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Development and Verification of Life-Size Humanoid with High-Output Actuation System

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Abstract— **Life-size humanoids which have the same joint arrangement as humans are expected to help in the living environment. In this case, they require high load operations such as gripping and conveyance of heavy load, and holding people at the care spot. However, these operations are difficult for existing humanoids because of their low joint output. Therefore, the purpose of this study is to develop the high-output life-size humanoid robot. We first designed a motor driver for humanoid with featuring small, water-cooled, and high output, and it performed higher joint output than existing humanoids utilizing.**

In this paper, we describe designed humanoid arm and leg with this motor driver. The arm is featuring the designed 2-axis unit and the leg is featuring the water-cooled double motor system. We demonstrated the arm's high torque and high velocity experiment and the leg's high performance experiment based on water-cooled double motor compared with air-cooled and single motor. Then we designed and developed a life-size humanoid with these arms and legs. We demonstrated some humanoid's experiment operating high load to find out the arm and leg's validity.

I. INTRODUCTION

In recent years, many researchers have studied and developed robots that can perform the assistance of daily life. It is expected that humanoids can achieve various operations and tasks without any changes in human environments, because they have the same structure as the human body[1].

Humanoids should be able to carry not only lightweight objects, such as plates and a cup, but also heavy objects[2] [3], such as tables, desks, refrigerators, and humans in care field[4]. They are also required to move using the whole body, such as going up the ladder and performing tasks while caught in a high place, and also, when unexpected events occur, they are required to do avoidance behavior such as falling back at the moment [5]. The above actions require humanoids of high output and high velocity.

In order to make humanoid perform heavy load motion, we develop the whole body with high output joints. Urata et al. developed a high-speed large output motor-axis driver system[6]. They developed a biped robot 'HRP3-JSK-LEG' with such a high-powered actuator system and the robot can perform remarkable jump operations and fall prevention which need quick footwork [7].

This study aims to develop a life-size humanoid that can support everyday life with its high physical performance. In this paper, we develop a high output arms and legs and demonstrate the utility of their high performance. Then, we develop a life-size humanoid with the arms and legs, and demonstrate whole body motion.

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II. DESIGN AND DEVELOPMENT OF JOINT UNIT AND MOTOR UNIT FOR LIFE-SIZE HUMANOID

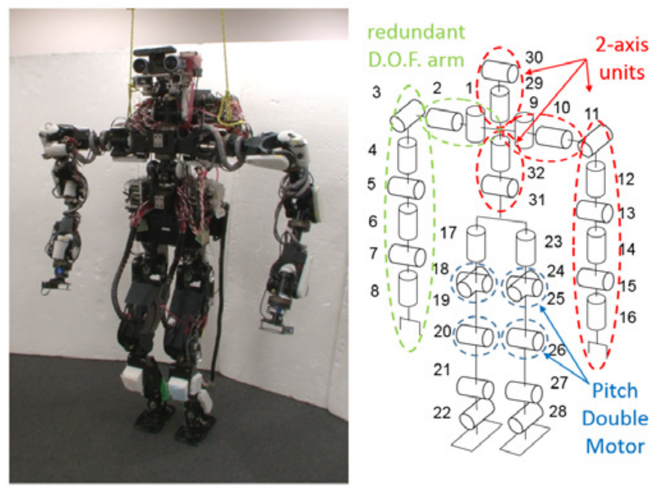

Fig. 1. Over view of high-output life-size humanoid

Table I
SPECIFICATION OF DEVELOPED HUMANOID

Dimension	Height[mm]	1,808
	Width[mm]	1056
	Depth[mm]	490
Weight[kg]		90
D.O.F	Total	32
	Head	2
	Waist	2
	Arm	8
	Leg	6

In previous section, we describe humanoid for human life support which requires the following point.

- Instantaneous force required in an emergency
- Range of motion in dual-arm operation for climbing up a high step
- Steady high-output in order to support high load

In order to solve these, a humanoid requires high performance of both large torque and high joint velocity, joint configuration with redundant degrees of freedom, and exhaust systems of heat generated by the steady load. The design proposals to meet these are below.

- High-output axial driven system

- Redundant D.O.F. arm that consists of 2-axis units with wide range of motion
- Leg with water-cooled double motor

Therefore, we design and developed the life-size humanoid. Fig.1 , Table I shows the appearance and specification. We use a water-cooled high-speed large-output motor-axis driver system developed for high output joint driven system[6]. In this paper, we describe new modules, which are 2-axis unit and water-cooled double motor. We will describe the detail in the following section.

A. DESIGN AND DEVELOPMENT OF 2-AXIS UNIT

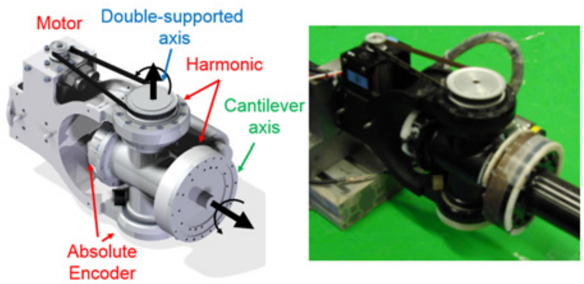

Fig. 2. Over view of 2-axis unit using high-output motor driver

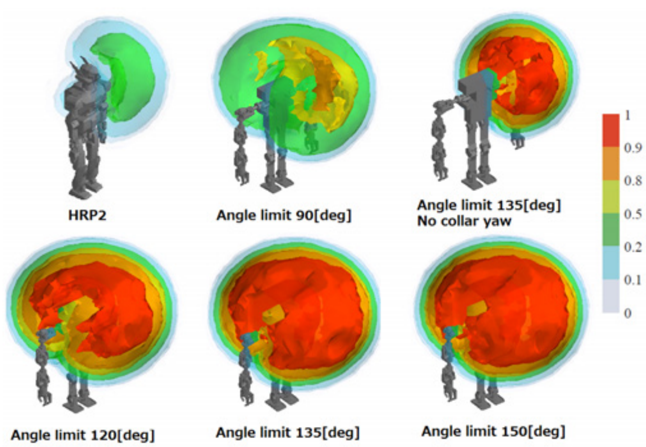

Fig. 3. Reachability comparison of HRP2 and developed humanoid arm by reachability simulator OpenRAVE

We developed 2-axis unit in which double-supported axis and the cantilever axis are orthogonal. Fig.2 shows the appearance of this unit. which have MAXON EC-4pole 30 200W motor, and harmonic drive reducer, and each motor in air cooling now. In the future, we can change the air-cooling motor to water-cooled motor at the joint of heavy load in the experiment, which enable arm to perform higher steady output. The unit has two type of axis. One is the double-supported axis with ±135 deg R.O.M.(Range of Motion) and another is the cantilever axis with ±180 deg R.O.M.. This R.O.M. is determined by the reachability simulator 'OpenRAVE'[8] developed by Rosen et al. Fig.3 shows the developed arm's reachability map. This reachability map is colored, based on the proportion of arrival direction to a certain point. The reachable points from every direction are colored red and the red region of the arm is much larger than that of HRP2. The points are also much larger than the double-supported axis's R.O.M. being 90[deg], 120[deg] or the arm being 7 D.O.F.. In this result, we determined this axis's R.O.M.

B. DESIGN AND DEVELOPMENT OF WATER-COOLED DOUBLE-MOTOR

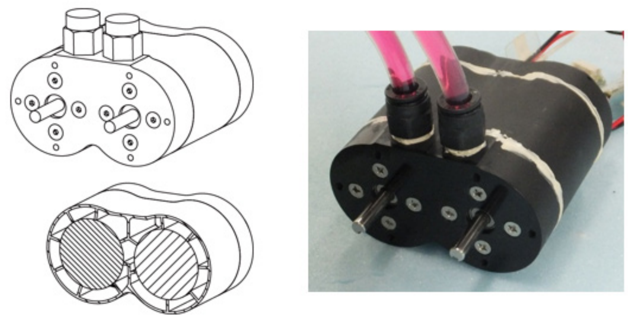

Fig. 4. The design of double motor unit

In this section, we describe a water-cooled double motor system. Some researches improve the joint torque by double motor [9][10]. The feature of our research is water-cooled system. Fig.4 shows water-cooled unit's appearance. The unit is sealed and coupled to the motor by sealing adhesive, and the inside is separated into 14 blocks where water is circulated. That's why motors are cooled efficiently without puddle layer. Another feature is the driving system of double motor. One motor is position controlled, and another motor is current controlled, which means current same as position controlled motor's one flows. This performs torque assist to the position control motor and enable double motor to prevent an increase in the internal force which occurs when two motors are position controlled.

III. DESIGN AND DEVELOPMENT OF LIFE-SIZE HUMANOID ROBOT WITH HIGH OUTPUT MOTOR DRIVING SYSTEM

We design and developed the life-size humanoid The appearance and specification was posted to Fig.1 and Table I . This humanoid's height is 180.8[cm], body weight is 90[kg], Total D.O.F. is 32, which include the head's 2 D.O.F. waist's 2 D.O.F., arm's 8 D.O.F., leg's 6 D.O.F.. The head, waist, head use high-output 2-axis unit above. This humanoid needs 2[l] coolant water which is circulated in the body. All motor drivers and knee and hip motor are water-cooled. Power source is external 13[F] capacitor, which is equivalent to 41.6[kWs] driven in 80[V]. We will describe the detail of the design of each arm and leg in the following section.

A. DEVELOPMENT Of ARM LINK WITH HIGH-OUTPUT 2-AXIS UNITS

In this section, we describe the design of high-output humanoid arm. Fig.5 shows the appearance of the high-output arm with high-output shaft drive system described above. The weight is 9.2[kg]. The link length between joints is 300[mm].

The point of the design of this arm is hand reachable area (reachability). When the reachability in front is wide,

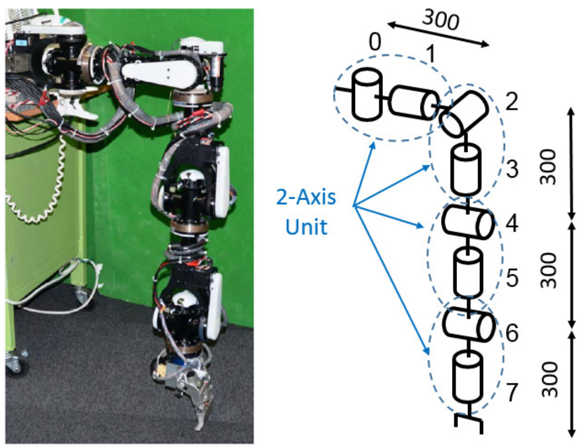

Fig. 5. Humanoid arm developed with four 2-axis unit using high-output motor driver

Table II
RANGE OF MOTION'S COMPERISION OF HRP2 AND DEVELOPED ARM

	Range of Motion [deg]	
Joint No.	Developed Arm	HRP2[1]
0	-135 to 135	no existence
1	-180 to 180	-180 to 60
2	-135 to 135	-95 to 10
3	-180 to 180	-90 to 90
4	-135 to 135	-135 to 0
5	-180 to 180	-90 to 90
6	-135 to 135	-95 to 10
7	-180 to 180	no existence

Humanoids can manipulate the objects on the desk without moving their body too much. In addition, the wide reachability in front enable humanoids to work easily with double arm. In particular, when they manipulate heavy loads, they are required to use double arm and perform the highest output. This arm is 8 D.O.F., and has an additional chest yaw joint to HRP2-JSK's 7 D.O.F. arm[11], which enable the arm to move widely to front area. Table II shows this arm's range of motion compared with HRP2. For simplicity of design and low cost, this 8 D.O.F. arm is developed with four 2-axis joint units

B. DEVELOPMENT OF LEG LINK WITH WATER COOLED DOUBLE MOTOR

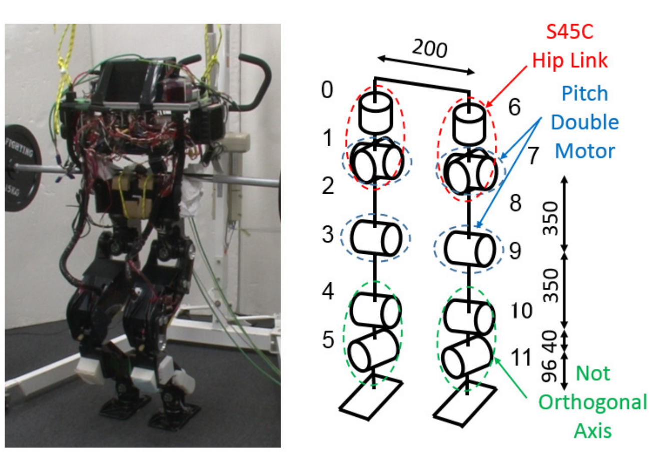

Fig. 6. Humanoid leg with water cooling double motor joint using high-output motor driver

Table III
RANGE OF MOTION'S COMPERISION OF HRP2 AND DEVELOPED LEG

	Range of Motion [deg]	
Joint No.	Developed Leg	HRP2[1]
0,6	-60 to 60	-45 to 30
1,7	-45 to 30	-35 to 20
2,8	-120 to 45	-125 to 42
3,9	0 to 150	-2 to 150
4,10	-90 to 90	-75 to 42
5,11	-60 to 60	-20 to 35

In this section, the detail of high-output bipedal humanoid leg with water-cooling double motor is introduced. Fig.6 shows the appearance of this leg. The weight is 50[kg] and the D.O.F. is 12 which is same as HRP2 and HRP3-JSK-LEG. The joints are axial driven using motor and harmonic drive reducer with pulley whose reduction ratio is 240:1. The link length between joints is 350[mm] which is 50[mm] longer than HRP2 and HRP3-JSK-LEG whose link length is 300[mm]. Table III shows the leg's range of motion compared with HRP2 and that the leg has wide range of motion. For wide angle range of motion, ankle pitch joint and ankle roll joint is not orthogonal axis whereas HRP2's ankle joint is orthogonal.

This leg is designed in the basis of the knowledge of humanoid walking from HRP3-JSK-LEG. The arrival point of the leg's tip is important for walking motion and this is largely related hip joint stiffness. The little modification of hip joint can lead to large error of the leg's reached point. So the hip link and joint are S45C which is SC steel with high stiffness, and other links and joints are A7075 which is extra super duralumin. In order to make the whole leg light and high stiffness, each link is made up of integrally machining. Because hip and knee joints require the large torque for controlling posture, these joints use larger harmonic drive reducer than other joints. This harmonic has ratcheting torque limit. In particular, these pitch joint use water-cooled double motor in order to perform high static output. Hip roll joint uses air-cooled motor now, so changing this motor to water-cooled motor enables this joint to perform higher static output. In life support action, the humanoid body and links contact with external environment. so the motors and electronic boards are placed inside of the link.

IV. THE PERFORMANCE EXPERIMENT BY DEVELOPED HUMANOID

In order to verify the high performance of developed arm and leg above, With developed arm and leg, we demonstrate some heavy lift operations. to show the arm's large output and high velocity. The detail is below.

A. THE HEAVY LIFT OPERATION WHICH SHOWS LARGE OUTPUT

In this experiment, we describe this arm's heavy lift operation which conforms its large output. Fig.7 shows the experiment. The experimental conditions is as follows. The 32.5[kg] heavy weight is attached to the arm tip and the arm lift up to 90[cm] high in 8[s]. Fig.8 describes each joint's motor current in this experiment. The max current is

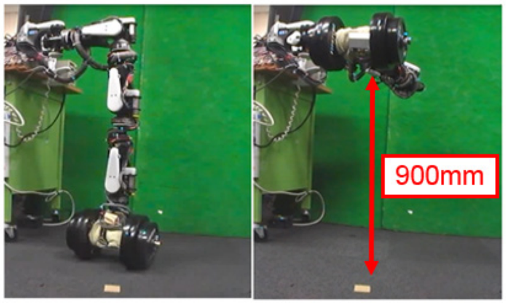

Fig. 7. 32.5kg Weight lifting experiment by developed humanoid arm

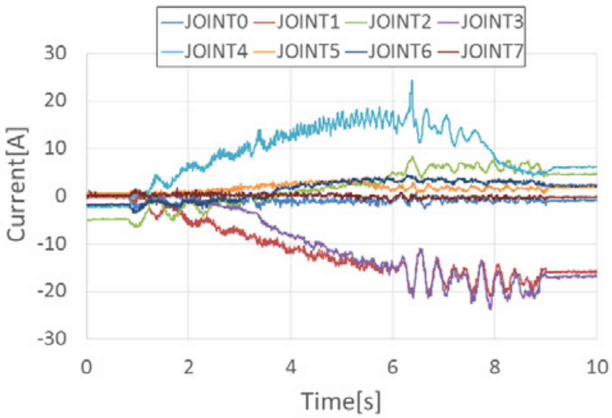

Fig. 8. Each joints' current value in weight lifting experiment

24.5[A] in the joint 4. Hence, the max torque is 158[Nm] calculated by this current and motor driving voltage 80[V]. Joint 1 and 3 performed as same torque as joint 4. This experiment shows that this arm can lift weight equivalent of the human body weight 65[kg] with double-arm. Ohmura et al. enable a bipedal humanoid to pull 66[kg] human doll closer based on load distribution by his arms' touch sensor [3]. The developed arm can perform as same high output as this humanoid by joint output.

B. THROWING LIGHT BALL EXPERIMENT BASED ON HIGH JOINT VELOCITY

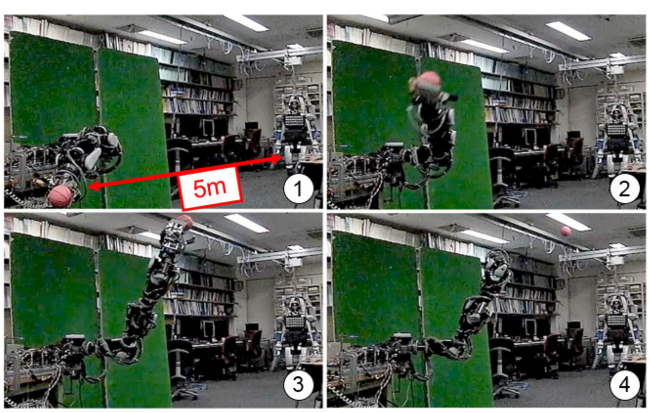

Fig. 9. Throwing ball experiment in max angle velocity 250deg/s by developed humanoid arm

In this section, we illustrate the throwing light ball operation which shows high joint velocity. Fig.9 shows how to throw the ball from a stationary state of the experiment In

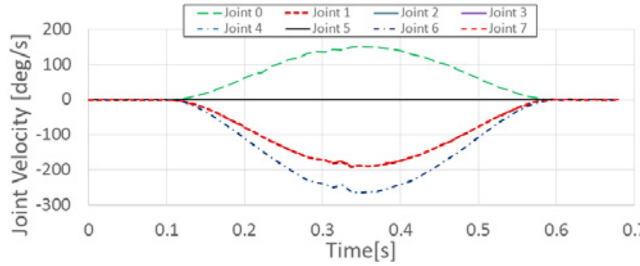

Fig. 10. Each joints' velocity value in throwing ball experiment

this experiment, each joint moves to a goal and stop quickly and the ball is removed from the tip of the arm. As a result, the ball reached about 5[m] front. Fig.10 indicates each joint velocity. This experiment shows that the max joint velocity is 263[deg/s] in joint 6. The motor voltage is 48[V], so when the voltage is 80[V] the joints can move 500[deg/s] which is calculated from motor spec. HRP2's same joint can move up to 264[deg/s] in the specification, so the developed arm took a speed equal to this maximum value.

C. THE TEMPERATURE COMPARISON EXPERIMENT OF WATER-COOLED DOUBLE MOTOR

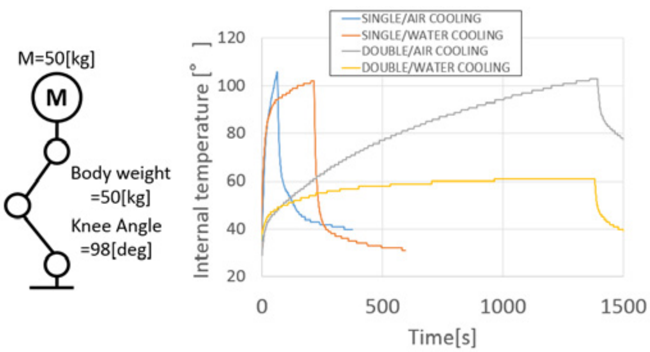

Fig. 11. Change of motor temperature in each situation by humanoid leg with 50kg weight

In this section, we conducted the experiment that indicates high static torque of water-cooled double motor. In this experiment, we compared the temperature with air-cooled single motor, air-cooled double motor, water-cooled single motor, and water-cooled double motor by squatting experiment which is the most stressful on the knee joint. In this experiment, motor voltage is 80[V], body weight is 100[kg] with weight, knee angle is 98[deg] and we measured the time of temperature reaching about 100[°C] Fig.11 indicates the experimental overview and motor temperature change. Single motor, which is both air-cooled and water-cooled, reach 100[°C] instantly. Air-cooled double motor keep up as a while, but it was also not to reach the temperature equilibrium state and it reached 100[°C] in the end. These results shows that 100[kg] humanoid always require water-cooled double motor when it operates.

D. BENDING AND STRETCHING WITH 100KG HEAVY WEIGHT EXPERIMENT BY DEVELOPED LEG

In this section, bending and stretching with heavy weight experiment is conducted by developed leg. Fig.12 shows

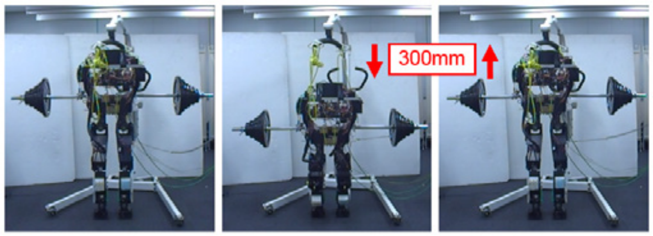

Fig. 12. Bending and stretching experiment by developed leg with 100kg weight

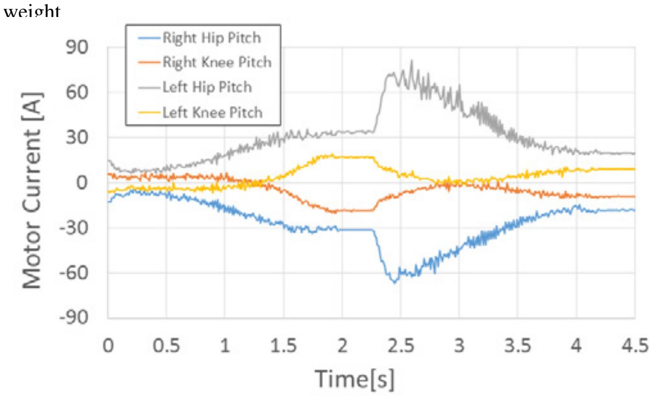

Fig. 13. Change of motor current in bending experiment

bending from the high position and stretching from the low position of the experiment. In this experiment, motor voltage is 80[V], 100[kg] weight is on the upper body and body weight is 150[kg], and the leg bends and stretches 300[mm] around 98[deg] knee angle at 4[s]. Fig.13 indicates the hip and knee joints' motor current change. The knee's max current value is 82[A] to double motor. Urata et al. demonstrated the 62.5[kg] heavy weight lifting experiment by water-cooled single motor with one foot[6]. So water-cooled double motor and two foot can lift 250[kg] weight but the leg can't lift more than 100[kg] because of harmonic's performance limit and torque limit of pulleys and belts of harmonic gears.

E. STEPPING WITH 100KG HEAVY WEIGHT EXPERIMENT BY DEVELOPED LEG

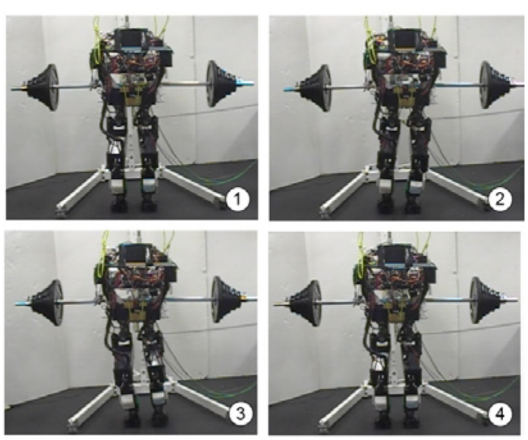

Fig. 14. Stepping experiment by developed leg with 100kg weight

We demonstrated stepping experiment with heavy weight on upper body. Fig.14 show the experiment. In this experiment, 100[kg] weight is put on the upper body, knee angle is 98[deg], the leg moved the center of gravity 50[mm] to left and right at 2.8[s], and it stepped by 2[cm]. Fig.15 and Fig.16 shows the floor reactions, motor current, and internal motor temperature at hip roll, knee, and ankle pitch joints which applied a load of stepping. In this experiment, C.O.G. leans front side and large torque is required at ankle joints. This is considered to improve by the implementation of the better posture stabilizer. The most heavy load occur at the weight retention in one foot. The max current is knee's 87.6[A] and hip roll's 34.8[A] at that time.

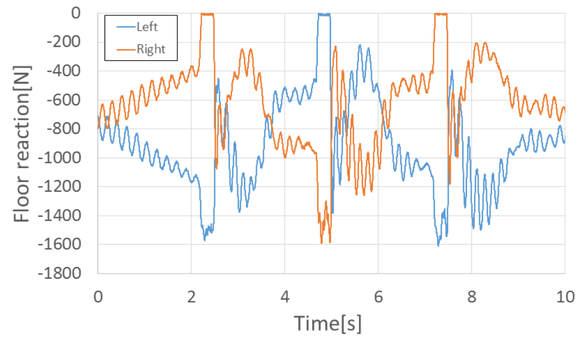

Fig. 15. Change of floor reaction force in stepping experiment

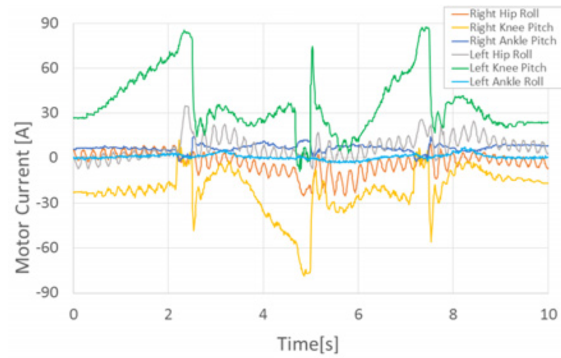

Fig. 16. Change of motor current in stepping experiment

HUBO FX-1 at KAIST[12], WL-16RV by Hashimoto et al.[13] are cited as an example in which the bipedal humanoid leg which can hold the heavy weight and walk. These can hold 100[kg], 80[kg] in the specification, and the developed robot can perform as high output as them.

V. GOING UP TO THE HIGH ALTITUDE EXPERIMENT BY DEVELOPED HUMANOID

With the developed humanoid, we demonstrated the going up to the high altitude experiment, which is one of the high load operation using whole body. Fig.17 ,Fig.18 shows the experiment appearance and the results. In this experiment, the humanoid puts his hands on handrail of 880[mm] height and goes up to 410[mm] stair which is difficult because it is longer than leg link length 350[mm]. First, humanoid puts on right foot on the stair (Fig.18 (a),(b)), after that, he raises the left root (Fig.18 (c),(d)) with load balancing to arm. The motion is generated in advance by ZMP position control in consideration the hand reaction force. In this experiment, hand reaction force is set up 200[N].

Fig.18 shows hand and foot reaction forces and motor current of elbow, knee, and hip joints which require high

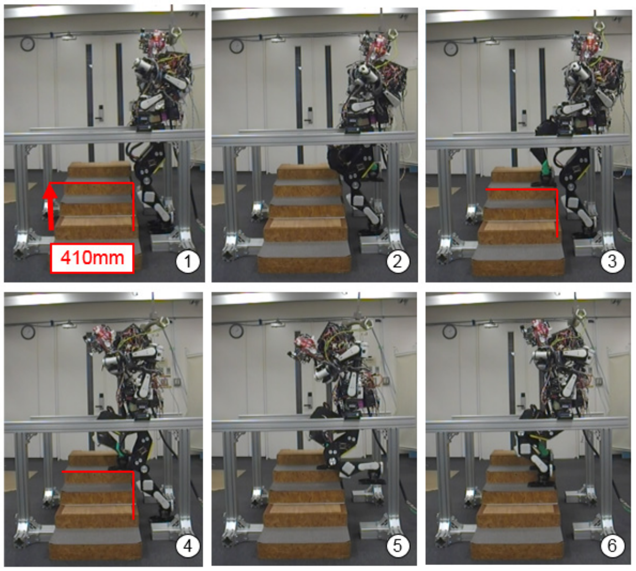

Fig. 17. Stepping the stool in the height of 410mm by developed humanoid

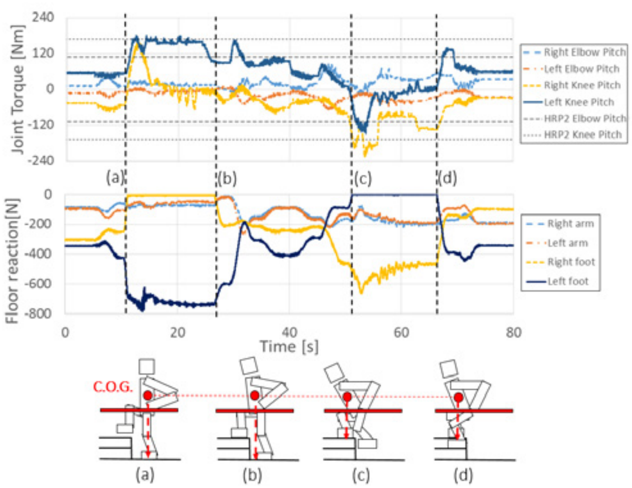

Fig. 18. Outline of stepping the stool experiment, motor current graph and floor reaction at each arms and legs

output. In this action, support leg require high output. In particular, when right foot raises the left foot (c), right knee joint performed 226[Nm] which is calculated by motor current 37[A], motor's calculation number 20.5[mNm/A], and reduction ratio 240:1. This torque is higher than HRP2's max one. This result indicates developed humanoid's efficiency. In addition, each tip of arms apply 100 to 200[N] force constantly. and this shows arms and legs' load balancing. Elbow joint performed 59[Nm] and max elbow's performance is 84[Nm]. This experiment shows the high output of the whole body and the physical performance in order to go up 410[mm] high using whole body.

VI. CONCLUSION

In this paper, we described the necessity of high output whole body for heavy load action to humanoid in order to help humans in daily life. We designed and developed humanoid arms, legs, and whole body with Urata's high output water-cooled motor driver.

The developed arm is characterized with wide reachability and 2axis joint drive unit. This arm can lift up 32.5[kg] weight and throw a ball by 263[deg/s] in joint velocity. The developed leg is characterized with the mechanical structure and water-cooled double motor. This leg can stretch and step with 100[kg] weight. Then the developed life-size humanoid with these arms and legs can perform high output in whole body and go a step elevation of 410[mm] These results can help consider humanoid's body spec at the point of current, torque, gear ratio, and so on.

In the future, we will demonstrate the high-load operation in static such as slowly lifting the weight. We will also demonstrate the dynamic movement based on instant high velocity.

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