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A Basic Study on Establishing the Automatic Sewing Process According to Textile Properties

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Abstract: This study aimed to establish an automatic sewing process for garment production according to textile properties. An automatic feeding system and a self-made template were introduced to an industrial sewing machine. Two types of stitches were performed on fabrics with various physical properties and surface roughness using this automatic sewing machine. The appearance, stitch length and width, seam strength, and seam efficiency were evaluated according to the sewing conditions, such as presser height and sewing speed. In addition, the correlation between textile properties, sewing conditions, and sewability was analyzed to derive a regression equation for sewability. The evaluation showed no difference in the lock stitch condition. On the other hand, under the zigzag stitch condition, the stitch width differed according to the presser height, which also affected the seam structure. The optimal presser height for each fabric was derived from the experimental results. In terms of the sewing speed, however, the seam strength was the best at 200 RPM in the lock stitch and 400 RPM in the zigzag stitch. The moderating effect of the presser height between textile properties and sewability in the lock stitch condition was confirmed. This result can be used as basic data for establishing an automatic sewing process for smart factories.

Keywords: smart factory; automatic sewing process; regression equation for sewability; garment production

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1. Introduction

The 4th revolution, also known as Industry 4.0, has been attracting attention from academia and industry since it was first introduced at the Hannover Exhibition in 2011 [1]. It was perceived as the informatization of the process of assembling and moving components of machines and mechanisms under the guidance and in communication with each other. In addition, it has been recently recognized as an effective energy-saving process based on maximum automation and intellectualization of the production process [2]. As Industry 4.0, the introduction of automation systems converged with technologies, such as Internet of Things (IoT), artificial intelligence (AI), and robots, has attracted attention [3,4]. Automation is defined as the operation and control of manufacturing systems using technologies, such as electronic, mechanical, and computerized systems [5]. As market competition becomes more intense and consumer demands diversify, automation is essential to improving the product quality and price competitiveness. Manufacturers can shorten the production time by increasing the production rate and labor productivity by introducing an automation system. In addition, the investment costs for automation can be recovered by reducing wages and increasing productivity, which can reduce the burden on investment costs. Advanced countries are already suffering from labor shortages due to aging and avoidance of manufacturing. Problems, such as high wages and labor shortages, can also be solved by introducing an automation system.

The garment manufacturing industry, which is a typical labor-intensive industry, is one of the areas where automation is relatively slow due to the weakness of digital technology upgrades in the production process [6]. In particular, the sewing process requires the most manpower in the production of the garments. Nevertheless, the sewing process is the most important joining method and an essential step in adding value to textile products. Garment sewing is divided into three steps: loading of fabric component, sewing of fabric component, and unloading of sewn component [5,7,8]. The loading of the fabric component includes picking up the fabric, arranging, folding, and pushing it under the presser foot of the sewing machine. In this process, a visual or touch sensor should be used to check the surface of the fabric, and special gripping technology is needed to pick up the fabric from the fabric pile. Sewing of the fabric component includes moving the sewing needle, guiding it until the sewing process is completed, aligning, measuring, and fixing it. Sewing technology is mechanized by the proximity sensor or the optical sensor, while the feed operation is performed manually as the system for adjusting the tension is required separately. Furthermore, clamp feed or template sewing is required to keep the fabric stable while maintaining size stability. The last step, unloading the sewn component, involves cutting the sewing thread, sliding, flipping, and folding process. In general, loading of the fabric component is performed manually, and the steps of sewing and unloading are partially automated.

To automate the sewing process without human resources, smart technology must be incorporated into the sewing machine. The cut fabrics should be transferred automatically to the sewing machine for feeding and must be sewn according to the stitch line that is previously designed. In the future of sewing factories, robots and automatic sewing machines will occupy these processes. Steve Dickerson, a founder of Softwear Automation and a professor at the Georgia Institute of Technology, studied robotics technology for sewing and launched “SEWBOT”, which is an automatic sewing system [6,9]. This system consists of an auto sewing machine, robotic arm, and conveyor system. With this system, T-shirts, jeans, floor rugs, bathroom mats, and pillow can be manufactured completely automatically. On the other hand, current automated sewing technology has limitations on the materials that can be used, i.e., only rigid materials such as cotton. Therefore, research is needed to extend the technology to various fabrics, such as cotton–PET blend fabrics, silk, and mesh fabrics, for garment manufacturing.

In our previous study [10], the automated manufacturing system for a smart sports bra was proposed by using various machines and technologies such as 2D–3D computer-aided design (CAD) program, automatic cutting machine, robot-based gripping system, and automatic sewing system. In particular, the automatic feeding system and template sewing was developed to realize automatic sewing without human intervention. However, there is a limitation that it is possible only for the selected fabrics and stitch patterns.

Therefore, to sew the fabrics automatically, considerable research for optimizing sewing conditions is required. Because the material of sewing parts, such as fabrics, is soft and flexible, its shape can be changed easily. Hence, it is difficult for an automatic machine to set the sewing line along the edge of the actual parts accurately and handle the sewing parts [11]. Generally, sewing damage is a problem in garment manufacturing, causing appearance problems and, consequently, degrading the quality of the final product. The main problems that arise from the actual stitch formation during the sewing process include skip or slipped stitches, staggered stitches, unbalanced stitches, variable stitch density, seam puckering, and needle, bobbin, or looper thread breakage [12]. Therefore, optimal sewing conditions must be set according to the fabric properties. Many researchers have found that the fabric property parameters, such as the fabric density, thickness, tensile strength, extensibility, and bending rigidity, affect the seam quality [13].

This study aimed to establish an automatic sewing process for garment production. For this purpose, a system was developed to feed the cut fabrics to the sewing machine automatically. The stitch pattern was designed as two types. The sewn appearance, stitch length, and seam efficiency were evaluated according to the sewing parameters of the automatic sewing machine and textile mechanical properties in each stitch pattern. In addition, statistical analysis was conducted to quantitatively evaluate the sewability of stitches formed through the automatic sewing process, and a regression equation for the sewability according to sewing conditions and textile properties was derived.

2. Materials and Methods

2.1. Development of Automatic Feeding System for Sewing

In this study, an industrial sewing machine (AMS-224, Juki, Tokyo, Japan), which is a computer-controlled cycle machine, was used [10]. An automatic feeding system suitable for the sewing area was developed using a motor and acceleration sensor so that the cut fabrics can be inserted automatically into the sewing machine. This system moves the sewing parts of the cut fabrics on the sewing machine to execute the sewing task along the generated sewing trajectory. Figure 1 presents a schematic diagram of the developed automatic feeding system.

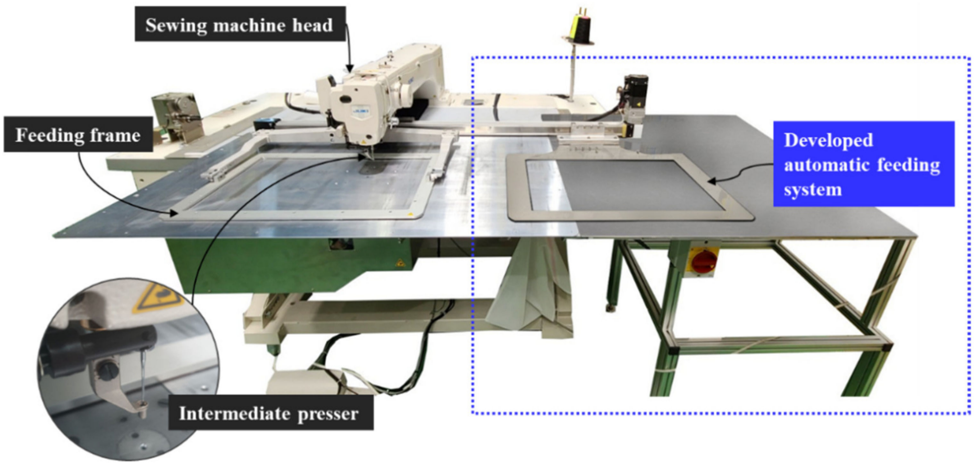


Figure 1. Industrial sewing machine and developed automatic feeding system.

A separate template was made to fix the fabric samples when the cut fabric was inserted automatically into the sewing machine. The fixation of the fabric was compared according to the template surface roughness by preparing two templates: flat and rough. As shown in Figure 2, a template made of polycarbonate was used as a template for a flat surface, and a tape with silicon carbide particles was attached to the template for a rough surface.

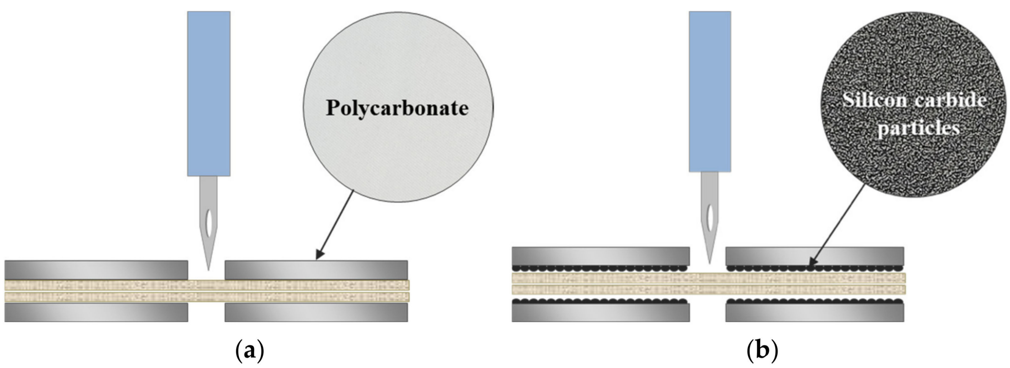


Figure 2. Diagram of the self-made template: (**a**) flat surface template; (**b**) rough surface template.

2.2. Preparation and Measurement of the Mechanical Properties of the Fabric Samples

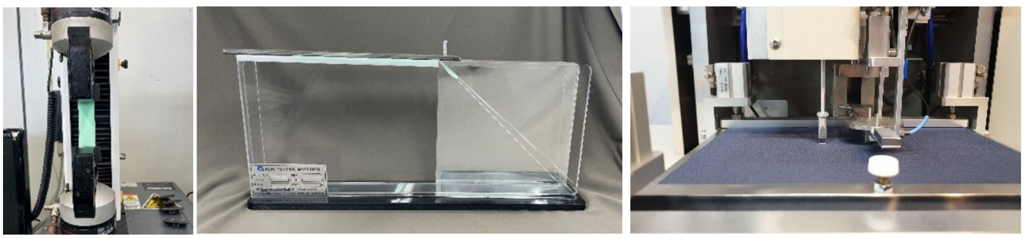
To analyze the sewing quality through an automatic sewing process according to the fabric properties, 12 types of fabrics with different thicknesses and fiber compositions were prepared. The fabric samples used in this study were commercially available; Table 1 lists the physical characteristics of the fabrics. The fabric weight and thickness were measured according to ISO 3801:1977 and ISO 5084:1996, respectively.

Table 1. Fabric samples for a sewing test.

Fabric Number	Structure	Thickness (mm)	Weight (g/m^2)	Composition	Description
1	Plain woven	0.08	39	Nylon 100%	Rip woven
2	Plain woven	0.10	68	Polyester 100%	Light weight woven
3	Plain woven	0.30	115	Nylon 70%, polyester 24%, polyurethane 6%	Span woven
4	Plain woven	0.38	170	Wool 40%, polyester 60%	Summer wool
5	Tricot knit	0.56	225	Polyester 79%, polyurethane 21%	Compression knit
6	Plain woven	0.76	271	Cotton 100%	Oxford
7	2-layer tricot	0.90	417	Polyester 80%, polyurethane 20%	Neoprene
8	Pile knit	0.94	316	Cotton 100%	Corduroy
9	Twill woven	0.94	411	Cotton 100%	Denim
10	Twill woven	0.95	362	Cotton 100%	Chino
11	3-layer tricot	1.06	342	Nylon 78%, polyurethane 22% (face), polyester 96%, polyurethane 4% (back)	Fleece knit
12	Double cloth woven	1.51	517	Wool 100%	Wool felt

The density of the fabric samples was determined by the number of warp (wale) and weft (course) yarns in a 1 inch × 1 inch surface area according to ASTM D 3775 for woven fabrics and ASTM D 3887 for knitted fabrics.

The tensile strength and elongation were determined using a constant rate of extension test machine in accordance with the ASTM D 5035-2011: 2019 strip method, while the stiffness was assessed by the ISO 4606: 2013 measurement method using a fixed-angle bending tester as shown in Figure 3a,b. All the samples were prepared with a size of 3 cm × 15 cm and were measured in the warp (wale) and weft (course) directions. The final values were obtained by averaging five measurements taken from different parts of the samples.



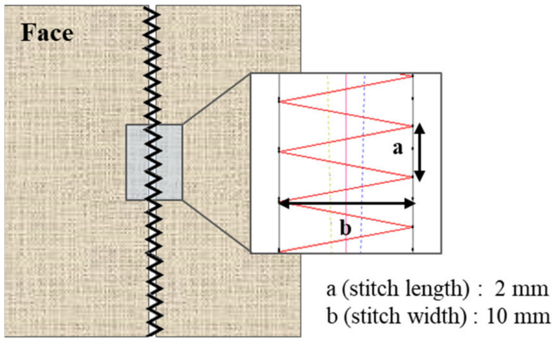
(a) (b) (c)

Figure 3. Images for mechanical testing: (**a**) extension test machine; (**b**) fixed-angle bending tester; (**c**) KES-FB4.

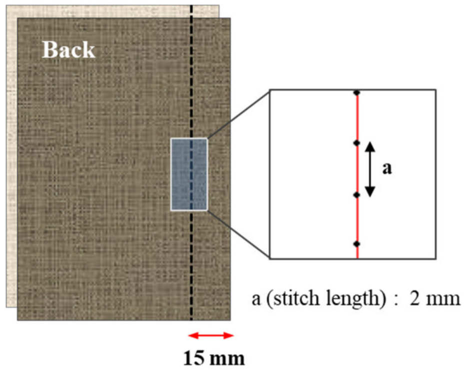
The surface roughness of the fabrics was measured using a KES-FB4 Surface Tester (Kato Tech Co., Ltd., Kyoto, Japan), as shown in Figure 3c. For each sample, each measurement was made three times on the fabric face and back, respectively. Standard size samples of 20 cm × 20 cm were tested in the warp (wale) and weft (course) directions, and six resulting values were averaged.

2.3. Sewing Pattern and Condition

For the sewing pattern, zigzag stitch and lock stitch were selected to evaluate the sewn appearance. The stitches were designed using PM-1 programming software (Juki, Tokyo, Japan), as shown in Figure 4. In the case of a zigzag stitch, the faces of the fabrics were put together, and then, the seam part was zigzag-sewn. For lock stitch sewing, the two pieces of cut fabrics were sewn by layering the fabrics facing up. In both cases, a self-made template was used to hold the two pieces of fabric so they could not move during the sewing process.



(a)



(b)

Figure 4. Sewing pattern: (**a**) zigzag stitch; (**b**) lock stitch.

2.4. Evaluation of Sewability at the Sewn Seam

The appearance and sewability of the sewn parts on each fabric sample were analyzed according to the presser height—0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, and 3.5 mm—and sewing speed—200, 400, and 800 rpm. For each sewing condition, the fabric sample was sewn along the warp or wale directions.

The sewn parts of the seam were observed and evaluated manually using the photos by a digital camera. By observing the appearance, the sewability was defined as the balance of the stitch [14–16]. At this time, the balance of the stitch was evaluated by measuring the stitch length and the width of the seam allowance after sewing for the lock stitch or the width of the stitch after sewing the zigzag stitch. The stitch density was measured by counting the number of stitches per inch (SPI).

The seam tensile strength was measured using the modified ISO13934-1 on a universal testing machine (Instron-3343, Instron, Norwood, MA, USA). A sample, 30 mm wide and 150 mm long, in the weft (course) direction, which is perpendicular to the sewn parts, was fixed in a clamp with a distance of 75 mm. The seam efficiency was then calculated as the percentage seam strength over the fabric strength using the following Equation (1):

$$\text{Seam efficiency } (\%) = \frac{Seam\ tensile\ strength}{Fabric\ tensile\ strength} \times 100, \quad (1)$$

For the statistical analysis of the relationship of the fabric properties and the sewing conditions, IBM® SPSS® Statistics (Predictive Analytics Software, IBM Corporation, Armonk, NY, USA) was utilized. Correlation analysis was performed to determine the statistically significant factors of the textile properties and the sewability. Based on the variable derived from correlation analysis, moderated multiple regression analysis was performed to confirm the moderate effect of the sewing conditions between the textile properties and the sewability. For the analysis, the textile properties were independent variables, sewability was a dependent variable, and sewing conditions were the parameter to observe the interaction effect.

3. Results and Discussion

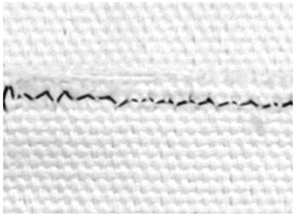
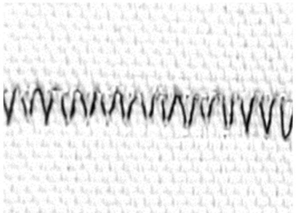
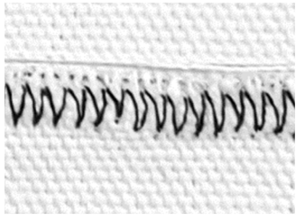
3.1. Comparison of the Sewing Appearance by Templates

The methods of automated sewing vary according to the design of the stitch line. Two-dimensional seams can be produced using a computer numerical control (CNC) sewing method. To automate the whole sewing processes, clamp feed or template sewing is required to keep the fabric stable while maintaining the size stability [5,7–9]. In this study, an automatic feeding system was introduced to an industrial sewing machine for the automatic insertion and sewing of cut fabrics. In the sewing process, a self-made template was designed to fix the cut fabrics without moving and changing the positions.

One of the main factors of sewing influencing the stability of stitch length is its feeding in the sewing process. The feeding conditions depend on the external forces, which are the load, pressing force, and inertial force. These factors influence the stitch length and appearance to stabilize stitch along the seam [17]. In this study, the template used in the feeding system was considered to be related to the load and pressing force. Therefore, to evaluate the sewing performance according to the surface of the template, zigzag stitching was sewn on the No. 6 fabric sample, which is oxford cotton woven. At this time, the presser height was fixed to 1.0 mm, and the sewing speed was set to 200 rpm.

Table 2 lists the appearance of a zigzag stitch formed on the No. 6 sample without a template or using a template with different surface roughness. As a result, sewing could not be performed without a template because no fixing force presses the sample in the four directions during the sewing process. Therefore, the sample could move according to the movement of the needle. On the other hand, as a result of evaluating the appearance of the sewn part on fabric according to the surface roughness of the template, the stitch that formed through the rough surface template was more balanced than that of the flat surface template. The measured stitch width values of the zigzag patterns were 4.0 ± 0.7 mm for the flat surface template and 4.3 ± 0.4 mm for the rough surface template, respectively. Sewing by the template with a flat surface produced a smaller width and a non-uniform stitch than sewing with a rough surface. Indeed, during the sewing process, the position of the fabric was not be fixed with a polycarbonate template with a flat surface. On the other hand, the template on the surface coated with silicon carbide particles did not show movement of the fabric during the feeding or sewing process due to the friction force between the fabric and template surface. This is because the template of the rough surface has a higher frictional force with the surface of the fabric than the flat surface. Therefore, the fabric is fixed more firmly during the sewing process. As proof of this, the sample using the rough surface template showed higher values with a seam strength and seam efficiency of 118.9 kgf/cm^2 and 94.7%, respectively. According to research from Juciene and Vobolis [18], seam quality is affected by the friction force generated by the pressing foot. They reported that the highest influence upon movement of a fabric has the design material of a pressing foot. In a flat metal pressing foot, the fabric moves much more, which featured a higher friction ratio. Although the system was different, it was presumed that the surface of the template for automatic sewing also worked with the same mechanism, such as that of the presser foot of the lockstitch sewing machine. Based on this result, subsequent experiments were conducted using a template with a rough surface. However, since the rough surface can damage the fabric surface due to friction, it was careful not to excessively rub the fabric surface and the template when loading the fabric into the sewing machine.

Table 2. Appearance and sewabilities of the sewn part according to the template surface.

Sewability	Without Template	Flat Surface Template	Rough Surface Template
Appearance			
Stitch width (mm)	1.0 ± 1.4	4.0 ± 0.7	4.3 ± 0.4
Seam strength (kgf/cm^2)	0.0	51.9	118.9
Seam efficiency (%)	0.0	41.3	94.7

3.2. Sewability According to Presser Height

Sewability can be defined as the ease of formation of shell structures and the ability of a material to be seamed effectively without fabric damage and provide suitable end-use performance [5,15]. The integration of various parameters related to the sewing thread, fabric, and sewing machine settings at their optimal level results in good sewability [16]. The sewing machine parameters that can affect the sewability are the thread tension, take-up lever, sewing speed, fabric feeding mechanism, and presser height. In particular, the automatic sewing machine used in this study has a different type of presser than the general sewing machine. Because the presser acts as a guide by contacting the cut fabrics between the fabric and the needle directly, it was determined to be the main sewing parameter.

To determine if the automatic sewing was done as well as the design, the appearance and sewability of the sewn parts with a lock stitch or a zigzag stitch were analyzed according to the change in the presser height. In this study, the presser height was defined as the clearance between the bottom end of the presser and the template with fabrics. This can be adjusted from 0 to 3.5 mm.

In the lock stitch pattern, the sewability was considered through the stitch length and the width of the seam allowance. Table 3 and Figure 5 show the results of measuring the stitch density, stitch length, and width of seam allowance according to the presser height adjusted at 0.5 mm intervals. In all samples, the SPI value was the same as 12.5~13.0, as shown in Table 3. As the height of the presser increases, however, thin or stretched fabrics, such as No. 1, No. 2, and No. 5, show skewed, struggled, and unbalanced stitches and seam puckering. In these samples, the width of the seam allowance decreased with increasing presser height. This is because the pressing force decreases as the presser height increases, and the fabric slips due to the movement of the needle during the sewing process. A thinner and smoother fabric requires less holding force by the template, and the effect of needle movement and thread tension on the stitch may be increased. The stitch stability depends on the rigidity of the material, and the deformation of the sewn fabric is a consequence of the internal frictions of the fabric [19]. Dobilait et al. [20] reported that the puckering nature of different fabric seams was influenced by the pressing foot force and sewing speed. Indeed, seam puckering and seam slippage were observed in some samples with low flex stiffness or flat surface roughness. In particular, the SPI of No. 5 increased with the increasing height of the presser; the maximum value was 16.0 when the presser height was 3.5 mm. Therefore, in the case of stretched and smooth fabrics, the stitch density increases due to slipping as the presser height increases, resulting in unbalanced sewing. On the other hand, the rigid or rough surface fabric showed a balanced stitch and seam allowance despite the presser height being increased to 3.5 mm.

Table 3. Sewability of the lock stitch on each fabric according to the presser height.

Sewability Factor	Fabric Number	Presser Height (mm)							
		0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5
SPI	1	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0
	2	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0
	3	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0
	4	13.0	12.5	13.0	13.0	12.5	12.5	13.0	13.0
	5	13.5	13.0	14.0	14.0	14.0	16.0	15.0	16.0
	6	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0
	7	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0
	8	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0
	9	13.0	12.5	12.5	13.0	13.0	12.5	13.0	13.0
	10	13.0	13.0	13.0	13.0	13.0	12.5	12.5	12.5
	11	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0
	12	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0
Stitch length (mm)	1	1.98	1.97	2.00	1.94	1.93	1.97	1.77	2.02
	2	2.15	1.95	2.05	2.10	2.07	2.06	1.95	2.12
	3	2.16	2.05	2.01	2.10	2.14	2.15	2.18	2.18
	4	2.05	2.11	2.08	2.07	2.06	1.97	2.06	2.04
	5	1.90	1.83	1.79	1.94	1.83	2.08	1.81	1.78
	6	1.84	1.86	1.88	1.91	1.91	1.86	1.86	1.92
	7	1.78	1.77	1.76	1.83	1.81	1.78	1.82	1.80
	8	1.86	1.87	1.90	1.84	1.88	1.88	1.87	1.80
	9	1.80	1.86	1.87	1.87	1.87	1.76	1.85	1.88
	10	1.76	1.85	1.84	1.83	1.82	1.90	1.88	1.86
	11	1.50	1.57	1.66	1.68	1.67	1.71	1.73	1.61
	12	1.62	1.63	1.56	1.62	1.62	1.61	1.59	1.57
Width of seam allowance (mm)	1	14.4	14.0	8.0	11.8	15.4	9.0	7.2	8.2
	2	13.8	11.6	13.4	12.4	12.4	11.8	10.5	11.4
	3	15.2	14.6	14.6	13.6	15.0	13.6	15.2	12.6
	4	16.2	15.0	13.4	14.4	13.8	14.6	13.6	17.0
	5	13.0	15.0	12.4	14.4	14.6	13.2	11.4	7.4
	6	14.8	15.4	15.8	15.0	15.0	15.6	15.2	15.0
	7	15.2	15.2	13.6	14.8	14.2	13.4	14.8	14.4
	8	15.0	16.0	14.0	15.0	14.0	15.0	15.2	16.2
	9	14.2	15.0	13.8	14.6	14.8	14.8	14.0	15.2
	10	15.0	16.2	15.0	15.6	15.0	15.8	14.2	14.0
	11	16.4	15.0	14.8	15.4	16.8	15.4	14.2	13.4
	12	15.2	15.6	14.6	15.6	14.2	15.6	15.8	14.8

Although there was no tendency of the sewability according to the change in presser height within one sample, the stitch length decreased linearly with increasing fabric thickness, as shown in Figure 5. When designing stitches in the software program, the stitch length was designed to be 2.0 mm. On the other hand, the length of the stitch appearing on the fabric surface could be shorter as the thickness of the fabric increased because the same length of the sewing thread was used. According to the research by Suh [21], the thickness of the fabric is considered to be the main factor in calculating the consumption of sewing thread through an analysis of the structure of the lock-stitched seam. Therefore, the thickness and surface properties of the fabric must be considered when designing a stitch pattern for sewing.

Figure 6 shows the seam efficiency versus the width of the seam allowance by sewing with a lock stitch. The seam efficiency increased with the increasing width of the seam allowance regardless of the samples or the presser height. The durability of the seam can be measured in terms of the seam efficiency. In addition, low seam efficiency values indicate that the sewn fabric is damaged during sewing [14]. The width of the seam allowance below the appropriate level could indicate damaged fabric or abnormal sewn during the sewing process. Therefore, the presser height was chosen as the optimal presser height for each sample when the width of the seam allowance is close to the design and the seam efficiency is high.

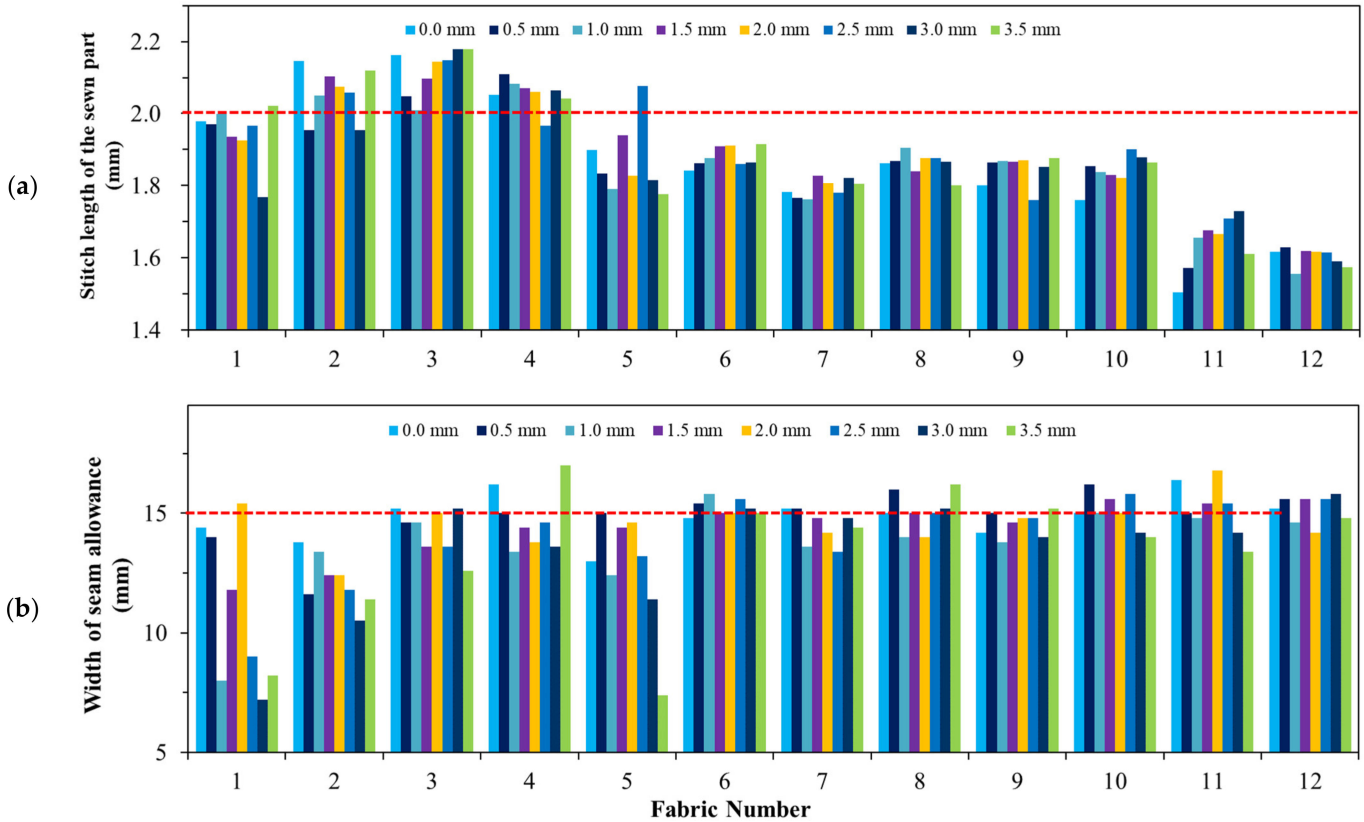


Figure 5. Sewability of the lock stitch according to the change in the presser height: (**a**) stitch length, (**b**) width of the seam allowance.

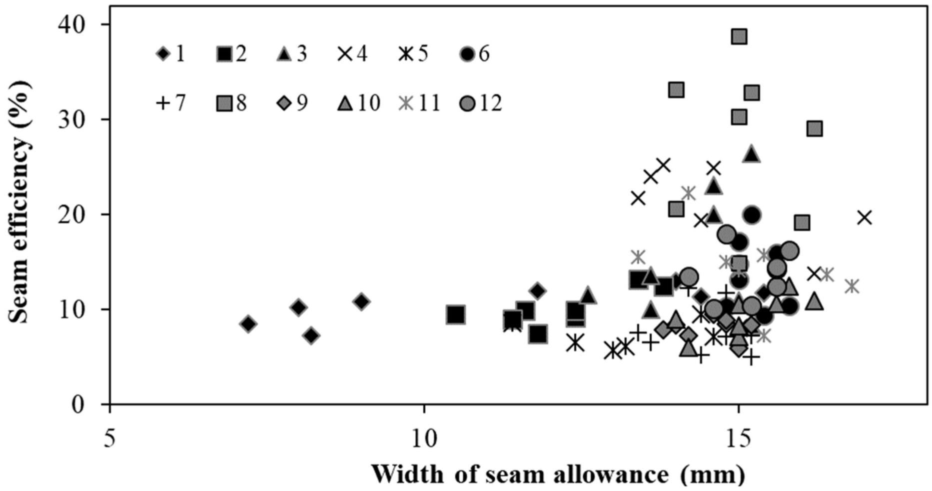


Figure 6. Seam efficiency of the lock stitch according to the width of the seam allowance.

The presser height for each sample was selected for lock stitch sewing based on the seam efficiency and stitch length values obtained through the experiment results: 0.0 mm for No. 1, No. 2, and No. 3; 1.0 mm for No. 4; 0.5 mm for No. 5; 2.0 mm for No. 6 and No. 7; 2.5 mm for No. 8, No. 9, and No. 10; 3.0 mm for No. 11; 3.5 mm for No. 12.

On the other hand, the zigzag stitch was chosen to join two pieces of fabric through an automatic sewing machine as a method to imitate a cover stitch or flatlock stitch in this study. Unlike the lock stitch, the zigzag stitch was expected to be affected by the movement of the presser foot and needle during the sewing process because the cut edges of the fabric were in contact with each other to sew, and the sewing needle moved repeatedly left and right of the seam line. Therefore, the experiment was conducted by setting the presser height larger than the thickness of the fabrics so that the presser foot does not contact the fabric during the sewing process directly. Furthermore, thin fabrics with a thickness of 0.5 mm or less, such as No. 1~No. 5, were excluded from this experiment. This is because the stitches were not formed properly as the fabric was moved by the automatic feeding system when the sample was automatically inserted in the sewing machine or the needle or sewing thread moving during the sewing process, despite using the template of a rough surface.

The width of the zigzag stitch and the seam efficiency through the seam strength were measured to analyze the zigzag stitch formed by the automatic sewing machine quantitatively. The results are shown in Figure 7. The stitch width tended to increase with increasing presser height in each sample. Under the condition of the presser height similar to the fabric thickness, the stitches formed unevenly because the fabric edge was contacted by the presser foot, which moved left and right of the seam. This is believed to be a phenomenon that appears when the position of the cut edges of the fabric is moved by the movement of the presser foot and needle during sewing and pulled by the sewing thread, despite raising the presser foot so that it was not in contact with the fabric. Therefore, the height of the presser should be increased to prevent the fabric located under the needle from being moved by the in zigzag stitch. On the other hand, stable stitches were formed when the height of the presser was approximately twice the fabric thickness. As in No. 6 and No. 7, if the height of the presser increased above an appropriate level, the sewing was not conducted properly because the fabric edge of the sewing part was not fixed by the presser foot during the sewing process. Moreover, the shape of the stitch of the samples differed according to the texture and thickness of the fabric. Rigid or rough surface fabrics, such as No. 9 and No. 10, had a wide zigzag width and uniform stitches around the edges of the seam, but flexible or smooth surface fabrics, such as No. 6 and No. 7, showed that the fabric edges were curled during the sewing process or the stitches formed were unbalanced.

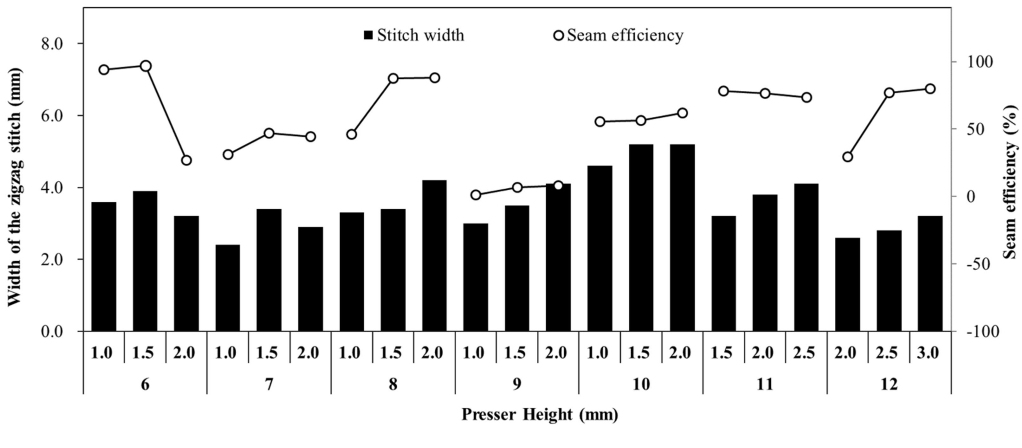


Figure 7. Stitch balance and seam efficiency of the zigzag stitch according to the presser height.

On the other hand, the seam efficiency was proportional to the stitch width. In each sample, the seam efficiency was highest under the condition with the longest stitch width. In this experiment, because the zigzag stitch was conducted in the form of a flat seam, the larger width of the zigzag stitch can mean that there are many sewing threads in a certain area. When the seam of the fabric was pulled by tension, a tensile force was applied not only with the fabric but also with the sewing thread. Therefore, the number of sewing threads that share the load increases, resulting in an increase in seam strength [13].

Consequently, thicker fabric and higher presser height result in more balanced stitches in the sewn parts. In addition, the seam strength increases with increasing width of the stitch, resulting in excellent seam efficiency. In this study, the condition of a high seam efficiency and the wide width of the stitch was chosen as the optimal presser height condition in each fabric for the zigzag stitch. The optimal presser height value for each sample was as follows: 1.5 mm for No. 6 and No. 7; 2.0 mm for No. 8, No. 9, and No. 10; 2.5 mm for No. 11; 3.0 mm for No. 12.

3.3. Sewability According to Sewing Speed

The sewing speed is related directly to productivity. The fast sewing speed shortens the production time and increases the production amount, reducing the cost. On the other hand, an excessively fast sewing speed may cause sewing damage. Lower sewing speeds are effective in controlling the overheating problems of the needles. At the same time, the number of yarn breakages is reduced [12]. To improve the productivity, it is necessary to derive the optimal RPM conditions that shorten the sewing time, while making a balanced stitch pattern according to the fabric properties. Therefore, the effect of the sewing speed on the sewability was examined according to the mechanical properties of each fabric. To this end, the sewing speed was adjusted to 200, 400, and 800 rpm to perform the lock stitch and the zigzag stitch according to the optimal presser height for each fabric sample identified above.

Table 4 lists SPI, stitch length, and seam allowance values of the sewn part by the lock stitch according to the sewing speed. As expected, the sewability worsened as the sewing speed increased. In the No. 1~No. 5 fabric samples, which are thin and lightweight, it was confirmed that a faster sewing speed resulted in a shorter stitch length and narrower seam allowance. This is because the samples slipped within the template without following the movement of the template as the sewing speed increased. On the other hand, in the thick fabrics of No. 6~No. 12 samples, the stitch length increased with increasing sewing speed. For fabrics with smooth surfaces such as No. 7 and No. 11, the stitch length increased and the SPI decreased with increasing sewing speed. Milda Juciene and Jonas Vobolis [22] reported that the sewing speed has the greatest influence on the stitch length. They reported that the dependencies of the stitch length show that different friction forces cause the variations of the stitch length in the range of 10~20%. Indeed, according to their experiment, the stitch length may vary up to 0.01 mm when sewing at a lower speed, whereas the stitching length may vary up to 0.03 mm when sewing by higher speed through a one-needle lockstitch sewing machine. Therefore, the friction force between the template and sample surface decreased with increasing sewing speed. The samples were more affected by the movement of the needle and the inertia force.

Table 4. Sewability of the lock stitch sewn parts on each fabric according to the sewing speed.

Sewability Factor	Fabric Number	Sewing Speed (RPM)		
		200	400	800
SPI	1	13.0	13.0	13.0
	2	13.0	13.0	13.0
	3	13.0	13.0	13.0
	4	13.0	13.0	12.5
	5	13.0	13.0	13.5
	6	13.0	12.5	12.5
	7	13.0	12.5	8.5
	8	13.0	13.0	11.5
	9	12.5	13.0	13.5
	10	12.5	13.0	13.0
	11	13.0	12.5	7.0
	12	13.0	13.0	13.0

Table 4. *Cont.*

Sewability Factor	Fabric Number	Sewing Speed (RPM)		
		200	400	800
Stitch length (mm)	1	2.0	2.0	2.0
	2	2.1	1.8	1.7
	3	2.2	2.2	2.1
	4	2.1	2.0	1.9
	5	1.8	1.7	1.6
	6	1.9	2.2	2.2
	7	1.8	2.1	3.2
	8	1.9	2.1	2.6
	9	1.8	2.0	2.0
	10	1.9	2.1	2.0
	11	1.7	2.0	2.7
	12	1.6	1.9	1.7
Width of seam allowance (mm)	1	14.4	10.0	10.8
	2	13.8	9.0	7.6
	3	15.2	14.4	14.0
	4	13.4	12.4	13.2
	5	15.0	12.2	12.4
	6	15.0	14.8	14.6
	7	14.8	14.4	14.4
	8	15.0	13.6	15.0
	9	14.8	14.0	15.0
	10	15.8	13.2	14.6
	11	14.2	14.2	15.6
	12	14.8	14.4	14.6

Figure 8 shows the change ratio of the seam efficiency with the sewing speed. The change ratio of the seam efficiency is the percentage of the seam efficiency value of the sewn sample at each sewing speed relative to the seam efficiency of the sample sewn at 200 rpm. At a sewing speed of 400 rpm, the seam efficiency of each sample decreased except for No. 8, No. 9, and No. 12. At 800 rpm, the seam efficiency of all samples decreased to a maximum of 30%. The needle thread is subjected to repeated tensile stresses and is affected by heat, bending, pressure, torsion, and wearing during the sewing process. The sewing speed influences the level of these stresses. Therefore, high-speed sewing operation leads to an overall reduction in the tensile properties of the needle thread [22]. Naeem et al. [23] reported that the seam strength decreases with increasing sewing speed because the needle heat rises linearly according to the speed. In addition, the percentage loss of the seam strength is much higher in lightweight fabric than medium or heavyweight fabrics. In this study, however, the seam efficiency of the three samples, No. 8, No. 9, and No. 12, increased slightly under 400 rpm sewing. These fabrics were less affected by the slip between the fabric surface or the movement of the needle despite the fast sewing speed because they were rough and thick. As a result, as the stitch length at 400 rpm was wider than at 200 rpm, the ability to withstand the tension force was improved further, and the seam efficiency was increased. Through the results of this experiment, 200 rpm was found to create the best conditions in all fabric samples for the lock stitch.

Table 5 shows SPI and stitch width of the sewn part by the zigzag stitch according to the sewing speed. Unlike the expectation that the sewability will deteriorate when the sewing speed is fast, some samples showed balanced stitches on the sewn part, even at high speed. When the sewing speed was increased to 400 rpm, most of the samples tended to increase both the SPI value and stitch width, and a very balanced stitch was made. Friction forces play an important role in the stitch formation process. The highest stitch length variation was at the lowest friction force and the highest rotation frequency of the main shaft. The stitch length variance decreased with increasing friction force, but the stitch length variance also increased with increasing rotational speed of the main shaft [24]. This suggests that if the sewing speed is rather slow, there is a time to move the fabric samples according to the movement of the sewing needle by the friction force and contracting the stitch by the tension of the needle thread. On the other hand, when the sewing speed was increased to 400 rpm, the inertia force canceled the frictional force and prevented the movement of the fabric by the needle. In contrast, when the sewing speed was increased to 800 rpm, the stitch width did not change significantly, except for No. 6, but the SPI value decreased. In addition, the stitches were unbalanced, staggered, or shrunken in appearance. This is because friction between the needle plate and the back of the fabric is canceled when the sewing speed increases. Inertial forces acting in the process of transportation depend on the sewing speed [19]. Therefore, as the excessive inertial forces affect the stitch-forming process, sewing was not performed because the needle moved, even before the stitch was formed at a fast sewing speed, as shown in No. 11 and No. 12.

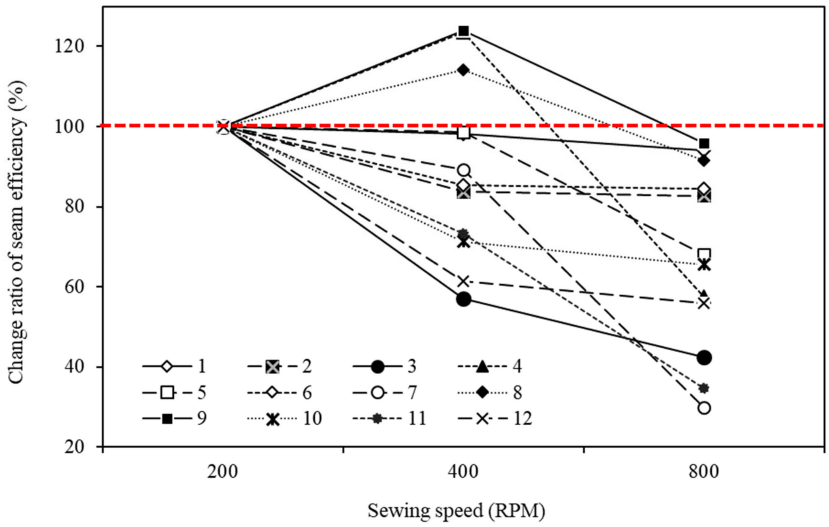


Figure 8. Change ratio of seam efficiency in lock stitch pattern according to sewing speed.

Table 5. Sewability of the zigzag stitch on each fabric according to the sewing speed.

Sewability Factor	Fabric Number	Sewing Speed (RPM)		
		200	**400**	**800**
SPI	6	12.5	13.5	13.0
	7	12.5	12.5	12.5
	8	13.0	13.5	13.0
	9	13.0	12.5	12.5
	10	13.0	13.0	12.5
	11	11.5	12.5	8.0
	12	11.5	12.5	9.5
Stitch width (mm)	6	3.9	4.6	3.4
	7	3.4	3.1	3.0
	8	4.2	4.9	4.9
	9	4.1	5.1	5.1
	10	5.2	5.7	5.9
	11	4.1	5.5	4.1
	12	3.2	4.8	3.3

Figure 9 presents the change ratio of the seam efficiency by zigzag stitch with the sewing speed. At a sewing speed of 400 rpm, the seam efficiency of each sample was maintained or increased except for No. 10. On the other hand, at 800 rpm, the seam efficiency of all samples decreased to a maximum of 60% except for No. 6, which failed to be sewn. This result is consistent with the appearance evaluation results. As mentioned earlier, in the zigzag stitches, the strength to withstand the tensile force increases when the stitch width is wide, thereby improving the seam efficiency. For this reason, the seam efficiency of the sample sewn by zigzag stitch at 400 rpm, where the stitch width was longer, showed the highest value. When the sewing speed was increased to 800 rpm, however, the seam efficiency decreased in all samples. Because the stitch itself was not formed properly, or even if it was formed, the sewing thread was subjected to more stress, and its tensile strength decreased. Through the results of this experiment, 400 rpm was the best condition in all fabric samples for a zigzag stitch.

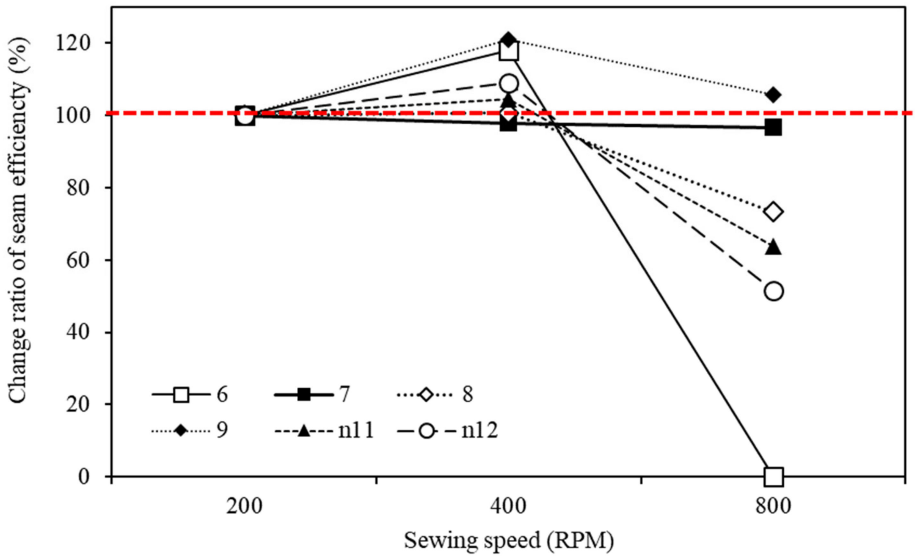


Figure 9. Change ratio of the seam efficiency in the zigzag stitch pattern according to the sewing speed.

3.4. Analysis of the Correlation between the Textile Properties and Sewing Conditions

During the sewing process, the fabric is subjected to various mechanical solicitations, such as shear, compression, and extension. The fabric properties, which are composition, weave, thickness, and strength, will govern its sewability and seam performance [19]. Therefore, it is important to understand the interaction between the mechanical properties of each fabric sample and the sewing parameters. Table 6 lists the mechanical properties and surface roughness of the fabric samples in this study.

Table 6. Mechanical properties of the fabric samples.

Fabric Number	Thickness (mm)	Weight (g/m^2)	Density	Tensile Strength (N/cm)	Elongation (%)	Flex Stiffness (mN·m)	Surface Roughness (mm)
1	0.08	39	361	71.2	42.5	0.04	1.25
2	0.10	68	270	124.0	35.9	0.10	1.75
3	0.30	115	204	113.3	51.3	0.04	3.52
4	0.38	170	137	57.7	34.4	0.06	7.02
5	0.56	225	186	59.7	285.7	0.04	0.95
6	0.76	271	116	145.7	17.4	0.30	12.87
7	0.90	417	194	302.5	257.5	0.61	1.31
8	0.94	316	84	100.8	14.8	0.48	10.08
9	0.94	411	120	244.2	26.3	3.18	5.75
10	0.95	362	108	211.2	20.9	0.80	6.82
11	1.06	342	207	91.0	219.2	0.25	2.35
12	1.51	517	84	111.0	49.4	1.19	2.29

Table 7 lists the results of Pearson's correlation analysis between the textile properties and sewability in the case of a lock stitch pattern. The stitch length was correlated with the fabric thickness, weight, and stiffness. On the other hand, the remaining sewability indices, the seam allowance and seam strength, were correlated with most of the fabric properties. Ebrahim [25] reported a correlation between the seam efficiency and the shear rigidity, extensibility, thickness, bending rigidity, weight, and tensile strength. In addition, the seam strength could be significantly different for the fabric thickness: the thicker the fabric, the greater the seam strength [26].

Table 7. Correlation coefficient between textile properties and sewability in the lock stitch.

Textile Property	Sewability Factor			
	SPI	**Stitch Length**	**Seam Allowance**	**Seam Strength**
Stiffness	−0.046	−0.233 *	0.254 **	−0.337 **
Thickness	−0.125	−0.414 **	0.566 **	−0.779 **
Weight	−0.160	−0.376 **	0.546 **	−0.781 **
Density	0.005	0.178	−617 **	0.746 **
Roughness	−0.019	0.111	0.392 **	−0.284 **
Tensile strength	−0.053	−0.068	0.204 *	−0.098
Elongation	−0.024	−0.137	−0.036	−0.322 **

*. Correlation is significant at the level of 0.05 (2-tailed); **. Correlation is significant at the level of 0.01 (2-tailed).

Table 8 lists the results of the correlation analysis of the sewing conditions and textile properties of the sewability. As a result, the presser height correlated the most with the thickness and weight in textile properties and seam strength in sewability. Therefore, the presser height should be higher with a thicker and heavier fabric. In addition, the higher presser height could decrease the seam strength. While the sewing speed was not correlated with any factors of the textile properties, it was correlated with the SPI and stitch length in sewability. The SPI decreased with increasing sewing speed and the stitch length increased.

Table 8. Correlation coefficient between sewing conditions and textile properties or sewability in the lock stitch.

Effect Factor		Sewing Condition	
		Presser Height	**Sewing Speed**
Textile properties	Stiffness	0.116	0.000
	Thickness	0.200 *	0.000
	Weight	0.193 *	0.000
	Density	−0.149	0.000
	Roughness	0.064	0.000
	Tensile strength	0.069	0.000
	Elongation	0.000	0.000
Sewability factor	SPI	−0.063	−0.264 **
	Stitch length	0.085	0.376 **
	Seam allowance	−0.027	−0.132
	Seam strength	−0.187 *	−0.026

*. Correlation is significant at the level of 0.05 (2-tailed); **. Correlation is significant at the level of 0.01 (2-tailed).

Based on these results, moderated multiple regression analysis was conducted to confirm the effects of the sewing conditions between the textile properties and sewability. Using the variable whose significance was confirmed by correlation analysis, the textile properties were independent variables, and the sewability was the dependent variable for the analysis. In addition, the interaction effects of the textile properties were confirmed by conducting a moderated multiple regression analysis using the sewing conditions as a parameter. As shown in Table 9, in the case of thickness, the result in model 1 showed no significant two-way interactions between thickness and presser height. On the other hand, the results of model 2 indicated a significant three-way interaction: $\Delta R^2 = 0.033$, $\Delta F = 10.674$, $p = 0.001$, $\beta = 0.459$. Therefore, the moderating effect of the presser height could be observed between the thickness and seam strength. In the case of weight, model 1 showed no significant two-way interaction between the weight and presser height. On the other hand, model 2 showed a significant three-way interaction: $\Delta R^2 = 0.030$, $\Delta F = 9.657$, $p = 0.002$, $\beta = 0.456$. Hence, the moderating effect of the presser height on the weight and seam strength was also confirmed.

Table 9. Moderated multiple regression analysis predicting seam strength in the lock stitch pattern.

Model			Unstandardized Coefficients B	Std. Error	Standardized Coefficients β	R^2	ΔR^2	ΔF
Thickness	1	(Constant)	61.145	3.383		0.608	0.001	0.291
		Thickness	−47.575	3.641	−0.772 **			
		Presser Height	−0.697	1.292	−0.032			
	2	(Constant)	71.110	4.458		0.641	0.033	10.674 *
		Thickness	−63.339	5.975	−1.029 **			
		Presser Height	−6.953	2.282	−0.318 *			
		T-×-P	9.135	2.796	0.459 *			
Weight	1	(Constant)	64.683	3.539		0.611	0.001	0.409
		Weight	−0.136	0.010	−0.774 **			
		Presser Height	−0.821	1.284	−0.038			
	2	(Constant)	75.074	4.779		0.641	0.030	9.657 *
		Weight	−0.179	0.017	−1.017 **			
		Presser Height	−7.411	2.456	−0.339 *			
		W-×-P	0.025	0.008	0.456 *			

*. Correlation is significant at the level of 0.05 (1-tailed); **. Correlation is significant at the level of 0.01 (1-tailed).

The following regression Equations (2) and (3) were obtained using the values obtained. T denotes the thickness of the fabric, PH is the presser height, and W is the weight of the fabric.

$$\text{Seam strength} = 71.110 + (-63.339 \times \text{T}) + (-6.953 \times \text{PH}) + (9.135 \times \text{T*PH}) \quad (2)$$

$$\text{Seam strength} = 75.074 + (-0.179 \times \text{W}) + (-7.411 \times \text{PH}) + (0.025 \times \text{W*PH}) \quad (3)$$

Table 10 shows the prediction results of the seam strength for random samples based on the regression Equations (2) and (3). As a result, the prediction values were an overall similar level to the experimental values, showing excellent predictive performance. Therefore, it was confirmed that the seam strength of the lock-stitching fabric using an automatic sewing process can be predicted through this regression model.

Table 10. Seam strength prediction result of regression model.

Testing Sample			Seam Strength					
			By Equation (2)			By Equation (3)		
	Thickness (mm)	Weight (g/m^2)	Experimental value	Predicted value	Error	Experimental value	Predicted value	Error
1	0.29	70	56.4	50.6	5.8	56.4	59.7	3.3
2	0.76	271	20.0	23.0	3.0	20.0	25.9	5.9
3	0.94	316	14.8	14.0	0.8	14.8	19.2	4.4

In case of the zigzag stitch pattern, the results of Pearson's correlation analysis of the relationship between the textile properties and sewability was listed in Table 11. The analysis result showed a difference from the lock stitch pattern result. SPI was correlated with most of the textile properties variables. On the other hand, the stitch width was correlated with the tensile strength and elongation of the fabrics. Moreover, the seam strength showed a correlation with the stiffness and weight of the fabrics.

Table 11. Correlation coefficient between textile properties and sewability in the zigzag stitch.

Textile Properties	Sewability Factor		
	SPI	**Stitch Width**	**Seam Strength**
Stiffness	0.086	0.019	−0.506 **
Thickness	−0.424 *	−0.168	−0.301
Weight	−0.354 *	−0.276	−0.369 *
Density	−0.348 *	−0.198	0.142
Roughness	0.503 **	0.256	0.207
Tensile strength	0.272	0.367 *	0.053
Elongation	−0.442 **	−0.354 *	0.051

*. Correlation is significant at the level of 0.05 (2-tailed); **. Correlation is significant at the level of 0.01 (2-tailed).

Table 12 shows the results of a correlation analysis of the relationship between the sewing conditions and textile properties of sewability in the zigzag stitch pattern. Similar to the result in the lock stitch, the presser height was most correlated with the thickness, followed by the weight and roughness of the fabrics. Therefore, with a thicker, heavier, and smooth surface, the presser height should be higher for a zigzag stitch. Furthermore, a higher presser height could reduce the SPI. On the other hand, the sewing speed showed no correlation with the textile properties and sewability.

Table 12. Correlation coefficient between sewing conditions and textile properties or sewability in the zigzag stitch.

Effect Factor		Sewing Condition	
		Presser Height	**Sewing Speed**
Textile properties	Stiffness	0.100	0.000
	Thickness	0.698 **	0.000
	Weight	0.470 **	0.000
	Density	−0.100	0.000
	Roughness	−0.376 *	0.000
	Tensile strength	−0.185	0.000
	Elongation	0.023	0.000
Sewability factor	SPI	−0.416 *	−0.155
	Stitch width	0.221	0.297
	Seam strength	−0.211	−0.235

*. Correlation is significant at the level of 0.05 (2-tailed); **. Correlation is significant at the level of 0.01 (2-tailed).

Similarly, moderated multiple regression analysis was performed for the zigzag pattern, but the results showed no significant three-way interaction. Therefore, the moderating effect of the presser height could not be observed between the SPI and thickness, weight, or roughness.

4. Conclusions

This study evaluated the appearance of the sewn parts by lock stitch and zigzag stitch and derived sewing conditions of each stitch pattern according to the properties of fabrics by using an automatic sewing machine.

An analysis of the sewability in each stitch pattern according to the presser height of the automatic sewing machine showed no difference in the appearance, SPI, stitch length, seam allowance, and seam strength according to the presser height in the lock stitch pattern. In terms of the fabric properties, however, the fabric thickness was thicker, and the stitch length became shorter. In addition, the overall seam strength tended to be proportional to the seam allowance. On the other hand, in the case of zigzag stitches, the seam strength showed a proportional change with the stitch width, resulting in a high seam strength under the condition of a wide stitch width for each sample.

An evaluation of the sewability according to the sewing speed showed that in the lockstitch pattern, as the sewing speed increased, the stitch length and the seam allowance tended to decrease in thin fabrics. Therefore, it showed poor sewing quality. On the other hand, in thick fabrics, the stitch length increased with increasing sewing speed. Therefore, it showed the best seam strength at 200 RPM in the lock stitch pattern. In the case of zigzag stitches, although the speed was increased to 400 RPM, the stitch was formed uniformly, and the seam strength was also superior to the 200 RPM condition. On the other hand, the sewing quality deteriorated when the sewing speed reached 800 RPM. Therefore, the 400 RPM condition was suitable for the zigzag stitch. Statistical analysis confirmed that the moderating effect of the sewing condition between the fabric properties and sewability was observed only in the lock stitch.

These results are expected to be used as basic data for research on the automation of the sewing process for a smart factory of garment manufacturing in the future. Nevertheless, the current study had limitations in that various types of fabric and stitch patterns were not used. In addition, just one thread was used, which is also a limitation to generalizing the research findings. Therefore, more experiments and evaluations of more diverse fabric samples, sewing conditions, stitch patterns, and sewing threads are needed.

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References

1. Sima, V.; Gheorghe, I.G.; Subic, J.; Nancu, D. Influences of the Industry 4.0 Revolution on the human capital development and consumer behavior: A systematic review. *Sustainability* **2020**, *12*, 4035. [CrossRef]
2. Arakelyan, E.K.; Kosoy, A.A.; Mezin, S.V.; Pashchenko, F.F. Application of the basic principles of "Industry 4.0" in the intellectualization of automated control systems of modern thermal power plants. *Procedia Comput. Sci.* **2021**, *184*, 865–870.
3. Ashima, R.; Haleem, A.; Bahl, S.; Javaid, M.; Mahla, S.K.; Singh, S. Automation and manufacturing of smart materials in additive manufacturing technologies using Internet of Things towards the adoption of industry 4.0. *Mater. Today* **2021**, *45*, 5081–5088.
4. Ribeiro, J.; Lima, R.; Eckhardt, T.; Paiva, S. Robotic process automation and artificial intelligence in industry 4.0: A literature review. *Procedia Comput. Sci.* **2021**, *181*, 51–58. [CrossRef]
5. Nayak, R.; Padhye, R. *Automation in Garment Manufacturing*; Woodhead Publishing: Duxford, UK, 2018; p. 290.
6. An, I.Y. The fourth industrial revolution: The potential impacts of artificial intelligence and automation technologies on gender equality. *Pitt Policy J.* **2020**, *11*, 108–123.
7. Kondratas, A. Robotic gripping device for garment handling operations and its adaptive control. *Fibers Text. East. Eur.* **2005**, *13*, 84–89.
8. Le, T.H.L.; Jilich, M.; Landini, A.; Zoppi, M.; Zlatanov, D.; Molfino, R. On the development of a specialized flexible gripper for garment handling. *J. Autom. Control Eng.* **2013**, *1*, 255–259. [CrossRef]
9. Suh, M. Automated cutting and sewing for industry 4.0 at ITMA 2019. *J. Text. App. Technol. Manag.* **2019**, 1–13. Available online: https://ojs.cnr.ncsu.edu/index.php/JTATM/article/view/16453 (accessed on 10 July 2021).
10. Lee, S.; Rho, S.H.; Lee, S.; Lee, J.; Lee, S.W.; Lim, D.; Jeong, W. Implementation of an automated manufacturing process for smart clothing: The case study of a smart sports bra. *Processes* **2021**, *9*, 289. [CrossRef]
11. Yoshimi, T.; Takezawa, K.; Hirayama, M. An improvement of trajectory tracking accuracy of automatic sewing robot system by variable gain learning control. *IFAC Paper OnLine* **2018**, *51*, 1–6. [CrossRef]
12. Thilagavathi, G.; Viju, S. *Process Control in Textile Manufacturing*; Woodhead Publishing: Duxford, UK, 2013; pp. 428–473.
13. Rajput, B.; Kakde, M.; Gulhane, S.; Raichurkar, P.P. Effect of sewing parameters on seam strength and seam efficiency. *Trends Text. Eng. Fash. Technol.* **2018**, *4*, 4–5.
14. Gurarda, A. Seam performance of garments. In *Textile Manufacturing Processes*; Intech: London, UK, 2019.

15. Haghighat, E.; Etrati, S.M.; Najar, S.S. Evaluation of woven denim fabric sewability based on needle penetration force. *J. Eng. Fiber Fabr.* **2014**, *9*, 47–60. [CrossRef]
16. Nayak, R. Sewing performance of stretch denim. *J. Text. Appar. Technol. Manag.* **2010**, *6*, 1–9.
17. Juciene, M.; Vobolis, J. Correlation between the seam stitch length of the sewing garment and friction forces. *Mater. Sci.* **2007**, *132*, 74–78.
18. Juciene, M.; Vobolis, J. Influence of fabric external friction force and certain parameters of a sewing machine upon stitch length. *Mater. Sci.* **2004**, *10*, 101–104.
19. Gribaa, S.; Amar, S.B.; Dogui, A. Influence of sewing parameters upon the tensile behavior of textile assembly. *Int. J. Cloth. Sci. Technol.* **2006**, *18*, 235–346. [CrossRef]
20. Dobilaite, V.; Juciene, M. Influence of sewing machine parameters on seam pucker. *Strain* **2007**, *56*, 286–292.
21. Suh, J.K. Analysis of the structure of lockstitched seam according to sewing thread tension. *Fash. Text. Res. J.* **2001**, *3*, 25–30.
22. Midha, V.K.; Kothari, V.K.; Chatopadhyay, R.; Mukhopadhyay, A. Effect of high-speed sewing on the tensile properties of sewing threads at different stages of sewing. *Int. J. Cloth. Sci. Technol.* **2009**, *21*, 217–238. [CrossRef]
23. Naeem, M.S.; Mazari, A.; Khan, I.A.; Iftikhar, F. Effect of sewing speed on seam strength. *Fibres Text.* **2014**, *2*, 24–29.
24. Vobolis, J.; Jucience, M.; Punys, J.; Vaitkevicius, V. Influence of selected machine and material parameters on the stitch length and its irregularity. *Fibers Text. East. Eur.* **2003**, *11*, 50–55.
25. Ebrahim, F.F.S. Influence of mechanical properties of cotton fabrics on seam quality. *Life Sci. J.* **2012**, *9*, 831–836.
26. Oh, H.; Oh, K.W.; Park, S. A study of the improvement of foam material sealing technology for wetsuits. *Fash. Text.* **2019**, *6*, 25. [CrossRef]