The 2010 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 18-22, 2010, Taipei, Taiwan

Novel and Safe Linear Actuator using ER Gel

Ken'ichi Koyanagi, Yasuhiro Kakinuma, Hidenobu Anzai, Koji Sakurai, Tomoya Yamaguchi and Toru Oshima

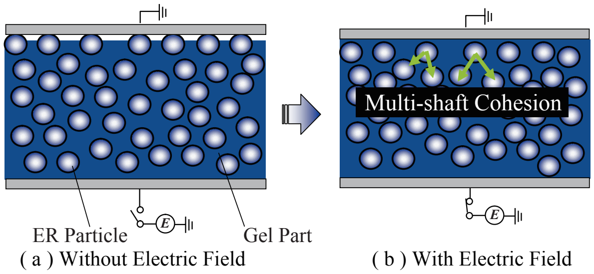
Abstract— **We aim to create a novel prototype linear actuator with new structure applying an ER (Electro-Rheological) gel, a recent functional material. The actuator will be an all-purpose actuator satisfying characteristics for human-coexistence application. Such actuators for the application need large generative force, high speed response, good controllability, high safety, low friction, backdriveability and so on. We have put emphasis on the backdriveability and safety. The actuator developed by us will contribute to create robots manipulated by human recently aggressively researched.**

I. INTRODUCTION

Power assistance, rehabilitation, surgical operation support and virtual reality are subjects of active research that involve devices coexisting and working with humans in their living space. Power-assist systems [1] can amplify the user's force and are typical examples of human-coexistence robots. It is expected they will be applied as welfare and production supports in factories. Robots are also being actively applied in rehabilitation that requires repetitive training over a long time [2]. In the medical field, there have been many proposals for systems such as support robots for surgical operations, such as da Vinci produced by Institutive Surgical, Inc. [3] and educational robots for medical treatments [4]. The field of virtual reality has produced many commercial robots that display force and touch sensations [5]. PHANToM produced by SensAble Technologies, Inc. [6] is famous for being applied in many applications. HapticMASTER produced by Moog FCS [7] is larger than PHANToM and used for applications such as design support.

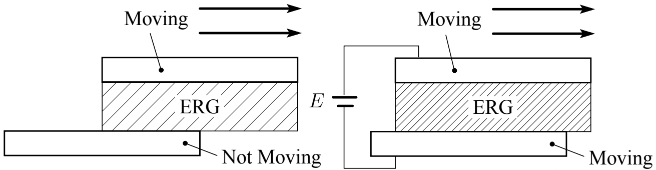
These robots are intended to be manipulated by handling their end-effectors in a relatively large working area, and thus they have requirements such as backdriveability, safety, a sufficiently large generative force, high-speed response and easy controllability. Among these, safety has been discussed by researches [8], [9]. On the other hand, a large degree of backdriveability is important for manipulation of the end points without a large effort or force. If actuators or structures fulfill the above requirements, then they can be applied to whole human-coexistence robots.

Common human movements are linear in real space despite the human body being formed of rotary joints; such as reaching, standing up, and lifting. Therefore, it is acceptable to use linear actuators in human-coexistence robots. Nevertheless, conventional linear actuators do not combine the features mentioned above.



(a) Without Electric Field (b) With Electric Field

Fig. 1. Mechanism of ER Gel Effect



(a) Without Electric Field (b) With Electric Field

Fig. 2. Image of an ER gel clutch

This study uses an electro-rheological (ER) gel, which is a new functional material, to create a linear actuator that has a novel structure that utilizes the characteristics of the gel. Koyanagi et al. presented features of the ER Gel Linear Actuator (ERGLA) [10], [11]. This paper shows the actuator as currently manufactured, and presents the basic characteristics of the actuator as investigated experimentally. The study aims to develop an all-purpose linear actuator by combining the features required of human-coexistence robots, especially safety and backdriveability discussed in the section V.

II. BASIC CHARACTERISTICS OF ER GEL

ER gels are functional materials. Dielectric polymer particles about 20 [μm] in diameter are dispersed in an insulating oil, and then a gelling agent is added. When an electric field is applied to electrodes sandwiching the ER gel, dielectric polarized particles and the gel component increase the shear stress of the surface of the ER gel several tenfold as shown in Fig. 1. ER gels are relatively young materials, being first reported in 2001 [12]. Since then, basic research on and the development of the physical and chemical characteristics of ER gels have been carried out. Recently, Kakinuma et al. developed ER gels that have large ER effects and can endure practical use [13].

K. Koyanagi, T. Yamaguchi and T. Oshima are with the Department of Intelligent Systems Design Engineering, Faculty of Engineering, Toyama Prefectural University, Kurokawa 5180, Imizu, Toyama, Japan
`koyanagi@pu-toyama.ac.jp`

Y. Kakinuma is with Faculty of Science and Technology, Keio University, 3-14-1 Hiyoshi, Kohoku, Yokohama, Japan
`kakinuma@sd.keio.ac.jp`

H. Anzai and K. Sakurai are with Fujikura Kasei Co., Ltd. 13-1,Sakurada 5-chome Washimiya-machi Kitakatsushika-Gun, Saitama, Japan
`h-anzai, k-sakurai@fkkasei.co.jp`

978-1-4244-6676-4/10/$25.00 ©2010 IEEE

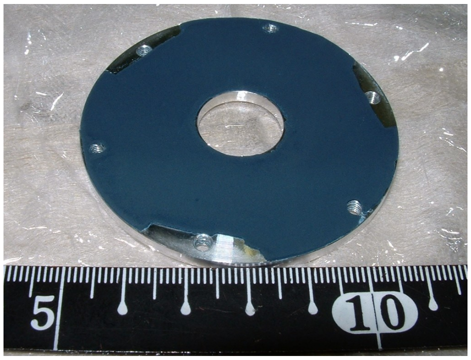


Fig. 3. Photo of an ER gel

For example, an ER gel can be applied to a clutch surface as shown in Fig. 2. While the ER gel is de-energized, the clutch input force is not transferred because of minimal shear stress. When the ER gel is energized by an electric field, the increased shear stress results in a force transfer; that is, the clutch is engaged. The magnitude of the transferred force can be controlled since the shear stress can be controlled by the magnitude of the electric field. Devices with ER gels have advantages over conventional metal friction brakes, powder clutches and other devices; for example, they do not burn out, they have good control of torque and they do not requiring sealing. The sealing is a mechanical design issue in ER and MR fluid devices. Nevertheless, devices with ER gels have scarcely been developed, except for a clamp system to hold workpieces developed by Kakinuma et al. [14].

Figure 3 shows one of the ER gels used in this study. The thickness of the gel is about 0.5 [mm]. The maximum magnitude of the electric field for the gel is less than 3.0 [kV/mm].

III. PROTOTYPE OF AN ERGLA

A. Scheme of ER Gel Linear Actuator [10]

The ERGLA we aim to develop is shown in Fig. 4. Figure 5 shows the structure of the center part. The ERGLA unit is attached to a fixed bar and connected to loads. The ERGLA unit moves on this fixed bar. The main parts of the ERGLA unit are two ER gel drums (ERGDs) including ER gels, a timing belt, guide rollers and a motor. The timing belt is tensioned and fixed on the external frames. The fixed bar is pinched by the conducting belt and guide rollers.

The inside part of the ERGD consists of the output disc engaging with the outside of the drum, the input disk connecting to the input shaft, and the ER gel as shown in Fig. 6. A sheet of ER gel is pressed on the output disk and sandwiched between the output and input disks, which stress the gel. The input shaft is rotated by the motor at a constant speed. Because the shear stress of the ER gel changes according to magnitude of the applied electric field, an arbitrary torque can be transmitted to the output of the ERGD. The advantage of this structure is that it is easy to increase the output force of the ERGLA using multiple ER gel disks in the drum.

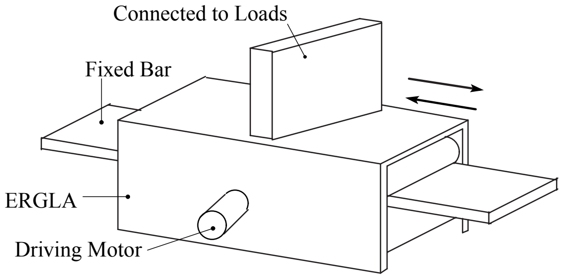


Fig. 4. Schema of the ERGLA

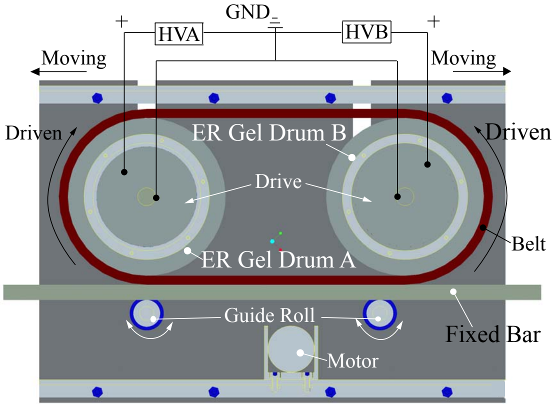


Fig. 5. Design of the ERGLA unit

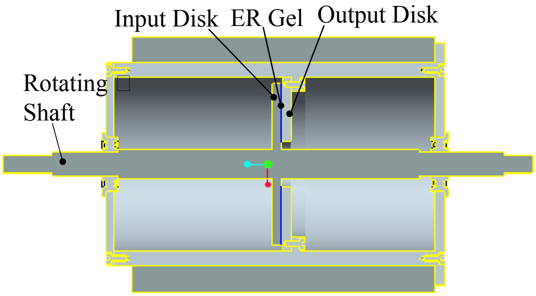


Fig. 6. Design of the ER gel drum

The ERGD input parts are rotated in opposite directions at the same rotational speed by one driving motor and reversing gears. Therefore, the ERGLA moves in different directions according to the application of the electric field as follows.

- No electric field applied: Because the shear stresses at the surfaces of the ER gels are very small, the electrodes slip each other. The torques of the input parts oriented from the motor are not transferred to output parts. Therefore, the ERGLA unit does not generate a driving force. In this case, it is easy to backdrive the ERGLA from the outside.
- An electric field applied to one ER gel drum: Since the shear stress at the surface of the drum increases with the magnitude of the electric field, the torque is transmitted to the output of the ERGD. Because the belt is fitted to the fixed bar by the guide rollers, the ERGLA unit moves along the fixed bar, and thus the ERGLA unit generates a driving force.

The moving direction of the ERGLA unit is determined

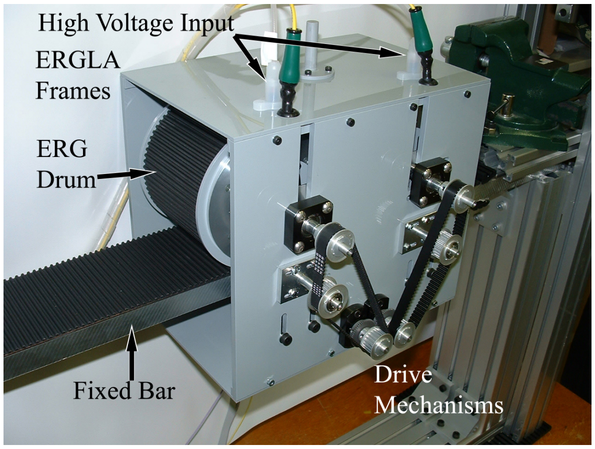


Fig. 7. Prototype ERGLA

TABLE I

DESIGN SPECIFICATIONS OF THE PROTOTYPE

	ERGD		ERGLA
Weight	1.24 [kg]	Weight	5.32 [kg]
Height	0.10 [m]	Height	0.22 [m]
Diameter	0.11 [m]	Width	0.26 [m]
		Depth	0.17 [m]
		Max. force	10 [N]

by which ERGD is energized. The generative force can be controlled by the magnitude of the electric field.

B. Prototype ERGLA [10]

A photo of the prototype ERGLA is shown in Fig. 7. The design specifications of the ERGD and ERGLA are listed in Table I. If the shear stress of the ER gel is 4.0 [kPa] with a 1.5 [kV/mm] applied electric field, the designed maximum torque of the ERGD is 0.55 [Nm] and the designed maximum force of the ERGLA is 10 [N].

While the mechanism of ER gel effects is considered as being different from that of ER fluids, a shaft set-collar is used to maintain the distance from the input disk of the ERGD to the output disk, according to a study on ER fluid actuators [15].

A timing belt is bonded to the fixed bar, and a double timing belt is used for transmission of the torque of the drum to the bar.

C. Basic Experiments for the Prototype [11]

Basic experiments for the ERGD were conducted using the test bench schematized in Fig. 8. The output torque of the ERGD was gauged while the motor rotated at a constant speed.

Figures 9 shows the results of the step response experiments for an ERGD. The step inputs of the 2.0 [kV/mm] electric field energized the ER gel at 3.0 [s]. The four responses in the figures differ in terms of the pressure on the surface of the ER gel. The pressures were able to be adjusted with weights on the input disk of the drum's shaft. Each result was averaged from raw data of ten experiment runs for the same condition.

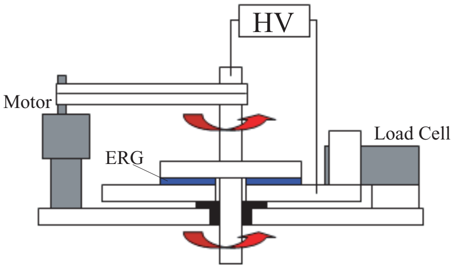


Fig. 8. Schematic diagram of the ERGD test

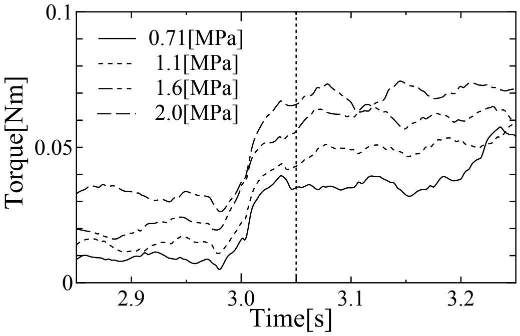


Fig. 9. Rise time of the ERGD torque

The results show that the response time of the ERGD torque was about 20–30 [ms]. It seems that the responses occurred several milliseconds before 3.0 [s]. The time difference might be due to torque ripples caused by an imbalance of the pressure on the gel. As the pressure on the surface of the ER gel increases, the torque of the ERGD before and after the application of the electric fields increases. Considering backdriveability, the pressure on the gel should be as small as possible. Nevertheless, responses became unstable when the pressure was too small. This is due to the thickness of ER gels decreasing when an electric field is applied.

Figure 10 shows the relationship between the applied electric field and the generative torque of an ERGD. The generative torque increases with the magnitude of the applied electric field. However, an effective thrust was not generated by the ERGLA in experiments owing to the instability of the generative torques of the ERGDs and the different torques for the two ERGDs.

The response of the ER gel may be acceptable for

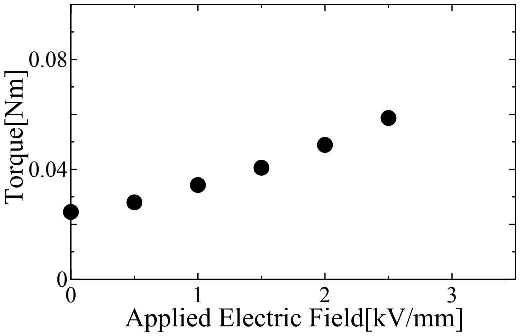


Fig. 10. Torque–electric field relation of the ERGD

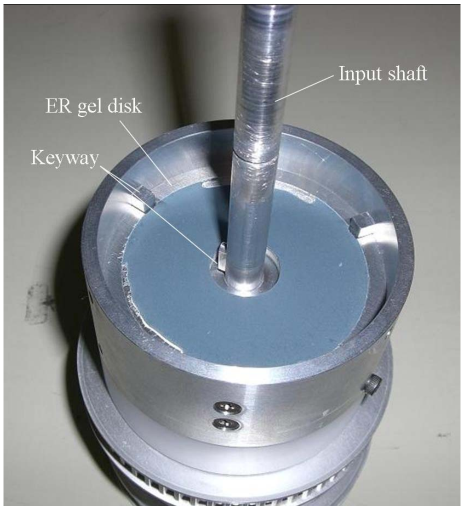


Fig. 11. Improved ER gel drum

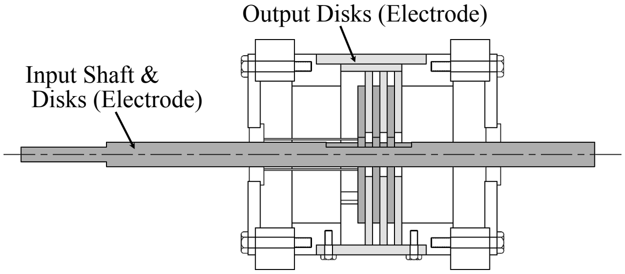


Fig. 12. Sectional view of the improved ER gel drum

mechatronics or robots like as welfare applications. However, uniformizing the pressure was an important issue.

IV. IMPROVEMENT TO THE MULTI-DISK ERGLA

The prototype ERGLA had limited stability and a small output. Therefore, we designed a new ER gel drum with more clutch disks and uniform pressure on each disk.

A. Improvement through Multiple ER Gel Disks

We investigated the increase in the torque of the ERGD as the number of clutch disks inside the ER gel drum increased. The improved multiple-disk ER gel drum is shown in Figs. 11 and 12. Clutch disks can slide in the axial direction through three-lines of key ways: input disks are on the input shaft and output disks are on the inside wall of the drum. ER gels are molded on both sides of the output disks. It was assumed that very little pressure was needed to work the ER gels because the gels were able to move in the normal stress direction.

Experiments to investigate the characteristics of the ERGD were carried out using the test bed mentioned in the previous section. Only the weight of the disks applied pressure to the ER gels (i.e., no dummy weights were used) so that an initial pressure of 80–320 [Pa] in accordance with the number of the ER gel disks was applied. A 60 [Hz] notch filter to remove noise from the power source and a 200 [Hz] software low-pass filter were introduced.

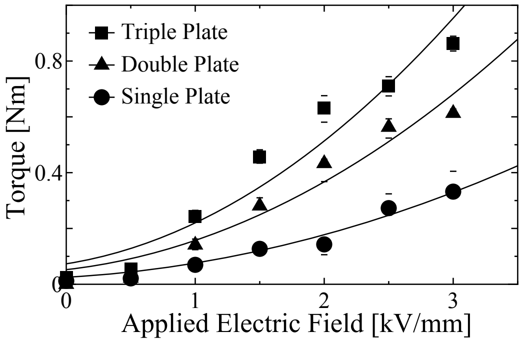


Fig. 13. ERGD torque with 1–3 gel disks

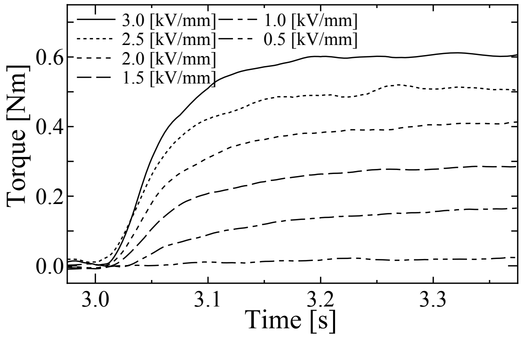


Fig. 14. Rise time of the ERGD torque with 2 gel disks

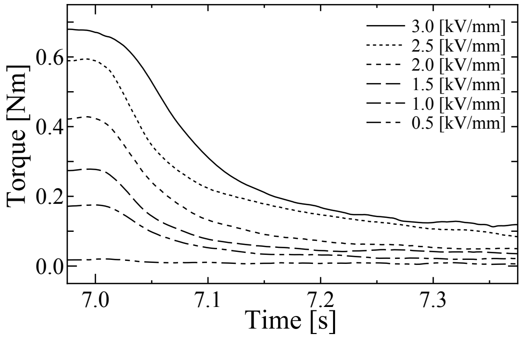


Fig. 15. Fall time of the ERGD torque with 2 gel disks

Data for the steady state after step inputs of electric fields were averaged. Means of values for 10 experiment runs are shown in Fig. 13. Curves are drawn using a quadratic approximation. The figure shows that the torque increased roughly proportionally with the number of ER gel disks. However, some variance occurred when the electric field was strong.

Fig. 14 and Fig. 15 show the results of the step response experiments for an ERGD with two ER gel disks. The ER gel was energized at 3.0 [s] and de-energized the gel at 7.0 [s]. Each result was averaged from raw data of ten experiment runs for the same condition. Nearly tenfold stable torques were generated from the ERGD against the results in Fig. 9. On the other hand, the response time was larger than 50 [ms], and much larger under smaller electric field applied. This would be because movable electrodes were not able to manage changes of the thickness of ER gels when an electric field was applied. Thus uniformizing of the pressure was still required for stabilizing and speeding up.

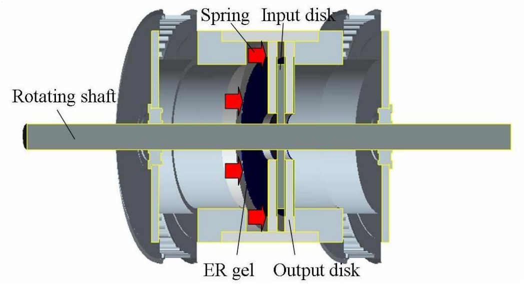


Fig. 16. Introduction of spring elements

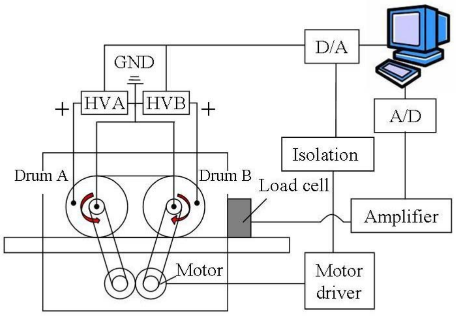


Fig. 17. Schematic diagram of the ERGLA test

B. Improvement for Stabilizing Responses

Spring elements were introduced to stabilize the pressure on the ER gels. Springs were set in six positions for the improved ERGD as shown by arrows in Fig. 16 to keep the input and output disks parallel. In this section, two ER gel disks were used in each ERGDs. Since the ERGDs are set to the ERGLA horizontally, only the spring forces act on ER gels as pressure. Pressure of 272 [Pa] was applied in this case.

To examine the improvement in stability, other parts of the ERGLA were reformed. The ER gel drum of the prototype needed a large external force to stretch the belt because the belt had a large width. As a result, the high load damaged the exterior frames of the prototype ERGLA. On the other hand, as shown in Figs. 12 and 16, the improved ER gel drum used two thin belts at each end of the drum. This reduced the burden on the frame in maintaining the initial belt tension. In addition, the exterior frames were reinforced with square aluminum pipes. At the same time, the weight of the ERGLA was reduced by 17% to 4.4 [kg].

A schematic diagram of the experiments on forces of the ERGLA is shown in Fig. 17. Step inputs of electric fields were introduced, and then a 60 [Hz] notch filter and a 200 [Hz] software low-pass filter were introduced as in the previous section.

Driving forces of the steady state after step inputs of electric fields were averaged. Means of values of ten experiment runs are shown in Figs. 18 and 19. The figures show small variances in the generative forces for the improved ERGLA of less than 1 [N] in both directions. This implies that the pressure on the surface of the ER gel was stabilized. The magnitude of the generative force was larger than the initial target of 10 [N].

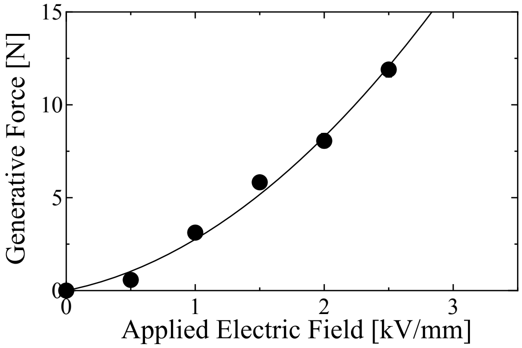


Fig. 18. Relation between the force and electric field for the ERGLA (left direction)

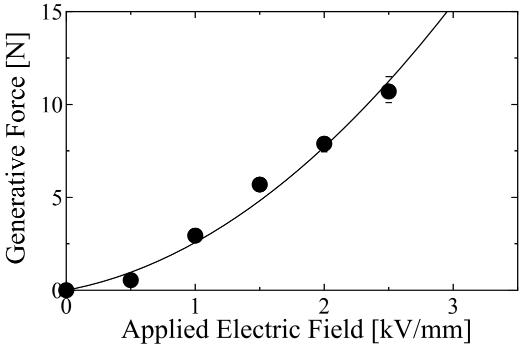


Fig. 19. Relation between the force and electric field for the ERGLA (right direction)

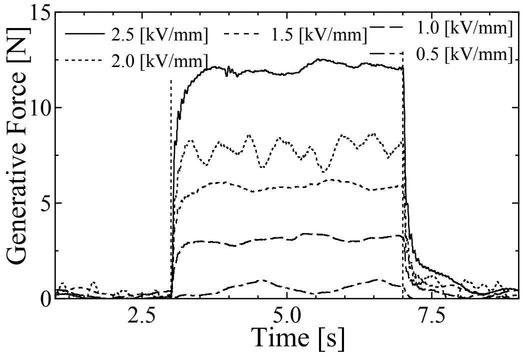


Fig. 20. Step responses of the ERGLA force (right direction)

To investigate the response time, step responses of the ERGLA are shown in Fig. 20 and Fig. 21. The time constant of the ERGLA can be read as about 40 [ms] and is smaller than that of the ERGD in the previous section. Spring elements would contribute to high speed and stable response. However, there was a large degree of waviness in some cases, which would be a cyclical variation due to the rotation of the input shafts. That is, the two ERGDs set on the ERGLA did not work in parallel with each other, and this is a matter for future research.

V. DISCUSSIONS

Actuators for human-coexistent robots require the following features.

- Backdriveability

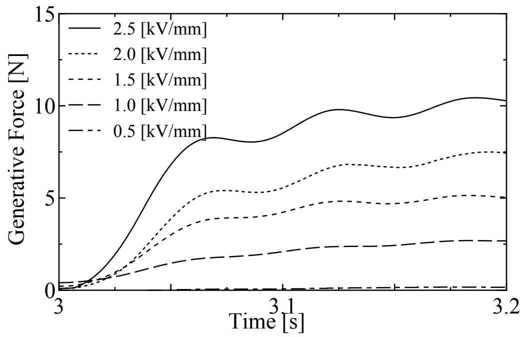


Fig. 21. Rise time of the ERGLA force (right direction)

- Safety
- Sufficiently large generative force
- High-speed response
- Easy controllability

Many types of linear actuators have come into practical use; in particular, many industrial robots use actuators of a pneumatic cylinder and linear guide and ball–screw driving system. However, each linear actuator has both merits and demerits for application to human-coexistent robots and none can be regarded as completely satisfactory. In particular, no linear actuator in practical use that can generate a reasonably large force can provide both safety and backdriveability.

On the other hand, the proposed ERGLA can generate forces greater than 10 [N], and it provides both safety and backdriveability as follows.

Essentially, the output part of the ER gel drum cannot rotate faster than the input motor, and so the ERGLA itself also cannot move faster than the speed corresponding to the input motor. That is, since the motor rotates at a constant low speed owing to a highly reliable driving method such as battery operation, the maximum speed of the ERGLA can be designed. Therefore, the ERGLA has small kinetic energy, and then has little risk of injuring a user even if the controller of the ERGLA runs away and the maximum electric field is applied to one of the ER drums. When the maximum electric field is applied to both ER drums as a result of the controller malfunctioning, the ERGLA does not generate an effective force to the outside because of antagonistic action.

When no electric field is applied to the ER gel, the gel hardly generates a shear stress as shown in Fig. 13, and thus the resistant torques at the ER drums are very small. Therefore, the ERGLA can be backdrivenby under 2 [N] force from Fig. 13 and a simple test with a pull scale. Because the ER gel is used under a sliding friction condition, stick–slip phenomena that often arise under static friction do not occur. Therefore, the backdriving characteristic of the ERGLA is good even when it is energized.

VI. CONCLUSIONS

This paper presents the structural plan of a novel linear actuator that uses ER gels, its improved design, and basic experiments to investigate its basic characteristics.

- A linear actuator was designed that uses ER gels and has a long stroke.
- It was confirmed that the use of multiple ER gel disks increases the generative force of the ERGLA.
- It was confirmed that spring elements stabilized the response of the ERGLA.
- The specifications of the most recent prototype are a mass of about 4.4 [kg] and a generative force of more than 10 [N]. Lightening the ERGLA is still an issue.
- The response time of the force was about 40 [ms]. It could be improved to around 20–30 [ms] as the ER gel itself.

In future study, more ER gel disks will be introduced to the ERGLA to improve the force–weight ratio. Controllability of the ERGLA will also be investigated in terms of force control and position control.

REFERENCES

[1] H. Kazerooni, "Human-robot interaction via the transfer of power and information signals," *IEEE Transactions on Systems, Man, and Cybernetics*, vol. 20, no. 2, pp. 450–463, 1990.

[2] J. Patton (Ed.), *Proceedings of the IEEE 9th International Conference on Rehabilitation Robotics*, IEEE, 2005.

[3] G. S. Guthart and K. J. Salisbury Jr., "Intuitive telesurgery system: overview and application," in *Proceedings of the IEEE 2000 International Conference on Robotics and Automation*, vol. 1, 2000, pp. 618–621.

[4] J. D. Westwood, S. W. Westwood, R. S. Haluck, H. M. Hoffman, G. T. Mogel, R. Phillips, R. A. Robb, K. G. Vosburgh (Eds.), *Proceedings of the 17th Annual Medicine Meets Virtual Reality Conference*, Aligned Management Associates, Inc. (2009).

[5] G. C. Burdea, "Haptics issues in virtual environments," in *Proceedings of Computer Graphics International Conference 2000 (CGI2000)*, 2000, pp. 295–302.

[6] T. H. Massie and J. K. Salisbury, "The phantom haptic interface: A device for probing virtual objects," *Dynamic Systems and Control*, vol. 55, no. 1, pp. 295–299, 1994.

[7] R. Van Der Linde and P. Lammertse, "Hapticmaster - a generic force controlled robot for human interaction," *Industrial Robot*, vol. 30, no. 6, pp. 515–524, 2003.

[8] D. Engel, J. Raczkowsky, and H. Wörn, "A safe robot system for craniofacial surgery," in *Proceedings of the 2001 IEEE International Conference on Robotics and Automation*, vol. 2, 2001, pp. 2020–2024.

[9] J. Furusho, K. Koyanagi, U. Ryu, A. Inoue, and K. Oda, "Development of rehabilitation robot system with functional fluid devices for upper limbs," *International Journal of Human-friendly Welfare Robotic Systems*, vol. 4, no. 2, pp. 23–27, 2003.

[10] K. Koyanagi, Y. Kakinuma, H. Anzai, K. Sakurai, T. Yamaguchi, T. Oshima, N. Momose, and T. Matsuno, "Basic structure and prototype of novel linear actuator with electro-rheological gel," in *Proceedings of the 2007 IEEE International Conference on Mechatronics and Automation*, 2007, pp. 3266–3271.

[11] K. Koyanagi, T. Yamaguchi, Y. Kakinuma, H. Anzai, K. Sakurai, and T. Oshima, "Basic research of electro-rheological gel drum for novel linear actuator," *Journal of Physics: Conference Series*, vol. 149, 012020, 2009.

[12] R. Hanaoka, S. Takara, H. Fujita, T. Fukami, K. Sakurai, K. Isobe, and T. Hino, "Electroviscoelastic properties in ER gel of disperse system under DC electric field," in *Proceedings of the Eighth International Conference on Electro-Rheological Fluids and Magneto-Rheological Suspensions*. World Scientific, 2001, pp. 493–499.

[13] Y. Kakinuma, T. Aoyama, H. Anzai, H. Sakurai, K. Isobe, and K. Tanaka, "Basic properties of gel-structured electro-rheological fluids," *International Journal of Modern Physics B*, vol. 19, no. 7-9, pp. 1339–1345, 2005.

[14] ——, "Application of ER gel with variable friction surface to the clamp system of aerostatic slider," *Precision Engineering*, vol. 30, pp. 280–287, 2006.

[15] K. Koyanagi and J. Furusho, "Study on high safety actuator for force display," in *Proceedings of SICE Annual Conference 2002*, 2002, pp. 3118–3123.