Energy Efficiency Improvement of a Robotic Finger With Ultra High Molecular Weight Polyethylene Gear

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ABSTRACT Improving energy efficiency of robots is an important issue for diffusion of robots in society. For reducing the energy consumption of robots, we focused on the gear weight and friction during drive, and investigated Ultra High Molecular Weight Polyethylene (UHMW-PE) for the robot joints as a lightweight, low friction, and high impact strength material. A simple UHMW-PE gear has already been proposed, and the friction and wear reduction effects of the gear alone have been verified. However, the energy efficiency improvement has not been investigated. We designed UHMW-PE gears for comparing to the conventional metal (CAC502) gear. Each gear was incorporated into a humanoid robot finger joint, and the energy consumption when the finger bended was compared. The UHMW-PE gear with excellent self-lubrication reduced energy consumption in the robot finger by around 3%.

INDEX TERMS Robotics, gear, UHMW-PE, energy efficiency, low friction.

I. INTRODUCTION Practical use of robots in various situations is beginning to progress. On the other hand, the energy shortage problem has become serious as a global problem not only in the robot field. Of course, most of robots that move with electrical energy cannot move if there is insufficient energy. Also, when energy efficiency of robots is low, energy will be wasted. If the energy efficiency of robots remains low, their spread to society will be limited, as in the case of automobiles decarbonization regulations. Therefore, improving the energy efficiency of robots is an important issue for the spread of robots in the near future.

Most of the energy consumption during robot operation is motor power rather than the power consumption of the robot controller, and it increases especially as the robot becomes larger and heavier. Therefore, in order to reduce the energy consumption of the robot itself, the weight reduction of the robot itself greatly contributes. In particular, the frame part of the robot needs to be strong enough to support its own weight, and metal is often used for life-sized robots [1], [2]. However, in recent years, plastics and carbon fiber reinforced plastics have also been used for further weight reduction. Gouaillier et al. have developed a compact and lightweight humanoid robot, Nao, by using plastic to reduce weight [3]. In addition, as an improvement in the design of structural members, a method using topology optimization as a shape design using optimization calculation has been devised in order to reduce the weight while maintaining the strength. Sha et al. used topology analysis to optimize design of simple 2-link robots and 5-degree-of-freedom upper body exoskeleton robots [4]. Ha et al. have proposed a method for
optimizing robot design according to the desired motion [5].

As other methods, it is effective to reduce friction in the drive unit and improve motor control. Korka et al. have confirmed that friction and driving noise was reduced by applying a fluoropolymer coating to the gears to reduce friction [6].

In addition, a method to devise by controlling the whole body of the robot has been proposed, and Buondonno et al. proposed an optimization framework for the design and analysis of underactuated biped walkers, characterized by passive or actuated joints with rigid or non-negligible elastic actuation/transmission elements [7]. In addition, there is also a method of storing energy inside the robot [8]. Otani et al. equipped the humanoid robot with carbon fiber reinforced plastic leaf spring to reproduce the joint elasticity value equivalent to that of human ankles and knees, and the resonance principle of the whole robot, and realizes a jumping motion [9]. Khalaf and Richter have proposed a trajectory optimization method for incorporating a capacitor in a robot joint and storing and using the consumed energy into capacitors during motions [10].

As a method for reducing the energy consumption of the robot, we focused on the gear in the joint of the robot as an important factor of not only lightweight hardware design of the robot but also energy consumption due to friction. Design methods have been proposed to reduce weight while maintaining strength [11], but the use of lightweight materials is important for drastic weight reduction. The use of plastic gears is expanding in various machinery fields to take advantage of their light weight and ease of molding [12], [13], [14], [15], [16], [17]. The design method of ABS gear bodies was proposed for lightweight vibration-reduction [18]. A laminated carbon fiber-reinforced polymer gear was proposed, and coefficient of friction was analyzed [19]. There are cases where small robots are designed lighter by using plastic gears [3], but the energy consumption in the robot joint was not considered. Especially, decreasing the friction between gears with a new material which has low friction is effective for decreasing energy consumption. Therefore, we focused on Ultra High Molecular Weight Polyethylene (UHMW-PE), which has characteristics of lightweight, high strength, and excellent sliding properties.

UHMW-PE generally refers to a type of polyethylene with a very high average molecular weight of at least $1.0 \times 10^6$, exhibits better sliding properties, abrasion resistance, and impact strength than normal polyethylene or other engineering plastics. A chemical structure of polyethylene is repeated structure of ethylene as shown in Fig.1. In case of UHMW-PE, this repeated structure is very long, and its molecular shape is like linear chain with few branches. This linear molecular chain has low intermolecular force due to the shape with low resistance and low surface free energy of C-H bonds. In addition, long molecular chains make many entanglements, resulting in high strength against stress. For these reasons, UHMW-PE exhibits excellent sliding properties and abrasion resistance. Furthermore, UHMW-PE has lightweight and high chemical resistance due to its chemical structure consisting only of carbon and hydrogen atoms. These characteristics suggest that UHMW-PE is suitable for gears of robots in high loads or high speeds, and is expected to reduce energy consumption due to its lightweight and sliding properties.

This study has the main contribution to robotics field as below. By installing the UHMW-PE gear, a reduction of about 3% in energy consumption was achieved by reducing friction in addition to reducing the weight of the robot joints. A simple UHMW-PE gear has already been proposed, and the friction and wear reduction effects of the gear alone have been verified. However, no verification of energy consumption has been conducted on a robot joint driven by a high load. Together with weight reduction, low friction is effective in reducing the energy consumption of robots.

This paper is organized as follows. In Section 2, we describe the design of the UHMW-PE gear and the robot for evaluation of the gears, and the experiment method. In Section 3, we present experimental results. In Section 4, we discuss the limitation and novelty of this work. Finally, in Section 5, we present conclusions and propose future work.

II. MATERIALS AND METHODS

A. MATERIALS

UHMW-PE materials used in this study were HI-ZEX MILLION™ (0.93 g/cm$^3$) and LUBMER™ (0.97 g/cm$^3$) supplied from Mitsui Chemicals respectively (Table.1) [20], [21]. HI-ZEX MILLION™ is a typical powdered UHMW-PE, and its gears for robot joints was made by cutting blocks. LUBMER™ is a special UHMW-PE that can be injection molded or extrusion molded with typical characteristics of UHMW-PE, excellent sliding properties and abrasion resistance. UHMW-PE is generally molded by compressing or cutting, because its melt viscosity is so high that injection or extrusion are difficult. For gears in robots joint, LUBMER™ is expected to reduce energy consumption and simplify gear molding. In addition to being easier to process than typical UHMW-PE, LUBMER™ is a material that is also consistent with a circular economy perspective because it can be recycled through melt-blending. In this study, the LUBMER™ gear is made by cutting its blocks same as HI-ZEX MILLION™ in order to unify sample conditions.
B. ROBOTIC FINGER USED IN THE EXPERIMENT

To validate the UHMW-PE gear, a worm gear to drive a robotic finger was fabricated in UHMW-PE in this study. We have developed a humanoid robot for achieving human-like sports motion such as pitching [9] (Fig. 2(a)). The robot finger is developed for a robot hand that grips a ball with the same force and speed as a human (Fig. 2(b)). To reduce weight, most of the parts of a robot finger and a hand are 3d-printed using PLA (Poly-Lactic Acid) material. Based on the study of the finger during human motion such as a ball pitching, the maximum flexion speed of the human finger is 3500 deg/s [22], and the maximum exerted force of the fingertip is 100 N [23]. The finger part has a 3-joint serial link structure. It uses an underactuated drive system, with a wire for active flexion of the finger in the finger abdomen and a spring for passive extension of the finger in the back of the finger (Fig. 3). When the wire traction is relaxed, the spring mounted on the back side of the finger contracts and the finger is extended. The wire running inside the finger is pulled by a brushless DC motor and a worm gear located at the finger base. By placing motors and gears on the forearms, the mass distribution of the entire arm can be designed to be comparable to that of a human. Power transmission from the forearm is achieved by passing a wire through a low friction tube. In order to generate a large fingertip force of 100 N during finger flexion, a worm gear with a high load capacity is used in the active drive unit.

C. DESIGN OF UHMW-PE WORM GEARS

Metal worm gear wheel and UHMW-PE worm gear wheels were fabricated to drive the robot finger (Fig. 4). In general, energy consumption in worm gears is influenced by the design parameters of the worm gear and the operational conditions of the worm gear [24]. Energy efficiency of worm gear is represented by the equation (1).

$$\eta = 100 * \frac{\cos \alpha - \mu \tan \gamma}{\cos \alpha + \mu \cot \gamma}$$

where, $\eta$ is efficiency of worm gear, $\alpha$ is pressure angle of worm gear, $\gamma$ is lead angle of worm gear, and $\mu$ is friction coefficient between worm and worm wheel. For improving the efficiency of worm gear, low friction coefficient is effective. However, important worm gear design parameters such as tooth module, tooth angle, and combination of materials influence to friction between the worm and worm wheel contact area [25]. Moreover, operational conditions are affected by the pressing force between the worm and worm wheel, torque, speed when driven, and lubrication [26], [27]. Estimation of gear friction coefficient is complicated problem and various methods have been proposed in recent years [28], [29], [30]. In order to match the experimental conditions, each...
TABLE 2. Specification of the fabricated worm gear.

| Parameter (unit)          | Worm | Wheel |
|--------------------------|------|-------|
| Tooth module             | 2    |       |
| Pressure angle (deg)     | 20   |       |
| Lead angle (deg)         | 5    |       |
| Reduction ratio          | 35   |       |
| Gear center distance (mm)| 46   |       |
| Reference circle diameter (mm)| 22 | 70  |
| Tooth width (mm)         | 30   | 12    |
| Surface processing       | Grinding | Cutting |
| Material                 | Metal (CAC502), HI-ZEX MILLION™, LUBMER™ |

Each gear was incorporated into a finger of the robot, and the current bending motion was performed was measured (Fig. 5). Generally, the power consumption of a motor at time \( t \) is expressed by equation (2).

\[
P(t) = u(t) i(t)
\]

where, \( P(t) \) is the power consumption at time \( t \), \( i(t) \) is the current flowing through the motor at time \( t \). The voltage \( u(t) \) applied to the motor can be obtained by equation (3) from the model of the electric motor [31].

\[
u(t) = Ri(t) + k\omega(t) + L\frac{di(t)}{dt}
\]

where, \( R \) is the electrical resistance of the motor, \( k \) is the counter electromotive force constant, \( \omega(t) \) is the number of revolutions of the motor at time \( t \), and \( L \) is the inductance of the motor. The output torque \( \tau(t) \) of the motor is calculated by equation (4).

\[
\tau(t) = k_i i(t)
\]

where, \( k_i \) is the torque constant of the motor. In theory, the torque constant matches the counter electromotive force constant \( k \). When using a low-inductance motor, the inductance effect is negligible. By substituting into equation (1), power consumption from the current and rotation speed of the motor is calculated in equation (5).

\[
P(t) = k_i \omega(t) i(t) + R i(t)^2
\]

In the experiment, equation (5) was used to calculate the power consumption of the motor, and total energy consumption was calculated by integral calculations as equation (6).

\[
E = \int_0^T \frac{k_i \omega(t) i(t) + R i(t)^2}{T}
\]

where, \( E \) is total energy consumption in Joule, and \( T \) is total time of an experiment. The specification of the motor used in the experiment is shown in Table 3. The motor was equipped with an incremental encoder and was connected to a motor controller. We used a motor controller ELMO Gold Twitter (ELMO Motion Control Inc.). As a simple bending motion, time-series angle reference was set for rotating the worm wheel 35 deg in uniform acceleration and deceleration (Fig. 6). The motor controller controlled the motor speed according to the preset motor rotation speed command with proportional–integral–derivative (PID) controller. The PID control gain was tuned for a motor without a gear using the software of Elmo Application Studio II. The motor controller acquired the motor angle, angular velocity, and current data and recorded them every 0.1 millisecond.

Experiments using each gear were performed 5 times. Generally, when using a metal gear, lubricating oil is required, but the UHMW-PE gear can be used oil-less due to its self-lubrication. In this experiment, a dry film lubricant for gears, GJS-0901 (Kohara Gear Industry Co.), was applied only for metal gears to improve lubricity. The experimental conditions are summarized in Table 4.

![Designed worm wheels.](image)

**FIGURE 4.** Designed worm wheels.

### D. EXPERIMENT METHODS

An experiment was conducted to compare the current consumption and energy consumption when using the metal gear, the HI-ZEX MILLION™ gear, and the LUBMER™ gear. Each gear was incorporated into a finger of the robot, and the current when the finger bending motion was performed was measured (Fig. 5). Generally, the power consumption of a motor at time \( t \) is expressed by equation (2).

\[
P(t) = u(t) i(t)
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where, \( P(t) \) is the power consumption at time \( t \), \( i(t) \) is the current flowing through the motor at time \( t \). The voltage \( u(t) \) applied to the motor can be obtained by equation (3) from the model of the electric motor [31].

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**TABLE 3.** Specification of the motor.

| Parameter (unit) | Value |
|------------------|-------|
| Manufacturer     | Maxon Motor |
| Motor name       | EC-4pole 22 |
| Part number      | 311536 |
| Rated power (W)  | 120   |
| Torque constant \( k_i \) (mNm/A) | 13.5 |
| Electrical resistance \( R \) (Ω) | 0.341 |

**TABLE 2.** Specification of the fabricated worm gear.

| Parameter (unit) | Worm | Wheel |
|------------------|------|-------|
| Tooth module     | 2    |       |
| Pressure angle   | 20   |       |
| Lead angle (deg) | 5    |       |
| Reduction ratio  | 35   |       |
| Gear center      | 46   |       |
| circle diameter  | 22   | 70    |
| Tooth width (mm) | 30   | 12    |
| Surface          | Grinding | Cutting |
| processing       | Metal (CAC502), HI-ZEX MILLION™, LUBMER™ |

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The measured average current data during the experiment is shown in Fig. 7. The standard deviations are also shown in the graph and were very small for all conditions. The time-series data of average power consumption is shown in Fig. 8 and the average total energy consumption of each gear is shown in Table 5. The experimental results show that the current consumption increased slightly when HI-ZEX MILLION™ was used compared to that of the metal gear, while the current consumption was reduced when LUBMER™ was used. Also, compared to the metal gear, the total energy consumption was increased around 1% in the case of HI-ZEX MILLION™, decreased around 3.4% in the case of LUBMER™.

### IV. DISCUSSION

The energy consumption of the LUBMER™ gear was lower than that of the metal gear, as expected. On the other hand, the energy consumption of the HI-ZEX MILLION™ gear was slightly higher than that of the metal gear, but this may be due to the fact that the metal gear was lubricated while...
the HI-ZEX MILLION\textsuperscript{TM} gear was non-lubricated. The LUBMER\textsuperscript{TM} gear is also non-lubricated, which means that the sliding properties of UHMW-PE are excellent and suitable for oil-less derive robot joint applications. Both HI-ZEX MILLION\textsuperscript{TM} and LUBMER\textsuperscript{TM} have good sliding properties of UHMW-PE characteristics but the energy consumption of the LUBMER\textsuperscript{TM} gear was lower than its of HI-ZEX MILLION\textsuperscript{TM}. This is because LUBMER\textsuperscript{TM} is a material with a particularly low coefficient of friction [21], and the difference in the coefficient of friction of each material affect the energy consumption. Estimating the energy transfer efficiency from the friction coefficient data summarized in Table 1 using equation 1, the transfer efficiency of HI-ZEX MILLION\textsuperscript{TM} and LUBMER\textsuperscript{TM} was 27.5\% and 32.0\%, respectively. According to this estimation, LUBMER\textsuperscript{TM} consumes 16\% less energy than HI-ZEX MILLION\textsuperscript{TM}. However, the results of the experiment in Table 5 showed 3.4\% reduction in energy consumption when LUBMER\textsuperscript{TM} was used with respect to HI-ZEX MILLION\textsuperscript{TM}. There are two possible reasons for the smaller difference in energy consumption in the experimental results compared to the trial calculation. One is that the coefficient of friction used in the estimation is measured when in contact with parts made of S45C. It is likely to change slightly when in contact with the SCM415 material used in the experiment. Another possibility is that when experimenting with the robot, the change in gears causes a slight change in controllability, but the PID control parameters are not optimized for each gear, resulting in a slight loss of efficiency. It is known that energy efficiency can be improved by optimizing the PID gain [32]. In the experiment, PID gain tuning was performed on a motor with no gears connected. If PID gain tuning is performed for each gear and optimal drive is performed for each gear, it is thought that energy differences that are a little closer to the estimation can be confirmed.

Oil-less robot joints do not require maintenance such as periodic oil changes, which is an important technology for the practical use of robots in the future. In addition, low-friction gears are known to reduce the noise during driving [33], [34]. Hirogaki et al. have demonstrated the low noise effect of gears made of cotton fiber-reinforced phenolic resin [35]. Driving noise data was also obtained in this experiment, but no significant difference was observed even in the case of the UHMW-PE gear, since almost no driving noise was generated even in the case of metal gear. Since the driving noise of a robot gives a bad impression to humans, silence will become an important performance feature when robots become more widely used in society.

In this study, the robot finger was driven while fixed to the base. Hence, the energy reduction during robot motion due to the light weight of the UHMW-PE gear was not verified. Considering light-weighting, when CAC502 metal gear with a density of 8.8 g/cm\textsuperscript{3} are replaced with the LUBMER\textsuperscript{TM} gear with a density of 0.97 g/cm\textsuperscript{3}, the weight of the gear can be reduced by approximately 89\%. Human-size robots include a lot of large gears, therefore replacing them with the LUBMER\textsuperscript{TM} gears will greatly reduce the overall weight of the robot. It also affects the energy efficiency improvement. Power consumption of a joint \( j \) of a robot is calculated in equation (7).

\[
P_j(t) = \tau_j(t) \omega_j(t)
\]

where \( P_j(t) \) is the power consumption of the \( j \) joint at time \( t \), \( j \) is the number of the joint, \( t \) is the time in the experiment, \( \tau_j(t) \) is the torque of the \( j \) joint at time \( t \), and \( \omega_j(t) \) is the angular velocity of the \( j \) joint at time \( t \). In general, the equation of motion of the robot joint is given by

\[
M(q)\ddot{q}_j + H(q_j, \dot{q}_j) + G(q_j) = \tau_j
\]

where \( M(q_j) \) is the inertial matrix; \( H(q_j, \dot{q}_j) \) is the Coriolis and centrifugal terms, \( G(q_j) \) is the coordinate of the \( j \) joint. The power consumed in each joint is calculated, and then the total power consumption is calculated by summing all joints power consumptions [36]. In particular, the reduced weight of the fingers and hands in this study contributes to a significant reduction in the moment of inertia of the entire arm when the robot moves the arm because the weight of the part far from the joint is added to the moment of inertia by the square of the distance between the mass and the joint. If the moment of inertia is reduced, the torque that must be exerted by the elbow and shoulder joints that move the arm is greatly reduced, thus reducing energy consumption. Equation (7) shows that the reduction of torque because of
decreasing the moment of inertia not only reduces energy consumption but also contributes to an increase in operating angular velocity. For the same joint power, the smaller the torque required for movement, the faster the joint can move. Therefore, the lightening of the robot’s limb ends with the UHMW-PE gear easily performs movements that require high-speed arm swing. The robot equipped with the developed fingers and hands can move. Therefore, the lightening of the robot’s limb ends with the torque required for movement, the faster the joint can move. Decreasing the moment of inertia not only reduces energy consumption, but it also results in lower arm swinging speeds.

V. CONCLUSION

1) We produced the UHMW-PE gears, which are expected to realize lightweight, low-friction, and oil-less drive.

2) Compared to the metal gear, the LUBMER™ gear is 89% lighter than a metal gear.

3) Comparing the energy consumption of the metal gear, the HI-ZEX MILLION™ gear, and the LUBMER™ gear when used on a robot finger during bending, the energy consumption of the LUBMER™ gear was lower at around 3.4% than that of the metal gear.

In the future, we will continue to evaluate energy consumption at higher loads and speeds, as well as verify the accompanying effects, such as an UHMW-PE worm, oil-less drive, wear resistance and low noise effect.

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