

Basic Study on Airbag-based Stationary Type Bracing System for Treatment of Scoliosis

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Abstract— Scoliosis is a condition characterized by an abnormal curvature of the spine, which may develop idiopathically during growth or as a result of neurogenic or myogenic diseases. As scoliosis progresses, it can exert pressure on internal organs, disrupt cardiac rhythm, and cause breathing difficulties, particularly in the sitting posture. Early detection and consistent use of an orthosis are essential to manage the progression of scoliosis effectively and to correct the patient's posture. Conventional orthotic devices face challenges in measuring and controlling the pressure applied to different areas of the torso, as well as in adjusting the bracing force in response to changes in symptoms. This study aims to develop a novel system incorporating airbags that can dynamically adjust the bracing force through air pressure modulation. The system is designed to measure and control the corrective force required for scoliosis treatment, in a sitting position, and to integrate with a chair for practical application. Its basic performance was evaluated through functional experiments. We developed a prototype system capable of automatically applying force at three specific points by adjusting the air pressure in airbags using solenoid valves and air pumps controlled by a microprocessor. To assess its performance, experiments were conducted on a mannequin to apply a prescribed corrective force to three lateral points. The pressure range tested was between 30 kPa and 80 kPa, with increments of 10 kPa. The results demonstrated that the system could reliably apply the prescribed pressure to the mannequin at all tested levels, with an error margin comparable to that of existing adjustable orthotic devices. In conclusion, the experiments confirmed the basic performance of the developed system for scoliosis treatment, indicating its potential utility in clinical applications.

I. INTRODUCTION

Scoliosis is a lateral deformation of the spine that can result from growth-related factors, neurogenic conditions, or myogenic diseases [1]. As the deformation progresses, it places pressure on internal organs when in a sitting position, causing breathing difficulties and other complications [2]. To prevent the progression of scoliosis and maintain proper posture, daily use of an orthosis and the continued application of appropriate corrective forces are essential [2][3]. However, the orthoses currently in widespread use are typically made of rigid materials, leading to discomfort as they fail to accommodate changes in body shape. This discomfort often results in discontinuation of use and issues like decubitus (pressure sores). Furthermore, these devices

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lack the ability to adjust the corrective force in response to changes in the severity or improvement of the spinal deformation [4][5].

Previous studies on orthoses have explored the use of soft materials to improve comfort, incorporating mechanisms such as linear actuators or airbags to adjust and maintain corrective forces in real time. However, a practical system that integrates the easy adjustment of corrective forces based on symptoms, precise measurement and control of applied pressure across both target and surrounding areas, and a design suitable for seamless use in daily life remains undeveloped [4][6][7].

Among the methods developed to adjust and maintain corrective forces, this study focuses on a system utilizing airbags [6][8]. Airbags can adjust the applied corrective force by measuring and controlling the internal air pressure. They are thinner and lighter than mechanical linear actuators and are flexible enough to deform, ensuring that the force is consistently applied to the body. Additionally, previous studies have demonstrated that braces incorporating airbags placed between the torso and the body are effective in treating scoliosis [8]. We hypothesize that placing multiple airbags around the torso and controlling their internal air pressure allows for precise measurement and regulation of corrective forces, leading to improved therapeutic outcomes. Furthermore, the air compressor controlling the pressure inside the airbags can be positioned independently from the torso. This design enables the development of a system that does not hinder the user's movements, enhancing its usability in daily life.

To develop a system capable of applying, measuring, and controlling the corrective forces required for scoliosis treatment while reducing discomfort during sitting—a posture that accounts for much of daily life—we designed an airbag-based system. This system applies force at three points on the torso based on the three-point pressure application method. The proposed approach, illustrated in Fig. 1, involves applying forces to the spine through the ribs or torso in a direction opposite to its curvature, thereby suppressing and correcting spinal deformities. This method is a fundamental approach in scoliosis treatment [9][10][11].

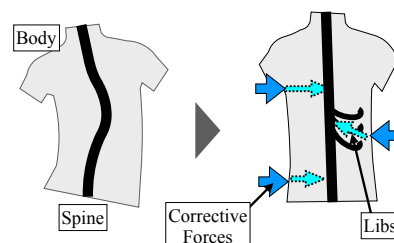


Fig. 1 Concept of three-points pressure application method

In this study, we propose and develop a scoliosis correction stationary bracing system that can automatically control the force applied to the torso by regulating solenoid valves and pumps based on the air pressure inside the airbag. This system is based on a three-point pressure application method and is capable of applying pressure perpendicular to the sagittal plane at three points on the left and right sides of the torso. In addition, we clarified the feasibility of this system for scoliosis treatment by applying specific forces to the torso through a basic experiment that applied specific forces to the torso of a mannequin.

II. SYSTEM DEVELOPMENT

A. System Configuration

An overview of the proposed system is presented in Fig. 2. In this research, the airbag unit, that is shown in Fig. 3, are placed vertically on both sides of the torso to realize the three-points pressure application method, which is one of the principles of scoliosis correction [9][10][11]. Therefore, these airbags apply force only perpendicular to the sagittal plane at three alternating points in the direction of correcting scoliosis to maintain correct posture using the frame and airbags. A

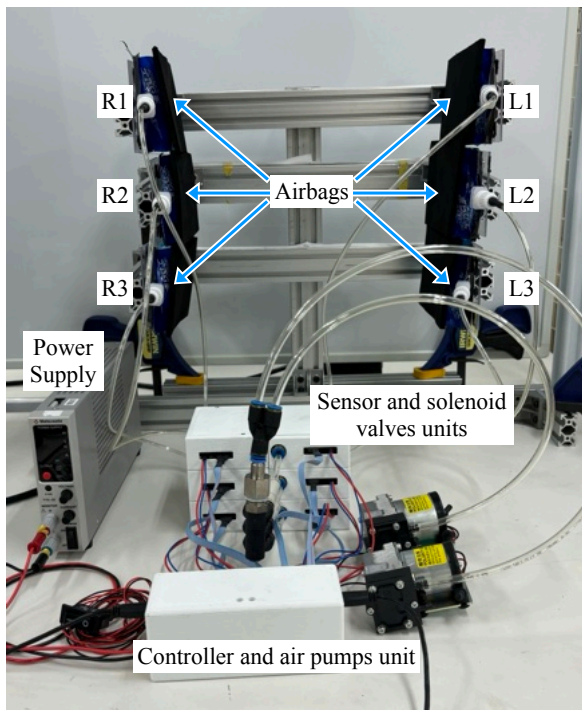


Fig. 2 Overview of the system

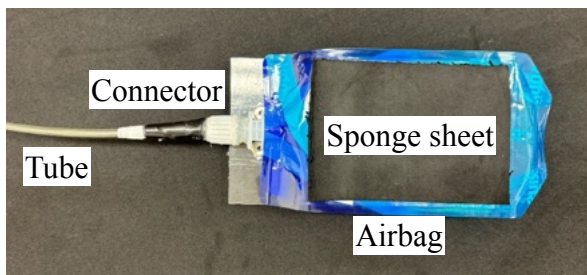


Fig. 3 Airbag unit

sensor/solenoid valve unit was attached to each airbag such that the force applied to the torso could be individually controlled by measuring and controlling the air pressure in each airbag. Each sensor/solenoid valve unit was connected to a control/pump unit that received signals from the sensors and controlled the solenoid valves, which opened and closed the solenoid valves, and supplied air based on the air pressure sensor values.

B. Airbag Unit

The airbag unit consisted of an airbag, a sponge sheet, a connector, and a tube for air intake and exhaust. The airbags used in this system are adapted from gusseted beverage containers, designed to undergo minimal changes in surface area when in contact with the human body, depending on the amount of air inside. A resin connector, fabricated using a 3D printer, was attached to the airbag's opening and connected to a urethane tube (CHIYODA TSUSHO, TE-4).

A sponge sheet with dimensions of 70 mm × 100 mm was affixed to the surface of the airbag in contact with the torso. To prevent interference between airbags, they were positioned with 20 mm gaps between the sponge sheets. The vertical

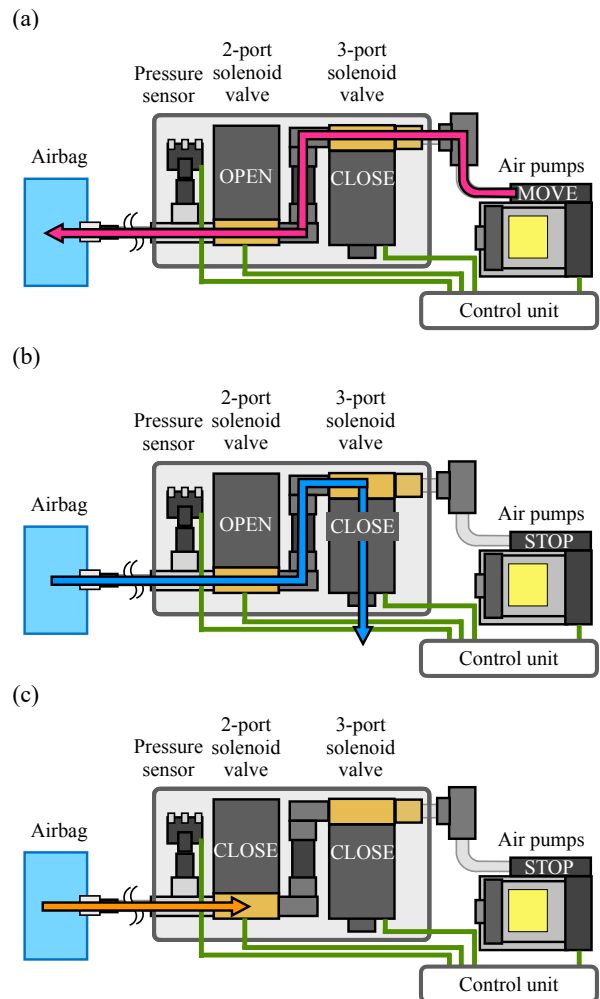


Fig. 4 operation of sensor and solenoid valves unit
(a) When insert air into the airbag. (b) When air is exhausted from the airbag. (c) When maintaining air in the airbag.

height of the three sponge sheets, arranged side by side, was 250 mm, sufficient to cover most of the 255 mm range corresponding to 95 % of young adults' armpit-to-iliac crest length [12]. This range is critical for applying forces in the three-point pressure application method.

The position of each airbag could be easily adjusted to fit the user's body shape by modifying the joint positions on the frame, ensuring a customizable fit. The airbag and aluminum frame function similarly to a conventional brace. When using this system, the user's spine should first be straightened by the support provided by the airbags and frame, as with conventional braces. The airbags should then be positioned at the points where force is to be applied using the three-point pressure application method. Any deformation or displacement of the torso when pressure is applied can be accommodated by changes in the airbag's thickness during inflation or deflation and by adjusting the frame accordingly.

C. Sensor/Solenoid Valve Unit

The sensor/solenoid valve unit consists of a barometric sensor and two solenoid valves. A barometric sensor (METRODYNE MICROSYSTEM, MIS-2500-015G) measured the air pressure inside the airbag. A 2-port solenoid valve (CKD, USB2-M5-2-0-DC12V) and a 3-port solenoid valve (CKD, USG2-M5-2-0-DC12V) were combined to supply and exhaust the air inside the airbag by controlling the opening and closing of the valve. When both the 2-port and 3-port solenoid valves are open, the path from the pump to the airbag is activated (Fig. 4-(a)). Conversely, when the 2-port

solenoid valve is open and the 3-port solenoid valve is closed, air is released from the airbag (Fig. 4-(b)). When the 2-port solenoid valve is closed, air is maintained in the airbag (Fig. 4-(c)).

D. Control/Pump Unit

The control/pump units consist of two microcontrollers and two air pumps. The microcontrollers (Espressif Systems, ESP-32 Dev. Kit) manage the two air pumps (Nitto Koki, DPA0105-X1) and the solenoid valves in the Sensor/Solenoid Valve Unit, based on the air pressure inside the airbag measured by a barometric sensor. The flowchart for pressure control, based on the air pressure in the airbag, is shown in Fig. 5. The flow chart loop has a period of 250 ms. For air pressure A [kPa] acting from the airbag and the target pressure D [kPa], the solenoid valves and pumps are controlled to maintain the air pressure if $D - k \leq A \leq D + k$, air is inserted if $A < D - k$, and if $D + k < A$, air is discharged. Additionally, D can be adjusted to move closer to A even if D is within the range $D - k \leq A \leq D + k$, if $D < A$ or $A < D$ persists for a certain time $t = t_s * 250$ s. In this study, k and t were set to 3 kPa and 2.5 s ($t_s = 10$) heuristically.

E. Derivation of the Function for Control.

The following tests were conducted to derive the equation relating the output voltage of the sensor in the sensor/solenoid valve unit to the force applied to the surface of the airbag and the air pressure inside the airbag.

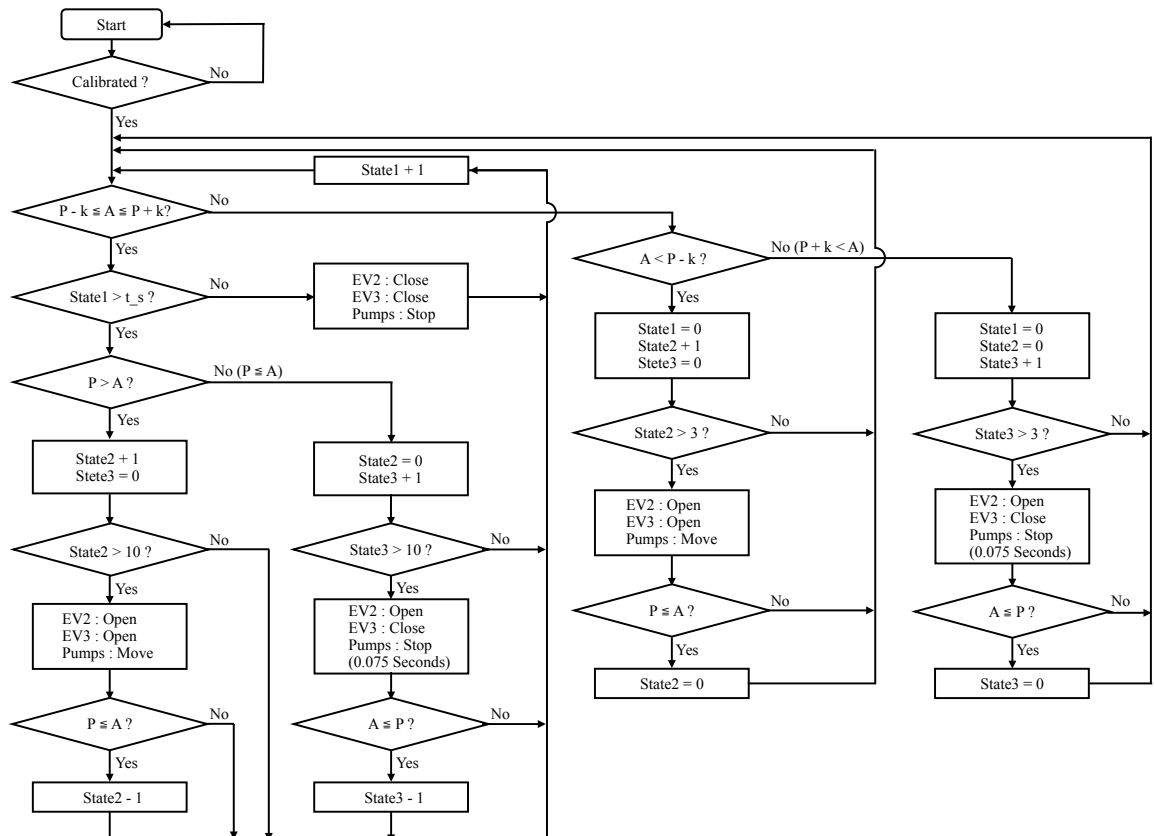


Fig. 5 Flowchart of controlling pressure based on air pressure in airbag.

First, the airbag used in the airbag unit was connected to the barometric sensor used in the sensor/solenoid valve unit. Next, the airbag and measurement pad of the pressure distribution measurement system (novel.de, Pedar) were placed in a jig with two plates that moved vertically up and down, with the upper and lower plates in parallel. The contact area between the airbag and jig was 70 mm × 100 mm. The upper plate of the jig was placed in contact with the tip of a digital force gauge (IMADA, ZP-1000N) attached to a motorized test stand (IMADA, EMX-1000N-FA) (Fig. 6). In this state, air was supplied and discharged from the airbag to adjust the force acting on its surface. The air pressure and the force applied to the airbag surface were measured using a digital force gauge at increments of 20 N within the range of 0 N to 600 N. The function was derived based on the results from the 200 N to 600 N range. This range was chosen because, from 0 N to 200 N, the pressure was applied sparsely, as shown in Fig. 7, and only a portion of the bag came into contact with the top plate of the jig. Additionally, in a study that investigated the pressure exerted on the torso by scoliosis braces [13], the maximum pressure exerted on the body

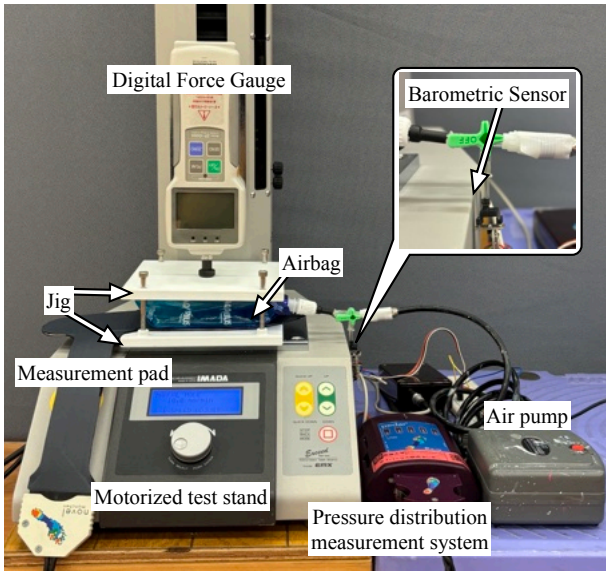


Fig. 6 Environment for load application experiment

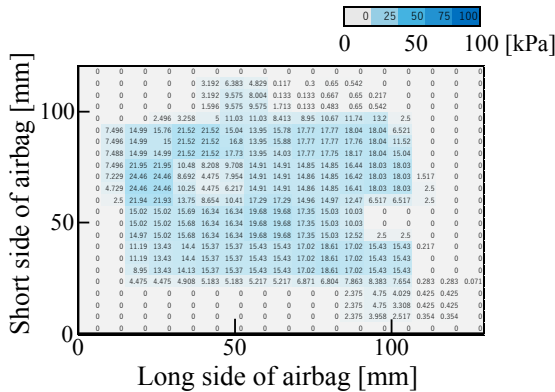


Fig. 7 Measurement results of the pressure distribution measurement system at 180 kPa

surface in a sitting position was approximately 80 kPa. Therefore, the force exerted from the surface of the airbag, which has a contact area of 0.0070 m² between the airbag and the jig, should be set to exceed 80 kPa.

For both the air supply and discharge cases of the airbag, the output voltage value of the barometric sensor was measured with respect to the value at 0 N and the measured pressure applied to the measurement pad for 3 s using a digital force gauge. The average of these values was used to derive the function. The average value of the pressure applied to the measurement pad in the pressure distribution measurement system was calculated by using a value that was at least 10% of the maximum value in the measurement, in order to exclude areas, such as the lower right of Fig. 7, where the pressure was believed to be measured due to contact with a jig other than the airbag.

The resulting correspondence between the voltage of the barometric sensor and the pressure measured by the pressure distribution measurement system is shown in Fig. 8. Fig. 8 shows that the relationship between the voltage and pressure applied to the airbag surface remained almost unchanged when air was supplied or discharged. Therefore, the least-squares method was used to obtain a linear approximation line between the voltage value of the barometric sensor V and the pressure measured by the pressure distribution measurement system P kPa, and the relationship became Equation (1).

$$P = 33.491 V + 8.482 \quad (1)$$

In this study, the pressure A kPa acting on the airbag surface was calculated from the voltage value of the barometric sensor based on function (1).

III. BASIC EXPERIMENT

A basic experiment was conducted to confirm that the airbag in the system could follow the torso surface and apply pressure. In this experiment, a mannequin was seated on the system to verify that the specified pressure was applied by the system. The mannequin was made of hard resin and was designed to imitate the upper body of a patient without scoliosis. In this study, the mannequin was treated as an upper body fixed with the spine in a straight position by the airbags and the frame, as described in Section II-B.

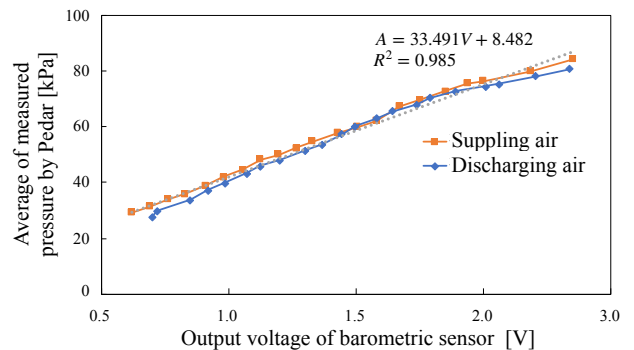


Fig. 8 Result of load application experiments

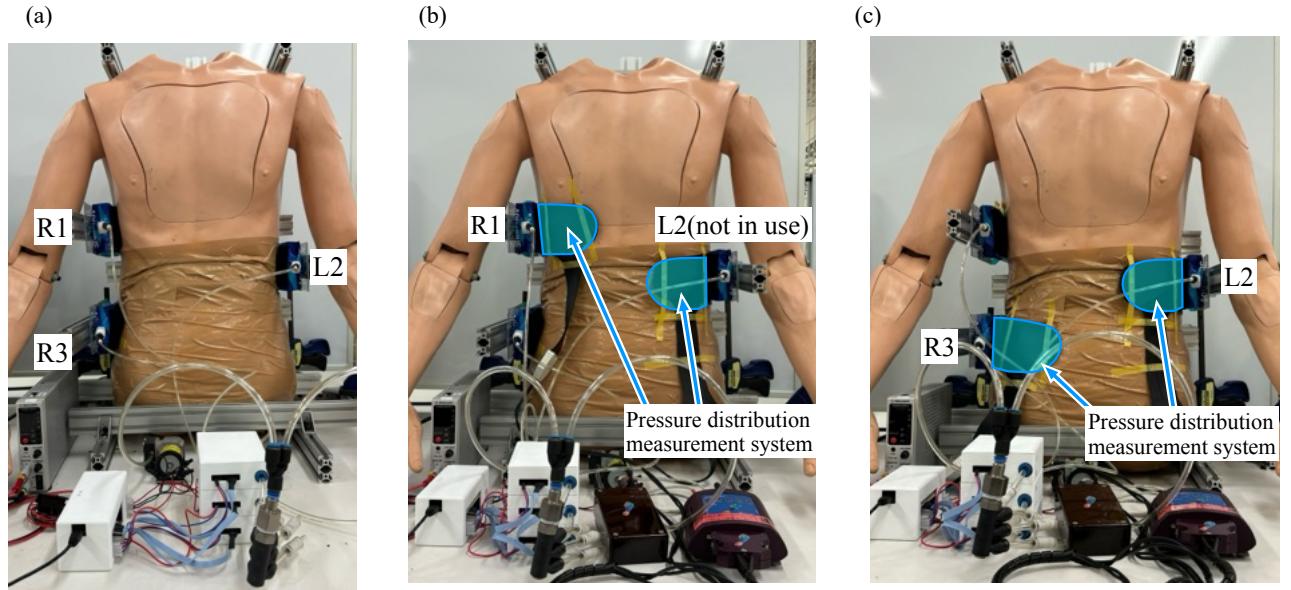


Fig. 9 Environment of measuring

(a) Environment for basic performance evaluation experiments. (b) Environment when measuring R1. (c) Environment when measuring L2 and R3

Table 1 Target and measured values and their absolute mean percent error in functional evaluation tests

Target Pressure (kPa)	R1		L2		R3	
	Actual Values (kPa)	MAPE (%)	Actual Values (kPa)	MAPE (%)	Actual Values (kPa)	MAPE (%)
80	75.80±0.61	5.54±0.87	85.41±1.12	6.33±1.23	80.07±1.02	0.91±0.80
70	67.12±0.70	4.30±1.08	75.19±1.36	6.88±1.72	70.32±1.30	1.63±0.61
60	57.28±0.67	4.76±1.22	64.17±1.20	6.47±1.74	60.74±0.48	1.21±0.79
50	47.31±0.67	5.70±1.49	54.50±0.90	8.23±1.50	49.51±0.18	0.99±0.37
40	36.48±0.81	9.68±2.46	43.09±1.05	7.12±2.28	39.50±0.13	6.68±0.37
30	27.38±0.68	9.61±2.63	30.43±0.54	1.86±1.09	27.54±0.05	8.95±0.20

In this experiment, the pressure was applied at three points, R1, R3, and L1 in Fig. 1, based on the three-point pressure application method [9][10]. Airbags R2, L1, and L2, which were not used in this experiment, were removed during the test to suppress the disturbances caused by these airbags (Fig. 9(a)). To measure the pressure applied to the mannequin by the airbags, the measurement pads of the pressure distribution measurement system (Novel.de, Pedar) were attached to the surface of the mannequin seated on the system, and the position of the airbag was adjusted so that it was in contact with the torso. To accurately measure the pressure exerted by the airbag on the torso, the measurement pad must cover the entire surface of the airbag in contact with the torso. Therefore, trials were conducted to measure only R1, as shown in Fig. 9(b), and R2 and L1, as shown in Fig. 9(c).

Prior to the experiment, the area of contact between the measuring pad and airbag was measured, and only the values in that area were used to calculate the average pressure. In addition, to remove outliers caused by incomplete contact between the airbag and mannequin, the average \bar{P}_a , P_{\min} and standard deviation σ_a of the pressure P_a applied within the area were calculated, and the average value \bar{P}_a of P_a , which satisfies the condition $P > \bar{P}_a - \sigma_a$, was calculated as the average pressure applied to the surface of

the mannequin. For the actual measured values, the average of the values from 30 to 90 seconds after the measurement started. This period follows after the air pumps were stopped once and a certain amount of time had passed. The pressures of the three airbags were set at intervals of 10 kPa, ranging from 30 kPa to 80 kPa, based on the pressure values applied in the sitting position from a study [13] that investigated the pressure exerted on the torso by scoliosis braces.

The trials and measurements were conducted five times for each pressure level, and the average errors between the measured values and the target values were evaluated.

In this study, the target and measured pressure tolerances were set at 13% based on the tolerances of a previous study that studied scoliosis treatment using airbags [6].

IV. RESULT

Table 1 presents the averages of the actual pressures at the points corresponding to R1, L1, and R3 of the airbag for each trial, as well as the average of the mean absolute percentage error (MAPE) between the target and actual values. In all trials, the MAPE remained within 13% of the tolerance, with the maximum mean absolute percentage error between the target and actual pressures being 12.24%.

V. DISCUSSIONS

Table 1 shows that the errors between the target and actual pressures were less than 13%, and these errors were within the tolerance determined in a previous study [6]. This indicates that the system has the potential to provide an adjustable corrective force, similar to braces with adjustable corrective force used in existing scoliosis treatments. Therefore, the basic performance of the developed airbag-based system for scoliosis treatment has been confirmed. However, from Table 1, it is observed that the actual pressure applied by airbag R1 to the mannequin's surface is slightly below the target value, while the actual pressure applied by airbag L2 is slightly above the target value. This is thought to be due to the presence of two airbags on the right side and one on the left side, with the force from the right-side airbags influencing the left-side airbag. It is believed that by improving the system and minimizing the interference between the pressures of the airbags, the influence of one airbag's pressure on others at a certain point can be reduced.

In this study, to apply a specified pressure to the torso using the airbags, it should be noted that the frame to which the airbags are attached is made from large, thick, and strong material. These characteristics of the current system may pose challenges for daily use at home. In the future, we plan to make the system more compact, thinner, and stronger. The updated system will be designed to be a chair-type system that a person can sit on or one that can be attached to a chair, making it more suitable for everyday use in the home. Regarding the direction of force, this study applied only force perpendicular to the sagittal plane, following the three-point pressure application method, which is a fundamental technique for treating scoliosis. However, we plan to improve the system to allow the application of force in various directions in the future. Additionally, after performing short-term experiments using mannequins, as done in this study, we plan to verify the applicability of the improved system for scoliosis treatment through experiments involving actual humans and tests that simulate extended use in a sitting position.

VI. CONCLUSION

In this study, we proposed and developed a scoliosis correction stationary bracing system that can automatically control the force applied to the torso by regulating solenoid valves and pumps based on the air pressure inside the airbag. We confirmed the feasibility of this system for scoliosis treatment through a basic experiment, in which specified forces were applied to the torso of a mannequin. The concept of this system could contribute to the development of new orthoses for scoliosis treatment, offering a more effective and less strain-intensive solution for patients using these braces.

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