoro, we adopted the idea of multi-functional skeletal structures to achieve both humanoid performance and human-like proportions and devised sensor-driver-integrated muscle modules for improved muscle control. Figure 5 shows the body specifications of Kengoro. To demonstrate the effectiveness of these body structures, we conducted several preliminary movements using Kengoro.

Kengoro is the successor version of Kenshiro and is also a human mimetic humanoid designed with anatomical fidelity to humans (39). One of the design goals of Kengoro was to achieve actions involving contact with the environment that required a flexible body and adaptability to the environment. Thus, multi-DOFs in not only the spine, but also in end effectors are important, because humans naturally contact the environment with their hands and feet. On this basis, Kengoro was equipped with human mimetic five-fingered hands and feet. The foot has multi-DOFs and multisensors to facilitate natural adaptation to the ground (40). The toe actuation was powerful enough to perform tip-toe standing with support by hands for balancing. The toe is actuated by a muscle connected to a 90-W motor placed on the lower leg link. In addition, the hand can hold the weight of its body, because a large grasping force can be generated by the muscles in its forearm (41). The forearm is composed of a radio-ulnar joint with a tilted joint axis and expands the variety of possible hand motions, such as that in sports or dexterous tasks (42). From a physiological point of view, a skeletal structure with artificial perspiration was developed to release the heat of the motors (43). The skeletal structure of Kengoro is composed of a combination of extra super duralumin (A7075) and carbon fiber-reinforced plastic for more strength and lightness. Several parts of the body, such as the outer cover, were made by 3D printing, as with Kenshiro. LiFe batteries were embedded into the skeletal structures of legs, and they enabled movement for about 20 min without any power cables.

Human mimetic humanoid “Kenshiro” (2012-)

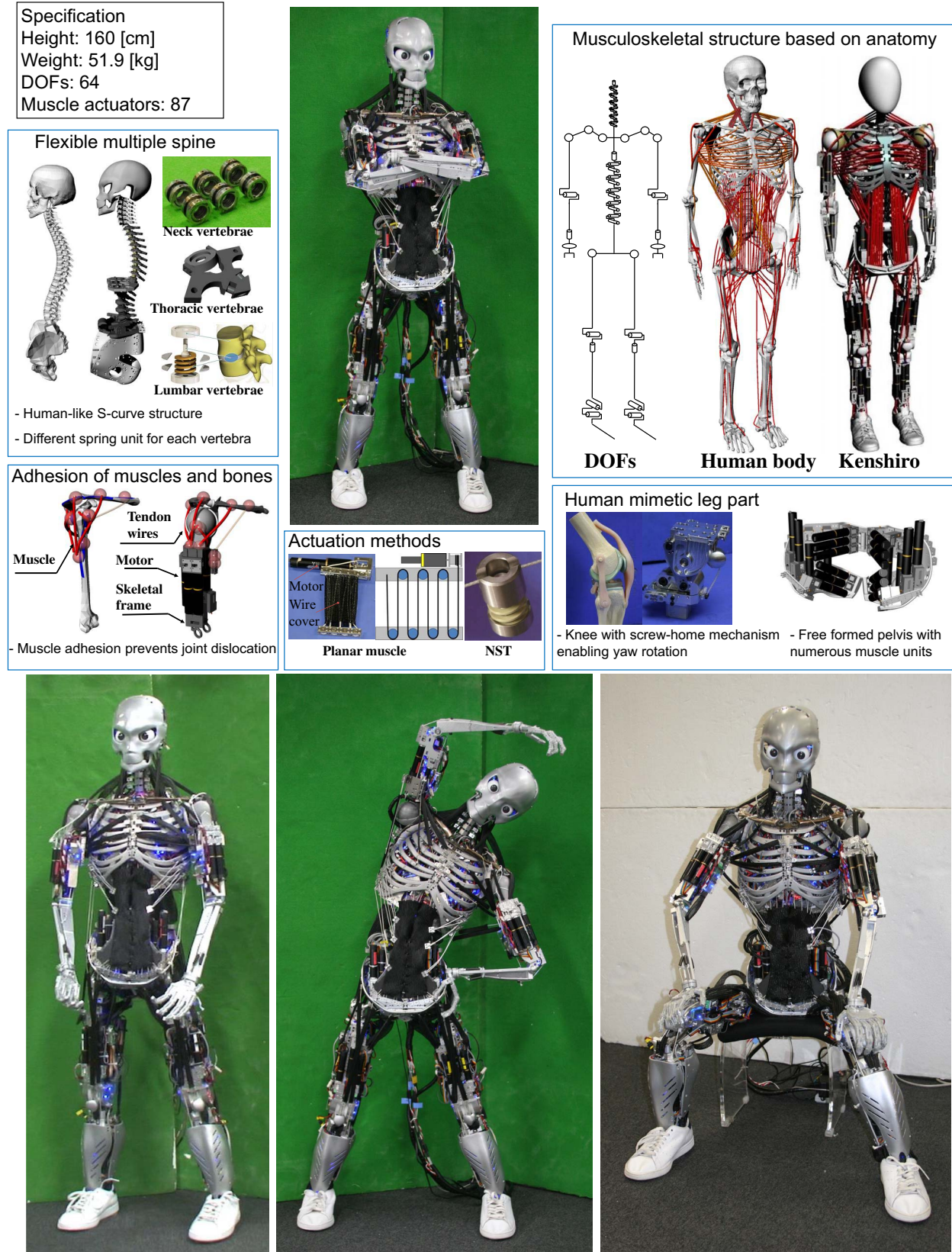


Fig. 4. Human mimetic humanoid Kenshiro.

Human mimetic humanoid “Kengoro” (2016-)



Fig. 5. Human mimetic humanoid Kengoro.

Muscle control using force was achieved using two types of sensor-driver-integrated muscle modules (42, 44). This is an all-in-one integrated module composed of electrical motor, motor driver, and sensors for force control. Motors were BLDC and those outputs were 90, 100, or 120 W for fundamental muscles. For narrow parts of the body, such as the forearm, 60-W BLDC motors were adopted. The use of this module provided active flexibility to Kengoro. Not only muscle space, but also joint-space torque controller for flexible and adaptive environmental contact was implemented (45). On the basis of human reciprocal innervation that suppresses co-contraction in muscle antagonism, we implemented antagonist inhibition control that contributed to arm movement in a wide range of motions (46).

SUPPLEMENTARY MATERIAL

robotics.sciencemag.org/cgi/content/full/2/13/eaq0899/DC1

movie S1. Movements of Kengoro.

movie S2. Motion comparison between Kengoro and Kengoro.

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