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Paper:

Active Cloth Fabricated by a Flat String Machine and its Application to a Safe Wheelchair System

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In this study, a pneumatically contracting active cloth has been developed; its application is proposed for a safe sitting-posture recovery system for wheelchair users to avoid fall-related accidents. The active cloth consists of thin artificial muscles knitted via a flat string machine. The safe wheelchair system is configured with an active cloth and seating pressure sensor. The seating pressure sensor, located on the seating surface of the wheelchair, estimates the inclination of the upper body of the user; when this reaches an angle that is dangerous for falling from the wheelchair, the active cloth contracts to correct the posture of the upper body. In this paper, we clarify the fabrication process and fundamental characteristics of the active cloth and indicate its potential as a mechanical element for welfare apparatuses by demonstrating a safe wheelchair system.

Keywords: pneumatic artificial muscle, active cloth, safe wheelchair system, welfare apparatus

1. Introduction

The McKibben artificial muscle is a well-known soft actuator. Its flexibility, light weight, and high generated force have led to its application in power assist devices [1–8]. In addition, integration methods for thin artificial muscles have been established [9–11]. Using these methods, cloth-like actuators with multiple artificial muscles were realized. However, these were fabricated manually, requiring a large working-time cost.

According to the Japanese Ministry of Health, Labor and Welfare, more than approximately 620,000 people have a lower-limb dysfunction in Japan; furthermore, there were 60,000 more in 2013 than in 2001 [a]. In addition, the Japanese society is aging faster. Based on this, it is estimated that there are over 200,000 wheelchair users in Japan [12]. In welfare facilities, some wheelchair users require continuous help from caregivers owing to the deterioration of their physical ability due to hemiplegia, muscle weakness, etc. Transference to and moving via a wheelchair require constant aid by a caregiver. However, one-to-one care is not always possible due to the shortage of caregivers and the user may have to wait in the wheelchair without a caregiver. Such users, with quite poor physical ability, could fall from the wheelchair while waiting as it is difficult for them to recover a safe seating posture from the inclined upper body state by themselves. The inclination of the upper body is a major factor and this study focuses on it as the cause of fall-related accidents. Various devices and systems have been researched to prevent such accidents [13–15]; however, conventional actual usage devices practically restrict the body of the user. By restricting even healthy body parts, the physical ability of the user may decline. Moreover, there is a risk of causing pressure ulcers at the point of contact with the wheelchair. In this study, we developed a novel method for fabricating integrated thin artificial muscles into an active cloth. By introducing a machine originally used for manufacturing flat strings, an easy process for fabricating the active cloth is established. The active cloth is then applied to the safe system of a wheelchair to demonstrate the effectiveness of the active cloth as an actuator for mechanical welfare systems.

2. Active Cloth

2.1. Pneumatic Artificial Muscle

The McKibben artificial muscle is configured with an inner rubber tube and a sleeve formed by knitted fibers. By applying pneumatic pressure to the inner rubber tube, the artificial muscle radially expands and axially contracts by changing the knitting angle of the sleeve fibers, as shown in **Fig. 1**. A thin artificial muscle has been developed, and its advantages of high flexibility and ease of embedding into mechanisms have been clarified [16, 17].

We used a thin artificial muscle, 2.5 mm in diameter. The fundamental characteristics were measured; **Fig. 2** shows the results. Similar to the general pneumatic artificial muscle, the graph shows the hysteresis and the max-

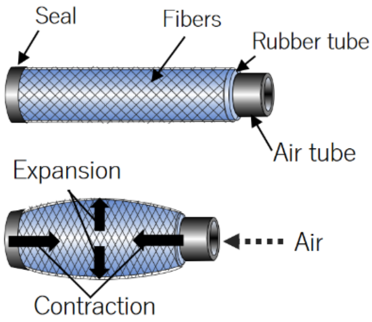


Fig. 1. Configuration of the McKibben artificial muscle.

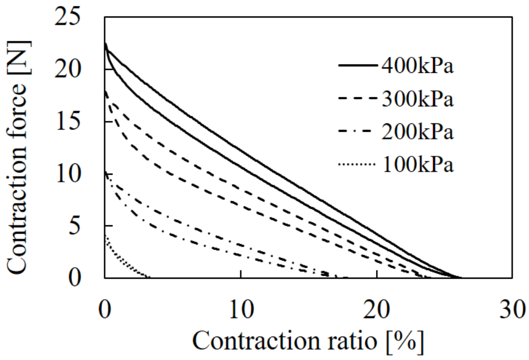


Fig. 2. Thin artificial muscle characteristics.

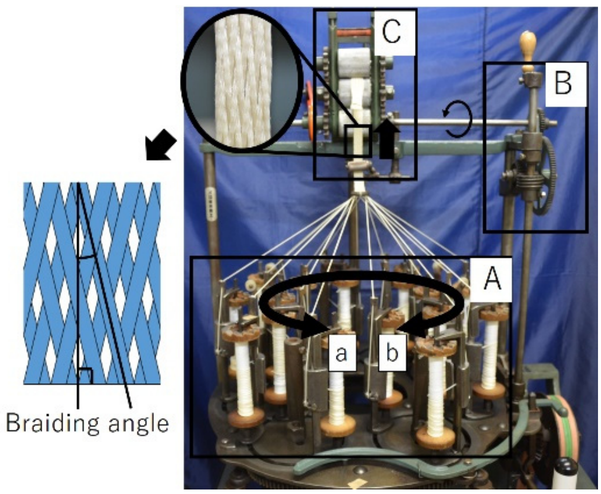
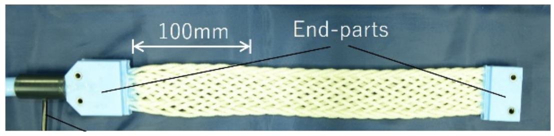


Fig. 3. Fabrication of the active cloth by the flat string machine.

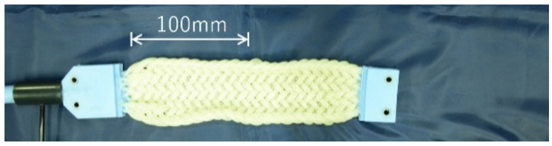
imum contraction force and ratio were 22 N and 26%, respectively, at 400 kPa.

2.2. Manufacturing Method of Active Cloth

Figure 3 shows the flat string machine. The machine has three main mechanical parts: A, the disk; B, the gear; and C, the reel-up. In general, the machine is used for making flat strings, e.g., a strap, shoelace, etc. In this study, the machine is utilized to fabricate an active cloth with multiple artificial muscles. There are 17 bobbins connected with carriers in the disk part. Thin artificial



(a) Initial state



(b) Driving state (400 kPa)

Fig. 4. The active cloth; (a) the initial and (b) driving state.

muscles are set into the bobbins. The carriers repeatedly move via the electric motor between the a- and b-points with following the ditch, crossing each other. The artificial muscles from the bobbins are simultaneously wound up by the roller in the reel-up part. The rotating force of the roller is transmitted from the electric motor through the gears in the gear part. The resulting thin artificial muscles are knitted into a flat string shape; this is hereafter referred to as "active cloth."

Using this fabrication method with a flat string machine, braiding the artificial muscles can be achieved dependent on the artificial muscles being set on the bobbins. The active cloth can be fabricated at a rate of approximately 10 mm/s.

2.3. Characteristics of the Active Cloth

Figure 4(a) shows the initial state of the active cloth and the braiding angle (the cross angle of the artificial muscles, defined in **Fig. 3**) is 7.65°. There are two end-parts; one is a manifold with an air supply tube and the other is a plug for preventing air leakage. These are attached to the active cloth. Both parts are made from a silicone rubber material and fabricated via a rubber molding process; hence, these parts are soft. In addition, the end with the air supply tube is a manifold structure, allowing all artificial muscles to be pressurized via a single air supply. The active cloth contracts under pneumatic pressure, as shown in **Fig. 4(b)**. The width of the active cloth is approximately 47 mm and 60 mm in the initial state and driving state at 400 kPa, respectively. The maximum pressure was set at 400 kPa as the active cloth sometimes broke at 500 kPa.

Figure 5 shows the characteristics of the fabricated active cloth. The maximum contraction force and contraction ratio are approximately 268 N and 33%, respectively, at 400 kPa. By integrating the artificial muscles into cloth form, the contraction ratio increased by approximately 1.3 times. Conversely, the contraction force per artificial muscle is 15.7 N and is reduced by approximately 30%. This phenomenon was also observed in previous reports [10, 11]. In these reports, the integration mechanisms of the artificial muscles were fabricated manually.

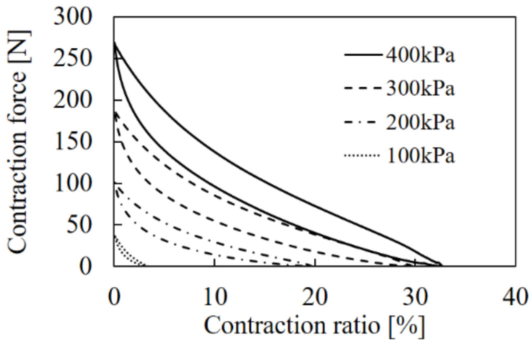
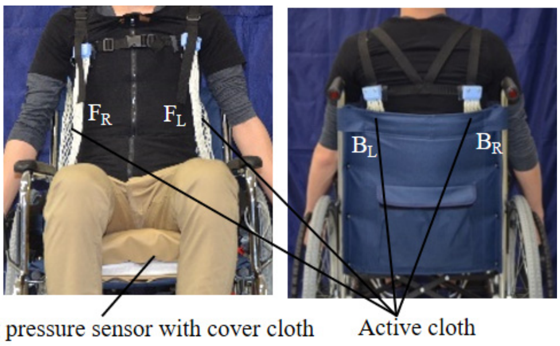
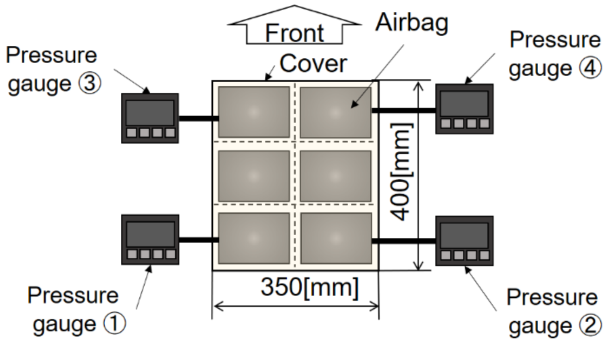


Fig. 5. Characteristics of the active cloth with 17 artificial muscles.



(a) Front view (b) Back view

Fig. 6. Configuration of the safe wheelchair system.



(a) Structure

(b) Fabricated sensor

Fig. 7. Seating pressure sensor.

3. Safe Wheelchair System

3.1. Concept and System Configuration

A safe wheelchair system has been developed as an example of an active cloth application. As mentioned in Section 1, a major reason for fall accidents from the wheelchair is that some wheelchair users cannot raise their upper body from the inclined state. Therefore, the developed system aims to support the upward movement of the upper body according to the inclined state. When the upper body is inclined at a certain angle, predetermined as dangerous for falling, the active cloth is activated and applies a force to pull up the upper body, without the intention of the user. It is assumed that the system is used while the wheelchair is motionless on a flat floor.

Compared to the use of the general McKibben artificial muscles, several tens of mm in diameter, which can generate the same level of contractile force in the active cloth, the active cloth has a thin structure and low bending rigidity. Therefore, it will be easy to embed in wearable cloth in the future; thus, aesthetics and comfort will not be of concern to the end-users.

The system consists of four active cloths (shown in **Fig. 6**) and a seating pressure sensor. One end of each active cloth is fixed to the seat of the wheelchair, and the other end is attached to the harness worn by the user; the active cloths are arranged on the front-right (F_R), front-left (F_L), back-right (B_R), and back-left (B_L) of the upper body. The seating pressure sensor used for estimating the inclination of the upper body is set on the seat of the wheelchair.

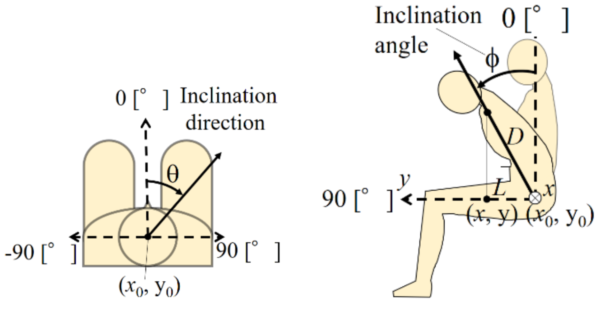
The methodology of the safe system is as follows:

1. The seating pressure sensor estimates the inclination of the upper body of the user.
2. If the inclination angle exceeds a certain threshold angle, set in advance as the limit angle, the active cloths are driven to help recover the orientation of the upper body.
3. The inclination angle is safe. The pneumatic pressure is released from the active cloths.

3.2. Seating Pressure Sensor

The seating pressure sensor used to measure the inclination direction and angle of the upper body of the user is shown in **Fig. 7**. Soft sensors using airbags have been reported [18, 19]. In this study, the developed sensor consists of six airbags; four bags are used for sensing and two bags are just structural elements.

By measuring the inner pressure of the four bags located at the front and rear via general pressure gauges, the



(a) Upper view (x-y plane) (b) Side view

Fig. 8. Definition of inclination direction and angle.

inclination direction and angle of the upper body were estimated. The load F_i ($i = 1,2,3,4$ corresponding to **Fig. 7**) added to each airbag is expressed by Eq. (1).

$$F_i = a(P_i - P_{0i}) \qquad (1)$$

P_i and P_{0i} are the measured and initial pressure of each airbag, respectively, and a is the experimentally investigated coefficient.

The inclination direction θ, and the inclination angle ϕ, are defined as shown in **Fig. 8**.

From the load F_i, the position of the center of gravity on the x-y plane is calculated using the following [20]:

$$x = \frac{87.5 \times (F_2 + F_4 - F_1 - F_3)}{\sum_{i=1}^{4} F_i} \qquad (2)$$

$$y = \frac{266.7 \times (F_3 + F_4)}{\sum_{i=1}^{4} F_i}. \qquad (3)$$

The position of the center of gravity on the x-y plane in the upright state is defined as (x_0, y_0). The moving distance of the center of gravity on the x-y plane L, is expressed as:

$$L = \sqrt{(x - x_0)^2 + (y - y_0)^2}. \qquad (4)$$

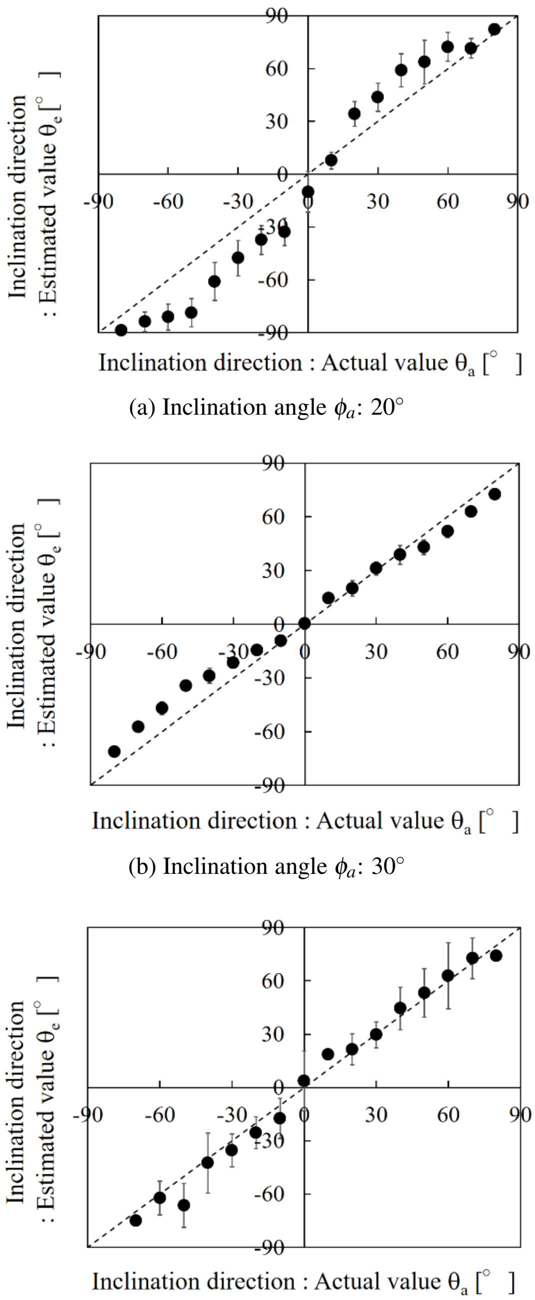
Therefore, the inclination direction θ and angle ϕ, are derived from the following:

$$\theta = \sin^{-1}\left(\frac{x - x_0}{L}\right) \qquad (5)$$

$$\phi = \sin^{-1}\left(\frac{L}{D}\right). \qquad (6)$$

D is the distance from the lumbar to the ninth thoracic vertebra. The ninth thoracic vertebra is said to be the center of gravity of the upper body in general [b].

The seating pressure sensor was experimentally evaluated for a healthy male subject. The estimated inclination direction θ_e and angle ϕ_e, were compared with the actual inclination direction θ_a and angle ϕ_a, which were detected via the conventional angle sensor mounted on the body surface around the ninth thoracic vertebra.



(a) Inclination angle ϕ_a: 20°

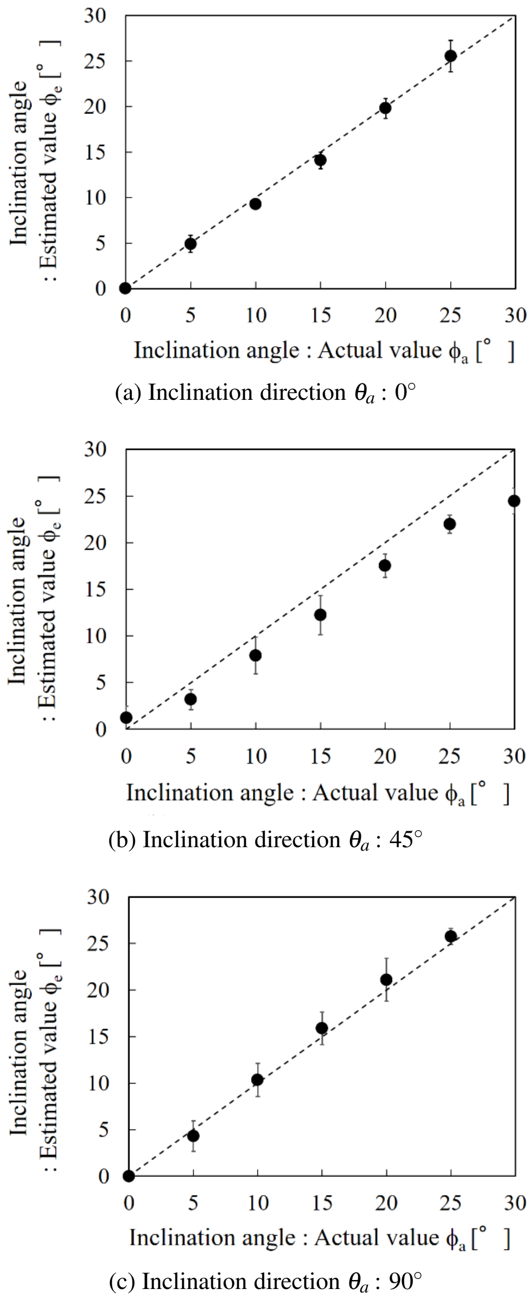
(b) Inclination angle ϕ_a: 30°

(c) Inclination angle ϕ_a: 40°

Fig. 9. Relationship between the actual inclination direction θ_a and the estimated inclination direction θ_e.

The subject reciprocates the upper body three times from inclination directions θ_a, between $-90°$ and $90°$ for approximately 30 s while maintaining an inclination angle ϕ_a, of 20°, 30°, and 40°. **Fig. 9** shows the results. The horizontal axis is the actual inclination direction θ_a, measured by the conventional sensor and the vertical axis is the direction estimated by the seating pressure sensor θ_e.

In the next experiments, the subject tilted his upper body with an increasing inclination angle ϕ_a, toward the inclination directions θ_a of 0°, 45°, and 90°. **Fig. 10** shows the results of the estimated inclination angle ϕ_e by the seating pressure sensor.



(a) Inclination direction θ_a : 0°

(b) Inclination direction θ_a : 45°

(c) Inclination direction θ_a : 90°

Fig. 10. Relationship between the actual inclination angle ϕ_a and the estimated inclination angle ϕ_e.

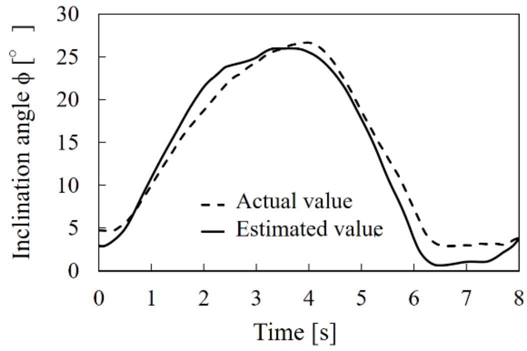


Fig. 11. Dynamic characteristics of the estimated inclination angle corresponding to **Fig. 10(c)**.

Figure 11 shows an example of the dynamic characteristics corresponding to **Fig. 10(c)**.

From the results shown in **Figs. 9–11**, the actual and estimated values from the seating pressure sensor are statically and dynamically moderately matched and the accuracy is considered permissible for driving the system as the threshold value of the angle can be set within a safety tolerance. The errors were due to the nonlinearity of the seating pressure sensor and the mechanical instability of the human body.

Although measurements of the inclination of the upper body can be performed by attaching conventional displacement sensors, angle sensors, etc., the seating pressure sensor has been developed and applied for the following two reasons: first, caregivers consider that the number of devices attached to wheelchair users should be reduced as much as possible. Second, there is a concept of adjusting the seated position and preventing pressure ulcers by airbag actuators on the sitting surface [20]. We assume that the seating pressure sensor will be able to be developed as an airbag sensor-actuator device with additional functions, such as adjusting the seated position and preventing pressure ulcers.

3.3. Driving System

The driving system was designed to be mounted on the wheelchair. The system comprises a compact air compressor with a tank (Koganei Corporation, DPP-AT), electric/pneumatic regulators (CKD Corporation, EVT500), a battery, a battery circuit, and a microcontroller (Cypress Semiconductor Corporation, CY8CKIT-059). These components can be attached to the backrest and backside of the seating face. The microcontroller calculates the offset pressure value to the active cloths from the physical information of the subject to adjust the initial length of the active cloths. In addition, it receives the pressure value of each airbag of the seating pressure sensor and estimates the inclination direction θ and angle ϕ of the upper body. If the estimated inclination angle ϕ_e exceeds the pre-determined threshold value, the microcontroller sends the signal to the electric/pneumatic regulator to drive the active cloths. The driving cloth is selected depending on the estimated inclination direction θ_e, as shown in **Table 1** and **Fig. 6**. Then, the estimated inclination angle ϕ_e becomes a safe value, i.e., an almost upright state of the upper body; the applied pressure to the active cloth decreases to the offset pressure.

To verify the performance of the system, a driving test was conducted. In this test, the subject inclined the upper body toward the inclination direction θ_a of 90°; the estimated inclination angle ϕ_e, and the pneumatic pressure in the active cloths were measured. The threshold value of the inclination angle ϕ was set to 30° and the applied pressure was released when the angle was within 5° due to the recovery motion.

Table 1. Driving active cloth depending on the inclination direction.

		Inclination direction θ_e [°]				
		$-90\sim-54$	$-54\sim-18$	$-18\sim18$	$18\sim54$	$54\sim90$
Active cloth	F_R	ON	ON			
	F_L				ON	ON
	B_R	ON	ON	ON	ON	
	B_L		ON	ON	ON	ON

ON: Driving

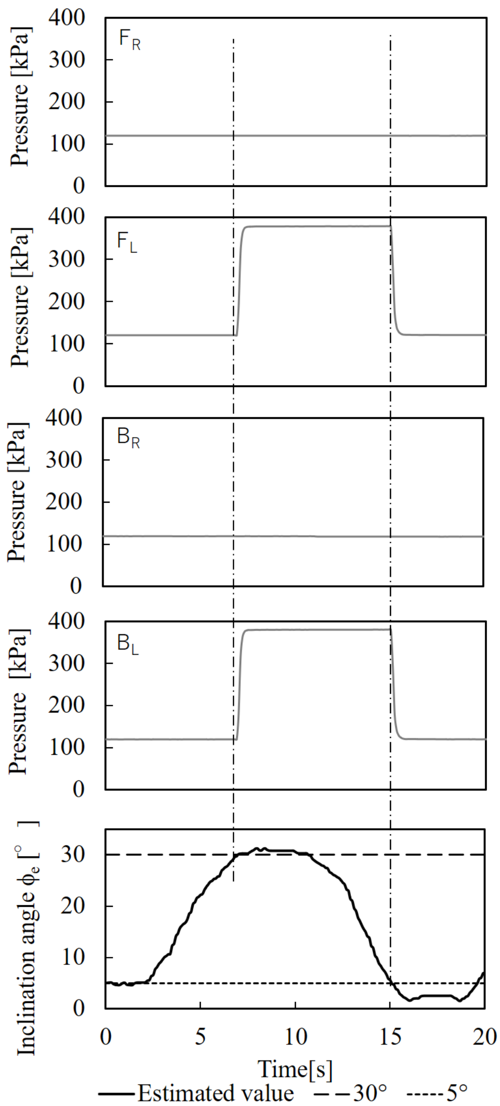


Fig. 12. Results of the fundamental experiment using a developed driving system.

Figure 12 shows the results of the fundamental experiments, during which the offset pressure was 120 kPa. It was found that pressure was applied to the active cloth F_L and B_L when the inclination angle ϕ_e exceeded the threshold value of 30° and when the inclination angle ϕ_e returned below 5°, the pressure was released. Furthermore,

Table 2. The measurement points of EMG.

		Inclination direction θ [°]				
		−90	−45	0	45	90
Back muscle	Right	○	○	○		
	Left			○	○	○

○: Measurement point

it was confirmed that pneumatic pressure was applied to the active cloth correctly for other inclination directions of −90°, −45°, 0°, and 45°, according to **Table 1**.

3.4. Evaluation Experiments

Evaluation experiments were conducted for five healthy adult males. The subjects were given the following instructions.

1. Sitting in the wheelchair.
2. Inclining the upper body at $\phi_a = 30°$ in a certain direction ($\theta_a = -90°$, $-45°$, $0°$, $45°$ and $90°$), with reference to the conventional angle sensor (the conventional sensor is only used for reference to ensure the correct experimental condition and is not used for driving the system).
3. Raising the upper body for 10 s with minimum muscle activity, i.e., as relaxed as possible.

During this motion, the electromyogram (EMG) of the back muscles was measured with a sampling period of 1 ms, and compared with the driving and non-driving case. Depending on the physical disease condition of the actual user, the EMG does not directly relate to the generated muscle force. Therefore, in actual usage, we cannot evaluate the effectiveness of the system using EMG. The experiments for healthy male subjects intend to verify that the system applies force to raise the upper body. If the EMG is reduced by the system, it indirectly indicates that some force is exerted on the upper body.

According to the inclination direction θ, we changed the EMG measurement locations (right side or left side of the back muscles), as shown in **Table 2**, for targeting the active muscles during the raising motion.

3.5. Experimental Results

Figure 13 shows an example of an EMG measurement. Here, the EMG was processed by rectification and a moving average of 300 points (average rectified value: ARV). The hatched area indicates that the active cloths are driven when driving the system. In this example, by driving the system, the EMG clearly decreases during the recovery (raising) motion of the upper body.

The EMG during the assisting range was integrated; the integrated values of the non-driving and driving case were compared and the decreasing ratio owing to the system

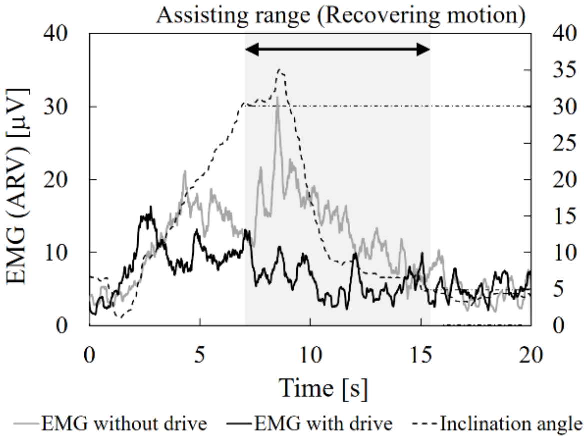


Fig. 13. An example of EMG (ARV) data.

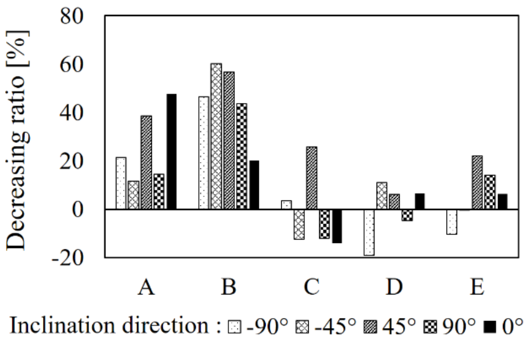


Fig. 14. The decreasing ratio of integrated EMG.

was calculated. **Fig. 14** shows the decreasing ratio for all subjects in the five inclination directions.

In a total of 25 experiments, a value reduction due to driving the system was confirmed in 18 cases. Conversely, it increased in 7 cases. The maximum decrease ratio is approximately 60%, and the maximum increase ratio is approximately 19%. The average reduction ratio, including the increased cases, is 15%. In addition, after the experiments, the subjects could choose one of the following descriptors concerning the feeling of assistance from the active cloths: strong, moderate, weak, very weak, or nothing. All subjects selected "Strong." However, as mentioned above, the integrated EMG value increased in some cases; it is considered that by suddenly applying an external force to the body from the active cloth, the muscles become active reflexively, even if the subjects are trying to relax. However, the experimental results comprehensively indicate the potential of this safety system.

4. Conclusion

In this study, an active cloth with multiple thin pneumatic artificial muscles was developed. By introducing a flat string machine, an automatic fabrication process for the active cloth was established. The active cloth is thin and flexible, and its contraction is higher than that of a single artificial muscle, although the contraction force per artificial muscle decreases. For the application of the active cloth, a safe wheelchair system was proposed and manufactured. This system works to prevent falling accidents from wheelchairs. To detect the inclination of the upper body, a seating pressure sensor was developed. The sensor can estimate the inclination direction and angle of the upper body. Fundamental experiments for healthy subjects were conducted, and the average EMG values decreased during the upper body recovered from the inclined state by the system. This indicates the positive possibility of the system for preventing accidents related to falling. Through this study, we showed the high potential for active cloth as a driving source for welfare apparatuses.

Acknowledgements

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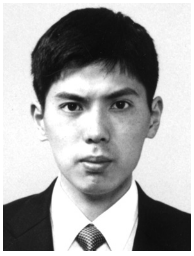

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