Performances of Artificial Intelligence Hybrid Models' in Prediction of Clothing Comfort From Fabric Physical Properties

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Abstract: The purpose of this paper is to compare different approaches toward the prediction of human psychological perception of clothing comfort performance from fabric physical properties. A series of running wear trial, which involved 8 sets of tight-fit garment and 38 subjects, was conducted in an environmentally controlled chamber. Thirty-three fabric physical property indexes were measured and 9 individual sensations (*clammy, sticky, breathable, damp, heavy, prickly, scratchy, tight and cool*) and overall comfort were rated by the subjects during the running period. Different predictive models were derived on the basis of human perception process to predict clothing comfort from fabric physical properties. Results show that hybrid models consist of data reduction (abstract fabric properties and sensations into physical and sensory factors respectively), self-learning capability (to learning the behaviour of individuals) and fuzzy reasoning (handle the fuzziness between sensory factors and overall clothing comfort) able to generate better predicted clothing comfort score than other predictive models in this study. The correlation between predicted and actual clothing comfort rating was 0.739, with significant level of 0.001.

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1. Introduction

Over the years, many researches concern sensory clothing comfort including behaviour of individual sensory perceptions toward sensory factors [9, 10, 12], relationship between sensory perceptions, sensory factors and overall clothing comfort [11, 13], and relationship between fabric mechanical behaviour and subjective judgement [1-8] have been conducted. These researches findings indicate that sensory clothing comfort is predictable and prediction model can be derived from statistics, linear model, neural network or fuzzy logic. However, each method has its own strengths and weaknesses, which would limit or reduce the accuracy of the prediction. In order to overcome these problems in the development of prediction model of overall clothing comfort on the basis of fabric physical properties, hybrid system, which is a combination of the

three prediction methods, is employed. The prediction of overall clothing comfort on the basis of fabric physical properties can be described as a multi-steps process, and the dynamic of consumers' subjective sensory perceptions and judgements on the basis of fabric-garment physical properties is complex. Therefore, the hybrid model should be able to reduce the sizes of sensations and fabric physical properties data sets without losing too much information and should be capable of learning the behaviour of individual in evaluating the sensory comfort performance of different garments.

This paper studied and developed different hybrid model to predict overall clothing comfort from fabric physical properties. However, only one of the models is discussed in details. The performances of the remaining models are used for comparison purpose.

2. Theoretical model

The perception of clothing comfort can be described as a progressive process, which involves three fundamental elements: (1) fabric physical properties, (2) psychological sensory perceptions and (3) subjective comfort evaluation. Furthermore, the second element can be abstracted into sensory factors. Therefore, the prediction of clothing comfort on the basis of the fabric physical properties can be obtained by following four potential theoretical modelling system, as shown in Fig. 1.

S1 model is a 1-stage prediction model, which subjective comfort is predicted directly from fabric physical properties. S2 is a 2-stages model, in which the first stage is to simulate each psychological sensory perception on the basis of fabric physical properties. Followed by using the simulated sensory perceptions to predict overall clothing comfort in the second stage. As too many parameters and variations involve in this model, therefore, S2, will be excluded in this paper. The third theoretical model, S3, is a 3-stages model. Psychological sensory perceptions are abstracted into independent sensory factors using statistical factor analysis in the first stage. Fabric physical properties are used to simulate these

sensory factors in the second stage. In the prediction of clothing overall comfort, the predicted sensory factors are used as independent input variables in the development of clothing comfort prediction models using linear model, neural networks and fuzzy logic. The major difference between S3 and S4 models, is that instead of using fabric physical properties to predict sensory factors, S4 model uses fabric physical factors, which are abstracted from fabric physical properties, to predict sensory factors. As mentioned in previous section, in order to improve the modelling technique in the prediction of clothing comfort, a hybrid model should consist the following features including: (1) data reduction, (2) self-learning capability and (3) fuzzy reasoning. Therefore, the S3 model was selected for detail discussion. Meanwhile, S1 and S4 are used for comparison purpose. The prediction process is divided into 3 different stages, as shown in Fig. 2.

The first stage of the process can be described as variable reduction, in which 9 individual sensations are abstracted into 3 sensory factors using statistical factor analysis. The objective of stage 2 is to predict 3 sensory factors from a set of fabric physical properties, which consists of 19 and 14 fabric mechanical and transfer properties respectively.

Fig. 1 Theoretical models of clothing comfort perception.

Fig. 2 Schematic diagram of the S3 hybrid models.

In order to achieve the objective, it is necessary to use a method, which is capable of handling the complexity of large number of subjects who evaluate a limited number of garments, and has self-learning capability. Therefore, neural networks is employed to learn the behaviours of sensory evaluation of individuals. In the final stage, overall clothing comfort will be predicted from the 3 sensory factors by using fuzzy logic, linear model and neural networks separately. By combining these 3 stages, three S3 hybrid models (TS-NN-FL, TS-NN-LM and TS-NN-NN) are developed. The name of these models describes their contents, where TS, NN, FL and LM stand for traditional statistics, neural networks, fuzzy logic and linear modeling respectively.

3. Experimental

3.1 Subjects

Thirty-eight young adults (28 female and 10 male) ages ranging from 18 to 35, participated in this psychological sensory wear trial. The mean and standard deviation, mean $\pm$ (s.d.), of the female height and weight were 165.2 $\pm$ (4.2) centimeters and 47.1 $\pm$ (4.1) kilograms

respectively. And for male, they were 175.4 $\pm$ (5.2) centimeters tall and 63.0 $\pm$ (5.7) kilograms in weight.

3.2 Garments

Eight types of garments were selected for the trial. Five of them were sold in the market as active sportswear with high tech fabric, which provide great comfort to the wearer. The remaining three garments were sponsored by one of the fabric manufacturers in Hong Kong. The technical features of the garments are shown in Table 1.

Table 1 Basic descriptions of eight fabrics.

Fabric code	Weight (g/m ²)	Thickness (mm)	Fabric content (%(fibre))
N88P	280.0	0.84	88(P) & 12(S)
C98L2	179.0	0.73	98(C) & 2(L)
N85L15	215.0	0.57	85(N) & 15(L)
R95C	260.0	1.10	95(C) & 5(S)
P98L2	220.0	1.27	98(P) & 2(L)
E95C	240.0	1.01	95(C) & 5(S)
A92Np	360.0	1.12	92(N) & 8(L)
N95C	410.0	1.50	94(C) & 6(S)

C = Cotton L = Lycra N = Nylon
P = Polyester S = Spandex

The physical properties of the fabrics were measured mainly by using KES and MMT. Total of 33 physical properties were measured. Table 2 shows the definitions and units of 33 fabric physical properties indexes.

Table 2 Various fabric physical properties measuring system.

Test Method	Objective fabric measurement	Symbol	Unit
Shirley	Weight	W_f	g/cm^2
Shirley	Thickness	T	mm
KES-FB8	Air Permeability	AP	KPa.s/m
KES-FB7	Thermal Conductivity	TC	W
KES-FB7	Thermal Insulation	TI	
	Low air speed	TIL	$\bar{W}$
	High air speed	TIH	$\bar{W}$
KES-FB4	Surface		
	Frictional coefficient	MIU	-----
	Mean deviation of frictional coefficient	MMD	-----
	Geometrical roughness	SMD	μm
KES-FB3	Compression		
	Linearity of compressional thickness curve	LC	-----
	Compressional energy	WC	g.cm/cm^2
	Compressional resilience	RC	%
	Thickness	T_0	mm
	Thickness	T_m	mm
KES-FB2	Bending		
	Bending rigidity	B	gf.cm/cm
	Hysteresis of bending moment	2HB	gf.cm/cm
KES-FB1	Shear		
	Shear stiffness	G	gf/cm.degree
	Hysteresis of shear force	2HG	gf/cm
	Hysteresis of shear force	2HG5	gf/cm
KES-FB1	Tensile		
	Linearity of load –extension curve	LT	-----
	Tensile energy	WT	gf.cm/cm^2
	Tensile resilience	RT	%
	Tensile strain	EMT	%
MMT	Moisture Management Tester		
	Wetting time (Upper)	WTU	sec
	Wetting time (Lower)	WTL	sec
	Maximum absorption rate (Upper)	MARU	% / sec
	Maximum absorption rate (Lower)	MARL	% / sec
	Maximum wetted radius (Upper)	MWRU	mm
	Maximum wetted radius (Lower)	MWRL	mm
	Spreading speed (Upper)	SSU	mm / sec
	Spreading speed (Lower)	SSL	mm / sec
	Accumulative one-way transport index	AOTI	%
	Moisture management index	MMI	-----

3.3 Wear trail

The running trial took place in an environmentally controlled laboratory, which temperature and relative humidity were maintained at $29 \pm 2^\circ\text{C}$ and $85 \pm 3\%$ respectively. Subjects were rested for 30 minutes before they ran on a treadmill with a randomly selected garment, at a constant speed of 4 miles/h. Nine individual sensory

perceptions (*clammy, sticky, breathable, damp, heavy, prickly, scratchy, tight and cool*) and overall clothing comfort, which can be described as a comfort perception, which combines different types of comfort with other factors together and make the final judgment, were rated by each subject in a 7 points scale before (time = 0), during (time = 5, 10 and 15) and at the end (time = 20) of

the 20 minutes running session. Subjects required repeating the trial with another garment after they rested for 30 minutes

4. Development of the S3 model

4.1 Sensory factors

Nine sensory perceptions were abstracted into three independent sensory factors: *thermal-wet comfort*, *tactile comfort* and *pressure comfort* by using statistical factor analysis with rotation. Result is shown in Table 3.

Table 3 Factor loadings.

	Factor		
	<i>Thermal-wet comfort</i>	<i>Tactile comfort</i>	<i>Pressure comfort</i>
clammy	.893	-2.76E-02	.175
sticky	.895	.199	8.756E-02
breathable	-.787	1.012E-03	9.050E-02
damp	.906	-7.89E-03	.157
heavy	.743	.343	.102
prickly	.596	.761	-1.06E-02
scratchy	.600	.742	1.161E-02
tight	.368	1.211E-02	.900
cool	-.835	.173	.147

Thermal-wet comfort factor consists of *clammy* (0.893), *Sticky* (0.895), *breathable* (-0.787), *damp* (0.906), *heavy* (0.743) and *cool* (-0.835). *Tactile comfort* consists of two sensations, *prickly* and *scratchy*, with the loadings of 0.761 and 0.742 respectively. *Pressure comfort* consists of *tight* (0.900) sensation. The percentages of variance of these sensory factors are 65.1, 11.4 and 8.9 respectively. This result indicates moisture and thermal related sensations influence the perception of comfort the most, followed by tactile and pressure related sensations respectively.

4.2 Prediction of sensory comfort factors

Feed-forward backpropagation neural networks model was used in the prediction of sensory factors. The basic structure of a feed-forward backpropagation neural

network model for predicting *thermal-wet comfort* factor is presented in Fig. 3. The input layer consists of 33 input neurons, which represents 33 fabric physical properties, followed by a hidden layer, which consists of 35 hidden neurons with log sigmoid transfer function. These hidden neurons are connected to a single output neuron, which has pure linear transfer function in the output layer. In the prediction of sensory comfort factors, the output neuron consists of the scores of the *thermal-wet* sensory factor, which was abstracted from 10 individual sensations by using statistical factor analysis.

Fig. 3 Feed-forward backpropagation model for *thermal-wet comfort* factor.

The structure of the network shows that a set of fabric physical properties are associated with a single sensory factor score, this can be described as a set of input value is associated with a single target value. Therefore, supervised learning algorithm is selected. The advantage of using this method is that the network outputs can be compared to the targets. The sequence of the learning process began with the fabric physical properties of the 2 garments, which wore by the 1st subject with the related sensory factor score, followed by the garments properties related to 2nd, 3rd, ..., 25th, 26th and 27th subjects and their sensory factor scores. When the training process completed, the neural networks began to predict the sensory factor score of the 28th subject on the basis of the inputted fabric physical properties of the garment wore by the 28th subject. For the

sensory factor score of the 29th subject, the numbers of subject involved in the training process increased to 28, as the learning process of the 28th subject was added to the training data set. By following this sequence, the numbers of subject involved in the training process increased to 28 for predicting the sensory comfort score of the 29th subject. In total, 90 cases of *thermal-wet comfort* factor score are predicted. Significant linear relationship is found between predicted and experimental sensory factor score with $r = 0.608$, $p < 0.05$. The same methodology is applied to derive predictive models for factors *tactile comfort* and *pressure comfort*. Significant relationships are observed between predicted and experimental *tactile* and *pressure* factor scores with r values of 0.602 and 0.598 respectively.

4.3 Prediction of overall clothing comfort

In the prediction of overall clothing comfort, three hybrid models (*TS-NN-FL*, *TS-NN-LM* and *TS-NN-NN*) are developed and compared. TS, NN, FL and LM stand for traditional statistics, neural networks, fuzzy logic and linear modeling respectively. The major difference between these hybrid models is the methodology used in the third stage. Fuzzy logic, linear modeling and neural networks were used individually to predict overall clothing comfort on the basis of the result of predicted sensory factors.

5. Results

5.1 Model 1: TS-NN-FL

Each sensory factor score was considered as an input of the fuzzy logic model, which each fuzzy variable consists of 5 different membership functions. The fuzzy output related to the overall clothing comfort consists of five generalized bell-shaped membership functions, which is best to describe the sensory factor data as it is normally distributed.

These membership functions of the fuzzy inputs and output are 'linked' by different fuzzy rules, which are

based on the IF...OR/AND...THEN logic operations. Then all the predicted result was defuzzified (from linguistic based to numerical based) and compared with the experimental comfort rating. There are 50 rules, which 48 and 2 of the rules are operated in AND and OR operations. The perception of *very uncomfortable* can be determined by only a particular sensation, such as *very hot*. Therefore, OR operator is employed.

To obtain the prediction of overall clothing comfort from fuzzy logic, predicted sensory factor scores of thermal, tactile and pressure, which derived from artificial neural networks, were inputted into the fuzzy input variables of *thermal-wet*, *tactile* and *pressure* comfort factors respectively. These fuzzy inputs are in numerical format, which must be fuzzified according to the specific fuzzy linguistic sets (membership functions), such as thermal status is very hot, tactile status is very prickly and pressure status is very tight. Once the inputs have been fuzzified, they are then connected together with the output by the corresponding fuzzy rules. For example IF *thermal* status is very hot, *tactile* status is very prickly and *pressure* status is very tight THEN *comfort* status is very uncomfortable. All the rules are evaluated in parallel using fuzzy reasoning. The results of the rules are combined and defuzzified. Therefore, the final outcome of the predicted comfort scores become numerical form. The correlation between predicted and experimental clothing comfort was $r = 0.596$ ($p < 0.001$).

5.2 Model 2: TS-NN-LM

The procedures of obtaining predicted sensory factor scores of *thermal-wet*, *tactile* and *pressure* by using neural networks are similar to TS-NN-FL model. The only different is linear model was used in the final stage of the process instead of fuzzy logic in the prediction of overall comfort ratings. Sensory factors and their related weightings were defined as dependent variables and related coefficient in the linear model respectively. The predicted comfort score, C_p , was defined as the dependent

variable. The linear equation of the model is shown in equation 1. Linear relationship is found between predicted comfort factor scores, which generated from the linear model and the experimental comfort ratings. The correlation between predicted comfort factor rating and experimental comfort rating is significant at the 0.029 level with $r = 0.231$.

5.3 Model 3:TS-NN-NN

In this S3 hybrid model, neural networks were applied in the prediction of clothing comfort. When the three predicted sensory factor scores were obtained, another feed-forward backpropagation neural networks model, which consists of 6 hidden neurons with log-sigmoid transfer function and a single output neuron representing the overall comfort rating, were used to predict clothing comfort. Similar to the previous stage, the learning process at this stage follows the sequence of subject by subject. This allows the model to learn the behavior of individual subject towards clothing comfort. Linear relationship is also found between predicted and experimental overall clothing comfort rating. The correlation between predicted and experimental clothing comfort was 0.647 ($p < 0.001$).

6. Discussion

This paper demonstrates the process of predicting overall clothing comfort by using different S3 hybrid models. By comparing the performance of neural networks on predicting *thermal-wet comfort*, *tactile comfort* and *pressure comfort* sensory factors on the basis of fabric physical properties, the correlation between predicted and experimental *thermal-wet comfort* sensory factor score was strongest, followed by *tactile comfort* and *pressure comfort* sensory factors respectively.

In the prediction of overall comfort rating, fuzzy logic, linear model and neural networks were employed in the hybrid model separately. Amongst these three proposed hybrid models, *TS-NN-FL* and *TS-NN-NN* able to derive

reasonable and reliable prediction of overall comfort ratings. The hybrid model with the application of neural networks had better performance than the hybrid model with fuzzy logic. The hybrid *TS-NN-LM* model had the poorest performance in the prediction of overall comfort rating, suggesting the linear model cannot handle the fuzziness of subjective judgment and dynamic learning process in the simulation process.

7. Conclusion

This paper shows the using hybrid model to predict clothing comfort from fabric physical properties has better outcome than using one single method. Amongst different hybrid models, S4 with fuzzy logic had the best performance compares with other hybrid models. The advantage of this model is that it abstracts 33 fabric physical properties and 9 individual sensations into 8 fabric physical and 3 sensory factors respectively. Application of neural networks allows the model to learn the behaviours of individual subject in evaluating the sensory comfort factors of different garments. Furthermore, fuzzy logic, which has fuzzy reasoning, allows the model to handle the fuzziness between sensory factors and overall comfort.

Based on the findings in this paper, we can conclude data reduction, learning capability and fuzzy reasoning are the three key elements in the prediction of clothing comfort from fabric physical properties.

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