2025 IEEE/SICE International Symposium on System Integration (SII)
January 21-24, 2025, Munich, Germany

Cloth-Climbing Robot for Body Surface Inspection Without Clothing Removal Using Magnetic Gears

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***Abstract*— This study proposes a novel robot designed for inspecting body surfaces while attached over clothing. This inspection robot consists of a driving unit with a motor and a camera unit with a camera for observing the body surface. The camera unit is placed inside the clothing, while the driving unit is positioned outside, and both units are attached through magnetic gears over the clothing. The motor's driving torque from the drive unit is transmitted to the wheels of the camera unit via the magnetic gears, allowing both units to move in parallel. This enables the robot to move across the clothing and inspect the body surface underneath. The robot is envisioned for applications such as checking the body surface condition of individuals who have difficulty changing clothes. This study also derives the conditions necessary for the robot to move effectively over clothing. The effectiveness of the robot is demonstrated through experiments.**

I. Introduction

This paper presents a new inspection robot designed to examine body surfaces without the need to remove clothing. Currently, the nursing and care fields are facing a serious shortage of workers worldwide [1]. If this situation continues, the burden on nursing and care workers will only increase. One potential solution to this issue is simplifying healthcare tasks through the use of robots. This study focuses on the inspection of body surfaces in nursing and caregiving tasks. Early detection of skin injuries or damage allows for early recovery and reduces the workload for nursing and care staff. Fig. 1 shows the developed new inspection robot. This robot is primarily intended for individuals who are unable to recognize the condition of their body surfaces due to paralysis or dementia. Until now, the observation of body surfaces has been conducted through visual inspection with the patient undressed. No robot has been conceived that allows for visual inspection of the body surface while the patient remains clothed. One possible approach is to develop a robot that can move freely over the clothing and equip it with visual inspection capabilities. Some robots can move over the clothing. For example, P. Birkmeyer et al. [2] developed a small robot that climbs using six legs to pierce the fabric with its spikes. Y. Lu et al. [3] developed a robot that climbs on a clothing using the gripper to grip the clothing. G. Chen et al. [4] developed a robot with a concept similar to [3]. A. Sathya et al. [5] developed a small robot that moves along rails attached to clothing. A. Dementyev et al. [6] developed a miniature robot that can move on clothing using magnetic rods as wheels. Since these robots operate outside of the clothing, the acquisition of information that requires visibility inside the clothing has not been considered. Therefore, they lack a structure that enables them to inspect beneath clothing. One possible solution to visually inspect the skin surface is to provide a robot that moves inside the clothing and equips a camera. With this in mind, this study presents a novel robot consisting of an inner robot equipped with a camera (camera unit) that moves inside the clothing, and an outer robot with a motor (driving unit) that operates on a surface of the clothing, as shown in Fig. 1. The camera unit and driving unit are connected through clothing by magnets and magnetic gears. The magnetic gears can transmit torque even when there is a gap between them due to magnetic forces. The driving torque generated in the driving unit can be transmitted to the gear in the camera unit through clothing. Therefore, if moving the driving unit, the camera unit inside the clothing also moves in sync with it.

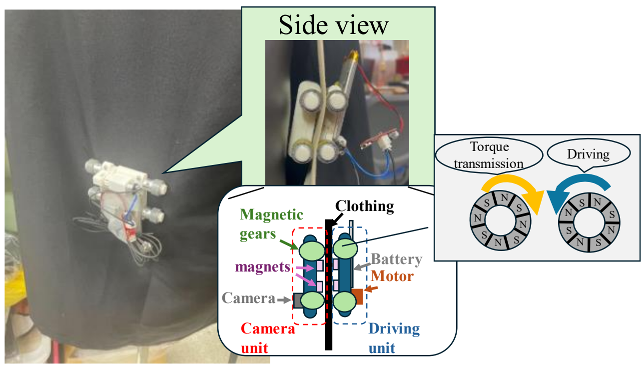

Figure 1. Overview of the developed cloth-climbing robot for body surface inspection using magnetic gears

In recent years, many robots that adhere to hard walls and glass have been researched and developed for cleaning and inspecting walls [7]. Among these, the following are the wall-running robots that use magnets. T. Tajiri et al. [8] developed a bridge inspection robot using rimless wheels with permanent magnets attached. F. Tâche et al. [9] developed a two-wheeled robot with a magnetic wheel to inspect structures of complex shapes. Z. Xu et al. [10] developed a wall climbing robot to label an oil tank scale using magnetic suckers. S. Fujiwara [11] developed a net side underwater moving robot with magnet-embedded tires. F. Ren et al. [12] an amphibious robot using

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magnetic tracks. Wall-climbing robots that uses other mechanisms other than magnets also have been developed. G. Lee et al.[13] developed multi-linked track robot with suction adhesion. T. Lam et al. [14] developed a tree-climbing robot using tactile sensing with a gripper. Although many kinds of robots have been developed, their primary focus has been climbing on rigid surfaces. In contrast, the target in this study is soft and flexible materials, such as fabric or clothing. Climbing on a soft surface presents a significant challenge. Clothes are soft and easily deformed, so they easily wrinkle. In particular, wrinkles easily form when moving objects move over the clothing. In addition, wrinkles tend to become larger. One solution is to create intentional wrinkles by gripping the fabric with a gripper, similar to [3]. However, in this case, installing a robot for inspection inside the clothing is not easy. Another solution is to use magnetic wheels, as shown in [6]. They inserted a magnet rod inside the clothing to attach magnetic wheels, which are made from magnet rods, to the clothing. Although this method is effective to some degree, it has limitations. As demonstrated in their video, the robot does not move unless the clothing is pulled to a certain extent. This study proposes a more effective method using magnetic gears. The developed robot has front and rear wheels. By sandwiching the clothing between the inner and outer robots' magnetic gears corresponding to the front and rear wheels, tension is applied to the clothing in the area where the robot makes contact. Therefore, pulling the clothing is not necessary to move the developed robot. Based on the analysis, this study will also present the conditions for moving on the clothing. The analysis shows that rear-wheel drive is easier to climb than front-wheel drive. The validity of the analysis and the effectiveness of the developed robot are demonstrated through several experiments.

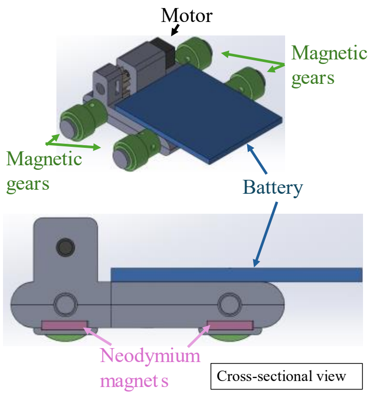


Figure 2. Structure of the driving unit

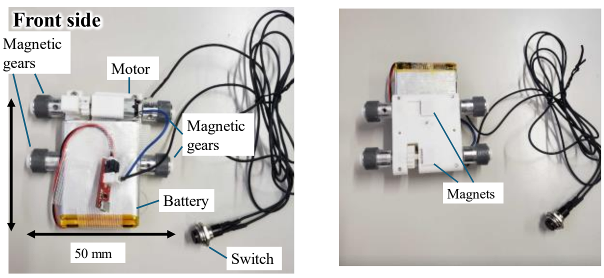


Figure 3. The photo of the driving unit

II. Structure of Robot

A. *Functional Requirements*

The functional requirements of the robot are as follows:

1) The robot can climb on clothing.

2) The robot can capture the body surface without removing the clothing.

B. *Robot design*

To inspect body surfaces without removing the clothing, the robot should be able to move on the clothing while being equipped with a unit that moves inside the clothing and captures the body surface visually through a camera. For the purpose, we developed a robot primarily consisting of the driving unit and camera units, as shown in Fig. 1. The driving unit is responsible for moving on clothing, while the camera unit is responsible for inspecting the body surface inside the clothing through a camera. The driving unit and camera unit sandwich the clothing, and the magnets hold them in place, allowing the camera unit inside the clothing to move in sync with the driving unit. This fixing also serves to hold the driving unit and camera unit in place on the clothing. Both units have four wheels and use magnetic gears as wheels as show in Fig. 1. Magnetic gears are a mechanism that uses magnetic forces to transmit torque even when there is a gap between the gears. In the developed robot, the magnetic gears transmit the driving torque from the driving unit's gear to the camera unit's gear through the clothing, enabling the camera unit to move in sync with the driving unit. Another advantage of using the magnetic gears is that it simplifies the unit's structure by providing magnetic force to hold the drive unit and camera unit on the clothing. To enhance the magnetic force for the holding, two neodymium magnets are attached to both units. Furthermore, by sandwiching the clothing with the magnetic gears, tension is applied to the fabric between the front and rear wheels, reducing wrinkles and making movement across the clothing smoother.

The main bodies of the driving unit and camera unit were printed on a 3D printer (Bambu Lab) and made of PLA. Fig. 2 shows the structure of the driving unit while Fig. 3 shows its photo. The motor (Uxcell, Micro Speed Reduction Motor) and a battery (DATA POWER TECHNOLOGY, lithium-ion polymer battery) were attached on the main body of the driving unit, to provide the driving force and power for the motor, respectively. To facilitate the evaluation of the developed robot, a switch was installed to turn the motor on and off. Fig. 4 shows the structure of the camera unit while Fig. 5 shows its photo. The camera (KEENSO, HBV-1466FF) and its processing system were installed to the camera unit, to capture the body surface for the inspection. A battery that comes with the camera was installed to provide the power for the camera ant its processing system. The camera is equipped with LEDs to enable clear images of body surfaces to be acquired even in the dark environment inside clothing.

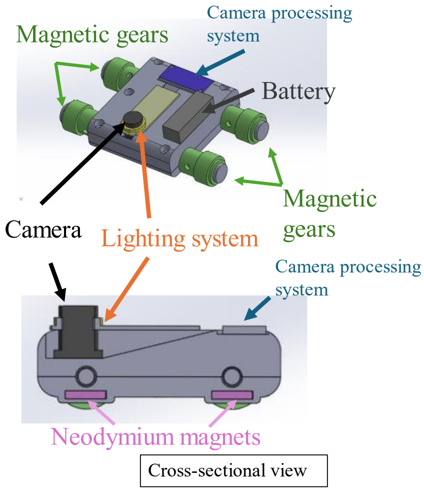


Figure 4. Structure of the camera unit

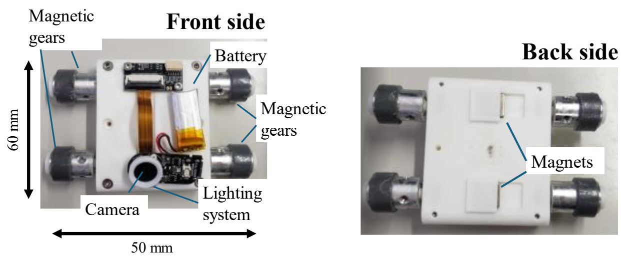


Figure 5. Photo of the camera unit

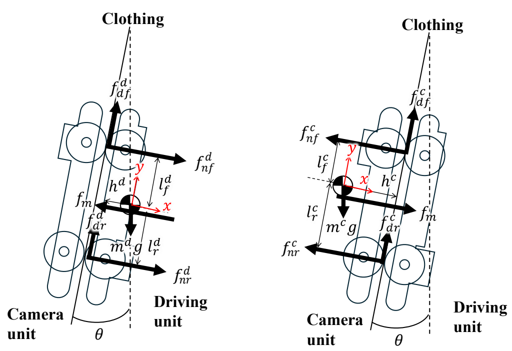


Figure 6. Model and nomenclature for the analysis

III. Analysis of Drive Mechanism

Here, we consider the condition for the robot to climb on clothing. For the simplicity, two-dimensional analysis was conducted. Fig. 6 shows the model and nomenclature for variables in the analysis. First, we consider the case of rear-wheel drive. The driving force at the front wheel is $f_{df}^i = 0\ (i \in \{d, c\})$ where the superscript d and c indicates the driving and camera units respectively. In order for the robot to remain on the clothing, the driving force must be applied to the rear wheel of both the driving and camera units to counteract the gravitational force in y direction:

$$f_{dr}^i = m^i g \cos\theta \ (i \in \{d, c\}) \tag{1}$$

where m^d and m^c represent the masses of the driving unit and the camera unit, respectively, g gravitational acceleration, and θ represents the angle of inclination of the robot. In order for the driving unit and camera unit to remain stationary in the x direction and the rotational direction with respect to the center of gravity, the forces and moments in each direction must be balanced in each unit:

$$\begin{aligned} 0 &= f_{nf}^i + f_{nr}^i + m^i g \sin\theta - f_m \\ 0 &= f_{nr}^i l_r^i - f_{nf}^i l_f^i - f_{dr}^i h^i \\ &(i \in \{d, c\}) \end{aligned} \tag{2}$$

where f_{nf}^i and f_{nr}^i are the normal forces at the contact between the clothing and the front and rear wheels, respectively, f_m represents the sum of the magnetic adsorption forces, l_f^i and l_r^i are the distances along y axis between the center of gravity and the front and rear wheels, respectively, and h^i is the distance between the clothing and the center of gravity. Here it is assumed that the magnetic force is uniformly applied to the robot. If considering the non-uniform magnetic force, instead of the center of gravity, the center of force field including magnetic and gravitational forces should be considered. From (1) and (2), we have

$$\begin{aligned} f_{nf}^i &= l_r^i/l(f_m - m^i g \sin\theta) - h^i/l\, m^i g \cos\theta \\ f_{nr}^i &= l_f^i/l\,(f_m - m^i g \sin\theta) + h^i/l\, m^i g \cos\theta \\ &(i \in \{d, c\}) \end{aligned} \tag{3}$$

where $l = l_f^i + l_r^i \ \ (i \in \{d, c\})$.

Letting $\mu_r^i\ (i \in \{d, c\})$ be the coefficient of friction at the rear wheel, the condition for the robot to remain on the clothing is

$$\begin{aligned} f_{dr}^i &= m^i g \cos\theta \le \mu_r^i f_{nr}^i \\ &= \mu_r^i l_f^i/l\,(f_m - m^i g \sin\theta) + \mu_r^i h^i/l\, m^i g \cos\theta \\ \therefore \rho_r &= \frac{\mu_r^i l_f^i}{l}(f_m - m^i g \sin\theta) + \left(\frac{\mu_r^i h^i}{l} - 1\right) m^i g \cos\theta \\ &\ge 0 \\ &(i \in \{d, c\}) \end{aligned} \tag{4}$$

Next, we consider whether the motor can produce the required driving force given in (1). Let r_r be the radius of the rear wheel and let ϕ (< 1) be the transmission efficiency of magnetic gears. Then, from (1), the motor torque τ_d required to generate f_{dr}^c and f_{dr}^m is given by

$$\tau_d = r_r(m^d + m^c/\phi) g \cos\theta \tag{5}$$

τ_d should be less than the maximum torque, τ_d^{max}, that the motor can generate:

$$\tau_d = r_r(m^d + m^c/\phi) g \cos\theta \le \tau_d^{max} \tag{6}$$

Lastly, we consider the case of front-wheel drive. The analysis can be done similarly. (1) becomes

$$f_{df}^i = m^i g \cos\theta \ (i \in \{d, c\}) \tag{7}$$

(4) becomes

$$f_{df}^{i} = m^{i} g \cos\theta \leq \mu_{f}^{i} f_{nf}^{i}$$

$$= \mu_{f}^{i} l_{f}^{i} / l \, (f_{m} - m^{i} g \sin\theta) - \mu_{f}^{i} h^{i} / l \, m^{i} g \cos\theta$$

$$\therefore \rho_{f}$$

$$= \frac{\mu_{f}^{i} l_{f}^{i}}{l} (f_{m} - m^{i} g \sin\theta) - \left(\frac{\mu_{f}^{i} h^{i}}{l} + 1\right) m^{i} g \cos\theta$$

$$\geq 0$$

$$(i \in \{d, c\}) \tag{8}$$

where μ_{f}^{i} $(i \in \{d, c\})$ represents the coefficient of friction at the front wheel.

If comparing (4) and (8) under the assumption that the friction coefficients are nearly the same ($\mu_{f}^{i} \approx \mu_{r}^{i}$), it can be seen that rear-wheel drive is more likely to meet the conditions by an amount of $\mu_{j}^{i} h^{i} / l \, m^{i} g \cos\theta$ $(j \in \{f, r\})$, allowing the robot to climb clothing more easily.

(6) becomes

$$\tau_{d} = r_{f} (m^{d} + m^{c} / \phi) g \cos\theta \leq \tau_{d}^{max} \tag{9}$$

where r_{f} represents the radius of the front wheel.

A. Evaluation

The experiments were conducted to determine under what settings the conditions in (4) and (8) would be met, allowing the robot to climb on clothing. The value of ρ_{j} $(j \in \{r, f\})$ given in the conditions (4) and (8) were examined when the weight of the driving unit is varied. The angle of inclination (θ) of the robot was also examined to see the effect of θ on the conditions (4) and (8).

Fig. 7 shows the experimental setup where the developed robot moved up on the fabric (Polyester) worn by a mannequin from the start position to the goal position. The starting position was located around the lower back of the mannequin. The goal position was set 400 mm above the starting position. We investigated whether the robot could reach the goal position. If the device can move up 400 mm, it is referred to as 'F' (Finish); if it stops midway, it is referred to as 'DNF' (Do Not Finish); and if it cannot move, it is referred to as 'DNS' (Do Not Start). The weight of the driving unit is normally 130g. By attaching weights of 20g, 40g, and 60g to this body, the weight of the driving unit was changed. We conducted three trials for each condition. Table I shows the values of the parameters used in the calculation of ρ_{j} $(j \in \{r, f\})$. These values were experimentally obtained.

Table II shows the results and Fig. 8 shows the robot's ability to climb up the clothing and the value of ρ_{j} $(j \in \{r, f\})$, respectively. When comparing front-wheel drive and rear-wheel drive, as the analysis shows, it is clear that rear-wheel drive has a higher ability to climb up clothing. As the weight of the driving unit increased, the ability to climb up the clothing decreased, in both rear-wheel and front-wheel drives. The reason will be considered later with the change in the angle of inclination (θ). A small positive value of ρ_{j} suggests that ρ_{j} could become negative, causing the robot to stop, as its value fluctuates with the movement of the robot and fabric. Then it can be said that the analytical results are consistent with the experimental results. Note that the motor used can produce a torque of 0.04 Nm, which was large enough to generate the required driving force f_{dr}^{i} given in (1).

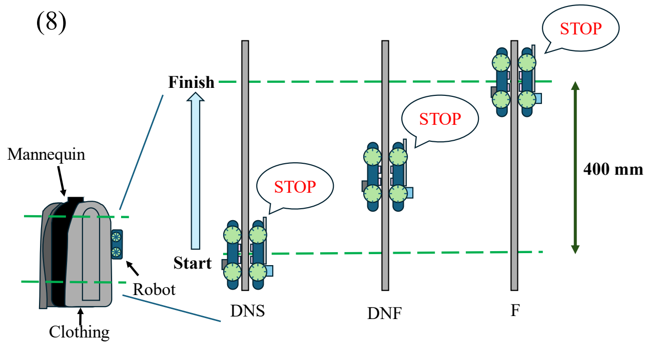


Figure 7. Experimental setup for the evaluation of the analysis

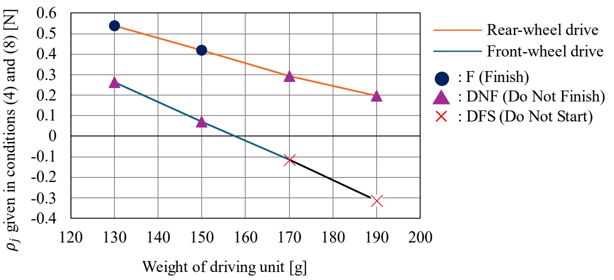
TABLE I. PARAMETER VALUES USED

Parameter	Values				
	Driving unit				Camera unit
Weight (g)	130	150	170	190	75
Front-wheel drive					
l_{f}^{i} (mm)	24.4	24.3	24.1	24.1	18.4
l_{r}^{i} (mm)	11.6	11.7	11.9	11.9	17.3
h^{i} (mm)	10	10	10	10	10
μ_{f}^{i} (mm)	0.4	0.4	0.4	0.4	0.4
μ_{r}^{i} (mm)	0.4	0.4	0.4	0.4	0.4
Rear-wheel drive					
l_{f}^{i} (mm)	11.6	11.7	11.9	11.9	17.3
l_{r}^{i} (mm)	24.4	24.3	24.1	24.1	18.4
h^{i} (mm)	10	10	10	10	10
μ_{f}^{i} (mm)	0.4	0.4	0.4	0.4	0.4
μ_{r}^{i} (mm)	0.4	0.4	0.4	0.4	0.4

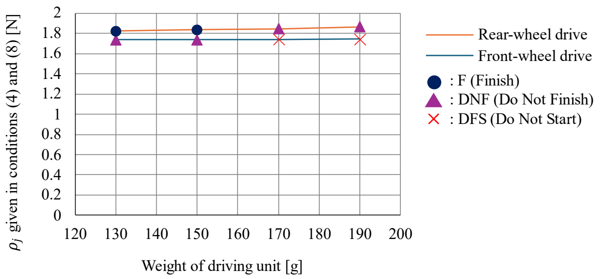
Fig. 9 shows the angle of inclination (θ). As the weight of the drive unit increased, θ also increased in both rear-wheel and front-wheel drive systems. When θ increases, the required driving force f_{dr}^{i}, as given in (1), decreases, while the normal force at the driving wheel also decreases. The reduction in normal force leads to a decrease in the available friction force, which corresponds to the maximum generable driving force. Therefore, it was more difficult for the robot to move as its weight increased. Note that the angle of inclination (θ) is determined by the moment balance of the entire robot, including both the driving and camera units. When using rear-wheel drive, the center of gravity of the driving unit is close to the front wheel, and the normal force on the front wheel of the driving unit becomes large. The position of the center of gravity, combined with the increased weight of the driving unit, may lead to a significant increase in θ.

TABLE II. RESULTS ON WHETHER THE ROBOT HAS COMPLETED THE COURSE

Weight of driving unit	Drive Method	Number of times		
		F (Finish)	*DNF (Do Not Finish)*	*DNS (Do Not Start)*
130	Rear-wheel drive	**3**	0	0
150		**3**	0	0
170		0	**3**	0
190		0	**3**	0
130	Front-wheel drive	0	**3**	0
150		0	**3**	0
170		0	0	**3**
190		0	0	**3**



(a) Driving unit



(b) Camera unit

Figure 8. Relationsip between the weight of driving unit and the values the value of ρ_j ($j \in \{r, f\}$) given in the conditions (4) and (8)

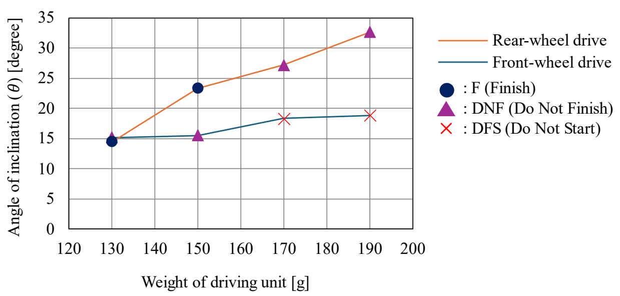


Figure 9. Relationsip between the weight of driving unit and the angle of inclination (θ).

IV. EXPERIMENTAL EVALUATION OF THE ROBOT'S FUNCTION

The functions of the developed robot were evaluated through experiments.

A. The ability to climb clothing as the fabric type changes

We investigated the robot's ability to climb clothing as the fabric type changes. Fig. 10 shows the experimental setup for the investigation. The robot was attached to the starting position on the clothing worn by a mannequin. The starting position was located around the lower back of the mannequin. The robot used was rear-wheel drive and its drive unit weighed 130 g, which is the setting that was found to have a high ability to climb the clothing in the previous experiment. We investigated whether the robot could reach the goal position when the type of clothing was changed. The goal position was set 400 mm above the starting position. The closing used was polyester, blended fibers (60% acrylic, 40% rayon) and cotton. We conducted three trials for each condition. Table III shows the results and Fig. 11 shows the robot climbing the three types of clothing. Table III demonstrates that the robot was able to climb all the clothing without any issues. The results indicate that the robot has a high ability to move on different types of clothing.

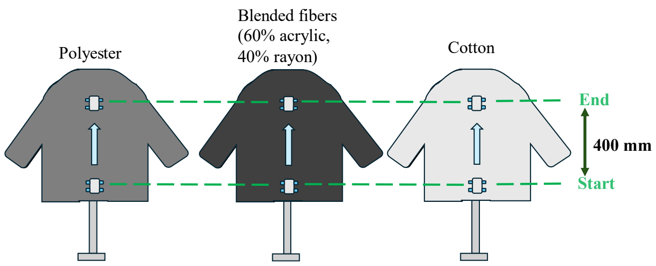


Figure 10. Experimental setuup for the investigation of the robot's ability to climb clothing as the fabric type changes

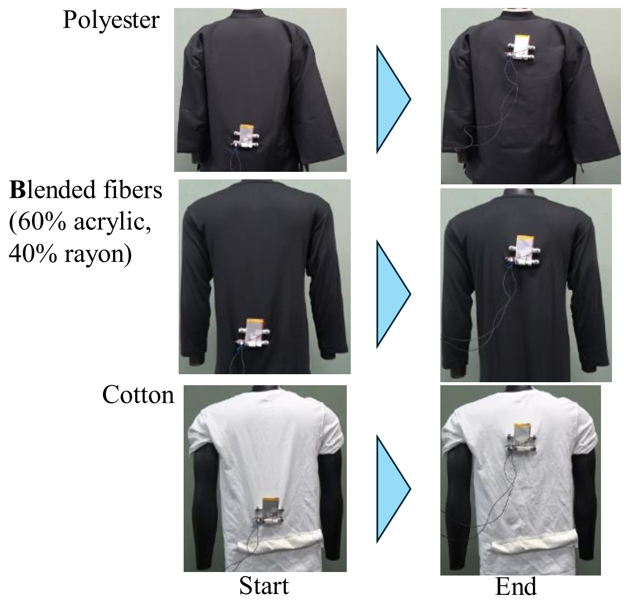


Figure 11. Overview of the investigation of the robot's ability to climb clothing as the fabric type changes

TABLE III. RESULTS OF THE INVESTIGATION OF THE ROBOT'S ABILITY TO CLIMB CLOTHING AS THE FABRIC TYPE CHANGES

Material	**Number of times**		
	F (Finish)	***DNF (Do Not Finish)***	***DNS (Do Not Start)***
Polyester	**3**	0	0
Blended fibers(60% acrylic, 40% rayon)	**3**	0	0
Cotton	**3**	0	0

B. Camera Test

The purpose of the developed robot is to inspect the body surface without the need to remove clothing. Then, we investigated whether the robot could capture the body surface. In this investigation, during while the robot was moving on the clothing, the body surface of the mannequin was photographed by the camera unit inside the clothing. Fig. 12 shows the experimental setup. In order to make it easier to evaluate the robot's inspection ability, a yellow tape with the letter A written on it and a white tape with the letter B written on it were attached to the mannequin. We investigated whether it was possible to take a photo that could distinguish between the letters on the white and yellow tape. The robot was attached to the starting position on the clothing (Polyester) worn by a mannequin. The starting position was located around the lower back of the mannequin. The robot used was rear-wheel drive and its drive unit weighed 130 g, which is the same setting as the investigation in the previous section. The robot climbed the clothing until it reached the goal position set 400 mm above the starting position. During the movement, the camera unit captured images of the mannequin's surface. We verified whether it was possible to extract text from the images captured after the movement. Fig. 13 presents the results showing the captured images and their positions on the mannequin. The figure clearly displayed the letter 'A', part of the letter 'B', and a detailed image of the mannequin's surface. These results demonstrate that the robot can effectively observe the body surface.

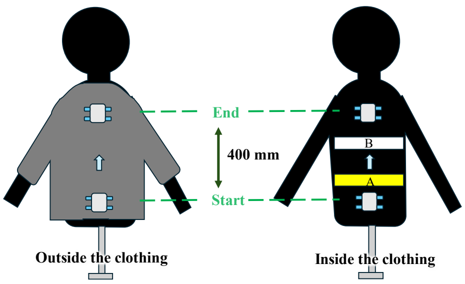


Figure 12. Experimental setup for camera test

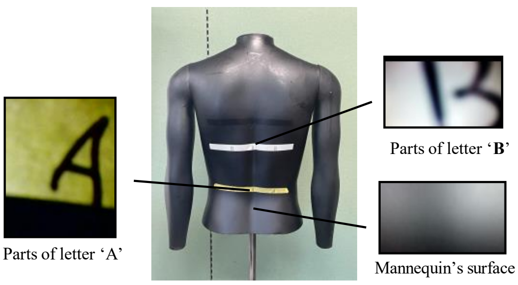


Figure 13. Results of the camera test: The captured images and their positions on the mannequin

C. The ability to climb over clothing worn by a person

We confirmed the practicality of attaching the robot to clothing worn by a person and capturing images while in motion. Figure 14 shows the experimental setup. The robot was initially attached to a designated starting point on polyester clothing worn by a test subject. The robot used equipped with a rear-wheel drive system and a 130 g drive unit, was configured to maximize climbing performance based on the findings of previous experiments. The target position was set 400 mm above the starting point. Figure 15 shows the robot in the process of climbing the polyester clothing, while Figure 16 displays the captured images of the subject's back. These results demonstrate the robot's potential usefulness for human applications.

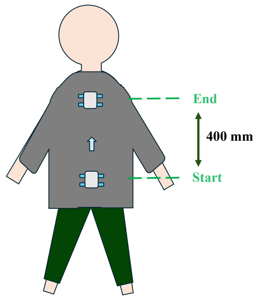


Figure 14. Experimental setup for the test

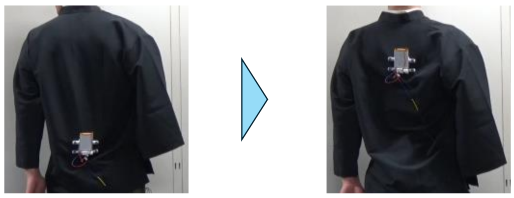


Figure 15. Overview of a study examining the climbing ability of polyester clothing worn by a test subject.

Figure 16. The captured images of the back

V. CONCLUSION

This paper presented a novel cloth-climbing robot for body surface inspection using magnetic gears, which does not require undressing. The core mechanism of this robot is that it attaches to clothing via magnetic force between a camera unit inside the clothing and a driving unit outside the clothing, with the wheels made up of magnetic gears. The camera unit is equipped with a camera for body surface inspection, while the driving unit is equipped with a motor for moving on clothing. Magnetic gears have the ability to transmit torque even when there is a gap between them. By utilizing this capability, the motor's torque in the driving unit is transmitted to the wheels of the camera unit, even though clothing, allowing each unit to operate in parallel. It was confirmed that the robot can attach to clothing and move up along it. The conditions for the robot to move up on clothing was also presented. Furthermore, experimental tests showed that the robot can clearly capture images of the mannequin's surface while moving on the clothing, making body surface inspection possible. These results demonstrate the effectiveness of the developed robot.

In the future, we aim to develop a robot that can move more freely on clothing by incorporating a mechanism to adjust rotation and speed. The developed robot features a two-wheel drive system powered by a single motor, designed to keep the robot lightweight, which is crucial for enhancing its mobility on clothing, as the presented analysis shows. A four-wheel drive system with separate motors for the front and rear wheels could not only enable rotation but also help smooth out wrinkles, improving mobility and allowing the robot to keep moving even when the clothing is heavily wrinkled or twisted. However, this could result in an increase in the robot's weight. Addressing this tradeoff is one of our future research goals.

Acknowledgment

This work was partly supported by JST [Moonshot R&D][Grant Number JPMJMS2034].

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