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Development of a fabric classification system using drapability and tactile characteristics

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Abstract

When producing clothing using virtual fitting technology or purchasing textile and clothing products online, it is challenging to make judgments or communicate information about sensory characteristics, such as drapability and tactile sensations, as there are no clear objective indicators for these factors. Therefore, the study aims to develop a classification system for the sensory properties of fabrics using drapability and tactile characteristics as quantitative indicators. The developed system was verified through subjective evaluations by an expert group, and it was found to be meaningful in reflecting classification levels in practice. The drapability and tactile sensation (softness; TS7) of the fabric were classified using fuzzy c-means cluster analysis, and the results were confirmed through a subjective evaluation by experts. The classification system was then used to predict the classification group, constituted by drapability and tactile characteristics, from mechanical properties using an artificial neural network. The network was trained on 534 fabric samples for drapability and tactile sensation (softness), and it correctly predicted 202 samples out of 243 validation data, with a forecasting accuracy of 83.5%. The developed classification system enables predictions and judgments about subjective characteristics like fabric drapability and tactile sensation based on the mechanical property values of various samples.

Keywords: Drapability, Softness, Panel evaluation, Classification, Clustering, Neural network

Introduction

The textile and fashion industry has been integrating IT technologies such as 3D visualization, big data, and artificial intelligence. In particular, the development of clothing simulation systems using 3D visualization technology has led to diverse uses in the textile industry, helping generate economic benefits online. 3D clothing simulation systems implement 3D images of textiles based on mechanical properties, such as bending, shearing, elongation, weight, and thickness. However, a technology that can objectively convey subjective sensory properties, such as drapability and tactile sensation is required. In addition, the sensory characteristics of textiles are subjectively determined by professionals in the textile and fashion industries, making objective communication challenging (Jang & Ha, 2023). When consumers purchase textiles and clothing products online, the lack of clear objective indicators for drapability and tactile sensation makes it difficult to assess these properties. Therefore, there is a need for a classification system that can objectively and quantitatively convey the subjective characteristics.

Drapability refers to the way fabric naturally hangs due to its own weight (Sanad et al., 2012). Drapability is influenced by the fiber type and fabric structure (Hamdi et al., 2014), and is directly related to the silhouette of the clothing (Yun & Yun, 2023). Fabric drapability is measured objectively by obtaining numerical values and subjectively by expert sensory evaluation. The objective measurement method for drapability typically involves calculating the drape coefficient, which uses the characteristic of a circular fabric draping over a support (Chu et al., 1950; Shin & Yun, 2023). A larger drape coefficient indicates a stiffer silhouette, while a smaller value means a drapery silhouette (Kenkare & May-Plumlee, 2005). Subjective measurements of drapability involve evaluators grade or ranking the tactile sensation felt in their hands, or comparing pairs of test items (Kim et al., 2005; Lee & Lim, 2014). However, objective evaluations of fabric drape characteristics can vary even with the same sample in repeated experiments, as they may not always produce the exact same shape, affecting the drape coefficient (Jeong, 1998). Subjective evaluations can vary according to the evaluator, and they are time-consuming and costly as they can only be done on a limited number of test items (Kim et al., 2005). Due to these limitations, studies combining objective and subjective evaluations are being conducted, with numerous studies comparing the correlation between objective numerical values of drapability and the subjective evaluations of experts (Collier, 1991; Orzada et al., 1997; Shyr et al., 2009; Stylios & Powell, 2003). However, in previous studies, the responses to the subjective evaluations of drapability were formed based on preference (Collier, 1991; Stylios & Powell, 2003), which could be influenced by changes in fashion trends over time and individual preferences.

Tactile sensation, the feeling when touching or rubbing the surface of fabric with hands, is one of the factors influencing consumers' purchasing decisions for textile products (Pan, 2006). Upon contact with a surface, a cascade of stimuli ensues, involving the integration of mechanical and thermal receptors beneath the skin, and exhibits connections with various brain regions. Consequently, elucidating the intricate relationship between human touch and the physical attributes of an object proves challenging (Chen-Yu et al., 2009). The perception of softness is inherently subjective, entailing both physical and psychological assessments, thereby giving rise to variations in individual interpretations. Hence, the need arises for an objective methodology to quantify fabric softness. Objective evaluation methods for fabric tactile sensation include the Kawabata Evaluation System (KES), Fabric Touch Tester (FTT), Fabric Assurance by Simple Testing System (FAST), and Textile Softness Analyzer (TSA). TSA is a device that measures the tactile sensation of a fabric through the sound spectrum of blade vibrations induced by surface roughness of the sample (Abu-Rous et al., 2018). There are two peaks in this sound spectrum that can be associated with the softness and smoothness of the fabric. TS7 peak located near 7000 Hz evaluates softness, which is a microscopic change transmitted from the microstructure, while TS750 peak located near 200–1200 Hz can measure smoothness, which is a macroscopic change transmitted from the macro structure (Blaisdell & Yun, 2021). TSA is capable of measuring both the microstructural roughness conveyed as softness and macrostructural roughness conveyed as smoothness (Blaisdell & Yun, 2021). Subjective evaluation of fabric tactile sensation is based on human sensory perception. However, subjective evaluations may yield different results depending on the evaluator's proficiency, making it challenging to quantify. Similarly, interpreting objective evaluation results in conjunction with human sentiment can also be challenging (Yıldız et al., 2016). Therefore, there is a need for research that combines objective and subjective evaluations. Most studies have focused on analyzing the relationship between data measured through experimental apparatus and subjective evaluations involving human participants (Abu-Rous et al., 2018; Pawlak et al., 2022; Wang et al., 2019).

Whereas traditional statistical methods have struggled to interpret nonlinear fabric characteristics, recent systems that use artificial intelligence techniques, such as artificial neural networks (ANNs) and fuzzy theory, have been developed to interpret nonlinear fabric characteristics. These systems can analyze and make judgments similar to human cognition (Yu et al., 2010). An ANN is a methodology of artificial intelligence that implements algorithms to process information by emulating brain structure (Park, 2016). According to previous research, the use of ANNs following a pre-classification operation using cluster analysis can lead to better classification accuracy over traditional statistical methods due to a reduction in dimensionality and training quantity (Kuo et al., 2010). Data clustering allows the target to be accurately understood and interpreted by dividing it into a small number of clusters consisting of similar entities (Yildirim et al., 2018). Fuzzy c-means is a cluster analysis method known for its robustness in handling outlier data and its ability to address membership noise and overlap. Consequently, it can achieve high accuracy in cluster classification (Bezdek et al., 1984).

This study aims to develop a classification system using objective numerical values for the fabric drape coefficient and tactile index and conduct a correlation analysis with subjective evaluations from an expert group to validate the developed classification system. We also intend to predict classification groups of drape characteristics and tactile characteristics by training mechanical properties with an ANN. Ultimately, we expect that a fabric classification system that uses drapability and tactile characteristics will assist online users in selecting or judging textiles based on these properties.

Methods

Sample characteristics and descriptive statistics

To classify subjective characteristics of fabrics using clusters generated from surface characteristic measurements and drape coefficient values, a total of 777 fabrics were used (out of 780 measurement data from preceding studies, excluding 3 outliers) (Lee et al., 2021; Shin et al., 2021). Descriptive statistics for the measured data of the 777 samples are shown in Table 1. The minimum value of the drape coefficient is 2.65 and the maximum value is 94.92, indicating a wide range of samples. The minimum value

Table 1 Descriptive statistics of measurement data

Variable	Number of samples	Minimum value	Maximum value	Average	Standard deviation
Drape coefficient (%)	777	2.65	94.92	32.53	21.87
TS7 (dB)	777	0.78	52.23	14.55	8.40
TS750 (dB)	777	1.74	609.88	72.95	87.21

for softness (TS7) is 0.78 and the maximum value is 52.23, indicating the inclusion of samples with both soft and rigid surfaces. Regarding smoothness (TS750), the minimum value is 1.74 and the maximum value is 609.88, indicating the inclusion of samples with both smooth and rough surfaces.

Drapability measurement

Fabric drapability was measured using an image processing test method in accordance with ISO 9073-9:2008(International Organization for Standardization, 2008). A circular sample with a radius of 15 cm was placed on a support, and the degree of draping was photographed at 80 cm from the support. The captured images were analyzed using Image J (National Institutes of Health, USA). The drape coefficient, which represents drapability, was calculated using Eq. (1), where A_s is the area of the draped sample, A_d is the area of the support, and A_0 is the area of the undraped sample.

$$Drape\ coefficient = \frac{A_s - A_d}{A_0 - A_d} \times 100 \tag{1}$$

Surface characteristic measurement

The surface characteristics of the samples were measured using a TSA (Emtec, Germany). Following ISO 187 (1990), the samples were cut into circles with a diameter of 10 cm and conditioned at a temperature of 23 °C ($\pm$1.5 °C) and a relative humidity of 50% ($\pm$5%) for 24 h before the measurement. Among the factors derived from the software processing the vibrations and sounds generated when the blade of the device contacted the sample, softness (TS7), and smoothness (TS750) were used. The measurements were repeated three times.

Weight and thickness measurement

The mass per unit area was measured in accordance with ISO 3801:1977. The sample (100 mm $\times$ 100 mm) was measured five times using an electronic scale (WBA-320, Daihan Scientific Group, Korea), averaged, and then converted to g/m^2 (International Organization for Standardization, 1977). The thickness was measured using a thickness gauge in accordance with ISO 5084:2011, and the average thickness (mm) measured at five different locations per sample was used.

Bending and tensile property measurement

The bending properties were determined by measuring the displaced length (mm) for warp and weft using a cantilever. The tensile properties were measured as the force (kgf) for 1% elongation (2 mm) in the warp, weft, and bias directions, and the coefficient of the quadratic function of the tensile-force graph (Kim et al., 2020).

Subjective evaluation of drapability and surface characteristics

Prior to the subjective evaluation, we conducted a preliminary evaluation to select an appropriate tactile index. We consulted experts to select a factor from two tactile indices, softness (TS7) and smoothness (TS750) measured by the TSA, that could be validated and utilized from the actual users' perspective. For this, the evaluators were asked to physically touch the samples to evaluate softness (TS7) and smoothness (TS750). Based on the preliminary evaluation results, the softness (TS7) factor was selected as the cluster for subjective evaluation because it was easier to distinguish by touch. That is, because the silhouette of a garment is mainly considered when selecting fabrics applied to clothes in the actual industry, we judged that softness (TS7) could be regarded as a more critical factor.

To investigate whether the developed classification system could be meaningfully applied in practice, a subjective evaluation was conducted. In line with studies suggesting that subjective evaluation consistency can be influenced by fashion-related professional knowledge (Orzada et al., 1997), we selected 10 individuals with a bachelor's degree in Clothing and Fashion and basic knowledge of fabrics as evaluators for the validation of this study (Park et al., 2000, 2001). Among the panel of evaluators, 50% were field experts with over 5 years of experience in the clothing and fashion industry, and the rest were general experts (Orzada et al., 1997).

Before the subjective evaluation, the evaluators were allowed to touch the samples representing the clusters, and we provided explanations about the groups to help them understand the cluster standards.

The evaluators were given 45 representative samples (5 per cluster) out of a total of 777 samples. The subjective evaluation of drapability was conducted by placing a 30 cm × 30 cm sample on the finger and naturally turning or wrinkling it. For the subjective evaluation of tactile sensation, the samples were placed flat on a table, and the evaluators were asked to feel the surface with their fingertips. To eliminate the influence of vision, the evaluation was conducted in a state in which visual information was blocked (Wang et al., 2019; Yuan et al., 2017). The evaluators recorded the scores for drapability and tactile sensation in their questionnaires, as shown in Table 2.

Statistical analysis

Fuzzy c-means (FCM) clustering analysis was performed to develop a classification system for objective numerical values. FCM clustering analysis was conducted using the drapability (drape coefficient) and the objective numerical values of two tactile characteristics, softness (TS7) and smoothness (TS750), of the 777 samples. FCM clustering analysis consists of an input layer, output layer, and fuzzy rules; the fuzzy rules are used to infer output based on input variables. The variables for the fuzzy rules were designated as the number of clusters, weight index, maximum number of iterations, and termination criteria. Subsequently, the initial location of the cluster center was estimated,

Table 2 Grading scale for the evaluation of drapability and softness

Subjective evaluation for drapability			
Scale	**1**	**2**	**3**
	Flexible	Medium	Not flexible
Subjective evaluation for softness			
Scale	**1**	**2**	**3**
	Soft	Medium	Not soft

calculations were repeated, and learning was terminated when the error value was less than the initially set value. Expert consultation was carried out to select the appropriate tactile index for subjective evaluation; as a result, the softness (TS7) and drape coefficient values were divided into three categories each—low, medium, and high—and nine groups were finally selected. The classification system was then subjected to a subjective evaluation to verify its practicality, and statistical analysis was performed using IBM SPSS Statistics v.25 to verify normality for the clusters classified by the objective values of drapability and softness (TS7) (hereinafter "FCM clusters"), as well as the clusters formed through the subjective evaluation (hereinafter "subjective evaluation clusters"). Subsequently, we conducted a Wilcoxon signed-rank test to verify the difference between the subjective evaluation clusters and the FCM clusters, and a Pearson correlation analysis was performed to verify the correlation between the subjective evaluation clusters and the FCM clusters. The verified classification system was used to train an ANN using nnet, developed by Ripley et al. (2016). Its aim was to predict which drapability and softness clusters the samples belong to using the mechanical properties (Kim et al., 2020, 2021).

Results and Discussion

Classification system development using fuzzy clustering analysis

The results of the fuzzy cluster analysis for the drape coefficient and TS7 are shown in Table 3. Here, the number of clusters was set to 3, the maximum number of iterations to 150, and the random number output state to 0, and it was stopped when the error reached the threshold of 0.00001, which is set in the software (Hamdi et al., 2017). The number of clusters (3) was set based on the prior expert interviews, statistical perspective to determine the degree of cluster membership, and the number of clusters in similar previous studies (Hamdi et al., 2017; Park et al., 2000, 2001). The values of the fuzzy cluster center of the drape coefficient were derived as 14.08, 39.85, and 70.85, respectively. Values of 7.57, 17.18, and 29.09 were derived as values of the fuzzy cluster center of softness (TS7).

The classification system was derived using the drapability and softness clusters obtained from the FCM analysis, with drape coefficients and TS7 as the two axes. The scatter plot results are shown in Fig. 1. The x-axis represents the drape coefficient, and the y-axis represents TS7. In each of the 9 clusters (3 × 3) reflecting the number

Table 3 Fuzzy cluster analysis results of drape coefficient and fabric surface characteristics

Variable	Group name	Cluster center value	Minimum value	Maximum value	Average	Number of samples corresponding to cluster
Drape coefficient (%)	A	14.08	2.65	26.81	14.77	391
	B	39.85	27.02	55.20	39.91	248
	C	70.85	55.30	94.92	69.60	138
TS7 (dB)	1	7.57	0.78	12.37	7.79	369
	2	17.18	12.38	23.08	17.22	294
	3	29.09	23.16	52.23	29.56	114

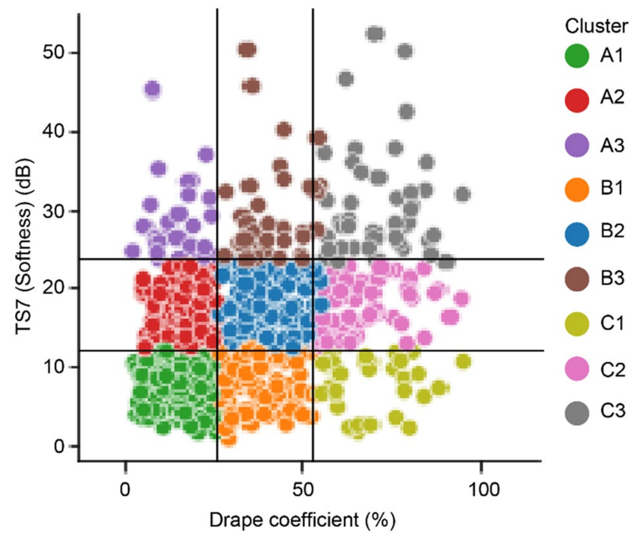

Fig. 1 Plot scatter result of clusters classified by drapability and softness

Table 4 Normality between FCM clusters and subjective evaluation clusters

	Statistic	Degrees of freedom	Significance probability
Drapability			
FCM cluster	0.232	45	0.000
Subjective evaluation	0.093	45	0.200
Softness (TS7)			
FCM cluster	0.219	45	0.000
Subjective evaluation	0.091	45	0.144

of samples for each characteristic value, the letters (A, B, C) represent silhouettes from drapery to stiff, while the numbers (1, 2, 3) indicate surfaces from soft to hard. For the samples in Cluster A1, the surface was soft and the drape coefficient was low, indicating a drapery silhouette. The number of samples in A1 was the highest at 236, followed by A2 with 123, B2 with 115, B1 with 96, C2 with 56, C3 with 45, B3 with 37, C1 with 37, and A3 with 32. The clusters characterized by a hard surface or stiff silhouette had fewer samples and were widely distributed.

Validity verification of classification system through correlation analysis between FCM clusters and subjective evaluation clusters

We performed a normality verification using the Kolmogorov–Smirnov test between the clusters classified based on drapability and softness (TS7) measurements using FCM clustering and the clusters formed based on subjective evaluation of drapability and softness (TS7). The results are shown in Table 4. The significance probabilities of drapability and softness (TS7) were 0.200 and 0.144, respectively, both of which were greater than the significance level of 0.050. This suggests that the distribution of each cluster for drapability and softness (TS7) was not normal.

Because the data do not follow a normal distribution, we employ nonparametric analysis to verify the differences between clusters (Massey Jr, 1951). Based on the normality verification results, we used the Wilcoxon signed-rank test, a nonparametric method, to verify the difference between each cluster. The results are shown in Table 5. The Wilcoxon signed-rank test assesses differences by assigning ranks to the absolute values of differences between two paired dependent variables. Negative rank represents the absolute value ranking of items with negative differences, while positive rank denotes the absolute value ranking of items with positive differences. The rank average is the mean of ranks associated with difference values, and the sum of ranks is the summation of ranks linked to negative and positive difference values (Wilcoxon, 1992). The z-value is computed based on negative rank, positive rank, and the sum of ranks, and the significance level is determined using the calculated z-value (Khan, 2004). In this investigation, given that $n > 25$, the significance level (p) was ascertained for the difference between the paired cluster analysis outcomes of drape and softness and the corresponding subjective evaluation results (Khan, 2004). The significance probability of drapability was 0.098, which is higher than the significance level of 0.050 at the 95% confidence level, indicating that the difference between the FCM and subjective evaluation clusters is not large and that the two clusters almost coincide. Similarly, the significance probability for softness (TS7) was also higher than the 0.050 significance level at 0.587, at the 95% confidence level, confirming that there is no difference between the FCM and subjective evaluation clusters.

Pearson's correlation analysis, a more stringent correlation measurement tool than the Wilcoxon signed-rank test, was combined with several statistical tools to enhance the measurement tool's reliability (Andrés et al., 1995). We attempted to verify the correlation between the FCM and subjective evaluation clusters, and the results of the Pearson's correlation analysis are shown in Table 6. The correlation analysis results for drapability showed that there was a very strong positive correlation between the FCM clusters and the evaluators' subjective evaluation clusters, with a significance probability of 0.000 at the 0.01 level and a correlation coefficient of 0.866. Similarly, softness (TS7) showed a correlation with a significance probability of 0.000 and a correlation coefficient of 0.512. This suggests that the 9-category classification system developed to reflect each

Table 5 Verification results of differences between FCM clusters and subjective evaluation clusters

	Number	Average rank	Rank sum
Drapability			
Negative rank	13	15.46	201.00
Positive rank	21	18.76	394.00
Z	−1.65		
Approximate significance probability (two-tailed)	0.098		
Softness (TS7)			
Negative rank	16	19.72	313.50
Positive rank	21	18.45	387.50
Z	−0.54		
Approximate significance probability (two-tailed)	0.587		

Table 6 Correlations between FCM clusters and subjective evaluation clusters

	FCM cluster	Subjective evaluation
Drapability		
Pearson correlation	1	0.866***
Significance probability (two-tailed)		0.000
N	45	45
Softness (TS7)		
Pearson correlation	1	0.512**
Significance probability (two-tailed)		0.000
N	45	45

***Significant at the 0.001 level (2-tailed)

**Significant at the 0.01 level (2-tailed)

characteristic of fabric drapability and softness closely matches the subjective distinctions made through actual human sensations, implying that the developed classification system can be meaningfully applied in practice.

ANN for classification system prediction

We tried to develop an ANN to predict clusters derived from drapability and softness (TS7) for which we knew the mechanical property values without having to directly measure the fabric's surface properties and drape coefficient, and then verified the prediction accuracy. An ANN is a multilayer perceptron structure with an input layer, hidden layer, and output layer (Park, 2016). We used a total of 10 attributes as input variables: thickness (Caliper), weight (Grammage), bending properties for warp and weft (M_{WARP}, M_{WEFT}), tensile properties for warp, weft, and bias directions (C_{WARP}, C_{WEFT}, C_{BIAS}), and the force required for 1% (2 mm) elongation in warp, weft, and bias directions (F_{WARP}, F_{WEFT}, F_{BIAS}). We set the number of neurons in the hidden layer to four and converted the drapability × softness (TS7) clusters into a constant array for the output value. To reduce computation, we normalized the data because of the large range of minimum and maximum values of the input variables. We designated approximately 70% of the data (534 out of 777) as training data, and the remaining 30% (243) as validation data. The training data was input according to 70% of each group. Figure 2 presents the visual results of the derived ANN analysis. The lines connecting the input variables (In) and hidden neurons (Hn) indicate the weight of each input variable. The darkness and thickness of the connecting lines represent the weight proportionally (Beck, 2018), indicating the relative importance of the variables (Kakati et al., 2022). Among the variables in the input layer, weight and bending properties of warp and weft (M_{WARP}, M_{WEFT}) are the most heavily connected to the hidden layer. This suggests that weight, and bending properties of warp and weft (M_{WARP}, M_{WEFT}) have a significant influence in forming the clusters derived from drapability and tactile sensation. Moreover, among the lines connecting the output layer and the hidden layer, those corresponding to the O4 (B1) cluster are the darkest. This suggests that the weight and bending properties of warp and weft (M_{WARP}, M_{WEFT}) variables are strongly correlated with the B1 cluster, which has medium drapability and a very soft surface. This finding aligns with previous studies, which consistently asserted a significant correlation between the bending properties

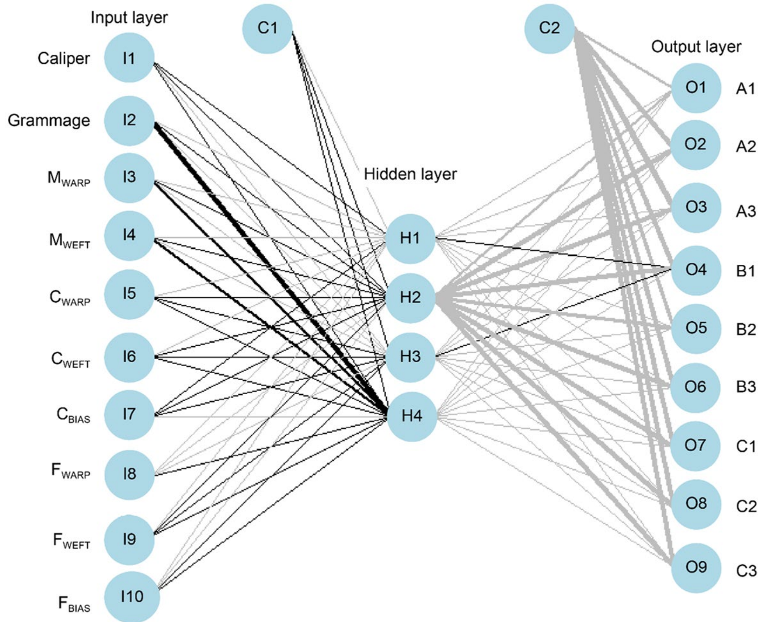

Fig. 2 ANN for group prediction through mechanical properties

and weight of the fabric with its softness and drapability (Bacci et al., 2012; Kim et al., 2021; Zhang et al., 2018). Based on the derived neural network, we can conclude that the cluster with highest prediction accuracy is B1. The developed neural network successfully predicted 202 out of 243 validation samples, yielding a forecasting accuracy of 83.5%. This level of accuracy suggests that the developed network is deemed reasonably effective with an accuracy of more than 80% (Lau et al., 2006; Yu et al., 2010; Zhou et al., 2022). if the physical properties of textiles applied in 3D simulation programs like CLO 3D are known, the network can be used to predict the textiles' group in the developed 9-category classification system without users having to directly measure the fabric's drapability and surface properties. It is also thought that enhancing the predictive success rate of the developed model will be improved by adjusting parameters or increasing the number of data sets (Doran & Sahin, 2020).

Conclusions

Drapability and tactile properties are subjectively judged by practitioners in the textile and fashion industry, which makes objective communication difficult. Since there are no clear indicators for these characteristics when reviewing or purchasing textiles online, objective indicators are needed. Accordingly, this study developed a sensory classification system based on drapability and tactile sensation and verified the system using subjective evaluations for meaningfully reflecting classification levels in practice. Using FCM clustering analysis, we classified measurements of the samples' drapability and two tactile factors, softness (TS7) and smoothness (TS750). Following an expert preliminary evaluation, we selected softness (TS7) as it was easier to distinguish clusters and had a greater impact on the clothing silhouette. Expert subjective evaluations were conducted using the classification system derived from 9 (3×3) clusters composed of drapability and softness (TS7). We used a nonparametric method to test the differences between the clusters, and the results indicated that the clusters for drapability nearly coincided, and there was almost no difference for softness (TS7). According to a Pearson's correlation analysis, both drapability and softness (TS7) showed correlations, signifying that textile categorization based on human senses highly coincides with the developed 9-category classification system. Subsequently, we trained an ANN to predict the classification groups of drapability and surface characteristics from the mechanical properties, and the network successfully predicted 202 samples, a forecasting accuracy of 83.5%. This suggests that if the physical properties of textiles applied in 3D simulation programs are known, this technique can predict the textiles' group in the developed classification system without users having to directly measure the fabric's surface characteristics and drape coefficient. We expect the classification system developed in this study which uses drapability and tactile characteristics to serve as a foundation for building systems where online users can search for textiles based on their properties and obtain recommendations for similar textiles. In further research, the prediction model will be improved by adjusting parameters or increasing the number of data sets.

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Authors' contributions
SL conceived the ideas, experimental design, performed the experiments, collected the data, interpretation of the results, and drafted the manuscript of the analysis. YH performed the experiments, participated in the manuscript writing. CY 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 conflicts of interest with respect to the research, authorship, and/or publication of this article.

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