A NEW APPROACH TO EVALUATE FABRIC HAND BASED ON THREE-DIMENSIONAL DRAPE MODEL

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Abstract:

Fabric quality and performance is assessed subjectively by the customer using an important and complex phenomenon of fabric hand. Objectively, it is evaluated with complicated and expensive instruments, such as Kawabata Evaluation System for Fabrics (KES-F) and Fabric Assurance with Simple Testing (FAST). The present research explores a non-touch objective approach, i.e., three-dimensional (3D) drape model to estimate fabric hand. Fabric hand prediction was testified on different commercial fabrics spanning a wide range of areal weight, thickness, yarn count, and fabric density. Fabric objective ranks based on drape indicators using principal component analysis (PCA) were compared with subjective ranks of fabric hand. Additionally, fabric drape is evaluated three dimensionally and a new drape indicator drape height (DH) is proposed. The cosine similarity results have proved fabric drape as an objective alternate to fabric hand.

Keywords:

3D drape; Comprehensive score; Cosine similarity; Fabric hand; PCA; Ranking

1. Introduction

The systems such as Kawabata Evaluation System for Fabrics (KES-F) and Fabric Assurance with Simple Testing (FAST) are in use for fabric hand assessment. These systems [1, 2] require more infrastructure, time, and expertise. Textile professionals and customers in common practice assess fabric hand subjectively. Therefore, approaches to predict fabric hand objectively have been the topic of researchers [1, 3].

Fabric hand is a psychological reaction obtained by subjective sensation, which links with customer preferences [4]. It is generally adopted for assessing fabric quality and performance in a specific end use. Both objective and subjective methods are commonly used for fabric hand evaluation.

Fabric hand with physical properties of fabric was first associated in 1930 [5]. KES-F is the foremost system that involves the relation and measurement of mechanical/physical properties for fabric subjective hand values [6, 7, 8]. Similarly, the FAST system also predicts the fabric tailorability and appearance. These systems indirectly correlate fabric hand with its physical and mechanical properties using expensive and delicate instruments [9, 10]. Moreover, they are limited in function for woven fabrics. On the other hand, direct method (PhabrOmeter) was developed to estimate fabric properties [1, 2], in which force–displacement curve was used from the metal nozzle. This method predicted fabric properties of various types such as woven, knitted, or nonwovens and achieved fabric performances such as stretch, wrinkle recovery, and drapability. However, issues involved in fabric hand prediction have not been resolved for the applications where instant information is

required, such as cyberspace shopping, because of the indirect interpretation and contribution of the physical instruments.

Fabric drapability is the most essential and considerable characteristics of its hand [11]. In the learning sources, many researchers have made efforts to resolve this issue. Recently, Xue et al. interpreted fabric tactile properties subjectively from the visual display of fabric drape [12]. Though, the method adopted was controlled and subjective in nature, they correlated drape vision with fabric hand. There are enough evidences to consider drape for the interpretation of fabric hand [13].

In the literature, drape indicators and fabric hand attributes correlated with each other. For instance, fold numbers and their shape have an association with fabric stretch. However, drape coefficient (DC) was correlated with the fabric stiffness [14, 15]. It was concluded that most important features of drape configuration were the area under the draped fabric, fold number, and their shape [16]. However, the most widely considered drape indicator DC [17] is inadequate to explain the complex deviations of drape shape and fabric hand attributes completely.

Three-dimensional (3D) image contains vast information than that of the two-dimensional (2D) drape projection. Scientists [18] explored the 3D scanned image for DC, number of nodes and their shape, perimeter, and area. However, improvement in the measuring accuracy of DC was 5% only. Thus, it is necessary to enrich drape literature three dimensionally to establish its objective relation with fabric hand.

The scope of this research is to find objective similarity

between 3D drape and subjective assessment of fabric hand. Multiple depth cameras were installed to reconstruct the 3D drape models. These (drape models) were explored to propose a new drape indicator. Three dimensional drape data were evaluated with principal component analysis (PCA) to sort comprehensive scores in the form of objective rank vectors. These vectors were compared mathematically with subjective rank vectors of fabric hand.

2. Experimental work

2.1. Materials

Thirty-five commercial fabrics (woven) were randomly collected for the experiment. The specifications of the samples are listed in Table 1. All the samples were evaluated under the standard ambient conditions as recommended by ASTM D1776/1776M-16, i.e., $21 \pm 1^\circ\text{C}$ temperature and $65 \pm 2\%$ relative humidity [19]. Samples were placed on our self-made drape meter (Figure 1) to extract the 3D drape models in the form of point cloud data. Drape meter consisted of a top disk, a support disk, and a pillar. The diameter of the support disk was 120 mm, which was similar to the commercially available XDP-1. The fabric samples (240 mm diameter) were hung freely in umbrella shape under gravitational force over the support disk.

2.2 Methods

Subjective ranking

Subjective rankings were sorted to set up a ground truth based on the fabric hand scores. In our test, overall hand, roughness (smooth–harsh), softness (hard–soft), bending (pliable–stiff), and stretch were assessed subjectively. Each attribute was evaluated on a 5-point scale numbered from 0 to 5. Smaller the value, less preferred, smoother, harder, pliable, and inelastic was the fabric.

For subjective assessment, 14 experts aged between 25 and 45 years were recruited including textile professionals,

university teachers, and students [20]. They were trained on a separate sample set of nine fabrics, other than the samples selected for the experiment. They washed their hands with hand wash and dried prior to the assessment. Assessment of samples by hand was conducted in the early hours of day to avoid mental and physical tiredness, where the experiment was repeated thrice by each expert in different consecutive weeks.

Subjective rank vectors for each hand attribute were computed using Eq. 6. This subjective vector for n observations is denoted as:

$$\varphi_i(g_1, g_2, \dots, g_n)$$

where $i = h, rg, s, b, e$; h is the overall hand, rg is the roughness, s is the softness, b is the bending, and e is the stretch.

Objective ranking

To predict the fabric hand from fabric drape, 3D drape models were processed to rank fabrics objectively, by extracting drape indicators including a newly proposed indicator drape height (DH).

Reconstruction of 3D drape

Fabric samples placed on the self-made drape meter as shown in Figure 1(a, b) were scanned at different locations by multiple RGB depth cameras to reconstruct the 3D drape models using a method developed elsewhere [21]. Before the scan of 3D drape models, the system of the depth cameras was calibrated with $3 \times 3 \text{ cm}^2$ boxes on six faces of T-shaped checkerboard [21]. Cameras can operate well within the range of distance 0.5–1.4 m. These cameras were placed on the 0.75–0.95-m-high tripod in the direction of drape meter at an angle of 45° with its main (vertical) rod. The surface of 3D draped samples was scanned (without moving the cameras after calibration) by the modification in the method with four depth cameras instead of six. There was no bottom surface of 3D drape models, except the fabric boundary, which was attained by the scan of outer

Figure 1. Scanning arrangement of 3D-drape models (a) arrangement of four multiple depth cameras (b) self-made drape meter.

Table 1. Fabric characteristics

Sample ID	Yarn type	Density (numbers of warp × weft yarns/inch)	Thickness (mm)	GSM (g/m ²)	Yarn count, warp × weft (Tex)
Y1	F	130 × 116	0.20	90	3.4 × 6.6
Y2	F	100 × 88	0.16	132	4 × 15
Y3	F	170 × 203	0.19	130	4 × 11
Y4	S	52 × 36	0.78	456	70 × 70
Y5	S	80 × 58	0.33	240	22 × 20
Y6	S	70 × 82	0.31	267	25 × 20
Y7	S	60 × 60	0.66	435	50 × 38
Y8	S	108 × 90	0.31	277	22 × 19
Y9	S	42 × 38	0.94	383	74 × 74
Y10	S	83 × 68	0.18	101	10 × 10
Y11	S	80 × 80	0.24	105	8.3 × 8.3
Y12	F	115 × 115	1.40	265	33 × 33
Y13	F	80 × 80	0.75	307	59 × 59
Y14	S	54 × 50	0.52	286	42 × 42
Y15	S	52 × 58	0.29	208	28 × 28
Y16	S	50 × 52	0.34	273	42 × 42
Y17	S	42 × 38	0.90	390	74 × 74
Y18	S	54 × 50	0.43	258	28 × 28
Y19	S	47 × 58	0.33	184	42 × 42
Y20	S	44 × 38	0.45	299	59 × 59
Y21	S	51 × 47	0.44	304	54 × 54
Y22	S	54 × 52	0.34	216	28 × 42
Y23	S	68 × 54	0.37	234	28 × 28
Y24	S	62 × 44	0.45	365	18 × 18
Y25	S	44 × 43	0.39	270	66 × 66
Y26	S	105 × 94	0.35	256	13 × 59
Y27	S	52 × 53	0.28	190	34 × 28
Y28	S	26 × 33	0.82	406	131 × 131
Y29	S	43 × 38	0.46	300	50 × 50
Y30	S	51 × 47	0.58	330	54 × 54
Y31	F	140 × 96	0.10	72	3.8 × 3.8
Y32	F	140 × 100	0.24	101	4 × 8.5
Y33	F	126 × 90	0.10	56	3.8 × 4.2
Y34	F	125 × 120	0.17	109	3.5 × 4.2
Y35	F	125 × 107	0.17	108	5.6 × 7

Abbreviations: F, filament; S, spun

surface; thus, two cameras were removed. After extracting the point cloud from multiple depth cameras, denoising (statistical outlier) of drape images was processed in Geomagic software. The average dimensional error of the final fabric model was around 2–3 mm.

Drape indicators

Twenty-four drape indicators were extracted to infer the fabric hand from its 3D drape shape, including the famous DC [22], as summarized in Table 2.

As an effort to benefit from the 3D drape information, the measurement of the new 3D drape indicator using slice function is shown in Figure 2(a, b) [34]. In the method, 2D planes on 3D drape model at ten vertical positions parallel to horizontal axis were utilized to make slice curves as shown in Figure 2(a, b).

Drape Height (%)

The intersection points between a series of equally distributed cutting planes and the 3D drape model generated a group of slice curves (Figure 2). Hence, a new 3D drape indicator 'DH'

is proposed to describe the drape configuration. This metric is the ratio of the difference between mean slice area (ten slices including top and bottom slice) and support disk area to the difference between original specimen area and support disk area as described in Eqs. 1 and 2.

$$S_{MA} = \frac{1}{m} \sum_{i=1}^m A_i \quad (1)$$

$$DH = \frac{S_{MA} - \pi r^2}{\pi (R^2 - r^2)} \times 100 \quad (2)$$

where DH is the drape height; A_i is the area (mm^2) of the i th slice curve on the 3D drape model; S_{MA} is the mean area of all slices; r is the support disk radius (mm); m is the number of slices between the highest points of 3D drape model and the highest point of boundary curve; and R is the radius of the original specimen.

2.3. Objective ranking and verification

Table 2. Drape indicators

Sr.No.	Drape indicators	Units	References	Sr.No.	Drape indicators	Units	References
1.	P_n	No.	[16]	13.	EC_r	mm	[29]
2.	DC%	%	[23]	14.	Fold height	mm	[30]
3.	P_{avg}	mm	[22]	15.	DH	%	
4.	V_{avg}	mm	[22]	16.	Radius half-amplitude	mm	[26]
5.	R_{avg}	mm	[24]	17.	A_{mp}	mm	[30]
6.	R_{var}		[25]	18.	MFS		[27]
7.	FDI		[25]	19.	Variability of fold severity		[27]
8.	%FD	%	[26]	20.	FW	mm	[31]
9.	C_{ir}		[27]	21.	FH	mm	[31]
10.	FD	mm	[28]	22.	F_p	mm	[32]
11.	f_{min}	mm	[28]	23.	$\bar{\alpha}_p$	Degree	[33]
12.	f_{max}	mm	[28]	24.	DU	%	[30]

Notes: A_{mp} , amplitude; $\bar{\alpha}_p$, average angle between consecutive folds; C_{ir} , circularity; FH , mean fold height; f_{max} , maximum drape; f_{min} , minimum drape; F_p , fold profile; FW , mean fold width; P_{avg} , average peak distance; P_n , number of folds; R_{avg} , average radius distance; R_{var} , radius variance; V_{avg} , average valley distance

Abbreviations: DC, drape coefficient; DH, drape height; DU, drape unevenness; EC_r , equivalent circle radius; FD, mean fold depth; %FD, percent fold depth; FDI, fold depth index; MFS, mean fold severity

Figure 2. Three dimensional drape model cut by slices, starts from the top of 3D drape model and end at the highest point of boundary curve (a) cross-sectional view of slices and drape boundary (b) front view of slices and drape boundary.

In collating with the literature review, 23 indicators were extracted to describe the drape shape of scanned models plus a newly developed drape indicator DH; there are totally 24 indicators. These were screened via PCA to find out the best rank that can describe the drape with the best similarity against subjective hand scores.

Principal component analysis was applied to understand the features embedded in fabric drape. If n drape indicators were selected to predict the shape of a fabric, the random vector $\mathbf{x}(x_1, x_2, \dots, x_n)$, can be replaced by an orthogonal vector $\mathbf{Y}$ through a matrix transformation that is:

$$\mathbf{Y} = \mathbf{xR} \quad (3)$$

where $R_1, R_2, \dots, R_p$ are the P eigenvectors corresponding to the p prior eigenvalues of descending order $\lambda_1 > \lambda_2 > \dots > \lambda_p$ of the correlation matrix $\mathbf{C}$ of $\mathbf{x}$. The vector $\mathbf{Y}$ is the vector with p uncorrelated dimensions. This property privileged us to use the relative importance of each principal component (PC; dimension) for further objective processing.

The relative importance w_j of each component $Y_j (j=1, 2, 3, \dots, p)$ in expressing the original vector $\mathbf{x}$ can be represented by the corresponding eigenvalue λ_j associated with the eigenvector R_j in terms of the ratio:

$$w_j = \frac{\lambda_j}{\sum_{j=1}^p \lambda_j} \quad (4)$$

If k_{nj} are the scores of n observations for P PCs, we can compute the comprehensive score for the n^{th} observation F_n as:

$$F_n = \sum_{j=1}^p k_{nj} w_j \quad (5)$$

where $j = 1, 2, \dots, p$

Comprehensive scores were sorted using Eq. 6 for the entire fabric sample ($n = 35$) to give rank vector,

$$F_1 \geq F_2 \geq \dots F_n \quad (6)$$

Since, for a particular hand attribute, we have two rankings, i.e., subjective vector $\varphi_i(g_1, g_2, \dots, g_n)$ and objective vector $\mu_i(o_1, o_2, \dots, o_n)$ for all the observations ($n = 35$), these rankings were compared using a mathematical approach 'cosine similarity'. Cosine similarity actually compares vectors in terms of the cosine of an angle formed between them as determined in Eq. 7. The angle between two vectors increases the cosine similarity decreases or vice versa. If the vector is positive, the cosine similarity is denoted as $\cos(\mu_i, \varphi_i)$

$$\cos(\mu_i, \varphi_i) = \frac{\mu_i \cdot \varphi_i}{\|\mu_i\| \|\varphi_i\|} \quad (7)$$

In our test set, we have five hand attributes; the subjective vectors φ_i and their corresponding objective vectors μ_i consist of five vector pairs, each consists of n elements (n is the number of observations),

$$i = h, rg, s, b, e$$

where h is the overall hand, rg is the roughness, s is the softness, b is the bending, and e is the stretch.

3. Results and discussion

Woven fabric samples were selected to establish a relation between fabric drape and its hand feel. The statistical analysis of the entire sample demonstrated strong cosine similarity between 3D drape and fabric hand scores.

3.1. Subjective ranking

Before setting up the subjective ratings as ground truth, the consistency of data was verified with Kendall's coefficient of

concordance (KCC) in Minitab-17 software. KCC ranges from 0 to 1; higher the value better the agreement or same evaluation standard is followed by the assessors.

Table 3 summarizes the KCC value of replicates (within) and among assessors' evaluations. The average of KCC replicates (within) for 14 assessors shows highly significant values of replicate ≥ 0.90 at $\alpha = 0.05$ for overall hand and stretch values, whereas minimum value was noted for roughness (0.858). It means same rating standards were followed or a strong agreement existed within the individual assessors' ratings. Furthermore, to evaluate the agreement among assessors' ratings, KCC between the average ratings was measured for all the selected hand attributes. Table 3 summarizes the acceptable level of agreements among the judges, where stretch and overall hand scored maximum and minimum KCC values, i.e., 0.79 and 0.56, respectively. The lowest KCC value for overall hand might be the reason for the specific assessment criterion that was followed.

A significant level of agreement among the assessors proves that the same criterion of hand assessment was considered.

The subjective scores using Eq. 6 were sorted for 35 fabrics. We have a ranking vector that consists of 35 elements. We denote this subjective vector as φ_i .

Table 3. Average KCC within individual and among 14 judges evaluations

Hand attributes	KCC (within)	KCC (between)
Overall hand	0.907*	0.567*
Roughness	0.858*	0.621*
Softness	0.890*	0.693*
Bending	0.860*	0.734*
Stretch	0.915*	0.789*

Note: *Significance level = 0.05

Abbreviation: KCC, Kendall's coefficient of concordance

3.2. Objective ranking

Twenty-four objective drape indicators (Tables 2 and S1) extracted from the 3D drape models were processed before PCA to remove redundant variables, because they did not contribute to fabric ranking. Consequently, 11 drape indicators were selected. The correlation coefficient within these selected drape indicators and with subjective attributes is summarized in Table 4.

Drape indicators were processed through PCA to compute the comprehensive scores. Correlation-based feature selection method was used to select the drape indicators for each corresponding hand attribute. The procedure is explained by considering an example of a hand attribute 'bending'. Drape indicators having high correlation with bending were $\bar{\alpha}_p$, FW , F_p , %FD, P_n , DC, V_{avg} , f_{min} , and DH . Correlation coefficient of drape indicators f_{min} and V_{avg} with dominant indicator DC is significantly high (i.e., $cr \geq 0.85$); hence, these indicators were

removed for further objective ranking.

PCA was used to allocate the variable weights objectively instead of any subjective method for the computation of comprehensive score. A number of PCs had $80\% \leq$ data variability (the total relative importance is the sum of variability explained by each selected PC), and a significant level of similarity with the corresponding hand attribute was selected. Table 5 summarizes the total variability explained by the selected PCs for each hand attribute. The maximum total relative importance (variability) explained by selected PCs was noted for 'roughness', i.e., 88.63%, whereas 'bending' explained the minimum variability (81.08%). Furthermore, PCA standard requirements of sample adequacy and data sphericity were satisfied. The importance of drape indicators (loadings) for each selected PC is summarized in Table S2. Comprehensive score for the n^{th} observation F^n , as described in Eq. 5, was calculated from the PC's relative importance (w_i) or weight multiplied by their respective scores (k_{nj}). Since we had totally 35 fabrics, objective rankings were measured using Eq. 6 in the form of vector μ_i for each corresponding 'i' hand attribute.

3.3. Ranking comparison

Both ranking vectors ' φ_i ' and ' μ_i ' on a given sample set are located intrinsically in positive space. We have used cosine similarity to investigate the relationship between φ_i and μ_i (Table 6). Interestingly, the cosine similarity between the vectors φ_h and μ_h (overall hand) was observed significantly high, i.e., 92%. The reason might be the combined effect of primary hand attributes (roughness, softness, bending, etc.). Drape indicator f_{min} has shown maximum contribution along with the 3D indicator DH. Leading contribution of DH was observed for all the selected overall hand and primary hand attributes in computing cosine similarity (Table S2). Figure 3a also support the findings as both subjective φ_h and objective μ_h rankings move in the same direction. This was due to the actual realization of drape area and mean slice area, instead of the projection area (DC). Projection area due to the variations in the boundary heights of the draped sample induced biasedness, especially in stiff samples. DH, on the other hand, considered drape area above the vertically highest point of the sample boundary. It also accounted the change in shape that occurred in the vertical direction of the 3D drape shape. The value of the mean slice area for stiffer samples was observed high compared with the softer fabric.

The best cosine similarity (94%) was achieved for 'bending'; it means that bending correlates strongly with drape shape, and this is due to the significant contribution of DC (Table S2). Our similarity results for bending were also coincided with the findings of Refs. [14, 16]. Highly significant results were also noted for softness i.e., 93% similarity. The reason is the leading contributions of V_{avg} and R_{avg} in the two selected PCs. The maximum rank difference for bending and softness (subjective and objective rankings) was observed 18 as shown in Figure 3(c, d). On the other hand, 'stretch' achieved least similarity, i.e., 83% with a maximum rank difference of 30 for sample number 11 in Figure 3e. On manual examination of this

Table 4. Correlation coefficients of 3D drape indicators and fabric hand attributes

	$\bar{\alpha}_p$	FW	FH	F_p	%FD	P_n	DC	R_{var}	V_{avg}	f_{min}	DH
FW	0.72	1.00									
FH	0.52	0.4	1.00								
F_p	0.22	0.59	-0.51	1.00							
%FD	0.19	-0.07	0.72	-0.69	1.00						
P_n	-0.79	-0.50	-0.18	-0.31	-0.20	1.00					
DC	0.27	0.29	-0.58	0.79	-0.71	-0.42	1.00				
R_{var}	0.36	0.46	0.48	0.00	0.39	-0.27	-0.42	1.00			
V_{avg}	0.18	0.30	-0.63	0.84	-0.87	-0.25	0.94	-0.31	1.00		
f_{min}	-0.58	-0.54	0.28	-0.76	0.45	0.71	-0.88	0.05	-0.81	1.00	
DH	0.36	0.30	-0.40	0.63	-0.36	-0.59	0.80	-0.25	0.67	-0.80	1.00
Overall hand	-0.20	-0.30	0.44	-0.67	0.57	0.26	-0.65	0.08	-0.70	0.64	-0.47
Roughness	0.11	0.04	-0.34	0.26	-0.28	-0.26	0.46	-0.25	0.43	-0.45	0.38
Softness	-0.16	-0.16	0.48	-0.57	0.60	0.23	-0.76	0.35	-0.76	0.69	-0.56
Bending	0.55	0.49	-0.23	0.66	-0.38	-0.67	0.76	-0.08	0.69	-0.86	0.71
Stretch	-0.27	-0.34	-0.09	-0.25	-0.07	0.32	-0.13	-0.26	-0.08	0.26	-0.19

Note: Significance level = 0.01**Abbreviations:** 3D, three-dimensional**Table 5.** PCA performance of objective drape indicators

Hand attribute	Drape indicators	Number of PCs	Variance explained
Overall hand	FW, FH, F_p, f_{min}, DH	2	87.40
Roughness	FH, P_n, V_{avg}, DH	2	88.63
Softness	$F_p, R_{var}, V_{avg}, f_{min}, DH$	2	86.72
Bending	$\bar{\alpha}_p, FW, F_p, \%FD, P_n, DC, DH$	2	81.08
Stretch	$\bar{\alpha}_p, F_p, P_n, f_{min}, DH$	2	87.69

Abbreviations: PCs, principal components; PCA, principal component analysis

Figure 3. Comparison of subjective and objective rankings for (a) Overall Hand (b) Roughness (c) Softness (d) Bending (e) Stretch.

Table 6. Cosine similarity between drape indicators and subjective hand attributes

Hand attribute vectors	Drape indicator vectors	Cosine similarity (%)
φ_h	μ_h	92
φ_{rg}	μ_{rg}	86
φ_s	μ_s	93
φ_b	μ_b	94
φ_e	μ_e	83

sample, it was found that fabric thinness and its loose structure were the reasons, which created a number of folds P_n , where fold numbers P_n along with f_{min} and DH played dominant role in revealing the similarity. These results matched with the earlier findings of Chu et al. [16], who stated that P_n contributed to the fabric stretch. Drape indicators Pn and DH also contributed in

the calculation of similarity for roughness. The cosine similarity for roughness hand value was observed 86% (Table 6).

As a whole, Figure 3 shows graphical ranking comparisons of ' φ_i ' (subjective overall and primary hand values) and ' μ_i ' (objective 3D drape indicators) for all the observations. This

Table 7. Cosine similarities of objective (drape indicators) and subjective rankings of verification set for fabric overall hand and primary hand attributes.

	Overall hand		Roughness		Softness		Bending		Stretch	
	Pr.	Sub.	Pr.	Sub.	Pr.	Sub.	Pr.	Sub.	Pr.	Sub.
X1	1	1	11	4	11	2	11	9	1	1
X2	8	8	5	6	6	5	8	5	7	7
X3	7	10	4	4	10	9	1	2	11	11
X4	10	4	10	8	8	7	5	6	8	10
X5	5	2	7	10	4	4	9	8	2	6
X6	4	5	8	9	1	2	7	10	3	3
X7	2	7	2	2	3	6	6	7	5	5
X8	6	6	6	5	7	3	10	9	4	4
X9	9	9	3	3	5	8	2	3	9	9
X10	3	3	9	7	2	1	4	4	6	8
X11	11	11	1	1	9	10	3	1	10	2
Cosine similarity (%)	92		93		87		96		91	

Abbreviations: Pr., predicted ranking; Sub., subjective ranking

is the first time we use a mathematical approach to prove that we can see the tactile property of the fabric without touching it. The cosine similarity between φ_h (subjective overall hand) and μ_h (drape vision) is greater than 90%; it means that these two feelings possess the similar orientation.

3.4. Verification of ranking

To verify the predictability of selected PCs for each corresponding hand attribute, 11 samples were randomly chosen from the original sample set. Each sample was mapped into 'p' dimensions projected by selected PCs. Table 7 summarizes the similarity comparison between predicted and subjective rankings for overall and primary hand values of the verification set. Strong cosine similarity results (above 90%) were achieved for overall hand, roughness, bending, and stretch. Relatively poor verification similarity was observed for softness (87%). This was due to the exceptional stiffness difference in warp and weft yarns of the sample X1. If this sample is excluded, cosine similarity for softness was observed 94%, which corresponded to the model similarity as summarized in Table 6.

4. Conclusions

The present research evaluates the possibility of fabric hand prediction from 3D fabric drape successfully. The results validated that 3D drape indicators including DH have significantly high similarity with fabric hand attributes. Newly proposed drape indicator DH has shown an enriching effect in revealing cosine similarity with all the selected hand attributes. It also accounts the vertical variations in the shape of 3D drape model. However, further research is needed to predict fabric hand for particular fabric materials by exploring more 3D drape variables.

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Appendix

Table S1. Description of drape indicators

Sr.No.	Drape indicator	Drape indicator definition	Mathematical formula	Description in figure no.
1	Peak	Geometrically, rough triangles of a peak and two adjacent valleys as vertices.	P_n	S1
2	DC	The ratio of the difference between projected and support disk area to the difference between original specimen and support disk area.	$\left(\frac{A-B}{C-B}\right) \times 100$	S2a
3	P_{avg}	The arithmetic mean of peak distance measured from the center.	$\frac{\sum_{i=1}^{P_n} (P_d[i] - r)}{P_n}$	S1
4	V_{avg}	The arithmetic mean of valley distance measured from the center.	$\frac{\sum_{i=1}^{V_n} (V_d[i] - r)}{V_n}$	S1
5	R_{avg}	The arithmetic mean of the distance from the specimen center to the end of the dropped fabric. n = number of points from specimen center to the projected boundary (we selected $n = 120$).	$\frac{1}{n} \sum_{i=1}^n R d_i$	S1
6	R_{var}	The measure of variability in projected drape shape.	$\frac{1}{n-1} \sum_{i=1}^n \left[(R d_i - R d_{avg})^2 \right]$	S1
7	FDI	The ratio of the difference between mean peak and valley lengths to the difference between the radius of the original sample and the support disk.	$\left(\frac{P_{avg} - V_{avg}}{R - r} \right)$	S1
8	%FD	The percentage of FDI.	$\left(\frac{P_{avg} - V_{avg}}{R - r} \right) \times 100$	S1
9	Cir	Circularity is the ratio of the actual projected area to the area of circle having same perimeter.	$\frac{4\pi \times A}{(\text{actual drape perimeter})^2}$	S2a
10	FD	The difference between mean peak length and valley length.	$(P_{avg} - V_{avg})$	S1
11	f_{min}	The minimal depth of folds.	$\sqrt{(R-r)^2 - (r - P_{avg})^2}$	S3
12	f_{max}	The maximal depth of folds.	$\sqrt{(R-r)^2 - (r - V_{avg})^2}$	S3
13	ECr	Radius of an equivalent circle having same drape projection area.	$\sqrt{A/p}$	S1, S2a
14	Fold height	One-half of the sum of the averages of peaks and valleys.	$(P_{avg} + V_{avg})/2$	S1

Sr.No.	Drape indicator	Drape indicator definition	Mathematical formula	Description in figure no.
15	DH	The ratio of difference between mean slice and support disk area to the difference between original specimen and support disk area.	$\frac{S_{MA} - \pi r^2}{\pi(R^2 - r^2)} \times 100$	2(a, b)
16	Radius half-amplitude	One-half of the mean fold depth.	$(P_{avg} - V_{avg})/2$	S1
17	<i>Amp</i>	The ratio of the radius half-amplitude to fold height	$\frac{P_{avg} - V_{avg}}{P_{avg} + V_{avg}}$	S1
18	MFS	Arithmetic mean of the ratio of peak height (<i>h</i>) to its width (<i>w</i>)	$MFS = \sum_{i=1}^n \frac{h_i}{w_i} \frac{1}{n}$	S2b
19	Variability of fold severity	The standard deviation of the MFS	$VS = \sqrt{\frac{\sum_{i=1}^n (MFS_i - \overline{MFS})^2}{n-1}}$	S2b
20	<i>FW</i>	Mean of all distances between two consecutive valleys	$\sum_{i=1}^n \frac{F_{wi}}{n}$	S1
21	<i>FH</i>	Mean of all distances from the line used to measure <i>F_w</i> to the fold peak point.	$\sum_{i=1}^n \frac{F_{hi}}{n}$	S1
22	<i>Fp</i>	The difference between mean fold width and fold height.	$FW - FH$	S1
23	$\bar{\alpha}_p$	Arithmetic mean of the angle between consecutive folds for draped sample.	$\frac{\sum_{i=1}^n (\alpha_{pi})}{n}$	S2a
24	DU%	The coefficient of variation of angle between consecutive folds	$\frac{\sqrt{\sum_{i=1}^n (\alpha_{pi} - \bar{\alpha}_p)^2 / (n-1)}}{\bar{\alpha}_p} \times 100$	S2a

Table S2. PC loadings corresponding to overall hand and primary hand attributes

Overall hand			Roughness			Softness			Bending			Stretch		
PCs	1	2		1	2		1	2		1	2		1	2
<i>FH</i>	-0.43	0.87	<i>FH</i>	-0.65	-0.69	<i>F_p</i>	0.88	0.25	$\bar{\alpha}_p$	0.62	0.71	$\bar{\alpha}_p$	0.72	-0.61
<i>FW</i>	0.58	0.79	<i>P_n</i>	-0.50	0.83	<i>R_{var}</i>	-0.24	0.97	<i>FW</i>	0.68	0.40	<i>F_p</i>	0.71	0.60
<i>Fp</i>	0.92	-0.03	<i>V_{avg}</i>	0.89	0.21	<i>V_{avg}</i>	0.93	-0.09	<i>F_p</i>	0.85	-0.36	<i>P_n</i>	-0.84	0.45
<i>f_{min}</i>	-0.93	-0.08	DH	0.90	-0.25	<i>f_{min}</i>	-0.92	-0.17	%FD	-0.48	0.81	<i>f_{min}</i>	-0.95	-0.15
DH	0.85	-0.16				DH	0.86	-0.08	<i>P_n</i>	-0.69	-0.60	DH	0.84	0.29
									DC	0.86	-0.39			
									DH	0.83	-0.11

Figure S1. Description of the fabric drape parameters, P , peak; P_d , peak distance from the center; V , valley of drape fold; V_d , valley distance from the center; R , radius of specimen; r , radius of support disk; ECr , equivalent circle radius; FW and FH are the fold width and fold height respectively.

Figure S2. Description of drape profile; (a) Cross-sectional view of drape profile; A, actual projection area; B, area of support disk; C, area of specimen; α_p , angle between consecutive folds; (b) Drape profile in polar coordinate system; h , peak height; w , peak width.

Figure S3. Description of f_{max} , maximum drape and f_{min} , minimum drape .