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Development of Hydraulic Tough Motors with High Power Density and their Application to a 7-axis Robotic Arm

Morizo Hemmi[1], Ryusuke Morita[1], Yoshiharu Hirota[1], Kiyoshi Inoue[1], Hiroyuki Nabae[1], Gen Endo[1], and Koichi Suzumori[1]

Abstract— **A combination of electric motors and speed reducers are widely used as robot actuators. However, owing to problems such as low impact resistance and poor backdrivability, it is hard to use robots in actual disaster environments. Hydraulic actuators used in construction machines are not only applicable to such environments, but they also have good force density and power density. However, most conventional actuators are large, heavy, and have poor controllability and it is difficult to apply these to robots. In this research, we developed two actuators (a semi-rotary motor and an axial piston motor) with the aim of improving miniaturization and reduce weight for use in robots and evaluated their characteristics. The developed semi-rotary motor utilizes pure titanium and a hollow shaft form. They contributed to weight reduction and facilitated hydraulic robot composing method. The developed axial piston motor is a combination of a remodeled off-the-shelf motor and a special tooth-type planetary gear reducer that is expected to have high backdrivability. Both the actuators can bear high input pressures (35 MPa) and equip servo valve, absolute encoder, and pressure sensors directly to enhance their applicability to robots. The semi-rotary motor (high output, medium output) and axial piston motor (medium output, small output) achieved T/M (torque / mass) ratios of approximately 88.5 [Nm/kg] and 105.2 [Nm/kg], respectively, which are 5.6 times and 8.2 times greater than that of conventional oil hydraulic motors. In the evaluation test, we confirmed the possibility of estimating the torque by using the pressure sensors and found that it is possible with an accuracy of approximately ± 13% of the rated torque for the high-output semi-rotary motor. In addition, as a prototype of a hydraulic legged robot, we developed a robot arm with seven degrees of freedom that is highly compatible with the four-limb electrically - actuated robot, WAREC-1, for use in disasters. WAREC-1 was mainly developed at Waseda University. The length of the developed robot arm is 1.2 m, which is similar to that of WAREC-1. The mass of the robot is 56 kg, which is heavier than WAREC – 1; however, the joint torques are equal or greater than those of WAREC-1. With respect to the movable range, it was able to be equal to or more than 214 degrees with WAREC-1 by using hollow shaft actuators and swivel joints. The power density and the backdrive torque ratio (backdrive torque / rated torque) of the developed actuators are 5.9 times higher and 1/26 smaller than those of the actuators of WAREC-1. In the demonstration, the arm succeeded in breaking a stuck of three concrete-boards, each 30mm-thick.**

I. Introduction

Currently, many disaster response robots are mainly driven by a combination of electric motors and speed reducers. Although this driving method has advantages such as good controllability, positioning accuracy, and ease of handling, it also has disadvantages such as low impact resistance and poor back drivability mainly because of the speed reducer. These disadvantages are obstacles for application of disaster response robots at disaster sites. Hydraulic actuators used in construction machines are not only highly applicable to such environments, but they also have good force density and power density. Their application to robots will make them more agile and powerful. However, many hydraulic actuators are large, heavy, and have poor controllability, and it is difficult to construct medium / small robots with multiple degrees of freedom. In this research, we developed hydraulic actuators with the aim of reducing their size and weight, adaptability to control equipment, and applying them to robots.

The actuators are designed for application in an electric legged robot called WAREC-1 [1] developed mainly at Waseda University. WAREC-1 is a legged robot platform developed for ImPACT Tough Robotics Challenge, which is a joint collaboration between industries and university and in which this research is also participating. WAREC-1 is developed for investigating and restoring in scenarios where investigating situation and restoring under circumstances where people cannot enter after large-scale disasters. The robot consists of four limbs with seven degrees of freedom .The limbs are the same design and have wide movement range. The length of each leg is 1.1 m and weighs 33 kg. Although the robot can perform advanced tasks such as climbing ladders and moving on uneven ground, there are still problems to apply it to a real disaster environment. Especially there is anxiety that the actuators cannot bear the impact load at the time of falling and using electric tools.

HyArm of IIT [2], arms of RL - H 1 L of Ritsumeikan University [3], and HYDRA - MP [4] of KNR System are a

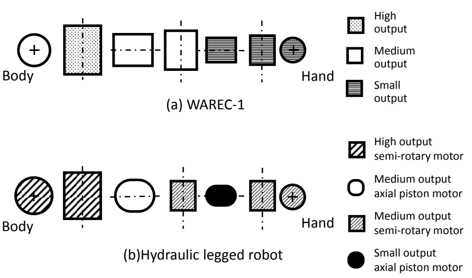

Figure 1. Configuration of one limb of WAREC-1 and the hydraulic legged robot

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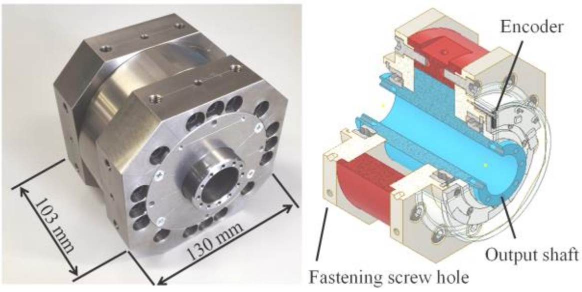

Figure 2. Picture and sectional view of medium output semi-rotary motor

Table 1. Specifications of hydraulic semi-rotary motor

	High output	Medium output
Rated pressure	21 MPa	21 MPa
Maximum pressure	35 MPa	35 MPa
Rated torque	552 Nm	249 Nm
Movable range	270°	270°
Volumetric displacement	33.8 ml/rad	12.7 ml/rad
T /M ratio (35 Mpa)	88.5 Nm/kg	63.8 Nm/kg
Absolute encoder resolution	20 bit	20 bit

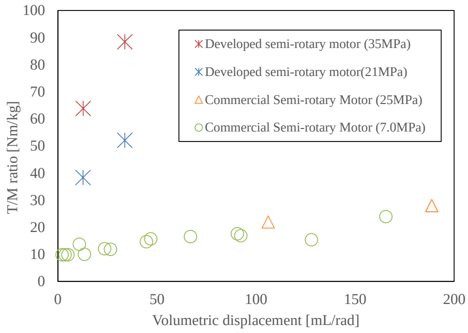

Figure 3. Comparison of T/M ratios with general semi-rotary motors

few well-known robot arms with hydraulic actuators. However, these cannot exhibit a constant torque for high degrees of freedom and wide operating angles such as WAREC - 1. For application in disaster sites, a disaster response robot must have multiple degrees of freedom, similar to that of humans. Furthermore, wider operating angles can help in performing different rescue tasks.

In this paper, we develop two hydraulic actuators (a semi-rotary motor and an axial piston motor) with the aim of improving miniaturization and reduce weight for use in robots. To achieve these objectives, we utilize pure titanium, change structure, and use special tooth form gears etc. In addition, we measure output torque in the axial constrained state and confirm the possibility of estimating the torque by using the pressure sensors. Furthermore, we develop a robot arm with seven degrees of freedom that is highly compatible with the four-limb robot, WAREC-1. Further, we compare these two robots.

II. Hydraulic Actuators for Robot

In this section, we will describe the correspondence of actuators between WAREC-1 and the hydraulic legged robot, as well as the specifications of developed hydraulic actuators. Figure 1 shows the configuration of WAREC-1 and the hydraulic legged robot. Because the maximum operating angle of each joint of WAREC-1 is 214 ° or infinite rotation, and constant torque is needed, a rotating-type hydraulic actuator is suitable for replacement. In this study, we used two

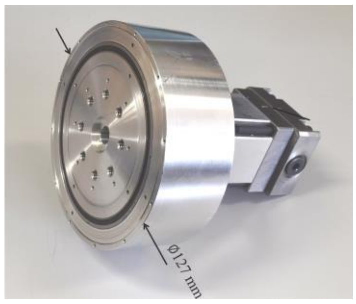

Figure 4. Small output swash plate axial piston motor

Table 2. Specifications of swash plate axial piston motor

	Medium output	Small output
Rated pressure	21 MPa	21 MPa
Maximum pressure	35 MPa	35 MPa
Rated torque	221 Nm	120 Nm
Volumetric displacement	13.8 ml/rad	7.0 ml/rad
Reduction ratio	applox. 1/54	applox.1/28
T /M ratio (35 Mpa)	105 Nm/kg	80 Nm/kg
Absolute encoder resolution	20 bit	20 bit
Incremantal encoder resolution	622,592 cpr	622,592 cpr

types of hydraulic actuators depending on the required operating angle. For joints with an operating angle within 214°, we developed hydraulic single vane semi-rotary motors that have a simple structure and low weight. Furthermore, for joints requiring more than one rotation, we developed compact swash plate axial piston motors that can obtain infinite rotation. WAREC-1 uses three types of high, medium, and small output actuators depending on the required output. In response to this, for hydraulic actuators, two types of actuators, each with different torque, are developed and set, so that the generated torque is close to or larger than the torque of each joint of WAREC - 1 when applying a pressure of 21 MPa. For a hydraulic legged robot, a pressure of 21 MPa owing to the limitation of using a servo valve. However, each actuator can be used at 35 MPa. To enhance the applicability of the robot, each actuator is equipped with a servo valve, an absolute encoder, and pressure sensors.

A. Hydraulic semi-rotary motors

High-output and medium-output hydraulic single vane semi-rotary motors were developed in cooperation with JPN. The specifications and images are shown in Table 1 and fig. 2. To achieve both lightweight and high operating pressure, we employed pure titanium for all parts, except for the output shaft. In the case of using a simply miniaturized general semi-rotary motor, there are inconvenient parts for robot applications such as fixing method of the main body, output form, piping method and the like. Therefore, the robot was designed using the method shown in fig. 2. In this system, the output shaft is hollowed and has a large diameter, and the shaft end face is directly used as the output flange. This not only facilitates fixation but also allows for the omission of flange parts, reducing size and weight, and using hollow diameters for piping. Moreover, the bearings used for the output shaft has sufficient capacity to support the robot's frames. Because of these devices, it is possible to develop hydraulic robots with multiple degrees of freedom by merely connecting each actuator. The T / M ratio, which is the ratio of the rated torque to the weight of the robot, of the high-output semi-rotary motor and medium-output semi-rotary motor were 5.6 times

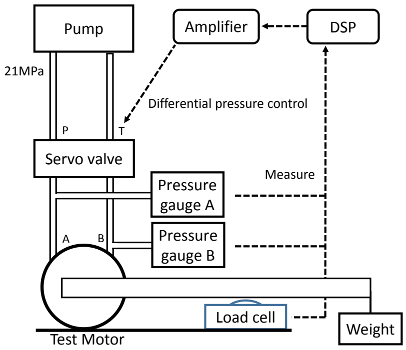

Figure 5. Schematic diagram of experiment


Figure.6 Experimental apparatus

and 4.7 times higher than those of commercially available single vane semi-rotary motors (fig.3) [5][6].

B. Swash plate axial piston motor

The medium- and small-output swash plate axial piston motors with speed reducers were developed in cooperation with KYB and Takako. The specifications and images are shown in table 2 and fig.4. The axial piston motors are made by remodeling Takako's off-the-shelf products to make it smaller, lighter, have a higher revolution, and operate at a higher operating pressure. The speed reducers are planetary gear reducers manufactured by KYB based on the tooth form developed at Yokohama National University, and it has lower friction than conventional gear reducers. Although speed reducers act as obstacles to the shock resistance of actuators, we assumed it would be almost no problems in this application, because it is possible to lower the speed reduction ratio as the original torque is high. In addition, they are planetary gear speed reducers with relatively high back drivability and are used for the arm's twisting direction, which does not receive large or frequent shock load. The T / M ratio of the small-output motor and medium-output motor was 6.9 times higher and 8.2 time higher, respectively, compared with those of commercially available swash plate axial piston motors of similar sizes [7].

III. Evaluation Test

In this experiment, we measured the maximum torque of the actuator and the relationship between the applied pressure and generated torque. A schematic diagram of the experiment is shown in Fig. 5, and the experimental apparatus used is shown in Fig. 6. The thrust of the arm attached to the motor is measured with a load cell (LUK - A - 20 kN, Kyowa Electronic Instruments). Furthermore, a weight is attached to the tip of the arm and the experiment is performed with the compressive

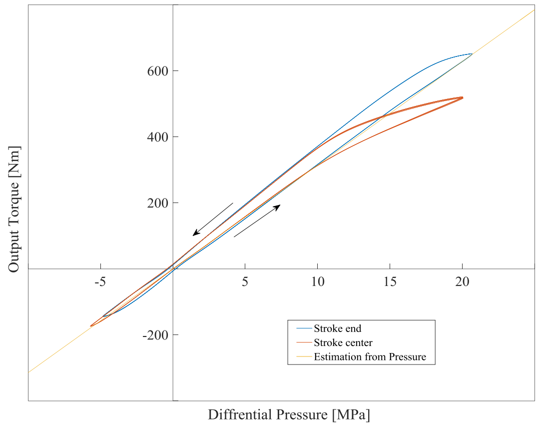

Figure.7 Relationship between differential pressure and output torque of high output semi-rotary motor

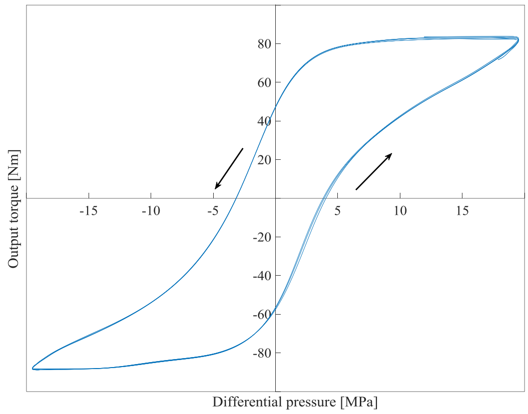

Figure.8 Relationship between differential pressure and output torque of small output axial piston motor

force always applied to the load cell to ensure that the measurement is taken in the vicinity of a differential pressure of 0 MPa. The difference in the pressure applied to each actuator port was controlled by a servo valve (HS 210, PSC), valve driver (CA250-003-001, PSC), pressure sensors (NAT 400.0 A, Trafag), and Digital Signal Processor (DSP; DS 1104, dSPACE). The command voltage is dithered by the function of the valve driver. The pressure command is performed with a sinusoidal wave of 0.05 Hz, and three cycles are measured and processed with a 1 Hz low-pass Butterworth filter. The controlled pressure is limited within a range at which the weight does not float.

For the semi-rotary motor, the measurements were taken at the stroke end and the center. The result of the high output semi-rotary motor is shown in Fig. 7. The hysteresis is relatively small as a result of the stroke end, while the torque is 651 Nm at the maximum differential pressure of 20.7 MPa; this is larger than the rated torque of 552 Nm. On the other hand, although the hysteresis is small even in the vicinity of the center of the stroke, the rise in the torque generated is gentle when the differential pressure is 11 MPa or greater. Furthermore, the torque generated at the maximum differential pressure of 20.1 MPa is 518 Nm, which is lower than the rated torque. This is probably due to the fact that the developed semi-rotary motor is a single vane type; thus, when the vane is at the center of the stroke, the internal pressure increases the load on the output shaft bearing. When the sliding resistance

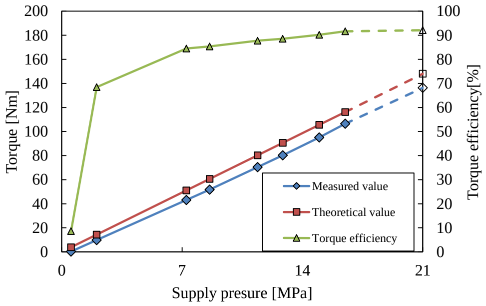

Figure.9 Measured torque while continuous rotation

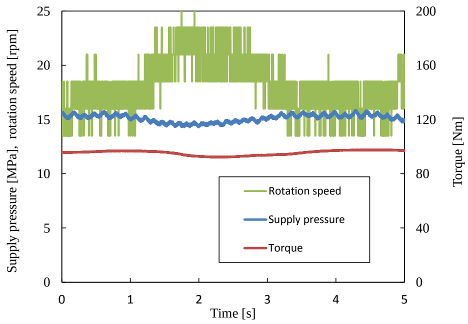

Figure 10. Time history data of torque measurement

is ignored, the torque T [N] generated by the semi-rotary motors is calculated by using the differential pressure P_{diff} [MPa], the outer and inner diameter of vane R and r [m], the vane length l [m], and the torque efficiency η.

$$T = 1/2\ \eta\ l\ (R^2 - r^2)\ P_{diff} \tag{1}$$

When the vane is in the vicinity of the stroke end and even in the center of the stroke when the differential pressure is within 11 MPa, the force generated can be estimated within ±22 Nm (±4% of the rated torque) at 0 MPa, ±52Nm (±9%) at 11MPa, and ±71 Nm (±13%) at 21 MPa using the differential pressure from the pressure sensor and the value η = 93% from the experimental result. It is considered possible to estimate output torque even for the differential pressure of about 11 MPa or more at the center of the stroke, if a correction is made by using the vane position

For the axial piston motors, the measurement was taken at one position. The results from the small output axial piston motor are shown in Fig. 8, and it shows that large hysteresis occurs. In principle, it is possible to estimate the torque generated from the pressure applied to the internal piston, even in piston motors; however, it is difficult to estimate the force from the pressure for this motor. In addition, the torque generated is 87 Nm at a differential pressure of 19.3 MPa, meaning that even if a generated torque of 21 MPa is obtained by extrapolation, it is around 90 Nm; this does not reach the designed value of 120 Nm. However, in the test conducted by the manufacturer (Fig. 9), the motor is predicted to achieve design values, when it is continuously rotated and loaded, if the experiments are extrapolated up to 16 MPa. Figure 8 also shows one of the time history data series at this time. As shown in Fig. 10, since the torque fluctuation during continuous rotation is small, it is considered that sufficient torque is obtained during continuous rotation and thus estimating the torque from the pressure is also possible. The piston motor is applied at the twist axis of the wrist and the shoulder, and the

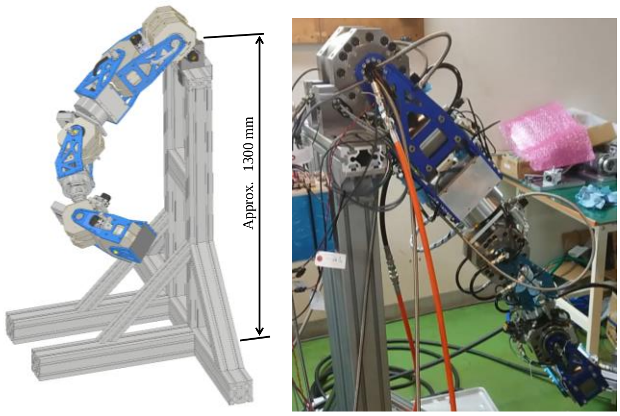

Figure 11. Hydraulic legged robot one limb model

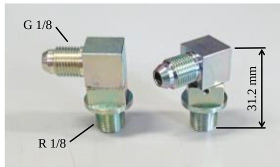

Figure 12. 1/8in size swivel joint

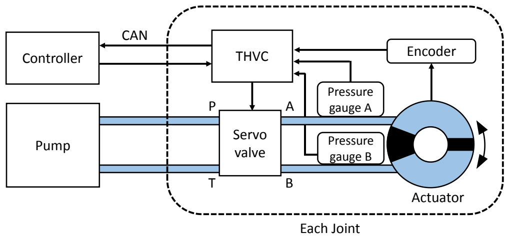

Figure 13. Control system of Hydraulic legged robot

application in which force control is required in this shaft is when the valve in the plant opens and closes. In such cases, this problem can be avoided by bringing the joint into contact with the handle while rotating it in advance, or by using the value of the encoder for control.

IV. Development of Hydraulic Legged Robot Single Limb Model

The hydraulic legged robot single limb model was developed using the hydraulic actuator described above. Figure 11 shows the provisionally assembled main body and a CAD image of the same.

A. Hydraulic and joint piping design

The hydraulic pressure is supplied externally to the one limb model and controlled by a servo valve attached directly to the actuator of each joint. When the entire hydraulic legged robot is configured, a pump and its power source will also be required, but for the experiment we used a hydraulic source with sufficient capacity without developing such a pump.

The joints have a wide movable range, and therefore, if hydraulic piping is employed for the actuators at the tip, the exposure hosing will increase. Therefore, a method of absorbing rotations by winding a hydraulic the hose around the

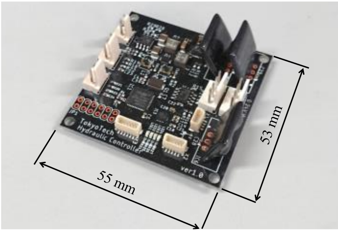

Figure 14. Titech Hydraulic Valve Controller

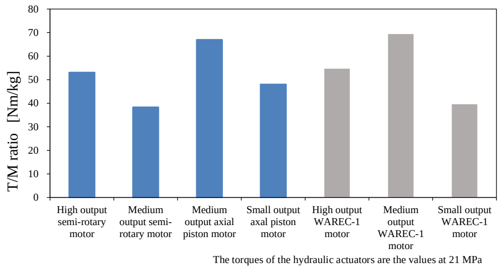

Figure 15. Comparison of T/M ratio

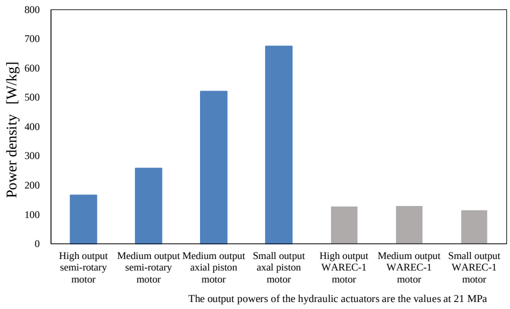

Figure 16. Comparison of power density

drive shaft is considered for wrist and shoulder twisting axes, where more than two rotations are required. For other joints, a 1/8-inch small swivel joint, developed for multi-finger tough robot hand [8], is used (Fig. 12). In the provisionally assembled state, the piping hoses are more exposed to the outside of the arm because the twisting axis is simplified and the specified length hydraulic hose is used. In the future, we plan to install a twisting axis, covers, and replace the hoses with the steel pipes.

B. Control system

Fig. 13 shows a schematic of a hydraulic-legged robot single-limb model control system. The servo valve (HS 210, PSC), servo valve control board (THVC: Titech Hydraulic Valve Controller, Fig. 14), magnetic encoder (AksIM MHA 8, RLS), pressure gauge (NAT 400.0 A, Trafag) are placed near the actuators. The THVC is a servo valve control and drive circuit board developed in our laboratory. The THVC is more compact and multifunctional than the conventional servo valve drive circuit. The control of each joint is performed by THVC, and the entire arm is controlled by the controller connected by CAN. Electric parts other than the control board are waterproof; thus, the entire arm can be made waterproof by sealing the board and connector.

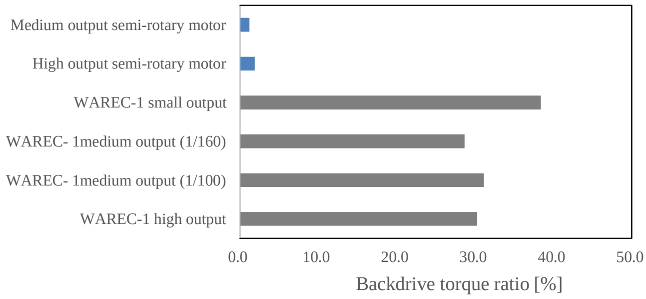

Figure 17. Comparison of backdrive torque ratio

Table 3. Operating range of developed single limb model and WAREC-1

	Body →						Tip
	Shoulder			Elbow	Wrist		
	Roll	Pitch	Yaw	Pitch	Yaw	Pitch	Roll
WAREC-1	-57 – 150	±107	±360	-38 – 163	±360	±93	±106
Hydraulic legged robot	-80 – 160	±109	±360	-41 – 165	±360	-72 – 117	-95 – 105

C. Comparison to WAREC-1

Table 3 shows the operating range of the developed single-limb model and WAREC-1. The ranges are set to be the same or larger than that for WAREC - 1; however, some wrist axes are smaller than that for WAREC-1.The frame strength and rigidity requirements are unified with WAREC-1; however, the weight of the main body for the single-limb model is about 56 kg, and its total length is 1.2 m, which is larger than the WAREC–1 by about 33 kg and 1.1 m. This weight increase is affected by reducing the actuator type to be developed, and by replacing actuators with an output larger than that of the original and the fact that the weight of the semi-rotary motor cannot be reduced considerably. Although it can be made lighter using hydraulic cylinders, the movable range and compatibility between WAREC-1 has higher priority. Fig. 15 shows the T / M ratio of the hydraulic actuator developed, and the actuator used in WAREC-1; Fig. 16 shows their power density. With regard to the power density, the mass of the hydraulic actuators is the sum of the main body, port block, and servo valve; the output power is the product of the maximum output of the servo valve and the efficiency of the actuator. In terms of the T / M ratio, the developed actuator has almost the same or worse value than that for the WAREC-1; however, the power density is improved with all actuators. In Fig. 17, the actuators of WAREC-1 and the developed actuator were compared with the back drive torque ratio determined by the ratio of the torque required for the back-drive and rated torque. The back drive torques of the actuators of WAREC-1 are obtained from the reference [9] as the sum of the back-drive torque of the speed reducer and the resistance torque of the oil seal, and the seal bearing multiplied by the reduction ratio. The resistance of the semi-rotary motor is the minimum operating pressure provided by the manufacturer. For the piston motor, it was not calculated because the minimum operating pressure was not measured. From the figure, the semi-rotary motors achieve back-drive torque ratios of 1.2 % (medium output) and 1.9 %(high output), which are less than 1/20 of that of the WAREC-1

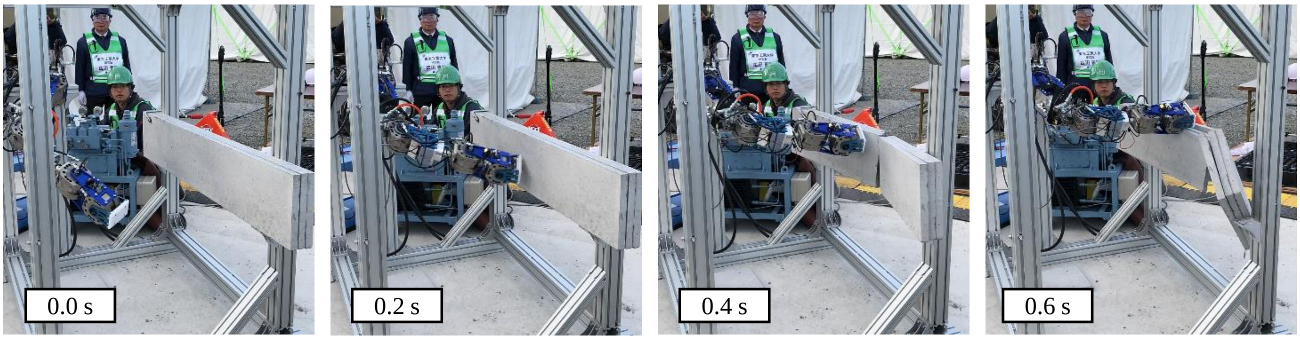

Figure 18. Pictures of concrete-board breaking demonstration

motor. Further, when using frictional resistance at 21 MPa obtained from the force measurement experiment in the previous chapter, the ratio for the high-power fluctuation motor is 12.9%. Although the resistance obtained from the force measurement is larger than the minimum operating pressure in all ranges, the ratio is lower than the ratio of WAREC-1, and it is predicted that a good back drivability will be exhibited even when high pressure is applied.

Furthermore, we conducted a concrete-board breaking demonstration as a motion requiring force, speed, and impact resistance. The pictures of the demonstration are shown in Fig. 18 and the video is uploaded on YouTube [10]. In this motion, the tip of the arm is directly struck to a stack of three concrete-boards. Each concrete-board has 1720 mm length, 297 mm height, and 30 mm thick. No damage was seen in the arm after this operation. We will record and evaluate data in the future.

V. Conclusion

Hydraulic semi-rotary motors and axial piston motors for robots were developed and evaluation experiments were carried out. The proposed motors achieved about 5.6 times and 8.2 times higher T/M ratios than those for typical conventional hydraulic motors. These actuators also achieved higher power densities and lower back-drive torque ratios than WAREC-1's actuators. In addition, we designed the hydraulic-legged robot single-limb model, which is highly compatible with WAREC-1, using the developed components. The power density and the backdrive torque ratio (backdrive torque / rated torque) of the developed actuators are 5.9 times higher and 1/26 smaller than those of the actuators of WAREC-1. In the demonstration, the arm succeeded in breaking a stuck of three concrete-boards, each 30mm-thick.

In the future, we install covers and replace the hoses with the steel pipes. In terms of control, we measure controllability such as positioning accuracy and low speed operation and apply torque control using the pressure sensors. Further, we record and evaluate data of concrete-board breaking. And we plan to other operational tests that utilizes developed hydraulic actuators' advantages for example, handle plant valve, and backdrive by human.

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References

[1] Kenji Hashimoto, Shunsuke Kimura, Nobuaki Sakai, Shinya Hamamoto, Ayanori Koizumi, Xiao Sun,Takashi Matsuzawa, Tomotaka Teramachi, Yuki Yoshida, Asaki Imai, Kengo Kumagai,Takanobu Matsubara, Koki Yamaguchi, Gan Ma, Atsuo Takanishi: "WAREC-1 - A Four-Limbed Robot Having High Locomotion Ability with Versatility in Loco-motion Styles", IEEE International Symposium on Safety, Security and Rescue Robotics, 2017

[2] Bilal Ur rehman, Michele Focchi, Claudio Semini:" Design of a Hydraulically Actuated Arm for a Quadruped Robot" , Proceedings of the International Conference on Climbing and Walking Robots, 2015.

[3] Kensuke Izawa, Sang-Ho Hyon,:" Design of Arm for a Hydraulic Humanoid Robot" , ROBOMECH 2014 , 1A1-I01, 2014 (in Japanese)

[4] KNR Systems HYDRA-MP http://www.knrsys.com/portfolio/hydraulic-based-robot-2

[5] parker HRN series http://www.parker.com/literature/Literature%20Files/actuator/Cat/english/1800HRNC.pdf

[6] Kyoji Co.,Ltd. Tricolour product catalog (in Japanese)

[7] Bosch rextoth A10FM series https://www.boschrexroth.com/en/us/products/product-groups/goto-products/goto-hydraulics/motors/a10fm/index

[8] Tohru Ide, Hiroyuki Nabae, Yoshiharu Hirota, Akina Yamamoto, Koichi Suzumori:" Development of compact low sliding hydraulic actuator and its application to multi-finger tough robot hand "The 35th Annual Conference of THE ROBOTICS SOCIETY OF JAPAN, 2017 (in Japanese)

[9] Shunsuke Kimura, Nobuaki Sakai, Kenji Hashimoto, Xiao Sun, Ayanori Koizumi, Shinya Hamamoto, Tomotaka Teramachi, Takashi Matsuzawa, Atsuo Takanishi :" Development of a disaster response robot that can work under extreme environments (10th Report: High Output Actuator Unit with Hollow Structure) ", The 34th Annual Conference of THE ROBOTICS SOCIETY OF JAPAN, 2C2-01, 2016 (in Japanese)

[10] Suzumori Endo Robotics Laboratory, "Tough Robot Breaking a 90mm Concrete Board!" Online video. YouTube, 2018