Design of the Musculoskeletal Trunk and Realization of Powerful Motions Using Spines

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***Abstract*— We are developing the novel musculoskeletal humanoid that is able to do coordinated motion with arms, legs and especially trunk body. In this research, we designed and implemented the trunk consisting of redundant articulated spine joints which can hold up and drive the upper body and pelvis. Furthermore, we confirmed that this trunk body ability to do fullbody motion, by an experiment of spine rotation motions with the real humanoid developed.**

I. INTRODUCTION

The trunk structure of the human body is a very fundamental part where four limbs and a head are linked, in doing dexterous fullbody motions. For example, thanks to spines' multiple DOFs and powerful muscles skillfully of the trunk, we human can realize large movable ranges of limbs, maintain postures flexibly against various disturbances, and do natural various motions.

Based on this standpoint, we have developed the fully tendon-driven redundant humanoids, which have spine structures like human body, and studied on how to control such a complicated bodies through the relationship between actuator outputs and sensor inputs [1], [2]. In realizing trunk bodies structures of these humanoids, one of the most difficult point is simultaneous pursuit of powerful muscle driving for fullbody motions and multi-DOFs structure for flexible and natural motions. More actuators need to be embedded in order to control more multiple joints. Because of the limitation of the robot size, so as to install many actuators, designers must choose smaller actuators, which are too low-powered to realize powerful motions. As a result, most of the robots with spines developed[3] have the same problem that it is difficult to move their whole bodies powerfully due to this trade-off between powerful muscle driving and multi-DOFs system.

In this research, we design the humanoid trunk body structure which has both a multi-DOFs flexible spine and powerful driving, and we actually embedded this structure to the next-generation musculoskeletal humanoid lower body[4]. This design point is **how to pack high-powered actuators into the pelvis and chest bones, and how to arrange passive viscoelasticity elements between spines for supporting fullbody motions.** This paper describes firstly general consideration about trunk structure with a spine including human cases in **II**, and the specification and concepts of the developed trunk body in **III**. Finally we presented an experiment on powerful motions using its spine in **IV**.

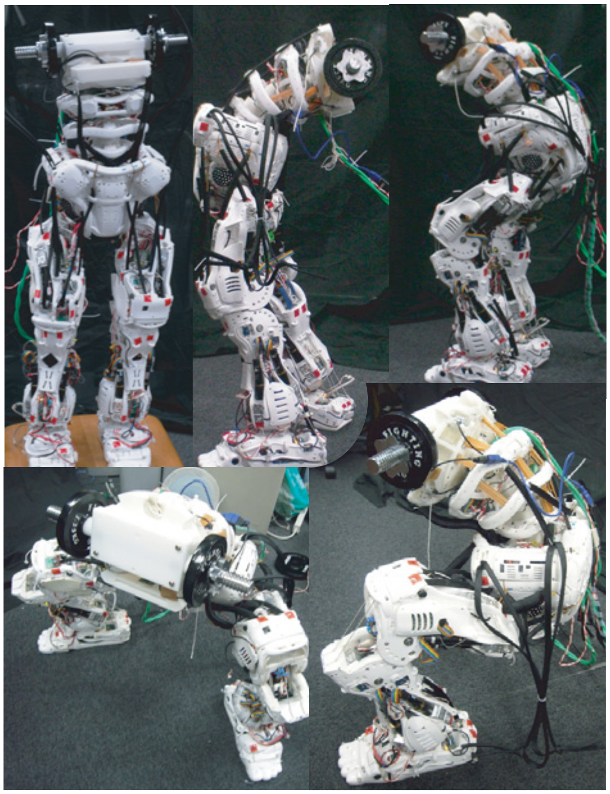

Fig. 1. A newly developed musculoskeletal humanoid with a spine structure

II. MUSCULOSKELETAL TRUNK WITH SPINE

This section shows the characteristic of the human trunk structure [1], and our musculoskeletal humanoid approach for implementation of this structure.

A. Human Trunk Structures

Human spines, the main parts of a human trunk body, consist of serially-connected multi-joints and are driven by various large and small muscles. A spine bone has a 6-DOFs joint consisting of a spherical bone and two plane-like bones which sandwich its ball. Actually it can be considered as a 3-DOFs rotational joint because its translation DOFs are very small[5]. Each spine ball joint rotates little, but a series of spines realize so large movable range that we human can do

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[1] In this paper, we define a trunk as a musculoskeletal structure ranging from a thigh bone to a chest bone via a pelvis and spines

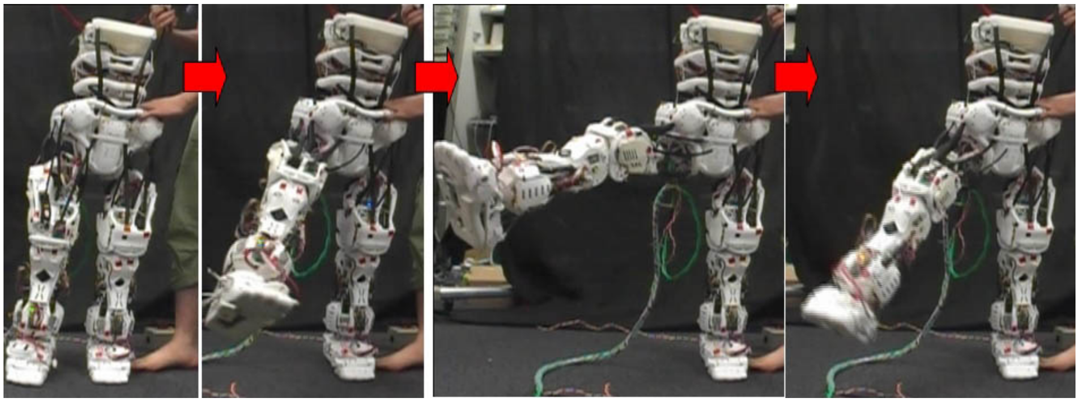


Fig. 2. The rotation motion of hip joint

natural flexible motions. And also there is elastic element, which enables to stabilize these spine structures, between these joints.

B. Musculoskeletal Humanoid Approach

Musculoskeletal structure has advantages when realizing an articulated structure, such as spine joints. If an articulated structure consists of serial rotational joints actuated by rotational motor, then each motor has to generate torque that is enough to move or hold the mass and inertia of the descendant parts. In case of a tendon-driven structure, on the other hand, several actuators cooperatively work for moving one joint, and each actuator can determine the posture of one joint; this feature is called 'coupled drive'[6].

Especially in case of the trunk body structure, some muscles can be put in the position where they have large moment arms, such as multi-articulated muscles attached between a pelvis and a chest bone. These muscle arrangements enable to reduce the weight and size of each muscle driving motor, because the larger moment arm of a muscle leads to reduction of the gear ratio of the driving motor.

Another advantage of musculoskeletal robots is easiness of installing mechanical elasticity and viscosity. Joints of muscle-driven skeletal robots are, in general, passive joints, and the structure around a joint is relatively simple.

III. CONCEPT AND IMPLEMENTATION OF THE MUSCULOSKELETAL TRUNK

Table I shows specifications of this trunk body, such as weight, quantity of joints, motors, sensors and electric circuit boards.

A. The Spine Structure

In implementation of the musculoskeletal humanoid trunk body, it is difficult to imitate human spines consisting of nearly 30 joints completely. Therefore, we implemented four articulated 3-DOFs joints as a vertebra(Fig.3), and adopted a ball-and-socket joint, which has spherical joint angle sensors[7], as each joint structure. In case of human, thoracic vertebrae have few movable range because of the chest space which stores important organs, such as a heart and a lung, and so on.

TABLE I

THE SPECIFICATIONS OF THE TRUNK DEVELOPED

category	type	quantity
	weight	25kg
	height	105cm
DOF	1st joint 4th joint	3
	sum of DOF	12
actuators (40W AC motor)	pelvis bone	4
	2nd chest	16
	sum of actuators	20
boards	Motor driver	10
	Sensor board	1
	7port usb hub	4
	DCDC converter	4
sensors	tension sensor	20
	rotary encoder	20
	current sensor	20
	temperature sensor	20
	3-axes force sensor	6
	Joint angle sensor	4

Therefore, in this humanoid 3 out of 4 spine joints are arranged around lumbar vertebra in order to realize large movable range and the one joint is arranged under the chest, which has large space including many motors and motor driver boards for actuating head and arms.

The alternative link, which can fix a barbell of the same weight as under developing upper body structures(i.e. a head and arms and a first chest), is installed to this humanoid instead of the first chest bone. We designed these complex skeleton structures using 3D-CAD software. These parts are modeled by Rapid-prototyping.

B. The Range of Joint Movement

In case of the spine 4 articulated joints, the range of each joint motion is 20[degree] around roll axis, 15[degree] around pitch axis 45[degree] around yaw axis. The hip joint is the most movable among human joints. We designed the pelvis and thigh bone shapes carefully so that hip joints can move as widely as human's shown in Fig.2. Table II shows the range of spine and hip joints movement.

C. The Actuation System

Actuators of the trunk and lower legs are based on the combination of an AC motor, pulleys, chemical fiber (Vectran, Dyneema and Zylon), and a tension sensor(Fig.3). A

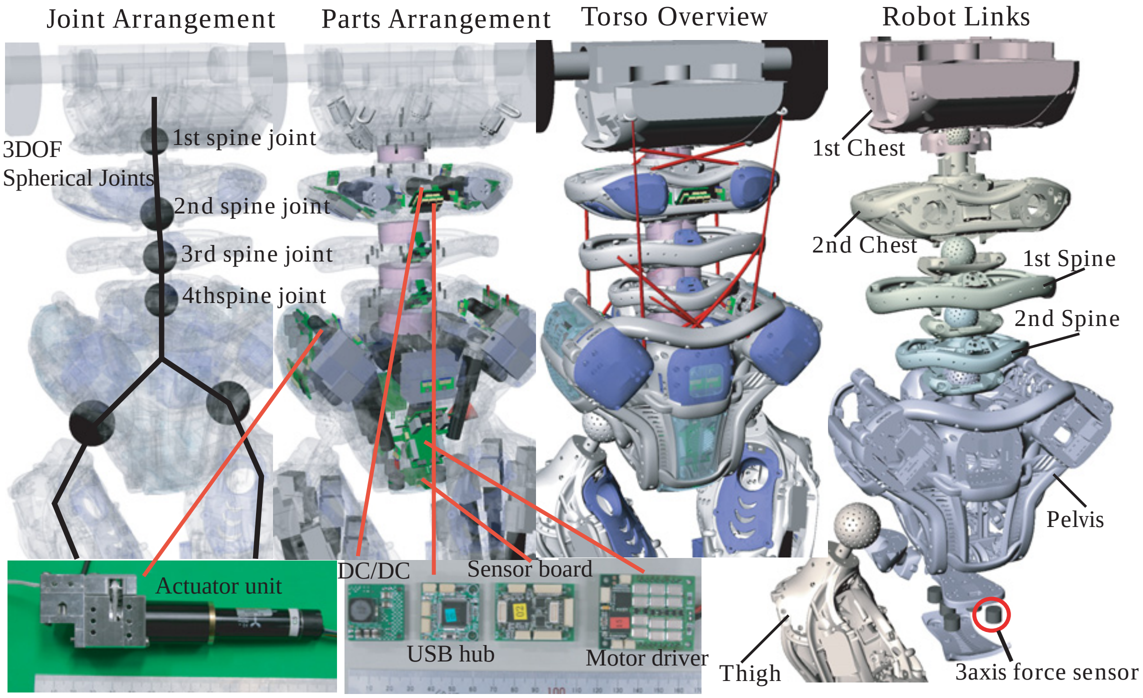


Fig. 3. The developed trunk structure with spines

TABLE II

MOVABLE RANGE OF THE SPINE AND THE CROTCH

	axis	crotch	spine
movable range	roll	-15 80	-55 55
	pitch	-20 90	-85 85
	yaw	-20 20	-45 45

TABLE III

THE SPESICICATION OF MOTORS

category	40WAC	4.5WDC
Declared power[W]	40	4.5
Nominal voltage[V]	32	24
Overall size[mm](including gear head)	ϕ 16 - 56	ϕ 16 - 44
Weight[g](including sensors, pulleys, gear)	270	110
Rated torque[mNm]	13.9	5.28
Rated RPM	37900	5070
Pulley inner diameter[mm]	16	10
Gear ratio	333	84
Rated muscle tension[kgf]	28.9	5.43
Rated muscle speed[cm/sec]	9.53	3.15

temperature sensor is attached on each motor surface, and it prevents motor burnout by controlling motor output based on the measured temperature.

After consideration of the possibility of pneumatic actuators, we decided to use electric motors with pulleys as this robot's actuators. Pneumatic has difficulty in the size of valves and controllability of pressure. A winding system by an AC motor with a tension sensor can control elasticity by feedback control. In particular, the lower body uses 40W AC motors of the three types of gear ratio(i.e. 333:high-powered, 128:middle-powered, 60:high-speed). Table III shows the specifications of these actuators, including 4.5W DC motors which are used on the older musculoskeletal humanoid Kotaro[8].

D. The Arrangement of Tendon-muscles

It is one of difficult problems to determine the appropriate arrangement of tendon-muscles among many arrangement solutions in the lower body with the redundant actuators and DOFs. The basic tendon arrangement has been selected according to anatomy data of human beings. And also we select more efficient tendon arrangement by calculating joint torques [9]. The position of motors(i.e. the end-point of tendon) is determined as shown in Fig.3. And there are many attachment points of tendons(i.e. another end-point of tendon) on the robot link, so as to try various tendon arrangements. The trunk body can adopt a variety of tendon arrangements(e.g. muscles around multiple joints) by re-selecting another end-points of tendons.

The initial determination of tendon arrangement is shown in Fig.4. Four muscles are arranged around each vertebral joint for binding 3-DOFs, i.e. the spine is driven by 16(= 4 x 4) muscles. 12 out of 16 motors are put within the pelvis bone, and they actuate the first chest, the first spine and the second spine. And the other motors are installed into the second chest and they bind the movement between the first chest and the second spine.

E. The Pelvis Bottom
-smooth shape and tactile for contact with environment-

A human pelvis and hip often contacts with environment in the case of sitting on a chair. Therefore, we designed the humanoid hip with an smooth outer shape, which enables the humanoid to easily move its pelvis during touching environments. It seems to be necessary especially at a exercise motion on a mat.

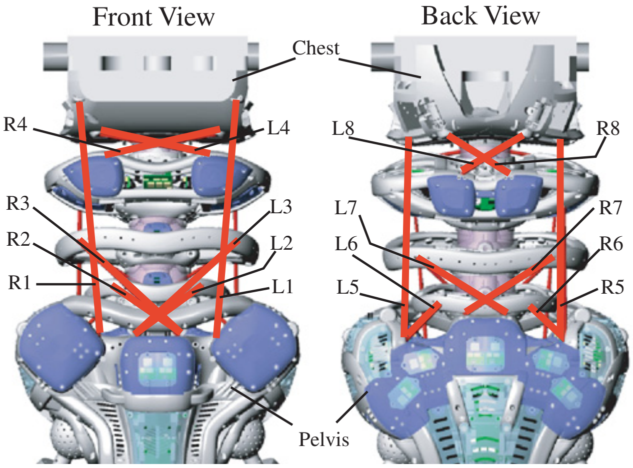


Fig. 4. Arrangement of muscles around spines

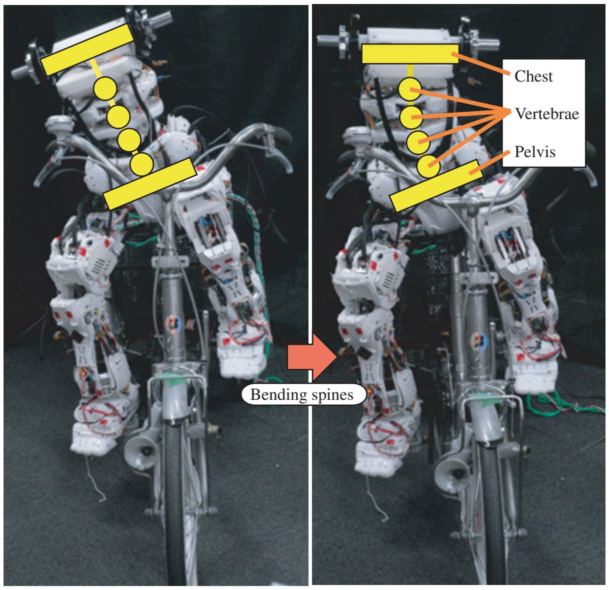


Fig. 5. Posture maintenance during riding on a tricycle

And also tactile sensors are required for maintenance of the trunk posture during sitting according to force information of contact with a seat. For example, in the case of riding on a tricycle, a humanoid should maintain trunk posture so as to prevent falling down from its saddle as shown in Fig.5. There are six 3-axes force sensors and a electric board for reading sensor value on the bottom of pelvis developed(Fig.6). This 3-axes force sensor can measure a vertical load and torques around orthogonal two axes in a horizontal plane. We obtains zero moment point and frictional force vector on the bottom of the humanoid pelvis from these sensors value.

F. Physical Elasticity and Viscosity

Human's spine has elasticity and viscosity of interspinal disk and ligaments between vertebrae. The viscosity absorbs the vibration, and makes motions gentle and supple. The elasticity has several functions. The elastic elements generate the force against the gravity when the spine bends, and can help the actuators. The elastic elements are embedded so that potential energy of the elasticity is lowest when the potential energy of the gravity is highest. The disks and ligaments also make the whole shape of the spine smooth.

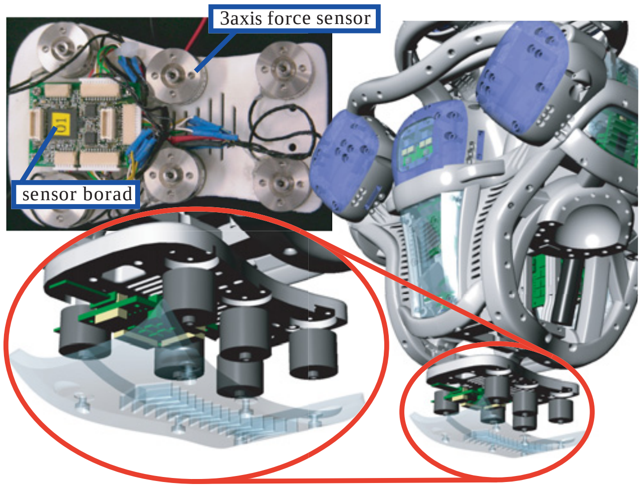


Fig. 6. Force sensors at the bottom of the pelvis

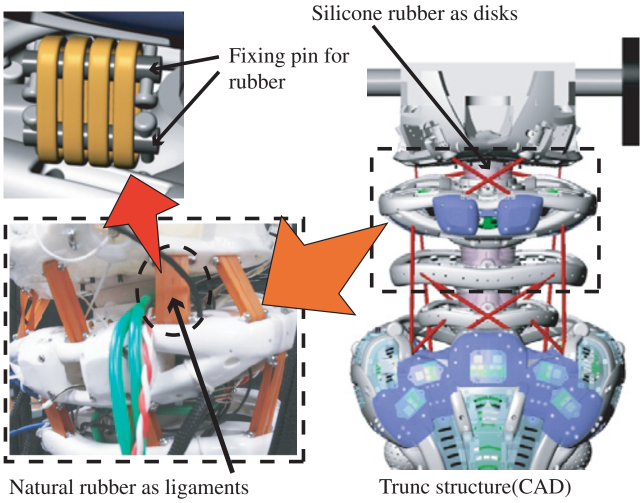


Fig. 7. Rubbers mounted on the spine

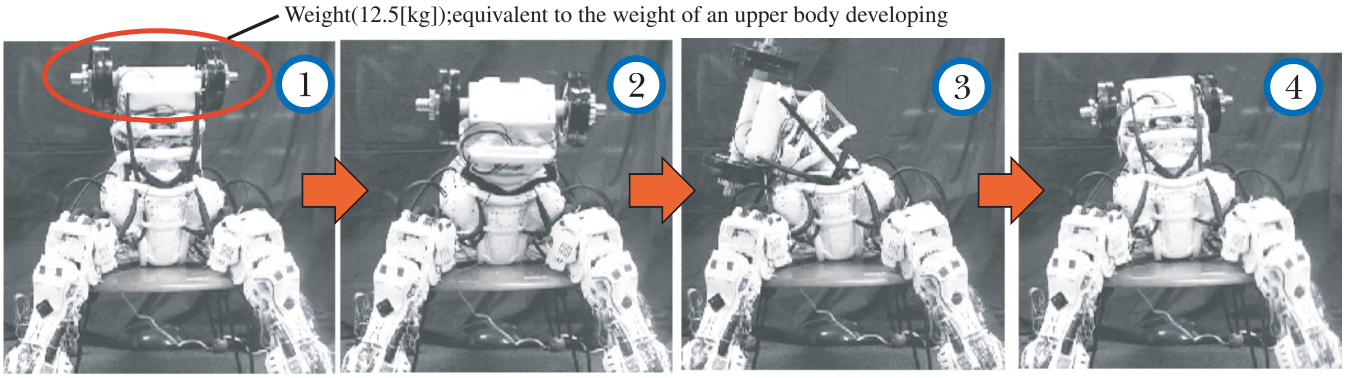
With reference to the structure, silicone rubber parts (as disks) and tension springs (as ligaments) are inserted between the older humanoid Kotaro's spine joints[8]. But, a spring has a problem that it disturbs joint movement due to contact with the joint structure when the spine bends widely.

In the trunk newly developed, we adopt elastic natural rubber bands instead of springs in order to avoid this problem.

Fig.7 shows the natural rubber bands, whose width is 4[mm] and thickness is 1.5[mm], embedded into the actual developed trunk body. Natural rubber is more stretchable than silicone rubber, and it can be attached on the further point from a spine joint, where it can generate more self-weight compensation torque thanks to a larger moment arm.

IV. EXPERIMENT OF BENDING SPINE JOINTS

First of all, we attached the 12.5[kgf] weight barbell, which is equivalent to the upper body under development, to the top



Default posture Bending forward Bending rightward Bending backward

Fig. 8. Spine rotation motion with iron dumbbell(12.5kg)

of the first chest link. As a performance test of the trunk body developed, we made an experiment that the robot bended its spines powerfully.

As the relation between joint angles and muscle lengths is not clear in this robot, it is difficult to order a motion for it using joint angles. Therefore, by direct teaching[2], we taught postures needed for the spine bending motion. Direct teaching can be performed by controlling the tension of all muscles using tension sensors so as to keep tension. In this condition human can teach a posture by directly move the joints of the robot, and memorize the posture by recording the lengths of the muscles. And then, the robot can play back the taught posture by controlling muscles' lengths so as to be the same as the taught lengths.

We confirmed the feasibility that this humanoid can do fullbody motion, by the demonstration of spine rotation motion in Fig.8. This trunk body have the ability to return to the default standing posture from bending postures at the limit of spine joints' movable range against gravity force of its own weight.

The graphs from Fig.9 to Fig.12 presents time transition of muscles(or motors) information at the spine bending forward and backward. Legend symbol R1, R2, R3 and R4 in these graphs denote the muscle in the trunk body in Fig.4. As shown in Fig.9, the muscle can generate fully tension (in case of R1 and R2 about 30[kgf] instantaneously). As R3 and R4 can generate more muscle force, we expects that the performance of trunk body would be improved, if we could install software which adjust whole muscles tension effectively. From Fig.10(muscle length[2]) and Fig.11(error between muscle real length and goal length), we confirmed that all muscles(i.e. motors) can follow their length control order on time; a certain level of error remains because of using PD control now.

Fig.12 shows motor revolutions per minute[rpm]. As the limit of rpm of motor is about 40000[rpm], the motor gear ratio of R2, R3 and R4 muscles, which have less moment arms, can be increased more. If its gear ratio is twice, the muscle can generates more force.

Fig.13 shows time transition of zero moment points(ZMP) at the hip bottom and legs during spine bending motion leftward and rightward. ZMP of hip is acquired from 6 3-axes force sensors in Fig.6 and ZMP of legs is acquired from 2 6-axes force sensors within foot bones. It is possible to obtain the clue of trunk posture from value of the hip ZMP. For example, using this sensing value, this humanoid will be able to maintain trunk posture so as to avoid falling down from a saddle during riding on a cycle like in Fig.5.

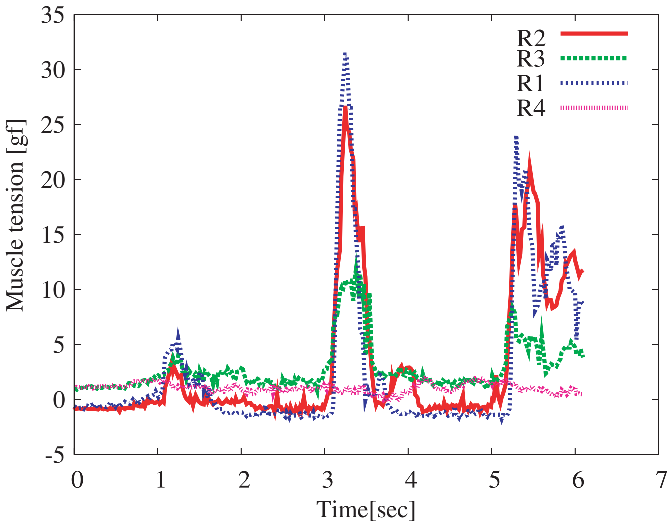


Fig. 9. Time transition of muscles tension during spine rotation

V. CONCLUSIONS AND FUTURE WORKS

This paper presents how to develop and implement the trunk body with vertebrae which has both forcefulness and large movable range, toward the next version of fully tendon-driven musculoskeletal humanoid. Currently our developed humanoid lower body has 60 motors and 28 DOFs and each motor can generate 25[kgf] tension force so that it can realize fullbody motion. It has physical flexibility by silicone rubbers (as spine disks) and natural rubbers bands (as spine ligaments) to support self-weight, and has tactile sensors consisting of 6 3-axes force sensors for maintaining and balancing spine posture contacting with environments. And also we show the

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[2] relative length of muscle based on length at the standing posture

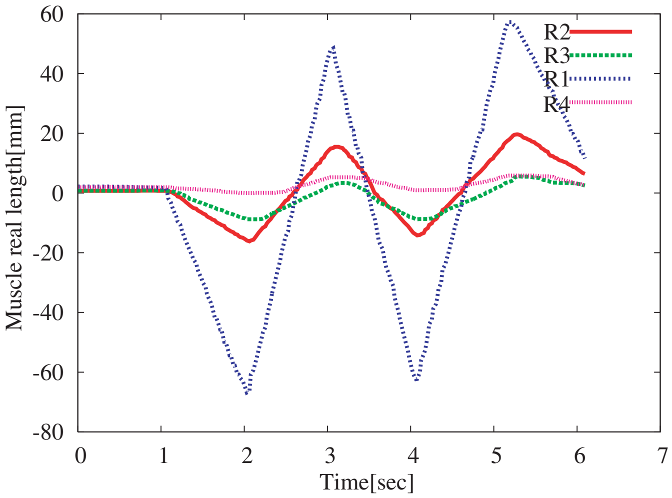

Fig. 10. Time transition of muscle length during spine rotation

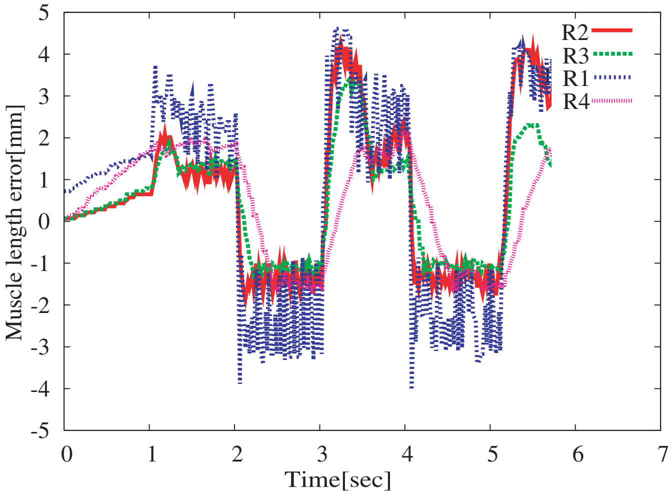

Fig. 11. Time transition of error of muscles length during spine rotation

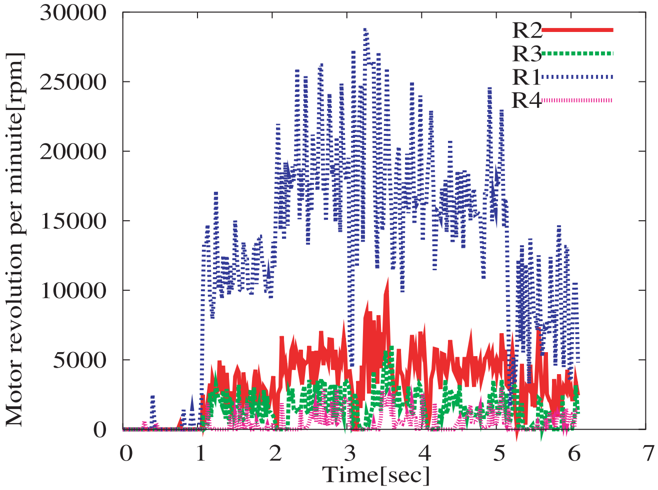

Fig. 12. Time transition of rpm of motors during spine rotation

feasibility of the fullbody motion using this spine, by the experiment of spine rotation by real humanoids.

Future works include combining this lower body developed and the upper body under development, and realization of various motions using flexibility of the whole body, and finding out a software system which can manage the complicated body with spines' redundant actuators and sensors, a framework of autonomous developing, and so on.

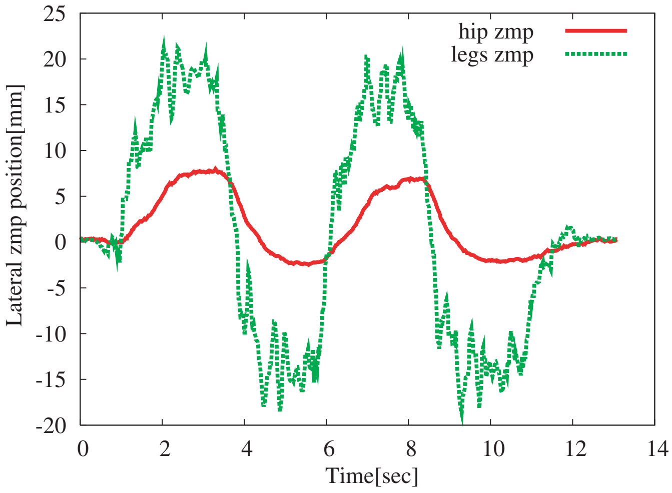

Fig. 13. Time transition of zmp at hip and legs during spine rotation

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