Tactile Fabric Comfort Prediction Using Regression Analysis

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Abstract: - In this paper we explore complex relationships between mechanical and sensory properties of fabrics, and the perceived tactile comfort. Mechanical properties, measured objectively by Kawabata Evaluation System for Fabrics (KES-FB), and handfeel properties, measured subjectively by sensory expert panel, are related to the tactile comfort of fabrics using statistical regression approaches. A universe of 48 fabrics is examined to analyze and map the relations. The initial 17 mechanical and 17 handfeel parameter sets were reduced to 4 and 5 properties, respectively. Adjusted R^2 values were 0.657 for mechanical and 0.863 for handfeel parameters, reflecting sound goodness-of-fit measures, and providing reasonable ways for prediction of tactile fabric comfort from mechanical and handfeel parameters.

Key-Words: tactile perception, fabric mechanical properties, regression analysis, textile property analysis

1 Introduction

Perception of tactile sensations is a complex process. Several stimulus factors are involved in the generation of responses on human skin, and such responses are fed to the brain for a perceived sensation of variable intensity. Analyzing the relationship between quantifiable characteristics of fabrics in the context of predicting the tactile perception has gained momentum because of the increased application of sophisticated fabrics for functional clothing systems. Models based on energy equations [1], finite element analysis [2, 3], stochastic formulations, [4] and Artificial Neural Networks [5] exist to identify the interrelationship between the structure of textile materials and their functional properties. Linear models to predict the tactile comfort of textile materials in terms of both subjective and objective measurements are also found [6]. Researchers have found that human tactile perception towards a textile material is complex [7], thereby limiting the application of the existing models. Moreover, these models are domain-specific and their extent of extrapolation is limited. In this paper, statistical regression approaches are used to analyze the underlying relationships between the mechanical and handfeel properties of fabrics, and the overall tactile comfort perception.

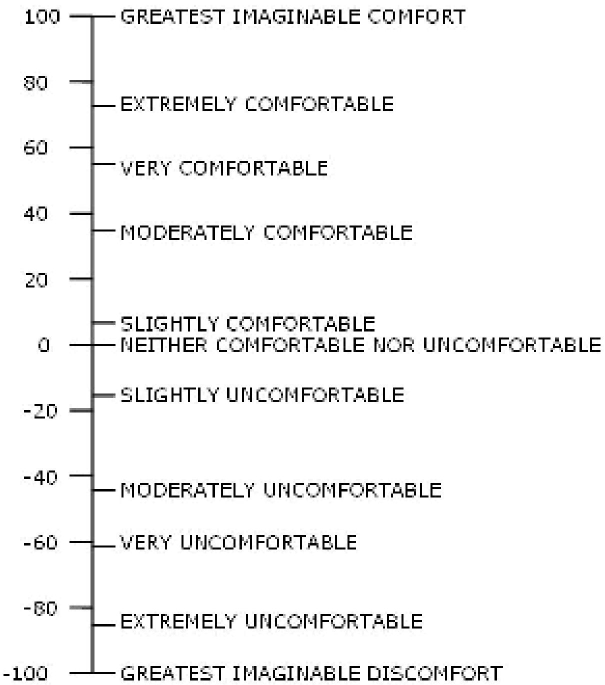
2 Data Collection – Mechanical, Handfeel Properties, and Tactile Comfort Measurements

A diversified set of 48 fabrics (universe of fabrics), including woven, knitted, and nonwoven materials, was selected for evaluation. Laminated fabrics with water-, fire-, and chemical-retardant finishes were included. The fabrics' mechanical properties, measured using the KES-FB Kawabata Evaluation System, are in Table I. While these 17 properties form the independent variables, a human perception score of tactile comfort is used as a dependent variable. The human perception score is measured using the Comfort Affective Labeled Magnitude (CALM) scale, shown in Figure 1. The scale, developed at the Individual Protection Directorate, US Army Natick Soldier Center, Natick, MA, ranges from –100 to 100 where a score of –100 represents the greatest imaginable discomfort, and a 100 represents the greatest imaginable comfort. The other labels are distributed in a progressive ratio scale [8].

Table 1
Range of Mechanical Properties as Measured Using KES-FB Kawabata Evaluation System

Property	Description	Minimum Value	Maximum Value
EMT	Elongation (%)	0.90	23.87
LT	Linearity of load-extension curve (LT)	0.15	1.13
WT	Tensile energy (gf cm/cm²)	0.52	[illegible]
RT	Tensile resilience (%)	22.16	63.26
B	Bending rigidity (gf cm²/cm)	0.01	[illegible]
2HB	Hysteresis of bending moment (gf cm/cm)	0.01	5.20
G	Shear rigidity (gf/cm degree)	0.45	23.31
2HG	Hysteresis of shear force at 0.5 degrees of shear angle (gf/cm)	[illegible]	[illegible]
2HG5	Hysteresis of shear force at 5 degrees of shear angle (gf/cm)	1.9	120.26
LC	Linearity of compression-thickness curve (LC)	0.23	0.9
WC	Compressional energy (gf cm/cm²)	0.03	1.56
RC	Compressional resilience (%)	[illegible]	[illegible]
MIU	Coefficient of friction (MIU)	0.1	0.44
MMD	Mean deviation of MIU (MMD)	0.01	0.13
SMD	Geometrical roughness (micron)	1.53	51.35
T	Fabric thickness (mm)	[illegible]	[illegible]
W	Fabric weight per unit area (mg/cm²)	[illegible]	61.33

Figure 1
Comfort Affective Labeled Magnitude (CALM) Scale



We repeat here the process of the developing the scale, after [8], as it completely defines the way our output variable, tactile fabric comfort, was formed. According to the scale developers [8] in order to develop a sensitive, reliable, and valid labeled magnitude scale of comfort, thirty-five volunteers, none of whom were members of the descriptive hand panel, were recruited from a random list. Word adjectives that could be used to modify the terms "comfortable" and "uncomfortable" to reflect intensity differences were compiled from previous scaling literature and from standard English language resources. The adjectives "greatest imaginable" and "greatest possible" were included to define scale values commensurate with a common fixed end-point of positive and negative affective experience, as used in previously developed labeled magnitude scales [8]. These adjectives were used to create forty-one word phrases, which in combination with two nonpolar terms ("neutral" and "neither comfortable nor uncomfortable"), resulted in a total of forty-three phrases to be used in scale development. The forty-three phrases were printed on separate pages and assembled in random order into testing booklets. Before testing, subjects were provided with written instructions on the procedure to be used in scaling the semantic meaning of the phrases. Oral instructions with an example were also provided. Subjects sequentially rated each of the phrases to index the magnitude of comfort or discomfort connoted by the phrase, using a modulus-free magnitude estimation procedure. In this procedure, subjects assign an arbitrary number to indicate the magnitude of comfort or discomfort reflected by the first phrase (positive numbers used for comfort, negative numbers for discomfort). Subjects then make all subsequent judgments relative to the first, so that if the second phrase denotes twice as much comfort as the first, a number twice as large is assigned; if it denotes one third as much comfort, a number one-third as large as the first is assigned, etc. All ratings were made in spaces provided in the testing booklet [8].

A subset of phrases was chosen to construct a labeled magnitude scale of comfort [8]. The criteria for selecting terms were low variability in perceived semantic meaning, parallelism in the terms used to describe comfort and discomfort, and selection of an equal number of comfortable and uncomfortable phrases (a decision based on evidence from the preference scaling literature showing that balanced scales are better for differentiating products).

Examination of the standard errors of the geometric means for each of the phrases [8] led to the elimination of several phrases (e.g., "mediocre comfort," "barely comfortable," "a little comfortable") due to their variable semantic meaning to the subjects. Other phrases were eliminated because of a lack of suitable parallelism in terminology for the purpose of establishing bipolarity (e.g., "superior comfort," "oppressively uncomfortable"). Applying the remaining criterion to the phrases resulted in the selection of eleven phrases for use in the scale: five associated with comfort, five associated with discomfort, and one neutral term ("neither comfortable nor uncomfortable") to define the zero point. The geometric mean magnitude estimates of the positive and negative phrases were transformed to range from 0 to +100 (positive phrases) and 0 to -100 (negative phrases). The phrases were then placed along a 100-mm vertical analogue line scale in accordance with their transformed values. The resulting labeled affective magnitude scale of comfort is shown in Figure 1.

The comfort affect labeled magnitude (CALM) scale shown in Figure 1 has several advantages over other comfort scales commonly used in the literature [8]. With this scale, the level of comfort or discomfort experienced by an individual can be readily indexed by simply placing a mark somewhere on the line. This stands in contrast to the difficulty often encountered by subjects using magnitude estimation procedures. However, by having positioned the phrases of comfort/discomfort along the analogue line scale at points representing the magnitude of their semantic meaning as determined by a magnitude estimation procedure, it becomes possible to treat the measured distances along the scale as ratio level data. This stands in contrast to category scales of comfort, which provide only ordinal data. The ratio nature of the CALM scale enables statements to be made about whether a particular sample is 20%, 40%, three times, etc., as comfortable (or uncomfortable) as another sample. In addition, it does not require that the data be normalized, as is the case with magnitude estimates. Last, by using the "greatest imaginable" comfort (or discomfort) as end-points on the scale, the scale enables better discrimination between samples/conditions that are either very high or very low in comfort/discomfort and establishes a common ruler by which comfort/discomfort ratings of different subjects can be compared.

A set of forty eight fabrics (universe of fabrics), including woven, knitted, and nonwoven materials, was evaluated subjectively for seventeen handfeel properties, and the property ranges of those fabrics are listed in Table 2.

Table 2
Range of Handfeel Properties

Property	Lower Boundary	Upper Boundary
Gritty	4.45	12.47
Grainy	2.27	12.28
Fuzzy (circular motion)	1.83	9.80
Thickness	2.75	14.41
Tensile Stretch	0.677	14.49
Hand Friction	4.28	12.04
Fabric to Fabric Friction	4.11	13.04
Depression Depth	1.56	12.15
Springiness	1.39	9.01
Force to Gather	1.78	14.78
Force to Compress	1.68	14.20
Fullness/ Volume	2.32	15.17
Stiffness	1.59	14.49
Compression Resilience	1.63	13.43
Compression Resilience Rate	1.56	13.64
Noise Intensity	1.48	13.20
Noise	2.52	13.28

Forty eight fabric specimens were selected for evaluation of mechanical and handfeel properties, and the same set of fabrics was evaluated by fifty human subjects for their perceived tactile comfort CALM score. The fabric samples were sequenced in random order for the subjects to evaluate.

The mechanical properties were tested with 5 replicates making a data set of 240 seventeen-dimensional vectors. The handfeel properties were tested with 27 replicates resulting in a data set of 1,296 seventeen-dimensional vectors. The above-mentioned vectors (mechanical and handfeel) were mapped to 2,400 tactile comfort scores (48x50). Averages were selected to represent the seventeen-dimensional vectors and their corresponding tactile comfort scores in both cases. The dimension variables for both handfeel and mechanical are defined below.

Handfeel attributes

1. Gritty – amount of small, round particles in the surface of the sample
2. Grainy – amount of small, abrasive, picky particles in the surface of the sample
3. Fuzzy (circular motion) – amount of pile, fiber, fuzz on the surface of the sample
4. Thickness – perceived distance between the thumb and the index finger (when the sample is placed between the two)
5. Tensile Stretch – degree to which the sample stretches from its original shape

6. Hand Friction – force required to move the palm of the hand across the surface of the sample
7. Fabric to Fabric Friction – force required to move the fabric over itself
8. Depression Depth – amount that the sample depresses when downward force is applied
9. Springiness – rate at which the sample returns to its original position after the downward force is released
10. Force to Gather – amount of force required to gathered the sample into the palm
11. Force to Compress – amount of force required to compress the gathered sample into the palm
12. Fullness/ Volume – amount of material felt in the hand
13. Stiffness – degree to which the sample feels pointed, ridged, and cracked; not pliable
14. Compression Resilience – perceived force with which the sample exerts resistive pressure against the cupped hands
15. Compression Resilience Rate – rate at which the sample returns to its original shape or rate at which the sample opens after compression
16. Noise Intensity – loudness of the noise
17. Noise pitch – pitch (frequency) of the noise

Mechanical Variables

Parameters	Description	Property definition
Tensile		
LT	Linearity of load/extension curve	It defines the stress, strain relationship at tensile loading conditions.
WT	Tensile energy	Work done on material (energy consumed by the material) to strain it to a particular limit.
RT	Tensile resilience	Energy absorbed by the material when deformed elastically.
EMT	Extensibility	The ability of material to be stretched without breaking
Bending		
B	Bending rigidity	Material resistance to bending
2HB	Hysteresis of bending moment	Energy dissipated by the material at time of bending
Shearing		
G	Shear stiffness	Material resistance to deformation at shear loading
2HG	Hysteresis of shear force	Energy dissipated by the material at time of shear loading
2HG5	Hysteresis of shear force	Energy dissipated by the material at time of shear loading

Compression		
LC	Linearity of compression/thickness curve	It defines the stress, strain relationship at compression loading conditions.
WC	Compressional energy	Work done on material (energy consumed by the material) to strain it to a particular limit.
RC	Compressional resilience	Energy absorbed by the material when deformed elastically.
Surface		
MIU	Coefficient of friction	Represents the resistance to sliding of two surfaces in contact.
MMD	Mean deviation of coefficient of friction	Represents the frictional roughness of the surface
SMD	Geometric roughness	Represents the geometrical roughness of the material
Construction		
T	Fabric thickness	
W	Fabric weight/unit area	

3 Methods

3.1. Regression Analysis

First, the mechanical properties data set was used to form a regression equation with the mechanical properties as independent variables and the tactile comfort score as the dependent variable. Then, the handfeel properties data set was used to form another regression equation relating the handfeel properties and the tactile comfort score. The equations are given below as (1) and (2), respectively. The corresponding variables are listed in Tables 3 and 4.

Tactile Comfort Score = 121.71 + 2.56 EMT – 24.28 LT – 1.12 WT – 0.81 RT – 30.02 B – 16.68 HB - 4.29 G + 1.78 HG + 0.063 HG5 + 4.40 LC + 58.57 WC - 0.067 RC - 178.95 MIU - 51.42 MMD -1.13 SMD - 210.65 T + 0.542 W_0 (1)

The equation fits with the R^2 value of 0.767 and the adjusted R^2 of 0.631.

Tactile Comfort Score = 80.73 – 3.75 Gritty – 2.92 Grainy + 2.30 Fuzzy – 2.56 Thickness + 1.47 Tensile Stretch -1.92 Hand Friction + 0.64 Fab-to-Fab Friction + 0.38 Depression Depth - 0.03 Springiness + 4.39 Force to Gather – 1.05 Force to Compress + 4.25 Fullness - 5.14 Stiffness + 3.98 Compression Resilience – 10.38 CR Rate – 0.28 Noise Intensity + 3.97 Noise Pitch (2)

The R^2 value of the fitted equation is 0.909 and the adjusted R^2 is 0.857.

The adjusted R^2 measures the proportion of the variation in the Tactile Comfort Score accounted for by the independent mechanical and handfeel variables. Unlike R^2, an adjusted R^2 allows for the degrees of freedom associated with the sums of the squares. Therefore, even though the residual sum of squares decreases or remains the same as new independent variables are added, the residual variance does not. For this reason, adjusted R^2 is generally considered to be a more accurate goodness-of-fit measure than R^2.

Table 3
Handfeel Variables for Tactile Comfort Score

Model	Variables	Unstandardized Coefficients	
All variables		B	Std. Error
	Constant	80.730	24.536
	GRITTY	-3.748	1.983
	GRAINY	-2.924	1.540
	FUZZY	2.302	3.936
	THICK	-2.560	3.620
	TEN_STR	1.472	1.012
	H_FRIC	-1.917	5.368
	F_F_FRIC	.640	2.211
	D_DEPTH	.380	3.841
	SPRING	-.029	3.868
	F_GATHER	4.368	9.057
	F_COMP	-1.046	8.787
	FULL_B	4.247	4.855
	STIFF	-5.141	3.131
	COM_RES	3.983	5.254
	COM_RR	-10.383	3.831
	NOIS_I	-.281	2.802
	NOIS_PI	3.970	3.148

3.2. Dimension Reduction Using Stepwise Regression Analysis

Both handfeel and Kawabata mechanical properties include seventeen independent attributes and one dependent attribute. Though all the independent attributes contribute in the regression equation to predict the tactile comfort score, a few of the attributes contribute more than others. If the

Table 4
Mechanical Variables for Tactile Comfort Score

Model	Variables	Unstandardized Coefficients	
All		B	Std. Error
	Constant	121.713	50.998
	K_EMT	2.558	3.273
	K_LT	-24.281	34.553
	K_WT	-1.119	2.007
	K_RT	-.808	.485
	K_B	-30.020	24.103
	K_HB	-16.678	21.508
	K_G	-4.292	3.439
	K_HG	1.783	.928
	K_HG5	.063	1.286
	K_LC	4.399	54.669
	K_WC	58.569	40.665
	K_RC	-.067	.341
	K_MIU	-178.951	147.507
	K_MMD	-51.417	119.303
	K_SMD	-1.129	1.246
	K_TO	-210.652	312.409

K_W	.542	.829

attributes that contribute the least to the prediction ability of the regression equation are eliminated, the overall dimension of the data set comes down. One of the mechanisms to reduce the dimension of the data is stepwise regression analysis.

Data containing the mechanical properties and the CALM score for 48 fabrics are used to formulate the stepwise (forward) regression equation and is given in equation (3). Out of the seventeen parameters, four were included in the equation based on their contribution to the overall variance of the data set. The corresponding values are listed in Table 5, while the excluded variables are deoicted in Table 6. The method behind the exclusion is summarized in Table 7.

$$\textit{Tactile Comfort Score} = 48.63 + 1.29\ EMT - 43.47B - 52.35LT + 0.992HG \quad (3)$$

The equation fits with a R^2 value of 0.687 and the adjusted R^2 of 0.657.

Table 5

Mechanical variables (reduced set) for Comfort

Model	KES variables	Unstandardized Coefficients	
		B	Std. Error
4	Constant	48.626	13.546
	K_EMT	1.292	.392
	K_B	-43.468	10.190
	K_LT	-52.352	15.510
	K_HG	.992	.328

Table 6

Excluded Mechanical Variables

Mo-del		Beta	Partial Correlation
		Standardized	
4	K_WT	-.291	-.086
	K_RT	-.116	-.183
	K_HB	.158	.050
	K_G	-.301	-.183
	K_HG5	-.303	-.097
	K_LC	.012	.020
	K_WC	.081	.133
	K_RC	-.007	-.012
	K_MIU	-.021	-.035
	K_MMD	-.049	-.076
	K_SMD	-.054	-.079
	K_TO	.006	.010
	K_W	-.011	-.011

Similarly, a regression equation relating the handfeel properties and the tactile comfort score is formulated using the set of attributes selected using the stepwise regression approach. The formed relation is given in (4), in which five out of the seventeen handfeel properties are included. The corresponding unstandardized and standardized values are listed in Tables 8 and 9, while the excluded variables are depicted in Table 10.

Tactile Comfort Score = 84.99 – 3.92 Gritty – 4.14 Grainy + 3.17 Fuzzy + 1.76 Tensile Stretch + 3.98 Compression Resilience (4)

The R^2 value of the fitted equation is 0.878 and the adjusted R^2 is 0.863.

Table 7

Mechanical variables entered

Model	Variables Entered	Method
1	K_EMT	Stepwise (Criteria: Probability-of-F-to-enter <= .050, Probability-of-F-to-remove >= .100).
2	K_B	Stepwise (Criteria: Probability-of-F-to-enter <= .050, Probability-of-F-to-remove >= .100).
3	K_LT	Stepwise (Criteria: Probability-of-F-to-enter <= .050, Probability-of-F-to-remove >= .100).
4	K_HG	Stepwise (Criteria: Probability-of-F-to-enter <= .050, Probability-of-F-to-remove >= .100).

4 Conclusion

A diversified set of 48 fabrics (universe of fabrics) was analyzed using statistical tools such as regression analysis and stepwise regression analysis. The initial 17 mechanical and 17 handfeel parameter sets were reduced to 4 and 5 properties, respectively. Adjusted R^2 values improved slightly from 0.631 to 0.657 for mechanical properties, and from 0.857 to 0.863 for handfeel parameters. The values reflect sound goodness-of-fit measures, and provide reasonable ways for prediction of tactile fabric comfort from mechanical and handfeel parameters.

The handfeel and mechanical variables, as well as comfort are described in terms of linguistic terms, thus, could be used with fuzzy logic analysis [9].

It is expected that an Artificial Neural Network approach [10, 11] will capture more complex relationships among the properties and the corresponding tactile comfort scores, and will result in higher adjusted R^2 values.

Table 8

Handfeel B Variables (reduced set) for Comfort

Mode l		Unstandardized Coefficients	
		B	Std. Error
5	Constant	84.991	13.796
	COM_RR	-5.908	1.090
	GRAINY	-4.140	.893
	GRITTY	-3.917	1.021
	TEN_STR	1.763	.622
	FUZZY	3.171	1.391

Table 9

Handfeel Beta Variables (reduced set) for Comfort

Model		Standardized Coefficients
		Beta
5	Constant	
	COM_RR	-.448
	GRAINY	-.299
	GRITTY	-.216
	TEN_STR	.206
	FUZZY	.137

Table 10

Excluded Handfeel Variables

Model		Beta	Partial Correlation
		Standardized	
5	THICK	.061	.088
	H_FRIC	-.054	-.060
	F_F_FRIC	.067	.117
	D_DEPTH	-.034	-.086
	SPRING	-.021	-.056
	F_GATHER	.091	.216
	F_COMP	.086	.206
	FULL_B	-.021	-.036
	STIFF	-.048	-.061
	COM_RES	.164	.201
	NOIS_I	.103	.131
	NOIS_PI	.018	.036

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