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Analysis of fabric movement and dust removal performance due to twist motion in a clothing care system

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Abstract

This study aims to explore effective dust removal methods for the improvement of clothing care systems by analyzing the fabric movement caused by the twist motion and examining its influence on dust removal performance. The finite element method simulation was used to model the tension at different vertical and horizontal positions of the fabric as a spring array, to calculate the fabric movements at each position over time when a twisting force was applied and enable comparison with experiments. When observing the fabric movement due to the twist motion with actual fabrics, silk showed the greatest movement, followed by cotton and linen. Cotton experienced decreasing force from the top to the bottom, with increased amplitude at the bottom due to fluttering caused by the bottom not being fixed. When examining the fabric movement according to the velocity, slower velocity did not effectively transmit twist force to the bottom, while faster velocity resulted in more small movements. The analysis revealed that greater force at faster velocity led to better dust removal performance. Therefore, for efficient dust removal, the force transmitted to the fabric should be increased. Most dust is removed within the first 10 min, so exerting a strong force for a short duration is important.

Keywords: Clothing care system, Twist motion, Simulation, Fabric movement, Dust removal

Introduction

Washing machines for clothing care are widely used in homes because they are suitable for removing contaminants such as soils and odors from clothes (Nayak & Ratnapandian, 2018; Pakula & Stamminger, 2010). However, frequent washing damages clothes (Kalayci et al., 2017; Laitala et al., 2011), which shortens their lifespan. In addition, frequent washing increases the use of water, detergent, and electricity, leading to environmental problems such as water pollution, water depletion, and greenhouse gas emissions (Laitala et al., 2020). Particularly, water used for washing has a greater impact on water depletion than the production stage of clothing (Busi et al., 2016; Fan et al., 2019; Perez-Urdiales & García-Valiñas, 2016). Clothes dryers are widely used along with washing machines due to their advantages, such as fast drying, sterilization, and reduction of housework, but they have problems such as microfiber release and excessive energy use (Davoli et al., 2022; Tao et al., 2022; Yamaguchi et al., 2011). Due to these problems, sustainable clothing care is needed in the society.

A new clothing care method has been proposed through the development of a home appliance called a "clothing care system" (Yu et al., 2021b). The clothing care system comprises movement, steam, and ventilation systems, enabling odor and dust removal, wrinkle reduction, etc. (Brenčič & Young, 2009; Park et al., 2023; Yu et al., 2021b). Through this, easy care of difficult-to-maintain clothing, such as coats and padded jackets, at home without the help of professional companies has become possible (Brenčič & Young, 2009). Accordingly, the clothing care system market is also continuously growing, and developing corresponding technologies for improving performance is necessary. Studies by Park et al. (2023) on the steam system and Yu et al. (2021b) on wrinkle removal examined the influence of conditions inside clothing care systems on fabrics. Further, studies by Baik et al. (2023) and Yoon et al. (2023) found that it is necessary to improve the performance of clothing care systems.

Research is lacking on the influence of the motion method, which affects fabric movement in the clothing care system, on the device's performance. In particular, dust removal in the clothing care system is greatly influenced by the mechanical system's physical movement, so a review of the movement is even more necessary. This physical movement shakes the clothes, thereby removing dust. Regarding the physical movement methods of clothing care systems currently sold in the market, reciprocating motion that involves left and right movement is predominant. Reciprocating motion is caused by a force acting parallel to the horizontal axis due to torque; the force is transmitted vertically to the fabric, allowing dust to be removed (Yu et al., 2021a). However, only reciprocating motion has been attempted in the mechanical motion of such clothing care systems. Hence, reviewing various types of motions is necessary.

The twist motion moves left and right in a semicircle around the central axis and increases the fabric's movement due to inertial motion by transmitting force to the entire fabric (Kadlowec et al., 2009). The twist motion is implemented by converting the motor's rotational movement into a reciprocating motion using a crank, which connects two bars on opposite sides of the hanger, each with a 180° phase difference. The twist motion in the clothing care system causes relative rotational movements at various positions of the fabric, depending on the fabric's flexibility and inertia (Traill-Nash & Collar, 1953). Compared to the existing movement method, it has the advantage of reducing the vibration and noise of the device. Therefore, this study sought to analyze fabric movement due to the twist motion method in the clothing care system. To this end, we simulated fabric movement inside the device under various twist motion conditions, and compared and analyzed it with actual movement. In addition, this study explores effective dust removal methods by examining the dust removal performance due to the twist motion. This study will serve as foundational data for clothing care systems with great potential for future development.

Experimental

Simulation

This study predicts the fabric movement due to the clothing care system's twist motion through finite element method (FEM) simulation and compares it with experimental results. The simulation analysis was performed using COMSOL Multiphysics, a representative FEM simulation tool. A modeled 2D spring array (Fig. 1) was applied to the FEM simulation. A spring model was used to represent the fabric's elasticity, incorporating mechanical parameters like modulus in the calculations based on the fabric's characteristics. Thus, the spring mentioned in this study should be regarded as a mechanical component used to simulate the properties of elastic materials like fabric. The springs were arranged to intersect at 5×6 points in the horizontal and vertical directions so that they could correspond to the points designated for observing the motion at each position in the experiment, and the position change over time at 30 points was calculated when a twisting force was applied from the top. These points were the same as the positions on the fabric measured in the experiment so that the motion could be directly compared with the experimental values. In Fig. 1, the spring constant k was calculated using the modulus value calculated based on the mechanical characteristics of cotton among the three fabrics (silk, cotton, and linen) included in the experiment. The spring constant in the vertical direction considered that the tension pulling the fabric downward due to gravity differs depending on the position. That is, at the top of the fabric, the downward pulling force increases due to the fabric below, so the spring constant becomes larger, and as it moves downward, the spring constant at each position decreases continuously. To apply this to the simulation, the mass was calculated through

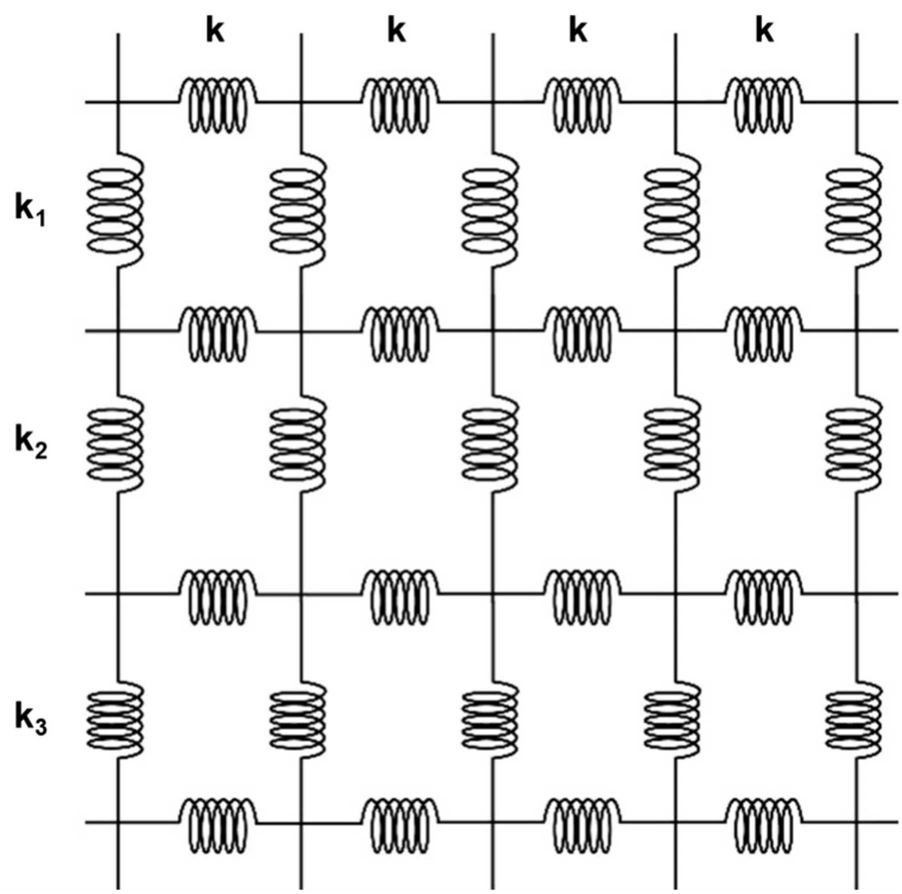

Fig. 1 Conceptual diagram of the model system applied to the finite element method

the amount of fabric below each position and the density value of the fabric, and the spring constants from k_1 to k_6 were estimated by adding the pulling force due to gravity. This was applied to the simulation.

The simulation calculated the displacement, velocity, and acceleration of the 30 points over time when a twist motion was applied from the top at velocities of 180 rpm and 250 rpm. The total time calculated through the simulation was 5 s, and the mechanical parameters of each point were calculated at 0.05-s intervals.

Clothing care system and samples

This study used a clothing care system ($445 \times 1850 \times 585$ mm^3) equipped with a system that implements the twist motion by moving the hanger at the top and transmits force to the fabric through the hanger (Fig. 2a). To facilitate the observation of the movement of the fabric inside the device, one side wall of the device was modified into a transparent window and the interior was colored black. The twist velocity can be adjusted from 120 to 400 rpm. To examine the impact of velocity based on the velocity of the conventional clothing care system (180 rpm), 180 rpm and 250 rpm were set as the twist velocity.

Since the fabric movement due to twisting differs according to the fabric's stiffness (ISO, 1995), which is affected by its weight, thickness, and Young's modulus, three fabrics with different stiffnesses were used; their characteristics are shown in Table 1. The size of the sample used for observing fabric movement was 90 cm × 20 cm.

Observation and analysis of fabric movement

As the force transmitted to the fabric due to the twist motion varies, the fabric movement differs. Thus, we observed and analyzed the movement at each fabric position. Based on the dust removal sample, the position of the fabric was divided into 30 points (five columns and six rows) (Fig. 2b), and circular stickers with a radius of 15 mm were attached at each position to facilitate analysis (Yu et al., 2021a).

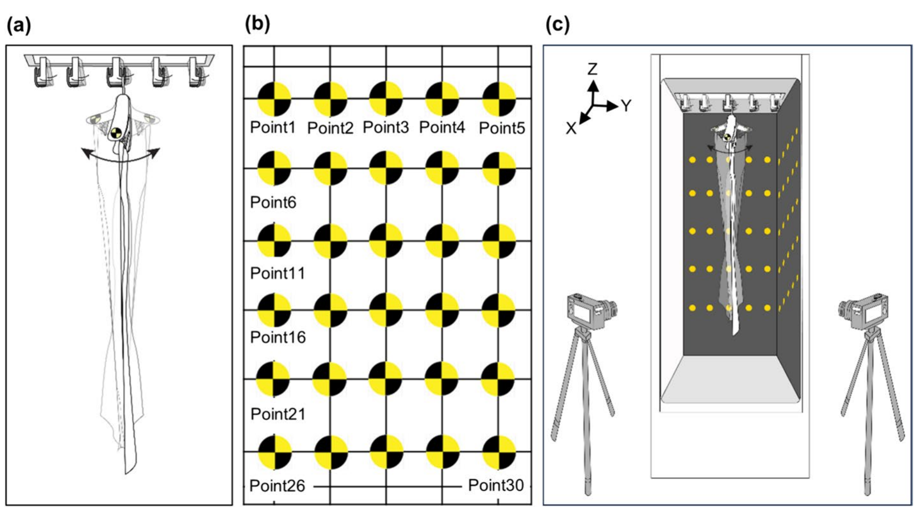

Fig. 2 3D analysis method for fabric movement: (**a**) Example of fabric movement due to twist motion, (**b**) 30 points for position-specific analysis of fabric, and (**c**) Observation conditions

Table 1 Fabric characteristics

Fiber content		Silk 100%	Cotton 100%	Linen 100%
Weave type		Plain	Plain	Plain
Weight (g/m^2)		29.67	85.83	129.89
Thickness (mm)		0.09	0.25	0.50
Stiffness	Warp (mm)	4.02	4.78	6.58
	Weft (mm)	3.50	3.74	10.68

To properly observe the fabric movement, the position was set at a 45° angle from the front of the clothing care system (Fig. 2c), and two high-speed cameras (IDT NX8S1, IDT CCM3525) were installed and synchronized for filming. Twenty-five points were set on the front and side of the clothing care system, and the actual distance between the points was used to generate an XYZ coordinate system. The X-axis represents the depth direction of the clothing care system, the Y-axis represents the horizontal direction, and the Z-axis represents the vertical direction. The fabric movement can be expressed numerically through this generated XYZ coordinate system. Using the 3D TEMA Motion Outline tracker (Image Systems), the movement of 750 frames (150 frames/s) for 5 s at 30 points was analyzed, and the XYZ coordinates at each position of the fabric were extracted.

Evaluation of dust removal performance

To evaluate the dust removal performance, threads (40 counts, 2-ply polyester 100%) were attached to the fabric to act as dust (Yu et al., 2021a), which is commonly used in the development of clothing care system in the industrial field. As shown in Fig. 3, in 30 regions (five columns and six rows), 180 threads measuring 1 cm-long (30 regions * 6 threads) were attached without adhesive. Because the adhesion of threads differs according to the fabric's surface characteristics, only cotton fabric was utilized out of the three fabrics to examine only the influence of fabric movement. The experimental time was set to 30 min in accordance with the standard course of the clothing care system. One detached thread was counted as "1" and one moved thread was counted as "0.5". To examine the effect over time, the number of threads detached at each position was divided into 10-min intervals for analysis.

Results and discussion

Simulation of fabric movement due to twist motion

When the displacement in the Y-axis direction caused by the twist motion at a point on the hanger fixing the fabric was plotted over time, it formed a perfect sine wave. Therefore, the fabric's movement was analyzed based on a sinusoidal signal. The displacement calculation results according to the vertical position of the fabric (top (P1–P5), middle (P11–P15), bottom (P26–P30)) at 180 rpm through simulation are shown in Fig. 4. At the top of the fabric, it showed a tendency to closely follow the twist motion applied to the fabric at all positions. The driving force to the fabric was slowly transmitted as it moved to the bottom of the fabric; in the initial 3–5 cycles, the sinusoidal displacement curve was observed, but as time elapsed, the displacement became irregular and

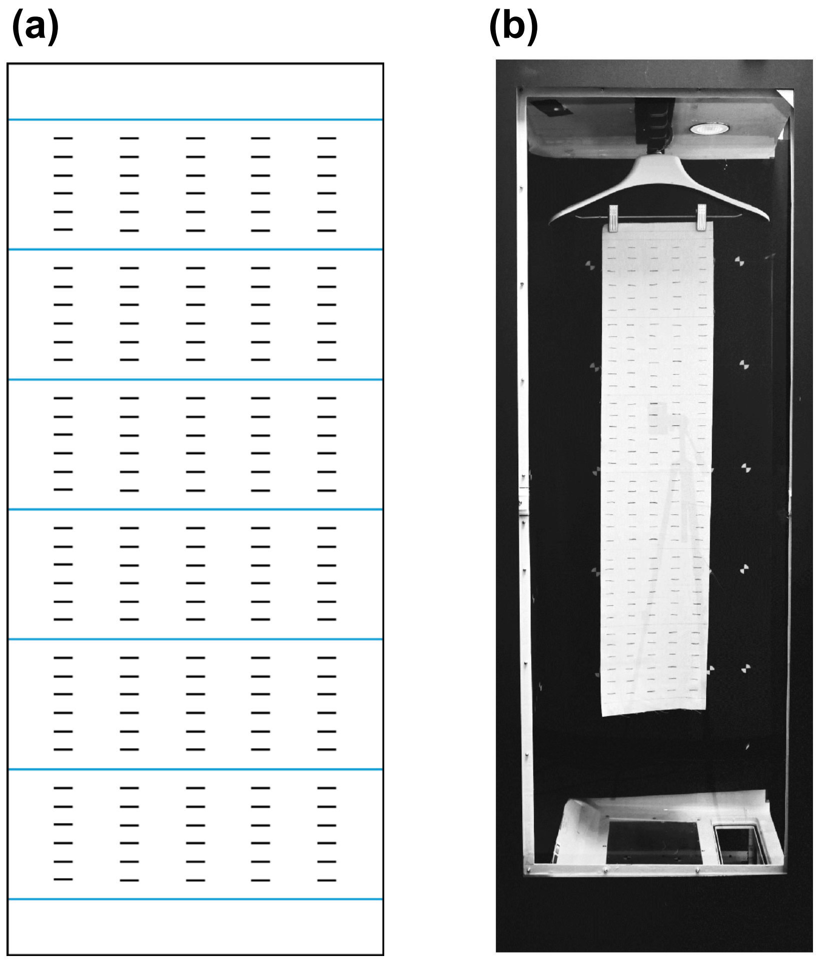

Fig. 3 Thread attachment for evaluation of dust removal performance: (**a**) Diagram of 180 threads attached to a fabric and (**b**) Example of dust removal evaluation in a clothing care system

the overall position of the fabric also moved away from the center. This could be related to the fluttering behavior described in the experimental results.

Figure 5 shows the displacement calculation results according to the vertical position of the fabric (top (P1–P5), middle (P11–P15), bottom (P26–P30)) at 250 rpm. At 250 rpm, similar to the 180 rpm results, the top closely followed the sinusoidal curve in accordance with the vibration frequency of the twist motion, while the middle and bottom showed decoupling from the vibration frequency. In addition, as with 180 rpm, the driving force was applied more slowly to the fabric as it moved from the middle to the bottom. Particularly, at 250 rpm, in the middle of the fabric, the displacement value was observed to deviate from the center to one side after about 2.4 s. This is attributed to the force applied to the fabric in the x-axis due to rotational motion proportionally increasing as it moved away from the center, and the force transmitted in the x-axis direction and the vertical direction (z-axis downward) complexly entangled with each other.

Figure 6 summarizes the measurement results of the fabric movement over time at the outermost measurement points of the fabric that are most greatly affected by the rotational twisting force, according to the vertical position. The behavior at the top

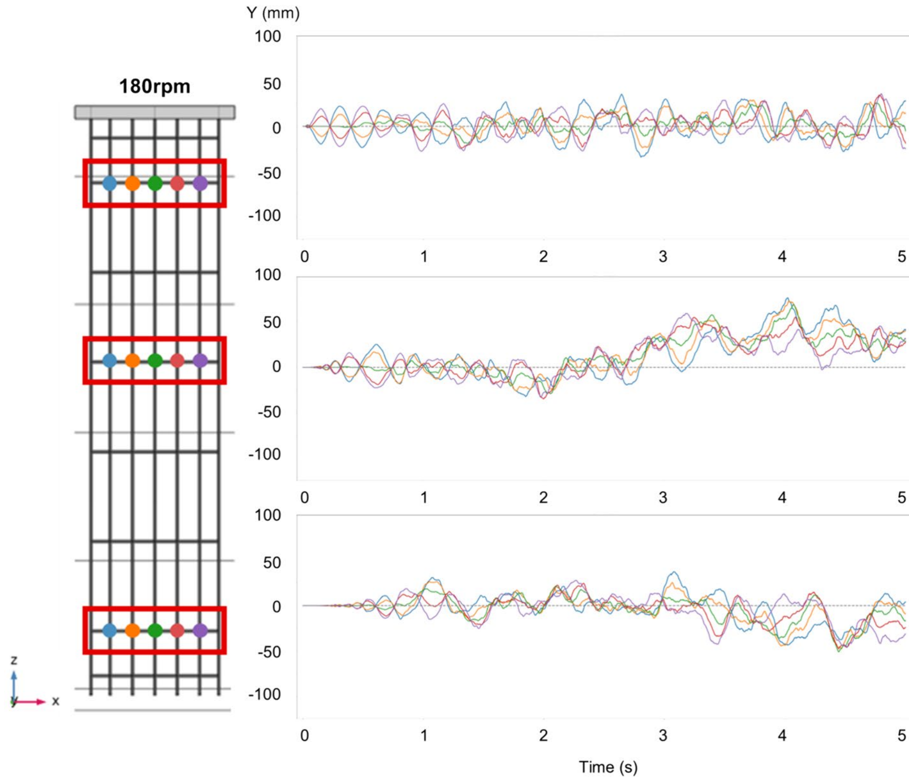

Fig. 4 Simulation results of fabric movement according to position at 180 rpm (Z value represents the vertical displacement from the bottom surface of the fabric, unit is cm)

position that directly receives the twisting force closely follows the sinusoidal reciprocating motion at both 180 rpm and 250 rpm, and even after 3 s, although the fluctuation becomes severe, it maintains the sinusoidal curve to a certain degree. On the other hand, as it moves downward, the sinusoidal behavior breaks relatively early, and the subsequent behavior is very irregular.

Influence of twist motion on fabric movement

Analysis of fabric movement according to fabric type

To compare and analyze fabric movement according to the fabric type, the motion velocity was fixed at 180 rpm, and the change of 30 points over time was observed using the Y value, which had the largest displacement among the XYZ coordinates. Since the starting Y value differed for each position of the fabric, the minimum value under each experimental condition was changed to 0 so that the displacement could be compared with other conditions. The positions of the fabric were divided into the following three groups for analysis: P1–P5, which were closest to the moving hanger; P1, P6, P11, P16, P21, and P26, which were the sides of the fabric; and P3, P8, P13, P18, P23, and P28, which were the central axis of the fabric.

First, the upper part of the fabric (P1–P5), where the fabric can receive the force of the moving hanger up close, was observed, and the results are shown in Fig. 7. Silk and linen showed similar sine curves due to the twist motion, and there was only the difference in amplitude according to the position. Among the upper parts of the linen, P1

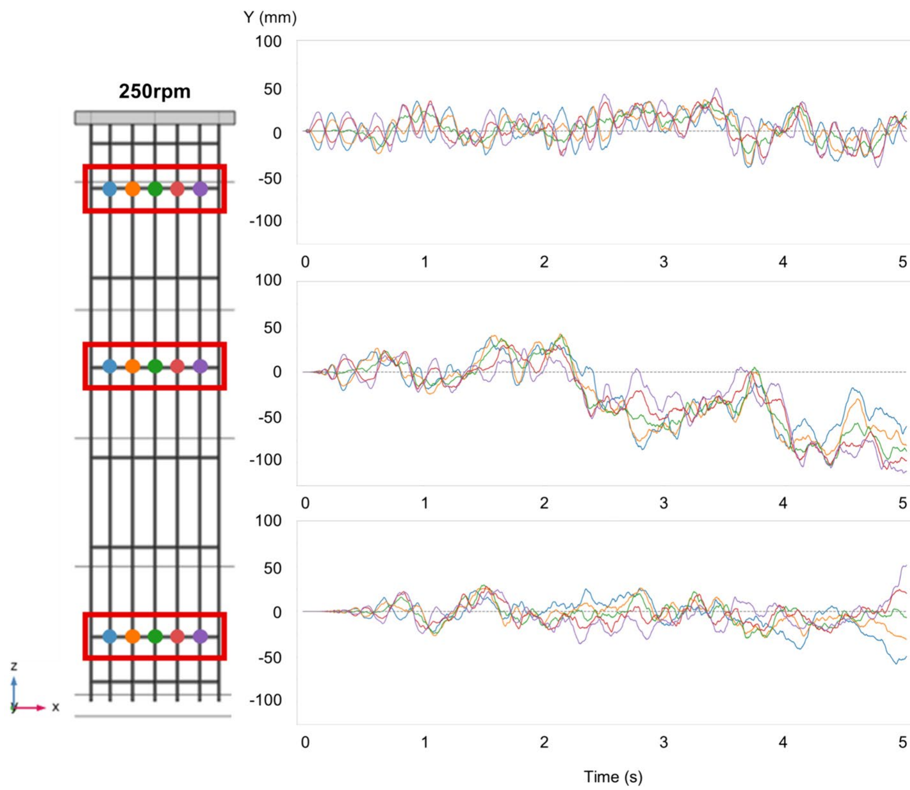

Fig. 5 Simulation results of fabric movement according to position at 250 rpm (Z value represents the vertical displacement from the bottom surface of the fabric, unit is cm)

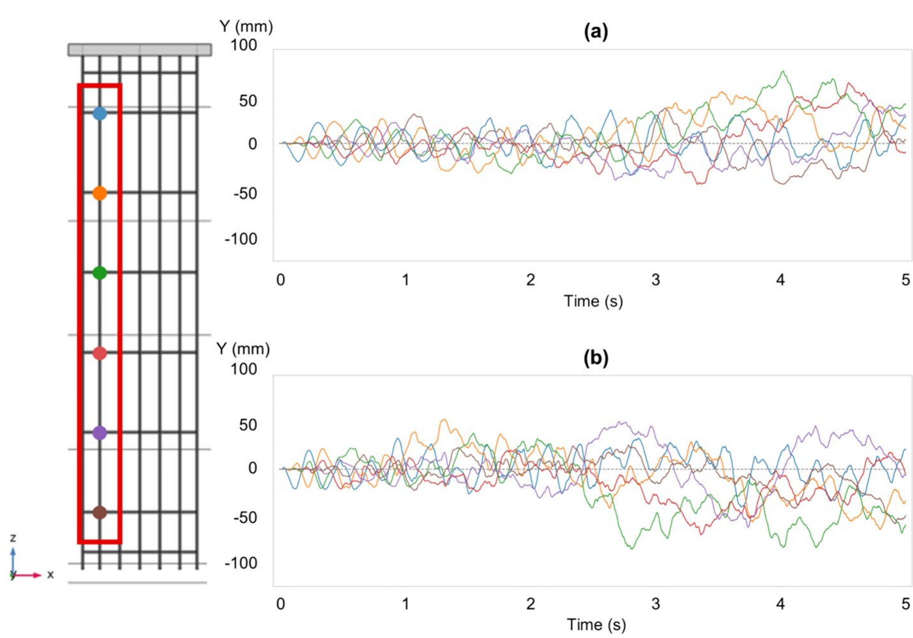

Fig. 6 Simulation results of fabric movement according to vertical position at the outermost edge in the horizontal direction from the center of rotation: (**a**) 180 rpm and (**b**) 250 rpm

and P5, which were farthest from the center, showed large displacements, and P3, which was located at the center, showed the smallest amplitude. However, in cotton, the movement at P1 appeared large, which could be influenced by the bending characteristics of the cotton fabric due to the superposition effect of the continuous force transmitted by the connection between the yarns. Due to this, while silk and linen showed 16 similar movements over five seconds, cotton showed eight repetitive curves. This could be related to the behavior of the displacement value significantly deviating from the initial point, especially after 2.4 s at 250 rpm in the simulation using cotton. That is, the entanglement of horizontal and vertical vibrations caused a singular superposition, which resulted in a different behavior from silk and linen due to the influence of cotton's bending characteristics.

P1 to P5 were the upper positions of the fabric; the moving hanger's movement due to the twist motion were expected to be directly transmitted to the fabric, forming left–right symmetry, but the influence of fabric characteristics, such as drape and weight, had an effect, resulting in different curves without achieving left–right symmetry.

To investigate the movement on the side of the fabric, P1, P6, P11, P16, P21, and P26 were analyzed, and the results are shown in Fig. 8. Compared to silk and linen, cotton had a large amplitude and long wavelength, indicating that the movement on the side was relatively large. However, silk had a smaller amplitude and shorter wavelength than cotton, showing frequent movements. This was attributed to silk's excellent drape, which transmitted the movement of the moving hanger. To examine whether the force of the

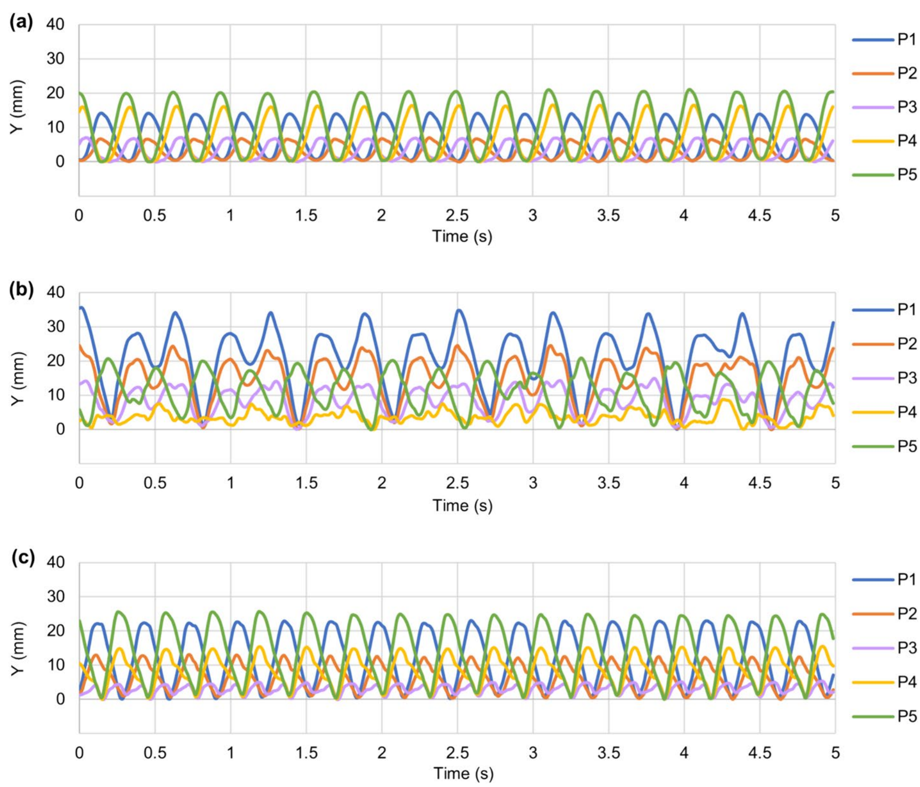

Fig. 7 Displacement of movement by the fabric over time at the top (P1–P5) (RPM: 180): (**a**) Silk, (**b**) Cotton, and (**c**) Linen

moving hanger is transmitted to the bottom of the fabric, P26 was examined. As the amplitude of silk increased toward the bottom (P26), it was judged that the force was transmitted to the bottom. On the other hand, amplitude for cotton and linen showed a tendency to decrease toward P26, with the amplitude of P26 decreasing the most in linen. The force transmitted to the bottom of the linen fabric was the smallest, due to its characteristics like high initial elasticity and low drape, as well as weight difference from the other fabrics. Cotton showed the largest amplitude at P11 and decreased toward the bottom, which was attributed to the force of the moving hanger being applied the most at P11 and then being offset. Although the force decreased toward the bottom, the amplitude increased at P26 for the cotton fabric, which was attributed to the fluttering phenomenon caused by the bottom not being fixed.

The central axis of the fabric showed a tendency to have smaller movement and amplitude compared to the upper and side positions of the fabric (Fig. 9). This could be due to the amplitude being the smallest at the center owing to the characteristics of the twist motion, so the transmitted force was also the smallest. However, cotton exhibited large displacement, which was due to the coupling effect in which force is transmitted through the connection between the yarns. This signifies that large movements can be added even at the central position due to the influence of cotton fabric's stiffness.

To observe the movement over time at all positions of the fabrics, the distance moved over 5 s was compared. The distance was visually represented using colors based on the average and standard deviation (dark blue < average—standard

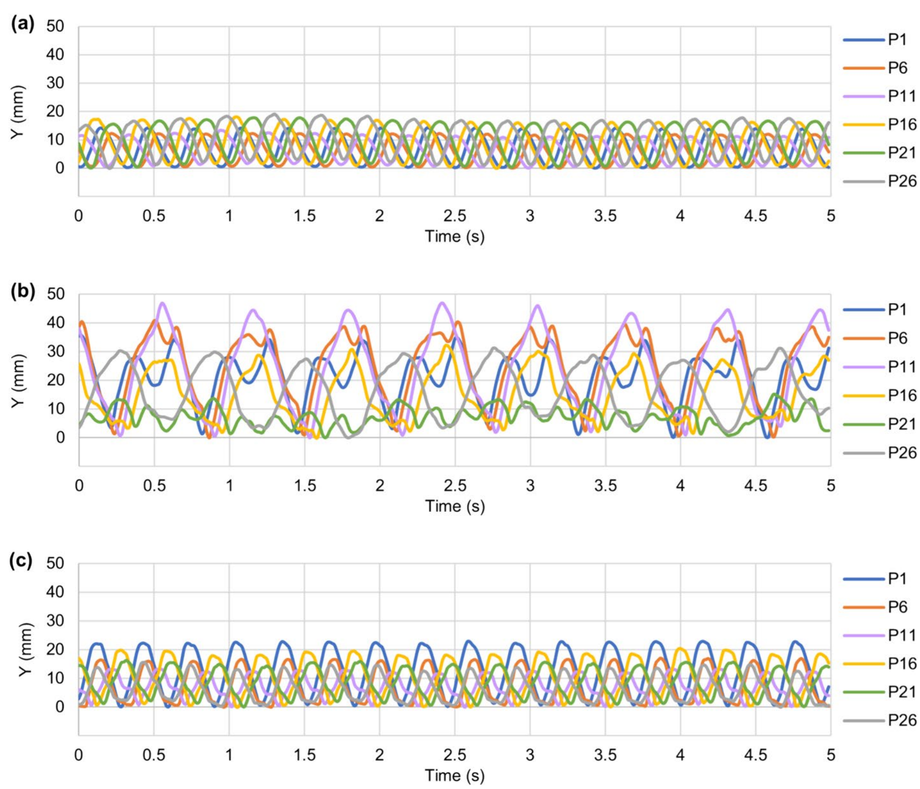

Fig. 8 Movement by the fabric over time on the left side (P1, P6, P11, P16, P21, P26) (RPM: 180): (**a**) Silk, (**b**) Cotton, and (**c**) Linen

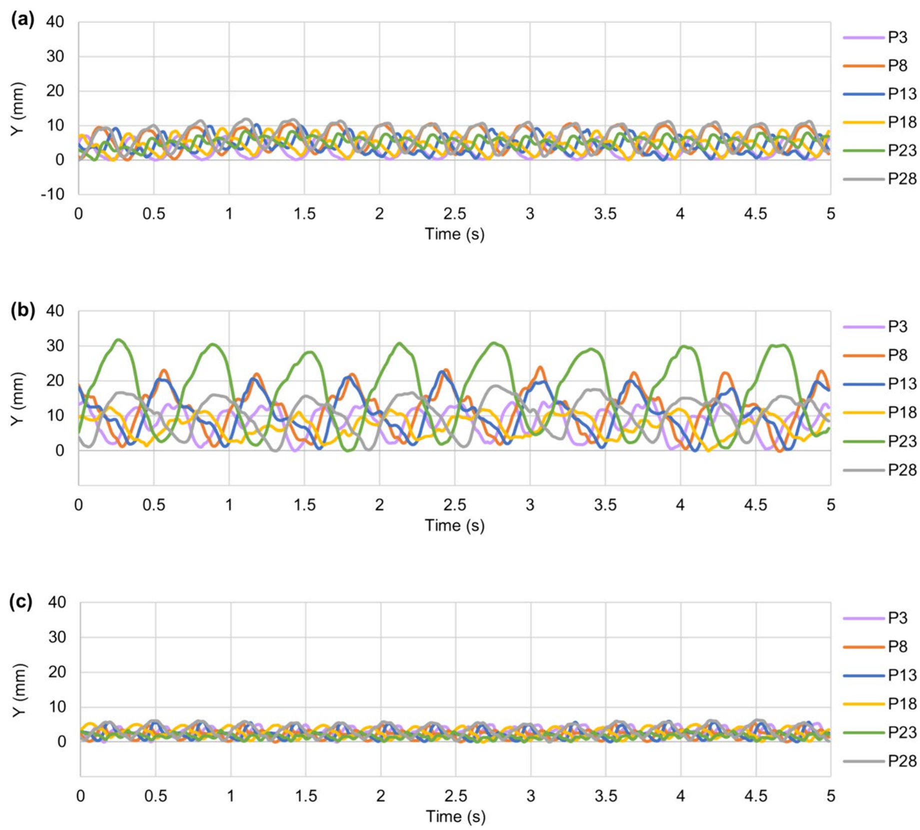

Fig. 9 Movement by the fabric over time at the center (P3, P8, P13, P18, P23, P28) (RPM: 180): (**a**) Silk, (**b**) Cotton, and (**c**) Linen

deviation < light blue < average < light pink < average + standard deviation < dark pink). For example, values between 'average – standard deviation' and 'average' are represented in light blue. The results are shown in Fig. 10. Examining the distribution of blue and red colors, although there were differences between fabrics, the movement at the center position was the smallest, and large movements were shown at the left, right, top, and bottom ends. This was because the twist motion operated at both ends based on the central axis, so the force transmitted to the fabric greatly influenced the movement of the left and right sides.

The large distribution of blue at the bottom of the silk suggested that the movement decreased toward the bottom of the silk fabric compared to others. On the left side of the fabric, there was a constant frequent movement, but on the right side, the movement tend to decrease toward the bottom. This was interpreted as a result of the fabric not achieving left–right symmetry due to its characteristics. Meanwhile, the large distribution of red at the bottom of the cotton was attributed to the fluttering phenomenon. Consequently, cotton showed a relatively long distance among the three fabrics at 602.5 mm. In the case of linen, although it showed a shape similar to left–right symmetry, the average distance moved was low compared to the other fabrics at 459.0 mm, indicating a small amplitude. This was because linen required a larger force to induce the same amplitude due to its larger stiffness.

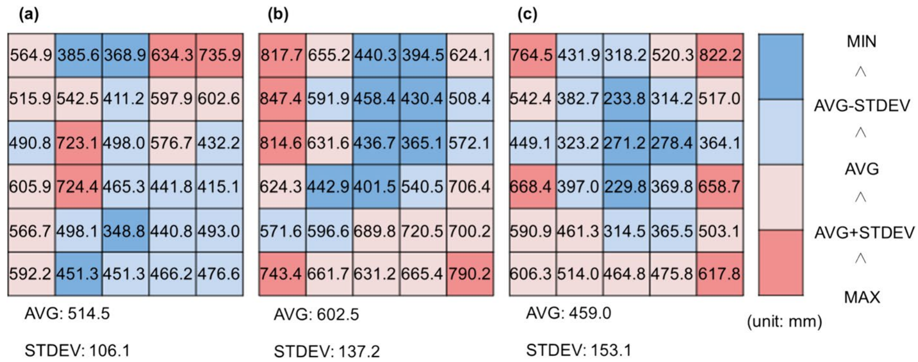

Fig. 10 Visualization of the distance moved over 5 s by fabric (RPM: 180): (**a**) Silk, (**b**) Cotton, and (**c**) Linen

Table 2 Comparison of amplitude and acceleration according to the position and fabric type

Type of fabric		Silk	Cotton	Linen
RPM		180	180	180
ω (rad/sec)		18.85	18.85	18.85
P3	A (m)	0.0033	0.0043	0.0018
	a (m/sec^2)	1.19	1.53	0.63
P5	A (m)	0.0098	0.0069	0.0119
	a (m/sec^2)	3.48	2.46	4.22
P30	A (m)	0.0057	0.0136	0.0049
	a (m/sec^2)	2.02	4.83	1.73

Based on the above results, to investigate the effect of fabric movement due to the twist motion on dust removal, the acceleration was analyzed at three positions (P3, the center of the top of the fabric; P5, the end of the top of the fabric; and P30, the end of the bottom of the fabric) that show the greatest change in movement, and the results are shown in Table 2. The force involved in dust removal is expressed as acceleration (a) according to Newton's laws of motion ($F = ma$). The acceleration here is proportional to the amplitude (A) and the square of the vibration frequency (ω), as shown in Eq. (1) below.

$$a \propto \omega^2 A. \tag{1}$$

Examining the positions that were greatly affected by the force for each fabric, silk and linen showed the highest acceleration of 3.48 m/s^2 and 4.22 m/s^2 at P5, respectively, indicating that the force of the moving hanger acted greatly on the side of the top of the fabric. The acceleration decreasing at P30 compared to P5 indicated that the force received by the fabric decreased toward the bottom of the fabric. On the other hand, in cotton, the acceleration increased to 4.83 m/s^2 at P30 compared to P5, and the moving hanger's force appeared to have acted greatly on the right side of the bottom of the fabric. This was attributed to the amplitude increasing due to the fluttering at the bottom, as explained earlier.

Analysis of fabric movement according to motion velocity

For the cotton fabric, the twist motion velocities of 180 rpm and 250 rpm were compared, and the fabric movement over time was analyzed using the Y value. The top of the fabric (P1 to P5), was examined, and the results are shown in Fig. 11. Although sine curves are shown due to the twist motion, the frequency and displacement differ due to the difference in velocity. This is because as the motion velocity increases, the number of movements per second increases, so the force transmitted to the fabric also increases as much as the increased movement. At 180 rpm, the amplitude was prominently large at P1, compared to P4. Conversely, at 250 rpm, the amplitude differences at each position are markedly reduced. This suggests that as the reciprocating velocity increases, the force applied to the fabric increases, so active movement occurs at all positions.

Figure 12 shows the results of fabric movement according to the reciprocating velocity at positions P1, P6, P11, P16, P21, and P26, which were the sides of the fabric. As in the previous results, under the 180-rpm condition, large movements appeared at the bottom due to fluttering. In contrast, at 250 rpm, many small movements appeared, which were attributed to the frequent direction changes caused by the increased number of times the moving hanger moved per unit of time. In addition, comparing P1 and P26 in the vertical position, although there was a difference according to the reciprocating velocity, a relatively large movement was shown at P26. This could be because even a small force transmitted to the bottom of the fabric results in a relatively large movement due to the influence of its own weight.

The fabric movement due to twist motion was observed by varying the velocity on the central axis of the fabric, and the results are shown in Fig. 13. Active movement appeared at all positions at 250 rpm, but the movement was small at 180 rpm. This occurred because the coupling effect resulting from the connection between fabrics was prominent at high reciprocating velocity. Comparing the reciprocating velocity, the amplitudes from P3 to P28 appearing similar at 250 rpm suggests that as the

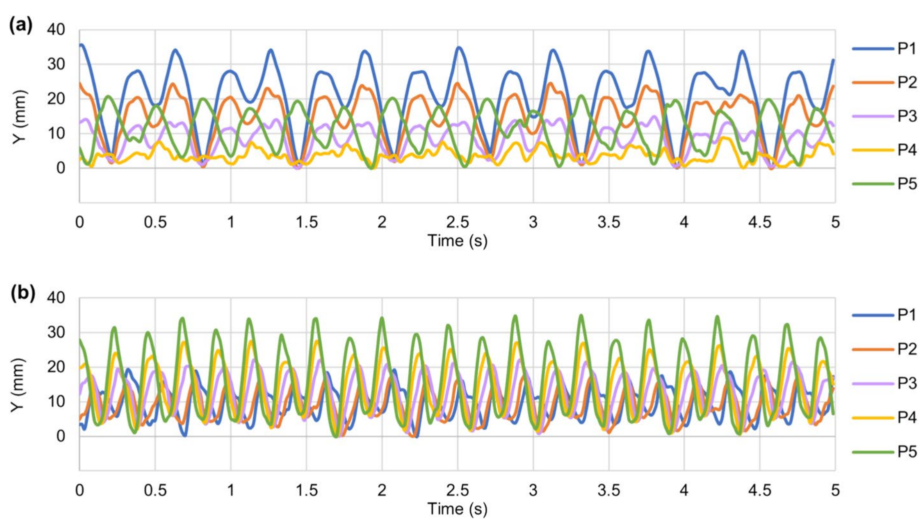

Fig. 11 Fabric movement according to velocity at the top (P1 to P5) (Fabric: Cotton): (**a**) 180 rpm and (**b**) 250 rpm

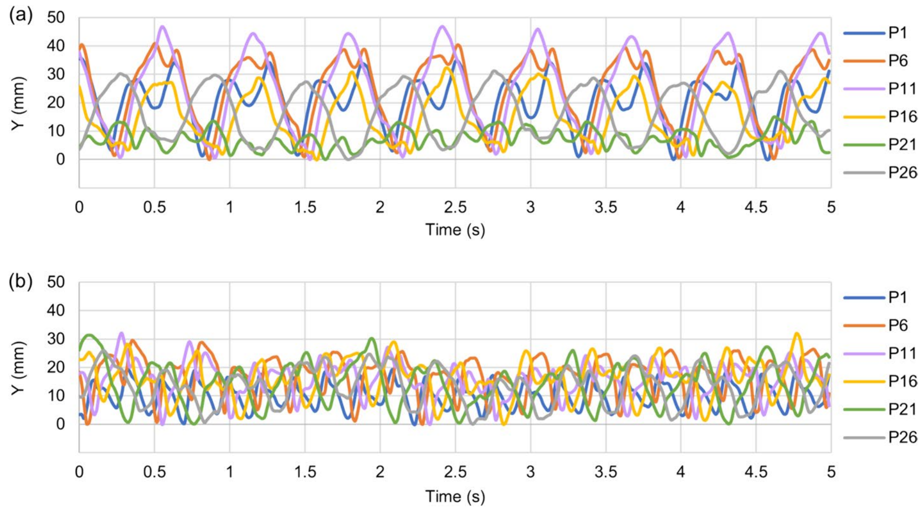

Fig. 12 Fabric movement according to velocity on the left side (P1, P6, P11, P16, P21, P26) (Fabric: Cotton): (**a**) 180 rpm and (**b**) 250 rpm

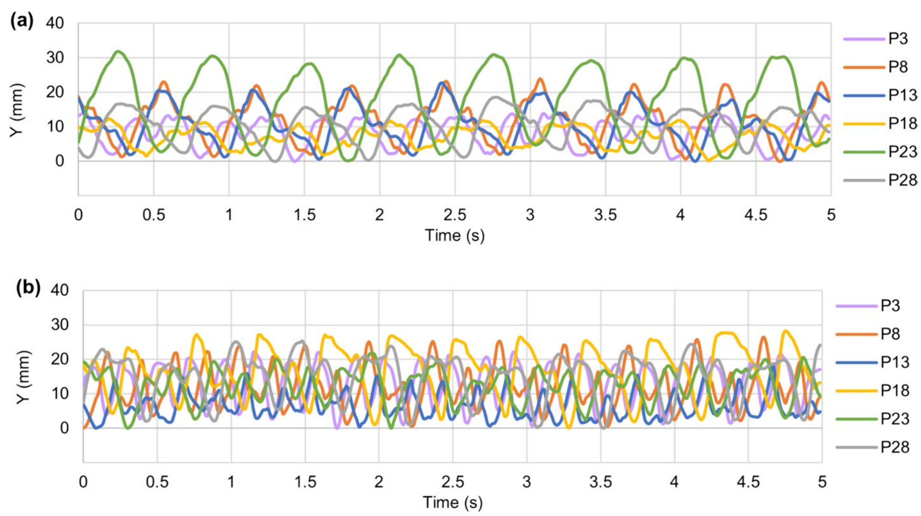

Fig. 13 Fabric movement according to velocity at the center (P3, P8, P13, P18, P23, P28) (Fabric: Cotton): (**a**) 180 rpm and (**b**) 250 rpm

reciprocating velocity increases, the force from the moving hanger is evenly transmitted from the top to the bottom of the fabric.

The distance moved over time and the number of reciprocations at all positions according to the reciprocating velocity were compared and analyzed, and the results are shown in Fig. 14. Figure 14a, b, comparing the number of reciprocations at the same time of 5 s, 180 rpm repeated the twist motion 15 times, and 250 rpm repeated it 20.8 times. The distance the fabric moved was longer under the 250-rpm condition than the 180-rpm condition. This was because the number of reciprocations increased with higher reciprocating velocity, so the distance moved increased based on the same time. Figure 14a shows a longer distance moved at the bottom, and Fig. 14b shows a longer distance moved at the top. This is attributed to the fluttering phenomenon at

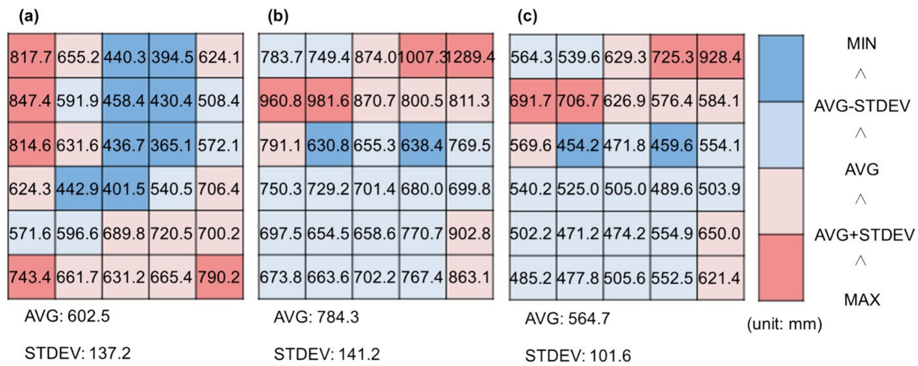

Fig. 14 Visualization of the distance moved according to velocity and number of reciprocations (Fabric: Cotton): (**a**) 180 rpm (5s, Repeat 15 times), (**b**) 250 rpm (5s, Repeat 20.8 times), and (**c**) 250 rpm (3.6s, Repeat 15 times)

Table 3 Comparison of amplitude and acceleration according to fabric position and reciprocating velocity

RPM		180	250
ω (rad/s)		18.85	26.18
P3	A (m)	0.0043	0.0084
	a (m/s^2)	1.53	5.74
P5	A (m)	0.0069	0.0106
	a (m/s^2)	2.46	7.24
P30	A (m)	0.0136	0.0097
	a (m/s^2)	4.83	6.66

the bottom at low reciprocating velocity, and at high reciprocating velocity, the force of the fabric applied at the top weakened as it moved toward the bottom. Comparing the two reciprocating velocities, the moving hanger's force appeared to be more evenly transmitted to the fabric at higher reciprocating velocity.

On the other hand, Fig. 14a, c, when compared with the same number of reciprocations (15 times), a longer movement distance appeared at 180 rpm than at 250 rpm. This was because at high motion velocity, before the force first applied was sufficiently transmitted to all positions of the fabric, the force that followed affected it, resulting in an offset due to the superposition phenomenon and reducing the range of fabric movement.

To examine the effect of force, the acceleration was analyzed using the amplitude of Y, and the results are shown in Table 3. The force of the reciprocating velocity of 250 rpm was large at all three positions; in particular, the acceleration was the highest at 7.24 m/s^2 at P5. This could be because P5 was located on the side of the fabric, so it received the force of the twist motion most closely, resulting in a large force. At 180 rpm, the force was the greatest at P30, which is attributed to the amplitude increasing due to the fluttering phenomenon at the bottom and the force being greatly influenced by the amplitude. Therefore, the 250-rpm condition showed greater force than the 180-rpm condition at all positions, which is attributed to the difference in acceleration caused by the reciprocating velocity as well as having a large difference in amplitude. In particular, at P30, even though the 250-rpm condition had a smaller amplitude due to the fluttering phenomenon, it received a greater force under the influence of acceleration. Hence, even if the amplitude is relatively small, raising the acceleration to increase force may be advantageous for dust removal using the twist motion.

Dust removal performance using twist motion

Based on the analysis of fabric movement and force, to examine the dust removal effect according to the twist motion, the dust removal performance was evaluated under motion velocities of 180 rpm and 250 rpm using cotton fabric. The dust removal performance results are shown in Table 4, with "0.5" indicated in red and "1.0" in green. The positions where dust was removed, indicated the parts colored in green and red, demonstrating the relation to the dust removal force. Dust removal occurred only at the bottom of the fabric at 180 rpm, suggesting that the dust was removed by force due to the large displacement caused by the fluttering of the fabric. At 250 rpm, dust removal occurred at relatively various positions and the number of removed dust particles was 7.5, exhibiting approximately double the performance of the 180-rpm condition. As examined earlier, a large displacement and high acceleration appear at 250 rpm, indicating that the force due to the twist motion was effectively transmitted to the fabric, resulting in better dust removal performance.

Dust removal effect over time was examined, divided into 10-min intervals, and conducted for 30 min. The results are shown in Table 5. Examining the effect of time, most of the dust was removed in the first 10 min, and dust removal did not occur after 20 min. These results indicate that after a certain time, even if the same force is applied, it does not affect dust removal. That is, dust removal is more effective when a strong force is applied for a short time rather than continuously applying force. This can be explained by the effect of the first 10 min, which was 57.1% at 180 rpm and 66.6% at 250 rpm. Thus, to remove dust from various positions, assuming that the same force is applied, applying various rpm for short durations is likely to be more effective than applying the same magnitude of force for a long period.

Table 4 Dust removal performance by fabric position for twist motion

RPM	180						250					
Column Row	1	2	3	4	5	Sum	1	2	3	4	5	Sum
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	1.0	0.0	2.0
4	0.0	0.0	0.0	1.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.5	0.0	0.0	0.0	0.5	1.0	0.0	1.0	0.0	0.0	2.0
6	0.5	0.0	0.0	0.5	1.0	2.0	1.0	1.0	0.0	0.5	0.0	2.5
Sum	0.5	0.5	0.0	1.5	1.0	3.5	2.0	2.0	1.0	1.5	1.0	7.5

Table 5 Dust removal performance by time period due to twist motion

		180rpm		250rpm	
		By section	Cumulative	By section	Cumulative
By time period (min)	0–10	2.0	2.0	5.0	5.0
	10–20	1.5	3.5	2.5	7.5
	20–30	0.0	3.5	0.0	7.5
Impact in the first 10 min (%)		57.1		66.6	

Conclusions

This study aimed to explore effective dust removal methods by examining the effect of fabric movement due to the twist motion in a clothing care system for cotton, silk and linen. Simulations were also conducted on cotton using FEM. The tension at each vertical and horizontal position of the fabric was modeled as a spring array, and when a twisting force was applied, the fabric movement at each position over time was calculated under conditions of 180 rpm and 250 rpm. These results were then compared with experiments. In actual experiments with the three fabrics, silk and linen showed relatively small amplitudes of fabric movement at all positions compared to cotton, and silk showed frequent movements. In addition, in all fabrics, the magnitude of the force decreased toward the bottom, but in the case of cotton, fluttering occurred, increasing the amplitude at the bottom. This showed that the fabric movement and force magnitude differ according to the fabric's characteristics, and the magnitude of the force received by the fabric is more important for effective dust removal. In addition, as the reciprocating velocity increased, the vibration frequency and moving distance increased, and the force received by the fabric increased, showing active movement at all positions of the fabric. This movement enabled dust removal even at the bottom of the fabric. Based on this, examining the actual dust removal performance of the cotton fabric indicated that due to fluttering, dust was removed at the bottom at 180 rpm, while at 250 rpm, dust tended to be removed evenly. Compared to the existing left–right reciprocation movement, the twist motion offers the advantage of achieving more thorough dust removal across all areas of the fabric. Furthermore, most of the dust was removed in the first 10 min, indicating that applying a strong force for a short time is more effective than continuously applying the same magnitude of force. In addition, it is necessary to explore effective dust removal methods that diversify the moving hanger's displacement and velocity to vary the force magnitude applied to the fabric by the twist motion.

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Author contributions
HK and HJ conceived the ideas, experimental design, performed the experiments, collected the data, interpretation of the results, and drafted the manuscript of the analysis. DY performed the experiments, participated in the manuscript writing. CY and SL supervised on the experimental design, experimental results, and manuscript preparation. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Competing interests
The authors declare no potential competing interest with respect to the research, authorship, and/or publication of this article.

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