Part I

Understanding and evaluating fabric hand

2

Concepts and understanding of fabric hand

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2.1 Introduction

In spite of its acknowledged importance, hand (or handle) remains, in most sectors of the industry, an inherently subjective characteristic of fabric and, as such, is affected by the whims and perceptions of the handler. Hand is used in the evaluation of fibre, yarn, fabric and garments as well as finishing technology. It remains one of the key components of the perceived quality of fabrics and garments and, as such, is the source of commercial dispute, claim and counter-claim. Over several decades, hand, which has been elusive and a matter of fierce debate within the industry, has come under close scrutiny. In recent years, something approaching consensus has been reached in some sectors of the textile industry, not only on the nature of the sensations that make up hand, but also on the terminology that must be used to describe them and the techniques that can be used in their assessment.

This chapter will outline the approaches that have been used to assess/measure/determine hand and the methods that have been adopted to standardise subjective assessments of hand. It will also describe two of the techniques that have been developed to objectively measure this elusive fabric characteristic.

2.2 Subjective evaluation of fabric hand

Considerable effort has been directed towards achieving an understanding of the nature of the tactile sensations making up hand and to determine the source of decisions made concerning hand.[1] There is a general recognition that subjective hand is a complex sensation consisting of a summation 'of the weighted contributions of stimuli evoked by the fabric on the major sensory centres' of the hand.[2]

The considerable research activity has been directed into a number of major areas:

- Understanding the concept(s) involved and terminology used. These studies have involved evaluations by panels and individual experts, supported by sophisticated statistical techniques.
- Analysis of the hand terms used and their relative contribution to the overall subjective assessment.
- Studies of the psychology and physiology of hand including the use of microprobes to measure nerve activity derived from handling fabric.
- Work to relate the sensory perceptions to measurable properties of the fabric.

Many studies have been conducted to identify the component parts of hand.[3–7] Two types of hand descriptor are normally used: single and bipolar. Examples are shown in Table 2.1. A rating can be obtained within any such descriptor using a single judge or a panel. However, to communicate the rating or to use this rating in a commercial context requires reference to meaningful standards against which any fabric can be assessed. The ASTM Committee on Sensory Evaluation developed terms that are used to describe hand (ASTM D123). The AATCC has also developed a standard protocol for hand evaluation (AATCC Evaluation Procedure 5).

Table 2.1 Hand descriptors

Single descriptor[13]	Bipolar descriptor[15]
Stiffness	Limp–crisp
Smoothnes	Scratchy–silky
Fullness	Fine–coarse
Liveliness	Light–heavy
Crispness	Smooth–rough
Scroopy	Thick–thin
Flexible and Soft	Firm–sleezy
Soft	Hard–soft
	Flexible–stiff

Fabric hand and its component parts are normally judged by comparison with something else, such as an agreed sample, a control or a standard, in order to form a better–worse decision. In a commercial environment, the ‘control’ may lie within the memory of the customer. The use of simple rankings and paired comparisons are the most widely used techniques to assess subjective hand, as there are several statistical methodologies that can be applied to analyse such judgements. These range from the Spearman Rank Analysis of rankings/ratings through analyses for paired comparisons, Multiple Factor Analysis to Spectrum Descriptive Analysis. The last two techniques are widely used in subjective and panel testing in all sectors of the food and cosmetics industry.

As early as 1926, Binns[8] reported the use of ranking techniques to compare fabrics and to compare the ranking of different panels of judges from different socio-economic groups. Various forms of factor analysis have been used in a large number of studies to identify key components of the judgement of overall hand in a range of fabric types. Using this technique, Howorth[4,5] observed that 86% of all decisions made by judges were made on the basis of nine descriptors: smoothness, softness, firmness, coarseness, thickness, weight, warmth, harshness and stiffness. The results of this work suggested that three 'dimensions' or factors could be used to explain the judgements made. The correlation between these factors and the descriptors was determined, with smoothness being the major characteristic dominating Factor A. Factors B and C were not so easily described but were tentatively identified with stiffness and thickness. Later analysis of Howorth's data determined that a better description was obtained using four factors: smoothness, stiffness, bulk, and thermal character. These have also been described in bipolar terms (roughness–smoothness, etc.).

Lundgren[2] described the analysis of hand in terms of the four descriptors above using ideas derived from Information and Decision Theories. In a series of articles in the *Bulletin of the Research Institute for Polymers and Textiles (Japan)*, Kobayashi[7,9] also described the use of discriminant analysis and information theory for the evaluation of terms used in hand and for distinguishing different 'types' of hand (silk-like, wool-like, etc.). On the basis of earlier Japanese work, the authors used a different set of hand terms from those derived in Europe. The four hand terms used, translated into English, were smoothness, softness, fullness and liveliness, which the authors were able to relate to specific fabric characteristics.

Principal component analysis was used to re-analyse the data from trials conducted to compare the hand assessment of international groups of judges.[10] Although the statistical technique did not allow identification of the five factors observed, it was found that different groups of judges placed different weightings on the various factors.

Prior to the late 1960s, none of the outcomes of these analyses had been adopted by the textile community in any systematic way to describe hand and there was no significant use of the outcomes in commerce. An important attempt to standardise the concepts and terminology used to describe and evaluate fabric hand was initiated in 1972 by the Textile Machinery Society of Japan. A full account of this activity is found in a number of review articles.[11,12] This initiative was part of a larger programme in Japan to develop an objective evaluation system for commercial use in the fabric and garment manufacturing industries in Japan. A committee (the Hand Evaluation and Standardisation Committee – HESC – under the chairmanship of Professor S. Kawabata) was formed to bring order into the evaluation, measurement and use of hand terms in trading and research.[13] This committee achieved remarkable progress, including, as it did, participants from industry and research, processing mills and universities. The terms of reference of this committee were derived from the observation that, although the textile industry in Japan had achieved much in terms of the application of modern manufacturing techniques to improve quality and speed of processing, there remained little agreement on the criteria on which hand, the key characteristic determining quality, could be judged. There was also recognition that the ongoing attempts to objectively measure hand characteristics that had been conducted since the 1920s were hindered by the lack of standardisation of description and assessment of subjective hand.

The first target of the research was the analysis of the technique by which Japanese experts made judgements on fabric hand. The work focused on the wool sector, particularly fabric finishing, reflecting the special importance of hand in the high-quality tailoring sector in Japan. This activity was aided in Japan by the concentration of the wool fabric and apparel manufacturing industries at that time, its progressive outlook and its strong commitment to R&D through its links with universities.

In spite of the acknowledged complexity of subjective hand, the approach used by the HESC was deceptively simple and consistent with earlier attempts to describe hand in terms of its component parts. In Japan, the terms used to describe hand had some professional recognition and there was some common understanding of the features of hand between experts. Kawabata and Niwa also recorded that 'visual appearance' was also an important factor in the expert judgement of hand.[11]

By observing around 12 experts, mostly from the wool weaving and finishing industries, it was noted that these experts rated the fabric for certain initial characteristics and then undertook a complex summation of these characteristics into an overall hand value. This observation was entirely consistent with the conclusions drawn by earlier researchers. Consensus was reached on the subjective fabric characteristics that were regarded as 'essential or important for the garment material required for a particular end use'.[11] The HESC called these characteristics 'Primary Hand Values – PHVs'. Importantly, it was agreed that it was 'not possible to replace each of these characteristics by a combination of other hand expressions'.[11] Finally, it was agreed that these primary hand values could be quantified in terms of their 'intensity'.

Not surprisingly, for some fabric types, the descriptors were quite similar to those developed in earlier studies in Europe (described above) and those developed by Matsuo, also working in Japan. However, the HESC studies demonstrated that the nature of subjectively assessed Primary Hand Values depended on the end-use of the fabric. In the initial publications of this work, only the primary hand values for men's summer and winter suiting were described. Later publications clarified the hand descriptors for a wider range of fabric types and end-uses.

Again, consistent with the judgements of former workers, it was observed that, after judging primary hand, experts formed an evaluation of the overall hand (or 'Total Hand Value – THV') based on a complex mental summation of these primary values in a two-stage process. It was observed that the manner in which PHVs contributed to the overall hand also depended on end-use.

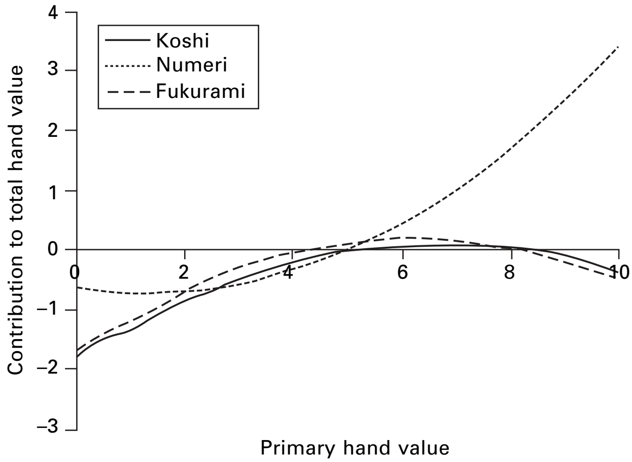
An important distinction was made between primary and total hand values. Each primary hand described the expert assessment of a specific characteristic. It was anticipated that primary hand values would be independent of the cultural and fashion preferences for overall hand and be a much more reliable standard for the subjective assessment of hand.

Having agreed on the concept of a two-step approach to hand evaluation, the HESC developed a series of standards to illustrate the subjective characteristics described by the primary hands (on a 0–10 scale). This involved the subjective evaluation by the 17 experts of around 500 winterweight men's suiting fabrics for each of the agreed primary hand values. Initially each expert graded the fabrics into three groups for each primary hand and then subdivided each group again into three subgroups. A set of potential standards was chosen from each of the grades. These tentative standards were again examined to confirm the grade. Once these standards had been agreed and confirmed, individual fabrics on which the ranking by the experts showed substantial agreement and which were close to unit values in the rating were chosen to establish the original definitive standard samples. These standards were chosen so that the scatter of the ratings was within 0.3 units. These standards were published as a series of reference 'documents'. A similar exercise was carried out for summer suitings, standards for which were also published. Later, 'books' of standard fabric were also published to describe the terms *Kishimi, Shinayakasa* and *Sofutosa,* which are relevant to ladies' wear fabrics.

During the assessment the experts also subjectively rated the total hand value on a 0–5 point scale (0 = unusable). Kawabata noted that it was necessary to exclude some judges in this latter process 'because of their extreme deviation of their ratings from the average'.[11] The effective number of experts was reduced to eight for this second process.

At the same time as this exercise was in progress, the mechanical, surface and physical properties of the fabrics were being measured. The outcomes of this exercise will be described in the next section of this chapter. The objectively measured PHVs and THVs also played an important role in the final selection of the standard fabric samples. The comparison of objective and subjective ratings of fabrics also determined their suitability for use as standards.

Obviously the major driver for this exercise leading to the publication of the standards was the need to improve technical and commercial communication about fabric hand. The HESC considered that the use of the PHVs and THV would be adequate to describe the hand of a fabric for commercial trading. It was considered that, even if the concept of good hand changed with time, culture or fashion, the change would be incorporated by redetermining the relative contributions of the PHVs. The contribution of the PHVs to the THV of winter suiting is seen in Fig. 2.1. It is clear that there are optimum levels for *Koshi* and *Fukurami* but that fabrics with the highest *Numeri* have a preferred hand.



2.1 Relationship between PHV and THV.

Various attempts have been made to determine the relevance of the Japanese studies to other textile markets. The translation of the Japanese PHV terms into English has been the subject of independent studies[14] and alternative English words to those originally used by the HESC have been developed. The differences are relatively small and probably subject to variation even within and between the various English-speaking countries.

The study by the HESC[13] was certainly not the last word on developing a model to describe fabric hand. An extensive study of 'Tactile Sensory Assessment' was published in 1980[15] using polyester and cotton fabrics. Rather than randomly selected fabrics, the authors chose 16 woven samples to represent the poles of stiffness–flexibility, smoothness–roughness and thick–thin. These fabrics were rated on a 99-point scale by each of 59 judges against nine pairs of polar adjectives and the data were transformed to normal deviates (so that the middle scores had a lower weighting) to create 'transformed sensory response values'. An ANOVA analysis related the four main criteria (listed above – plus fibre type) against the adjectival pairs. The work indicated that stiff and flexible fabrics were distinguished by all polar pairings, even those nominally not related to stiffness. For roughness, eight of the nine polar descriptors had significant F values. Moreover, the analysis revealed significant interaction between the chosen properties in the descriptions given. This work confirmed the observation of the HESC of the importance of interactions between subjective descriptors of fabric hand even where attempts are made to select samples on the basis of independent characteristics. The authors also drew attention to the particular impact of *stiffness* on sensory perception of this sample set, perhaps acknowledging the importance placed on this characteristic by Pierce.[16]

In contrast, a study was conducted in Australia using six bipolar fabric descriptors on a set of 110 wool and wool-rich suiting, jacketing, and trouser fabrics. It was found that smoothness–roughness ($r = 0.82$), extensibility–inextensibility and firmness–suppleness were the three most important attributes for Australian judges in assessing overall fabric hand. Studies of handle using the HESC set of fabrics were also carried out in the USA, China and other countries.

In spite of all the work in this area, the uptake of any standardised form of subjective hand assessment outside Japan has been limited. The major reason lies in the errors inherent in the process itself. Postle evaluated the repeatability and reproducibility of subjective assessments of a range of judging panels in an international hand survey using fabrics that formed part of the HESC data set. The minimum resolution of an individual judge on a scale of 0–5 was 1.6 for winter suiting and 3.1 for summer fabrics.[17] Extending the assessment outside national panels further increased the error. Such errors are high but can be reduced by the use of more than one judge. Unfortunately the use of hand assessment panels is not consistent with the day-to-day requirement for subjective assessment in industry and the requirements of a standardised system.

Cultural differences in the concepts of hand and emphasis have further impeded the adoption of a standardised system for international trade. Such errors, inherently recognised in Japan by the HESC, compounded by inconsistencies from a single judge, have been the driver for the development of objective measurement systems – notably the Kawabata Evaluation System for Fabrics (KES-F).

However, notwithstanding the cultural difference in the weighting of the various components of hand that are used to make decisions on overall hand, some form of consensus seems to be have been derived in the many studies of hand, namely:

- That overall hand is made up of component parts
- That the component parts can be determined in a semi-quantitative way against standards.

The following list represents a loose consensus of the relatively independent terms:

- Stiff–supple
- Rough–smooth
- Full–thin (lean)
- Warm–cool (cold)
- Lively–limp
- Stretchy–nonstretchy (inextensible)

Anomalies remain particularly around the use of word 'softness'. The usage of the term can differ considerably as evidenced by the relatively large number of antonyms or bipolar opposites that are used with this descriptor.

2.3 Objective evaluation of fabric hand

The objective measurement of fabric hand has been a 'holy grail' of research workers in this area since the pioneering work of Peirce in the 1920s.[16,18] As outlined above, it is widely recognised that subjective techniques are unable to meet the requirements of a very diverse marketplace or to overcome the loss of expertise in assessing fabrics caused by the retirement of experienced employees.

The link between measurable fabric properties and subjective fabric characteristics such as hand has been known for many years. The issues facing developers of fabric objective measurement (FOM) technology to measure hand have always been:

- To identify which measurable properties are related to hand
- To determine under what conditions such measurements should be made
- To describe quantitatively how these properties are related to hand.

Peirce identified fabric bending properties as a key component of hand, or more correctly of fabric stiffness, and developed a number of tests to measure fabric rigidity in bending. Since this time alternative tests for fabric bending properties have been developed[18] along with the recognition that hand is much more complex than can be predicted from bending measurements alone.

An ideal objective measurement technology would measure only those properties necessary to specify hand and control quality. It is claimed that this is now possible as a result of the development of instruments sufficiently sensitive to measure fabric properties at the low stress levels consistent with the measurement of hand and techniques for the handling of the large amount of data generated.[19]

Writing in 1958, Howorth and Oliver commented[4] on the large number of papers that had been written in the USA alone on the topic of hand and methods for its objective measurement. This work continued through the 1960s to the 1990s as more sophisticated techniques were brought to bear and simplifications of the complexity of hand measurement were developed.

The ASTM D123 identifies the physical properties of fabrics related to hand descriptors (Table 2.2).

Table 2.2 Properties correlating with hand[a]

Bipolar attribute	Related mechanical properties
Stiff–pliable	Bending
Soft–hard	Compressibility
Stretchy–nonstretchy	Extensibility
Springy–limp	Resilience
Compact–open	Density
Rough–smooth	Surface contour
Harsh–slippery	Surface friction
Warm–cool	Thermal character

[a]ASTM Standard D123-83a.

Kim and Vaughn[20] measured 20 physical and/or mechanical properties on a range of cotton, polyester and blend fabrics and found 14 of these exhibited good correlations with subjective ranking of the hand.

Similar studies were undertaken in Japan by Matsuo and co-workers[21] who related 'the basic mechanical properties' of fabrics to their hand descriptors using the Weber–Fechner Law, which was developed to describe the relationship between a stimulus and the response. This approach used the concept of the *differential limen*, a term used in psychology to describe the smallest change in a fabric property that will result in a perceptual change for the judge. The total response is given by the collection of the responses for the different properties. The key to this approach lies in the ability to determine the *differential limen* and to appropriately sum the several responses.

In his aforementioned series of articles,[9] Kobayashi determined the physical properties of fabrics that correlated with *fuai* (hand). Using principal component analysis, the authors conclude that liveliness related to flexural rigidity and crease resistance, rigidity to crease resistance, and coarseness to fabric surface properties. This study illustrates one of the problems caused by the interrelations of measured fabric properties. Crease resistance of fabrics is a function of the stiffness of a fabric and its stress relaxation characteristics. Both these properties are in turn determined by fibre properties and fabric structural characteristics. In this instance, the observed correlation between liveliness and crease resistance is indicative of their dependence on more fundamental fibre and/or fabric properties. There are grounds to question the universality of the use of crease resistance as a measure of subjective liveliness.

Since the initial work of Peirce, a large number of individual instruments have been developed to measure a number of properties under the low stress conditions consistent with the measurement of hand. In many of the studies above, simple instrumentation, which had been developed to measure a property rather than measure that property under conditions relevant to hand, was used. The development of the KES-F system sought to overcome this deficiency.

In this chapter only two sets of instruments will be discussed: the KES-F and the SiroFAST systems for Fabric Objective Measurement. In succeeding chapters, the range of alternative approaches developed to objectively measure hand will be outlined.

2.3.1 The Kawabata Evaluation System for Fabrics (KES-F)

The instruments that make up the KES-F system were developed from extensive work in Japan to ascertain the nature of the key fabric properties that affected hand, the appropriate mode of deformation to measure these properties, and the conditions under which the properties must be measured. The system, manufactured by Kato Tech. Co. of Kyoto, measures physical, mechanical and surface properties of fabrics using four separate instruments, two of which are used in each of two modes of deformation.

Detailed descriptions of the principles and outputs of these instruments appear in a large number of publications.[22,23] However, the instruments (Fig. 2.2) may be briefly described as follows:

- *KES-F1 Shear/Tensile Tester*
  This instrument measures the load–extension characteristics of a fabric (50 mm × 200 mm gauge width) sample to a load of 500 gf/cm (490 N/m). In its second mode of operation it measures the stress–strain characteristics of the same sample in cyclic shear deformation between a shear strain of +8 deg and –8 deg.
- *KES-F2 Bending Tester*
  This instrument measures the couple–curvature characteristics of a 200 × 10 mm sample in cyclic bending deformation between a curvature of 2.5 cm^{-1} and –2.5 cm^{-1}.
- *KES-F3 Compression Tester*
  This instrument measures the pressure–thickness characteristics of fabric up to a pressure of 50 gf/cm^2 (4.9 kPa).
- *KES-F4 Surface Tester*
  This instrument measures the frictional force generated when the fabric is moved under a metallic friction head. In its second mode of operation, it measures the vertical movement of a probe under a 10 gf load as it moves over the surface of the fabric.

The first machines were released in 1972. Later models, called the KES-FB series, were released in 1978 and were designed to reduce the time required for specimen preparation and testing. By 1984, the system had been adopted in Japan and, to a lesser extent, worldwide. Development of more

2.2 KES-FB instruments.

automated models of the instruments (called the KESFB-AUTO-A System), which includes automated sample loading procedures and thereby further reduces operator working time, were completed in 1997. Pictures and specifications of these instruments can be found on the Kato Tech. website (www.kesfkato.co.jp/english/).

All instruments have analogue outputs so that a very large number of parameters can be determined from the curves that are generated in the test. Computer interfaces to handle the data and to rapidly compute the key properties were developed by a number of R&D organisations and universities including CSIRO and the German Wool Research Institute (DWI). A commercial interface, which permits computer analysis of the analogue output of the instruments, is also available from Kato Tech. Co.

The 27 measurements (reduced to 16 by averaging warp and fill) used for the objective determination of hand are shown in Table 2.3. The exception is, somewhat surprisingly, the extensibility (Em) of the fabric, which, while measured by the KESF-1B and considered to be useful for assessment of the tailoring performance of fabric, is not used to calculate Total Hand Value. This reflects an important feature of the subjective evaluation of hand by

Table 2.3 KES-F measurements recommended by the HESC[13]

Instrument	Description	Symbol[a]	Measurement
KES-F1 Shear/Tensile Tester	Work to extend	WT	Warp and weft
	Tensile resilience	RT	Warp and weft
	Linearity of extension curve	LT	Warp and weft
	Extension at 500 gf/cm	Em	Warp and weft
	Shear rigidity	G	Warp and weft
	Shear hysteresis (measured at 0.5 deg)	2HG	Warp and weft
	Shear hysteresis (measured at 5 deg)	2HG5	Warp and weft
KES-F2 Bending Tester	Bending rigidity	B	Warp and weft
	Hysteresis in bending	2HB	Warp and weft
KES-F3 Compression Tester	Work of compression	WC	
	Compressional resilience	RC	
	Linearity in compression	LC	
	Thickness at 0.5 gf/cm^2	To	
	Thickness at 50 gf/cm^2	Tm	
KES-F4 Surface Tester	Coefficient of friction	MIU	Warp and weft
	Mean deviation in the frictional force	MMD	Warp and weft
	Geometric roughness	SMD	Warp and weft
Physical properties	Weight per unit area	WT	

[a]LT = 2 × WT/(500Em).
RT = 100 × WT′/WT where WT′ is the energy released in recovery (determined from area under recovery curve).
LC = 2 × WC/[50 (To – Tm)].
RC = 100 × WC′/WC where WC′ is the energy released in recovery (determined from area under recovery curve).

Japanese experts, who, unlike their Australian counterparts, for example, placed little significance on the extensibility of the fabric as a key characteristic of hand.

The project to determine the relationship between measured fabric properties and subjective hand was undertaken in parallel with the HESC activities to standardise subjective hand. Around 200 fabrics (selected to avoid overlap) were subjectively re-evaluated using the newly developed standards for primary hand, and their properties were measured using the KES-F instrumentations. The subjectively determined PHVs were correlated with the fabric properties using a block regression analysis.

Before inclusion in the regression equation, each mechanical property was 'normalised' using the mean and standard deviation derived from the total data set. This allowed for the difference of the relative impact of different properties on the various components of hand. In the second edition of the HESC manual, the logarithms of many of the measured properties were used in the regression equations instead of the values directly. Kawabata and Niwa reported that the prediction increased with an increasing number of blocks (of properties) but that the accuracy saturated after three or four blocks. Notwithstanding this observation, all properties are used in the published regression equations, although it is made clear that most of the latter properties add virtually nothing to the prediction.

Normalised value of property $P_i = (X_i - A_i)/\sigma_i$ (2.1)

where X_i is the value of the property (or its logarithm), A_i is the mean value of that property (or its logarithm) over the data set, σ_i is the standard deviation of that property (or its logarithm), and, i represents the 16 measured properties.

Primary Hand Value $H_i = C_0 + \sum(C_i \times P_i)$ (2.2)

for all 16 measured properties

Normalised value of PHV $Y_i = (H_i - M_i)/S_i$ (2.3)

Normalised value of PHV squared $Z_i = (H_i^2 - N_i)/T_i$ (2.4)

where H_i is the primary hand value
M_i is the mean value of the PHV
S_i is the standard deviation of the PHV
N_i is the mean value of the PHV squared
T_i is the standard deviation of the PHV squared

Total Hand Value THV $= K_0 + [K_1Y_1 + K_2Z_1] + \ldots$ (2.5)

for all PHV values
where K_0, K_1 and K_2 . . . are constants.

Around 100 separate fabrics were used to determine the accuracy of the prediction equations. The correlation coefficients for predicted and subjectively determined primary hand ranged from 0.93 for the *Koshi* of men's winter suiting (RMS error = 0.90) to 0.392 for *Fukurami* of summer men's suits (RMS error = 1.33).

The equations relating subjective Total Hand Value (THV) to the subjective primary hand values were applied to the objectively determined PHV to derive an objective THV. The correlations between objective and subjective THV were 0.90 for men's winter suits and 0.849 for men's summer suits; RMS errors were 0.33 and 0.35 respectively.

Recognising the difficulty of condensing and visualising the many values associated with the measured properties and calculated hand values, the HESC proposed the graphical representation of the data based on a 'snake diagram', shown in Fig. 2.3. The scale used in the construction of this snake also reflected the 'normalisation' process used for the properties based on the mean and standard deviation of that property within the data set.

There has been little controversy over the modes of deformation used and the methods of measuring shear, tensile, bending and compression properties used in the KES-F system. Some concern has been voiced over the surface measurements (KES-F4B) and the use of the metal fingerprint. The measurements made in this module (MIU, MMD and SMD), which contribute strongly to objective evaluation of *Numeri* (smoothness), have been less well accepted.

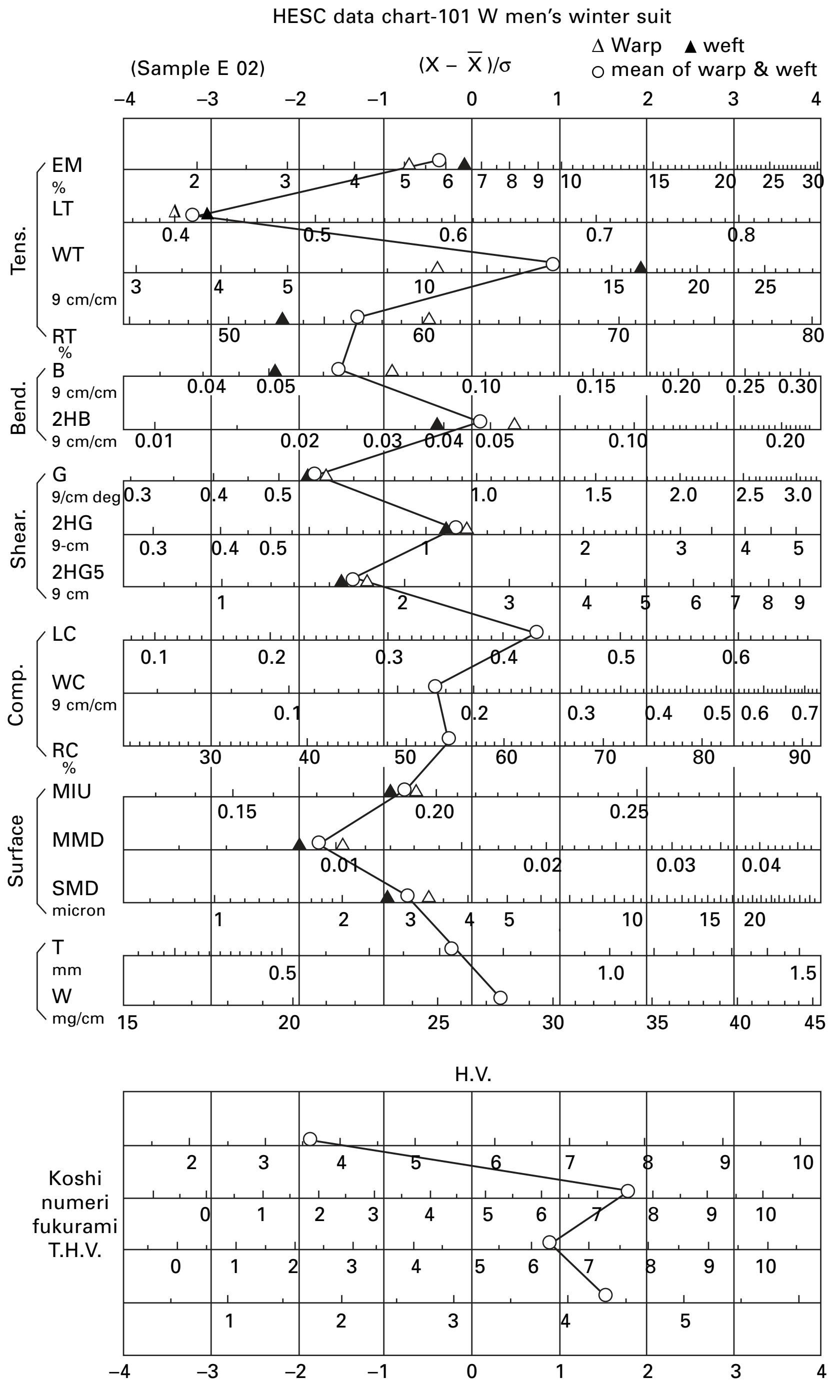
The statistical methodology used by Kawabata (block regression analysis) has also been the subject of some debate and alternative statistical techniques have been proposed. These will be discussed later in this chapter. None of the alternative statistical treatments have been adopted commercially.

Two interlaboratory trials of the precision and accuracy of the KES-F system have been published.[24–26] The results obtained are summarised in Table 2.4.

In the final analysis, in spite of the extensive work done to relate mechanical properties measured in the KES-F instruments to subjective hand using a variety of statistical techniques to massage the raw data, the objective measurement of overall hand or even elements of hand has not been widely adopted commercially. Commercial practice, where objective measurements are required, remains the identification and measurement of a small number of key properties that correlate well with the required hand change (such as stiffness and softness, etc.). Although expensive and sophisticated, the KES-F instruments remain eminently suitable for this role, measuring both deformation and recovery properties of fabrics with a high degree of precision. This allows comparison of those properties of fabrics most related to the observed differences in hand.

AWTOMEC – the Australian application of KES-F data

Australia was one of the first countries outside Japan to evaluate the use of KES-F instruments and the model developed by the HESC. This reflected the importance of wool in the high-quality men's tailoring sector at which the Japanese efforts had been directed. The Australian Wool Textile Objective Measurement Executive Committee (AWTOMEC), comprising representatives from the Australian Wool Corporation, the University of NSW, CSIRO Divisions of Textile Industry and Textile Physics as well as from the fabric and garment manufacturing industries and the Department of Defence, was



2.3 HESC fingerprint (from the HESC manual[13]).

Table 2.4 Reproducibility of measurements on KES-F instruments[26]

Property	Measurement	Critical differences[a]	
		Within laboratories	Between laboratories
Tensile	Extensibility	0.69	1.29
	Work to extend	1.06	2.38
	Linearity in extension	0.042	0.181
	Resilience in extension	3.56	10.95
Shear	Shear rigidity	0.060	0.171
	Shear hysteresis (0.5°)	0.135	0.392
	Shear hysteresis (5.0°)	0.193	0.536
Bending	Bending rigidity	0.005	0.018
	Bending hysteresis	0.004	0.117
Compression	Thickness (0.5 gf/cm^2)	0.044	0.114
	Thickness (50 gf/cm^2)	0.034	0.063
	Work to compress	0.023	0.033
	Linearity in compression	0.035	0.059
	Resilience in compression	2.7	10
Surface	Frictional coefficient	0.010	0.038
	Variation in friction	0.006	0.016
	Surface contour	0.78	2.35

[a]Based on three replicates.

formed in 1984. The group, financed by the Australian Wool Corporation, had three major objectives:[27]

- 'To evaluate the introduction of objective measurement in menswear, worsted fabrics and garment manufacturing sectors'
- 'To review the Japanese system of test data presentations and modify it as appropriate to Australian requirements'
- 'To establish an Australian database for worsted menswear fabrics'.

The first objective involved a comprehensive testing programme of pure wool and blend fabrics. It was aimed at determining the extent to which the KES-F system could be used in the Australian industry to specify fabric and garment quality. The second objective was to address the major concern over the complexity and extensive amount of data derived from the original HESC model and resulted in the reporting of an alternative set of data for fabrics (Table 2.5).

There were two sources of concern in the HESC recommendations for use of measurements derived from the KES-F instruments:

- The use of hysteresis measurements
- The relevance and methodology used for surface measurements.

Table 2.5 Measurements recommended by AWTOMEC

Properties	HESC recommendation (cgs units) Warp, weft, average	AWTOMEC SI units)[a]
Tensile	LT, WT, RT, Em	Em, [b]RT (warp, weft only)
Bending	B, 2HB	B, RB (warp, weft only)
Shear	G, 2HG, 2HG5	G, RS, 2HG5 (average only)
Compression	To, LC, WC, RC	To, C, RC
Surface	MIU, MMD, SMD	SMD (warp, weft only)
Dimensional stability		RS, HE (warp, weft only)
Derived		Formability (warp, weft only)

[a]RB($m - 1$) = 0.5 × 2HB/B
RS (deg) = 0.5 × 2HG/G
C (%) = 100 × (To − Tm)/Tm where Tm is the thickness at 50 gf/cm^2
RS (%) = Relaxation shrinkage % (derived from AWC test method no. 10)
HE (%) = Hygral expansion (dry–wet) %
Formability = B × El/49.035 where El is the extensibility at 49.035 N/m (50 gf/cm).
[b]Em (HESC) is used only in the determination of tailoring performance.

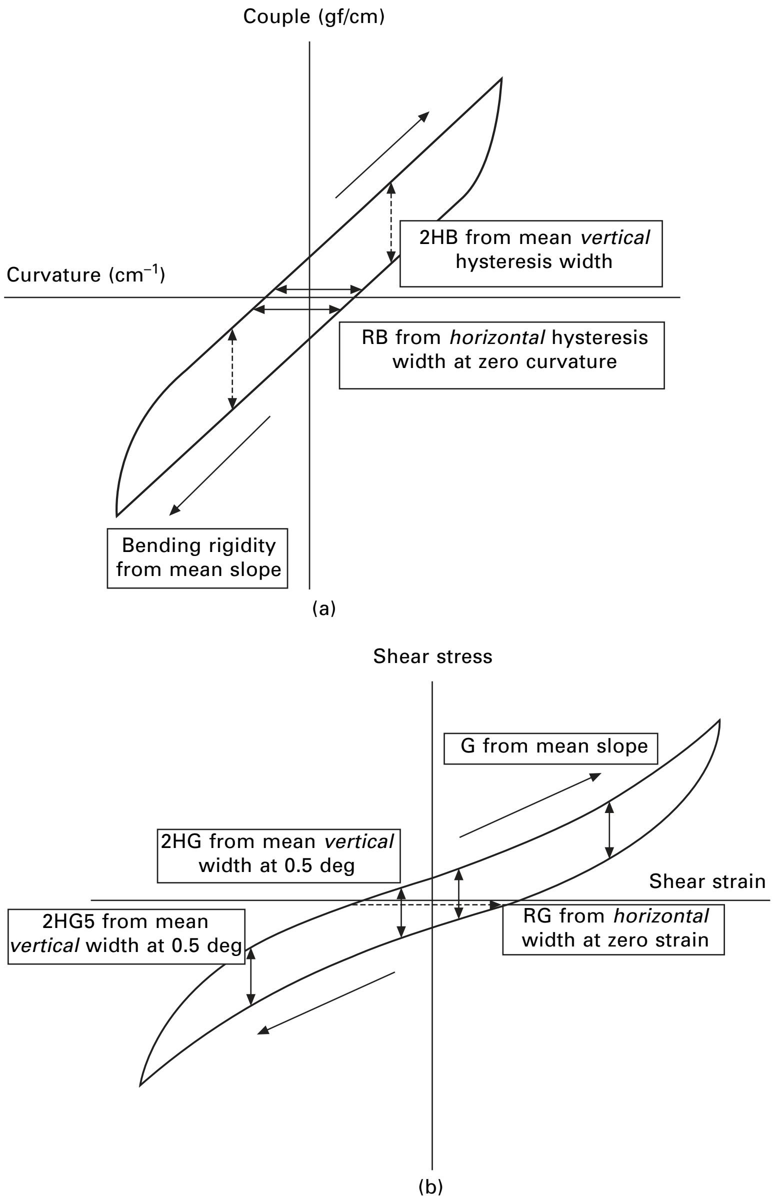
Concern over the use of hysteresis measurements by the HESC equations centred around the specific interpretation of 2HB, 2HG and 2HG5 rather than any disagreement on the need for measurement of hysteresis and recovery in some form. These measurements of hysteresis in bending and shear recommended by the HESC correlated extremely well within the fabric data set with the modulus-related properties B (bending rigidity) and G (shear rigidity). There was concern that two such well-correlated measurements added little to the understanding of the separate contributions of modulus and hysteresis in deformation. From the other potential measures of hysteresis in deformation in bending and shear, AWTOMEC elected to use the properties *Residual Curvature* (in bending) and *Residual Strain* (in shear). These measurements are shown in Fig. 2.4(a) and (b) respectively.

For a perfect curve, the following equations apply:

$$RB = 0.5 \times 2HB/B$$

$$RG = 0.5 \times 2HG/G$$

AWTOMEC adopted these calculations rather than the direct measurement of the residual curvature and strain. Direct measurement of RB can be affected by distortions of the bending curve at very low curvatures caused by the clamping mechanism on the KES-F2 bending meter. Moreover, both direct measurements were susceptible to electrical and mechanical noise in the instruments. Notwithstanding this difference, the committee decided to continue to report 2HG5 because of the importance placed on this parameter by Japanese garment manufacturers.



2.4 (a) Bending and (b) shear curves.

The concern over the surface properties measured by the KES-F system centred around the reproducibility of the measurements, given their importance in the prediction of *Numeri* (smoothness). There were some misgivings about the interpretation of results from the metal fingerprint for friction measurements.

However, there was less concern about the contour measurement – SMD, which is measured and reported in the AWTOMEC chart.

AWTOMEC also approved the reporting of *formability*, a term derived from Swedish work[28] on the relationship between fabric properties and performance in garment manufacture. Formability is a measure of the extent to which fabrics can be compressed in-plane before buckling and thus can be used to predict seam pucker.

$$\text{Formability} = \text{BR} \times \text{El}/49.035$$

where BR is bending rigidity (KES-F2 instrument) and El is the extensibility, directly measured at 50 gf/cm width (KES-F1 instrument). Alternative measurements and definitions of formability have since been proposed.[29–30]

The details of the testing procedures and the reporting of results were collated in the AWTOMEC manual. AWTOMEC also developed an alternative form of the fabric fingerprint (Fig. 2.5). This fingerprint uses linear scales to give a simpler form of data presentation. An important decision of the committee was to exclude calculation of primary and total hand values 'in order to concentrate initially on hand interpretation directly via the fabric mechanical and surface properties'.[27]

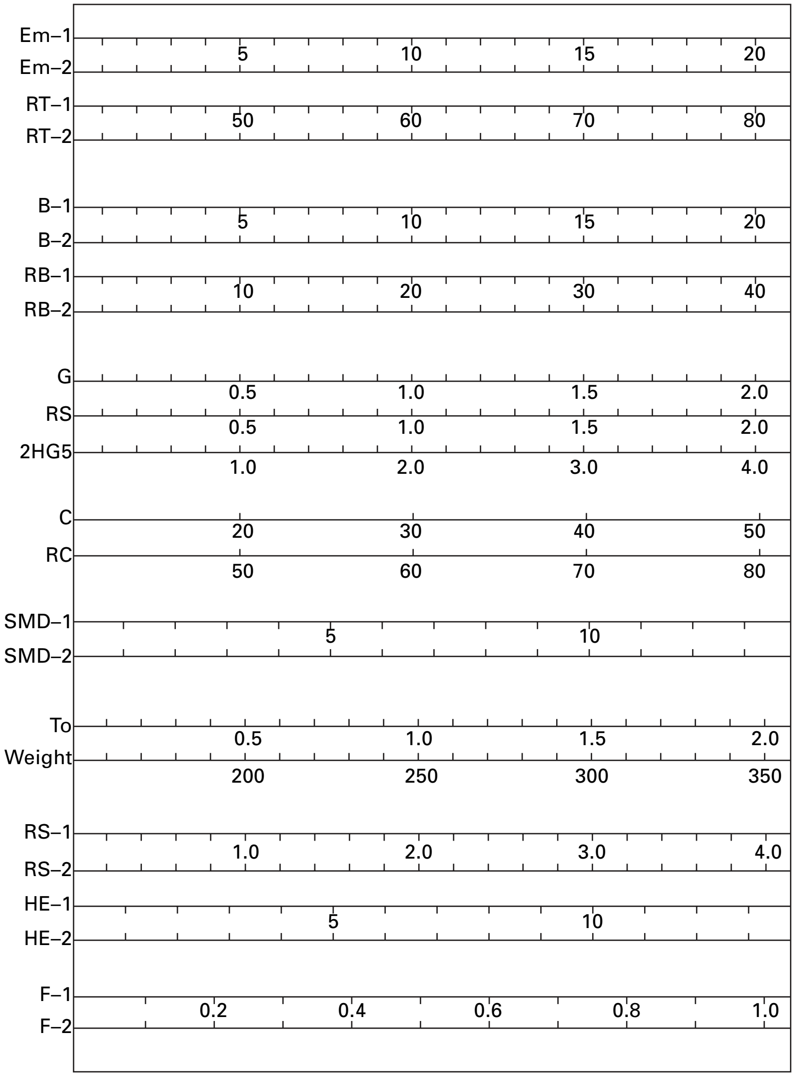
AWTOMEC continued its activities until 1991. In that time, the committee adopted a set of six bipolar hand descriptors that were thought to be more relevant to the Australian industry for the description of hand. A trial was conducted to determine the key mechanical properties involved in each hand characteristic (Table 2.6).

Before it completed its work in 1991, AWTOMEC also conducted a major fabric/garment tailoring trial, developed a video on the use of the KES-F system, circulated a series of case studies in the use of fabric objective measurement (mainly on the relationship between fabric/structure/finishing and subsequent properties) and held a seminar on the topic.

Alternative approaches to interpretation of KES-F data

Earlier in this section, reference was made to the concern expressed over the statistical techniques used to develop predictive hand equations from the fabric properties measured by the KES-F instruments. It is acknowledged that the 16 properties recommended by Kawabata contain a degree of overlap.

British workers[32] re-analysed the data on men's winter suiting published by Kawabata and suggested that alternative, independent variables could be used to describe the fabric and obtain the necessary correlation with subjective hand. The variables chosen (using the notation of the HESC) were W/B, SMD/T, T/B, SMD/W, SMD*B, W*T and their combinations with MIU. The regression equation



2.5 AWTOMEC chart.

$$\text{Hand} = 4.27(\text{W/B}) + 0.786(\text{T/B}) - 79(\text{SMD/T}) - 0.24(\text{MIU/T}) - 2.423$$

was found to correlate with overall subjective hand at a level similar to that given by the HESC equations. Moreover, this approach required only the measurement of surface properties (KES-F4), fabric weight, bending rigidity (KES-F2) and thickness (KES-F3). A number of alternative test instruments are available for the last two properties.

Table 2.6 Relationship between fabric properties and AWTOMEC bipolar descriptors[31]

Descriptor	Related properties[a]	Overall prediction[b]
Extensible – Inextensible	Tensile (0.87), Compression, Shear	0.92
Springy – Limp	Shear (0.80), Surface, Tensile	0.90
Firm – Supple	Shear (0.79), Surface, Tensile	0.90
Full – Lean	Surface (0.74), Shear, Compression	0.88
Smooth – Rough	Surface (0.68), Shear, Compression	0.88
Warm – Smooth	Weight (0.69), Compression, Shear	0.92
Overall handle	Surface (0,64), Compression, Shear	0.88

[a]Numbers in parentheses give the correlation coefficient between the handle characteristic and the most important group of properties.
[b]Overall prediction includes all properties measured.

In an alternative interpretation, Chinese workers used 88 'middle thickness' fabrics to derive an objective measurement of hand using the concepts of *Weighted Euclidean Distance*[33–35] and *Fuzzy Cluster Analysis*.[36] Using the 16 mechanical properties from the KES-F instruments recommended by the HESC, eight fabric *features* were derived. The authors claimed that these eight different and independent primary hand characteristics of fabrics specified fabric primary hand 'more completely and reasonably' than the PHVs developed by Kawabata. The eight characteristics were named stiffness, fullness, smoothness, crispness, elasticity, droopiness, roughness and softness depending on the subjective characteristic and/or mechanical properties with which they correlated most heavily.

Researchers in the USA also demonstrated that relatively fewer mechanical properties were needed to obtain good correlations with the subject hand characteristics of restricted ranges of fabrics. One recommendation used only nine of the 16 properties recommended by the HESC (LT, WT, RT, 2HB, 2HG, RC, T, MIU and MMD). In this instance the measurements were made in a universal tensile tester under conditions that duplicated those in the KES-F instruments.

The second edition of the HESC manual described the use of discriminant analysis to separate different types of fabric on the basis of primary hand values. The PHV values, which can be calculated from properties measured in the KES-F instruments, were combined in a linear equation to calculate one or more discriminators, which separated silk-like, polyester-like and cotton-like fabrics.

A comparison of the block regression analysis used by Kawabata with alternative models was also made:

- A linear model

- Weber–Fechner law: PHV = $a + \sum b_i \log x_i$
- Stevens' law: log PHV = $a + \sum b_i \log x_i$

In this work the HESC PHV standards were used to rate the set of fabrics, and all fabrics were tested in the KES-F system. The authors claim that Stevens' law was the most suitable for the prediction of PHV.[37]

A range of alternative approaches to condensing or visualising the KES-F data have also been proposed. In addition to the AWTOMEC chart and snake, alternative charts have been proposed, especially for applications of the KES-F for the prediction of performance in garment manufacture. A number of 'radar' plots have also been proposed based on properties measured on the KES-F instruments or derived from them to characterise the fabric.

Engineering evaluation and the SPRINT programme

The *SPRINT* project was funded by the EEC to allow 10 European research institutes to work together to stimulate the use of fabric objective measurement by fabric and garment manufacturers, not only for the prediction of performance in garment manufacture but also for the objective assessment of other related aspects of quality. The objective of the *SPRINT* group was to promote the philosophy behind objective measurements rather than promote specific instruments.

In the TNO Centre for Textile Research, work was done to simplify the operation of the KES-F instruments, the complexity of which was seen as a bar to commercial adoption.[38] The authors proposed a number of changes to the KES-F instruments and to the methodology for testing. The proposed attachment to the KES-F1 allowed a more distortion-free loading of samples so that more uniform shear curves could be obtained and the pre-tension required for the tensile test could be more accurately applied. The degree of tightening of the clamps on the bending meter was also highlighted as a point of difficulty, and in response to this perceived problem, a torsion socket was developed that can be used to tighten the bending with more consistent tension, thereby obtaining less distorted curves from the bending meter. The authors also formulated recommendations concerning the onset of the integration in the compression test, where the compression head can travel a significant distance without being in contact with the sample. In this zone, the integration value used to calculate WC should be zero.

In the shear test, the treatment of the tensile load required to prevent buckling has also been the subject of some discussion. Unlike the recommendations made for the use of a shear attachment for a tensile test machine,[39] the HESC recommendations for the KES-F1 instrument in shear mode do not subtract the effect of the tensile force. This is equivalent to 45 N/m with the heaviest pre-tension bar and 12 N/m for the lightest bar. In a recent study, measurements obtained in simple shear (using KES-F1) agreed well with measurements obtained in bias extension[40] when allowance was made for the effect on shear stress of the tensile load, which must be applied to avoid buckling.

Broader application of the KES-F instrumentation

Although the KES-F instruments were initially developed to measure the properties of woven apparel fabric, they can be used to measure the properties of woven fabrics as diverse as terry towelling and blankets[41] as well as those of warp- and weft-knitted fabric and non-woven fabrics. Plain knitted fabrics tend to curl and this can cause practical difficulties in their measurement. However, double knits and a number of other knitted structures can be tested with only a little more care (due to their ease of distortion) than woven fabrics. The measurement of the residual couple in knit fabrics can be used as a measure of their tendency to curl and the effectiveness of finishing operations.[42]

Modifications of the original test procedures developed for woven fabrics on the KES-F instruments have been described for the testing of shirting, women's thin dress fabric, outerwear knitted fabric, knitted fabric for underwear, and non-woven fabric.[43] These modifications include changes in the strain rates, maximum loads (or strains), and the measurement of different properties. For example, shear hysteresis of knitted fabric is measured at 0.5 deg and 3 deg (rather than the original 0.5 deg and 5 deg) or at 0 deg for high-sensitivity knitted fabric. New parameters are also recommended such as the 'yield curvature' in bending and 'yield angle' in shear on non-woven fabrics. The KES-F instruments can be adjusted to accommodate these changes; however, in some instances such as when there are changes in maximum loads, modifications are required to the formulas used to calculate parameters such as LC and LT from those shown in Table 2.3.

Studies of the mechanical properties of weft knits for outerwear use as a function of structure and density have been published.[44–45] The use of the HESC equations predicting subjective hand characteristics from the mechanical properties of knitted fabrics, although attempted, remains uncertain. It is argued that the equations were developed using a sample set composed of woven fabrics, for an end-use in which knitted fabrics are rarely used and to predict hand terms that may not apply to knitted fabrics. Notwithstanding this, the mechanical properties of a wide range of knitted fabrics can be used directly to gain information on hand.

A more complete study has been conducted in Japan on knitted fabrics.[46–49] Sensory evaluations of bending rigidity, thickness, compressibility, and coefficient of friction on a series of plain and rib weft-knitted structures made from cashmere and polyester textured yarns were found to be in fairly good agreement with the values measured on the KES-F system.

Undoubtedly the largest application of the KES-F instruments has been in the area of the prediction of the performance of woven fabric in garment manufacture. It had been known for many years, particularly following the research done in Sweden, that the mechanical properties important in the assessment of hand were also important in the manufacture of high-quality garments. During the development of the KES-F system, the tailoring industry had found that the measurements of fabric properties determined using the instrumentation could be used to predict performance in the manufacture of high-quality tailored garments. A large amount of research has been done in Japan to develop predictions of tailoring performance (TAV – Total Appearance Value) from measurements made on the KES-F system.[11]

A whole spectrum of predictors have been developed using the KES-F instrumentation and are described in the KN series of equations developed in Japan. More recent work describes TAV in terms of three primary components, called *formability, elastic potential* and *drape*, and uses predictive equations equivalent in form to those used to predict hand.

Charts similar to that of the HESC snake with various zones predicting problems in garment manufacture have also been developed.[50] A description of these studies lies outside the scope of this chapter but references to reviews of the use of the KES-F instrumentation in these applications are given at the end of this chapter.

The KES-F instruments have also been widely used to measure the effect of finishing operations on woven and knitted fabric.[51–55] By measuring the key fabric property affected by individual finishing operations, the extent of the desired changes and any side effects can be monitored and optimised.[56] The KES-F instruments can be used to compare the hand of series of fabrics or compare the effects of hand-modifying chemicals (e.g. softeners) and operations. Measurement of the shear hysteresis has been advocated as a measure of the effectiveness of softeners on a range of fabric types.[57] The measure has application in quality assurance or as a selection tool for fabric softeners.

Scottish workers[58] sounded a further note of warning in the use of the HESC predictive equations for fabric handle in the evaluation of finishing operations. These equations did not predict subjectively observed changes in the hand of cotton–polyester dress fabric in wash and wear cycles. Nevertheless, good correlations ($R > 0.9$) were obtained between the subjective rankings and selected mechanical (shear) and surface properties (SMD – contour).

2.3.2 Fabric Assurance by Simple Testing (SiroFAST)[59]

The SiroFAST system for fabric objective measurement of fabric mechanical, physical and dimensional properties was developed by CSIRO[60] in the late 1980s to overcome the perceived disadvantages associated with the KES-F system. In practice, at least outside Japan, the KES-F system had been found to be too complex and expensive for use in a mill environment. The SiroFAST system was designed to be simple to use and to provide robust measurements of fabric properties.[61,62]

An important feature of the SiroFAST system is that it was developed to measure those properties of fabrics important in the manufacture of garments (tailoring) rather than to measure the hand of fabrics in a manner analogous to the KES-F system.

The SiroFAST system consists of three instruments and a test for dimensional stability (shown in Fig. 2.6):

- *SiroFAST-1 Compression Meter*
  This instrument measures the thickness of fabric at two loads: 0.196 kPa (2 gf/cm^2) and 9.807 kPa (100 gf/cm^2). It uses a relatively novel principle of measurement in which a proximity detector measures the change in position of a metal disc when the fabric is placed between it and the detector and the further changes in the position of this disc as an increasing load is added to it.
- *SiroFAST-2 Bending Meter*
  This instrument measures the bending length of the fabric in both warp and fill direction using a cantilever bending test as described in British Standard 3356. The instrument offers advantages over previous cantilever bending instruments in that it uses optical sensors to detect the leading

2.6 SiroFAST instruments.

edge of the fabric and thereby eliminates the errors associated with the judgement of the operator in determining the end point.

- *SiroFAST-3 Extension Meter*
  This instrument measures the extensibility of the fabric in the warp and weft directions under loads of 4.9 N/m (5 gf/cm), 19.6 N/m (20 gf/cm) and 98.1 N/m (100 gf/cm). The instrument is also used to measure the extensibility of the fabric in the bias directions under a load of 4.9 N/m (5 gf/cm width).
- *SiroFAST-4 Dimensional stability test*
  This test method measures the wet relaxation shrinkage of the fabric and the hygral expansion of the fabric from wet to dry.

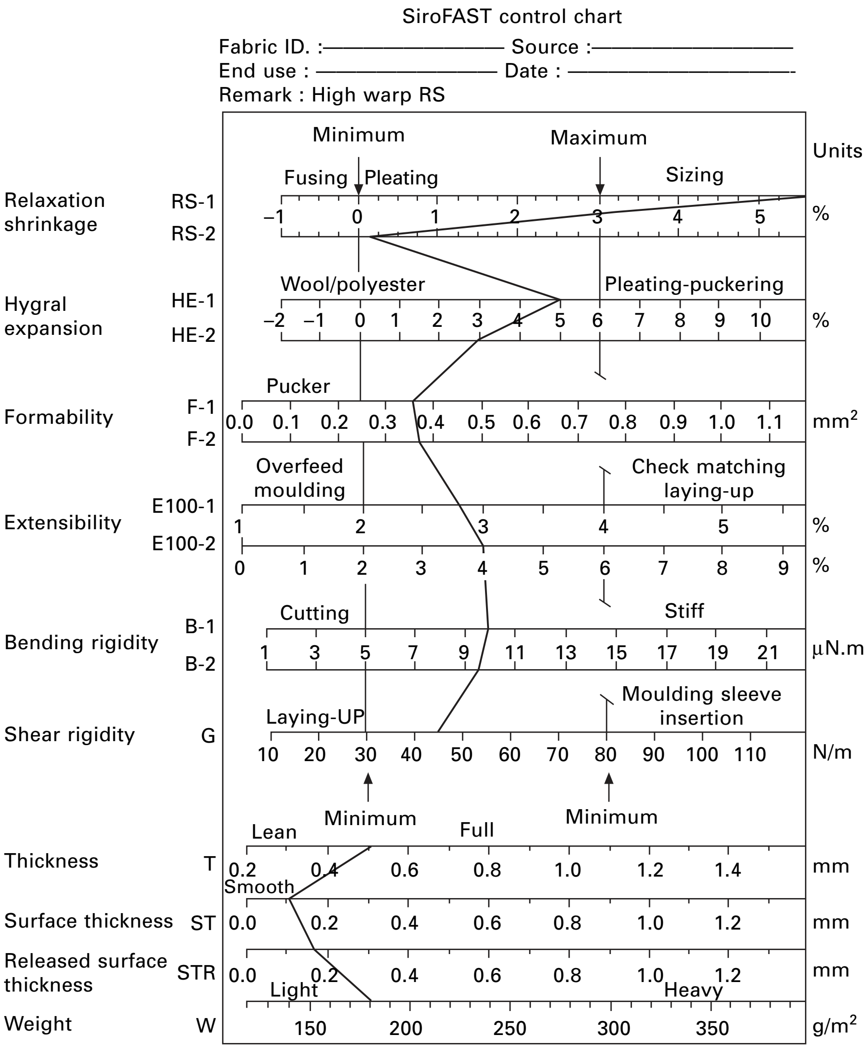
In addition to the measurements taken directly from the instrument, other properties of fabrics are also determined (Table 2.7). In recent times these measures have been further augmented by the concepts of *effective* and *stable flat set*.[63]

Table 2.7 Measurements made on the SiroFAST system

Instrument	Description	Symbol[a]	Measurement
FAST-1 Compression Meter	Thickness at 2 gf/cm^2 Thickness at 100 gf/cm^2 Relaxed thickness at 2 gf/cm^2 Relaxed thickness at 100 gf/cm^2	T(2) T(100) RT(2) RT(100)	
FAST-2 Bending Meter	Bending length	BL	Warp and weft
FAST-3 Extension Meter	Extensibility at 5 gf/cm Extensibility at 20 gf/cm Extensibility at 100 gf/cm Bias extensibility at 5 gf/cm Warp and weft	E(5) E(20) E(100) Eb	Warp and weft Warp and weft Warp and weft Bias
FAST-4 Dimensional stability test	Relaxation shrinkage Hygral expansion	RS HE	Warp and weft Warp and weft
Physical properties	Weight per unit area	WT	
Calculated measurements	Surface thickness Bending rigidity Shear rigidity Formability	ST BR G F	 Warp and weft Warp and weft

[a]$BR = WT \times (BL)^3 \times 9.807 \times 10^{-6}$
$G = 123/Eb$
$F = BR \times [E(20) - E(5)]/14.7$
$ST = T(2) - T(100)$

Although the measurement of fabric properties with the SiroFAST instruments is relatively simple, as with all systems for fabric objective measurement, interpretation of the data in a form that can be used by industry is more complex. Interpretation of the data requires an understanding of the mechanisms by which fabric properties affect its performance in garment manufacture. The SiroFAST system uses a graphical method of presenting and interpreting the data similar to that developed for all the KES-F. The SiroFAST chart is shown in Fig. 2.7. The annotations to the chart make it quite clear that the system has been designed for the predictions of problems in garment manufacture rather than the measurements of hand.



2.7 SiroFAST chart (from the SiroFAST Manual).

The system is supplied with a computer interface to simplify use of the instruments and also software to aid in the rapid interpretation of the data. The precision of measurements of the SiroFAST system has been determined in a series of interlaboratory trials[64] and the confidence intervals associated with the measurements are shown in Table 2.8.

Table 2.8 Reproducibility of measurements on SiroFAST system instruments

Property	Measurement	Critical differences	
		Within laboratories	Between laboratories
FAST-1	Thickness at 2 gf/cm^2	0.016	0.031
	Thickness at 100 gf/cm^2	0.008	0.024
FAST-2	Bending length	0.6	1.12
FAST-3	Extensibility at 5 gf/cm	0.11	0.37
	Extensibility at 20 gf/cm	0.14	0.43
	Extensibility at 100 gf/cm	0.24	0.61
	Bias extensibility (5 gf/cm)	0.27	0.83
FAST-4	Relaxation shrinkage	0.38	0.46
	Hygral expansion	0.60	0.91

The reproducibility of formability, dimensional stability and surface thickness are described in IWTO specifications:
Formability: IWTO Test Method 49
Dimensional stability: IWTO Test Method 50
Finish stability: IWTO Test Method 51.
Source: SiroFAST manual.

The key differences between the SiroFAST and the KES-F systems are:

- The SiroFAST system does not measure the hysteresis/recovery properties of fabrics (RT, 2HB, 2HG, 2HG5, RC). Shear hysteresis measurements have been found to correlate very well with certain aspects of fabric hand, particularly softness. The extent to which SiroFAST can measure hand in these instances is determined by the extent to which the modulus measurements (extensibility, bending and shear rigidity) correlate with the same subjective characteristics. In many instances, particularly in shear deformation, modulus measurements correlate well with hysteresis.[40]
- The SiroFAST system does not measure fabric surface properties (MIU, MMD, SMD). Notwithstanding concerns over the appropriate methods of measurement, the surface properties of fabrics are key determinants of hand. The SiroFAST system cannot provide information on those subjective hand characteristics that are primarily determined by the surface properties of the fabric (e.g. smoothness–roughness).
- The SiroFAST system measures dimensional stability.

Relaxation shrinkage and hygral expansion, determined using SiroFAST-4, do not affect hand but are key properties for predicting performance in garment manufacture and wear.

Although it does not purport to predict or measure overall hand, it is clear that, by measuring low-stress mechanical and physical properties of the fabric, the SiroFAST system can be used to obtain considerable information about fabric hand. All the knowledge obtained using the various alternative measurement systems on the relationship between fabric properties and hand apply equally well to the properties derived using the SiroFAST system. The SiroFAST User Manual supplied with the system recognises the usefulness of the individual fabric properties in determining fabric hand. However, the system does not use equations to predict hand characteristics, as has been done with the KES-F system, or use the concept of overall hand. The developers of the SiroFAST system noted and recommended the use of the relationship of specific objectively measured properties to subjective descriptions of hand.

2.4 Future trends

After the initial excitement and activity caused by the introduction of the KES-F and SiroFAST instrumentation and the prospect of objective measurement of hand using the HESC methodology, there has been a quietening of interest in both systems, particularly in Western Europe and the USA. Many of the high-value-adding producers, particularly of men's tailored garments, adopted and introduced the technology during the 1970s, 1980s and 1990s and have integrated the technologies into their regular testing regimes.

Both KES-F and SiroFAST continue to be used widely for the following:

- Prediction of performance in garment manufacture
- Development of new fabrics and new finishes
- Quality assurance.

In these applications both sets of instruments have now become regular tools of trade for fabric manufacturers, finishers and garment makers, with well over 100 SiroFAST systems and many KES-F instruments being used worldwide. Both systems will continue to be widely used in research and development by universities and research institutes.

It is anticipated that the future will see a wider adoption of objective measurement technology in developing countries. As quality improvements are made by fabric and garment manufacturers in these countries and as they seek to export high-value-added products into the sophisticated markets of Western Europe and the USA, they will need to demonstrate the quality of their products using KES-F, SiroFAST or suitable alternatives.

Attempts to include objective determination of overall hand as part of the trading system appear to have been limited to Japan. There has been little or no use of the methodology outside that country. Nevertheless, the use of sophisticated instruments for the measurement of specific fabric properties remains, and will remain, the method of choice for determining change in hand (due to finishing, etc.) or comparing the hand of a restricted range of fabrics. The exchange of information on such fabric properties will play an increasing part in commercial trade. However, it is unlikely that measurements of 'objective hand' using the KES-F or other types of measurement will be a significant part of commercial communication or trade in fabrics. Overall hand will remain, at least in the short term, a subjective decision.

It is anticipated that the use of the SiroFAST and low-cost alternative systems will continue to expand, particularly in Asia as the production of high-value fabrics and garments increases and quality assurance becomes an important issue. The expansion of the use of the more sophisticated KES-F instruments will probably be slower within the industry for the reasons that have been expounded before – complexity and price. However, it is likely that for both systems, their major use will continue to be in the prediction of performance in garment manufacture rather than for the measurement of any aspect of hand.

The impact of alternative measurement systems on the use of KES-F and SiroFAST remains speculative at this time. As will be discussed in later chapters, many of the measurements made using KES-F and all of the mechanical properties made on the SiroFAST system can be made on tensile test instruments (such as an Instron) with suitable attachments. Although measurement of bending properties on a tensile test machine requires quite sophisticated attachments, alternative simple instruments to measure bending properties are readily available.

Although the use of alternative, simple and less expensive instruments is an option for users of objective measurement equipment, the key to the successful use of fabric objective measurement technology lies not in the measurement but in the interpretation of the measurements made. The value of the existing systems lies in the application of the extensive published background information as well as in that contained within the manuals for the measurement system. Access to information on the interpretation of data and the use of that information in improving quality will remain the main driver for the uptake of the KES-F and SiroFAST systems.

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3
Developments in measurement and evaluation of fabric hand

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3.1 Introduction

Fabric hand may be considered as the first method of fabric testing ever created by humans. It is also one of the everlasting evaluation techniques of fabric. Even with today's technological advances in testing and evaluation, subjective fabric hand still remains one of the most reliable methods of fabric characterization. Through the touch and feel of fabric and with little experience, people can gain information that no other testing technique could fully yield. When fabric hand is compared with other subjective means such as vision, it is always found that the sense of touch has better ability to discriminate and recognize complex stimulus patterns than the visual system does. This is because human skin has a remarkable ability to detect even the slightest touch and any point on the human body can cause a sensation of touch. The primary human organ used for touch is the human hand, a very powerful organ which performs several sensory mechanisms supported by over 17,000 nerve endings that are sensitive to non-noxious mechanical deformation of the skin in the glabrous skin of one hand.

In general, the term 'fabric hand' describes the way a fabric feels when it is touched and manipulated by hand. It is an action noun that implies evaluation of fabric reaction to different modes of low-stress deformation imposed by the human hand. A more general term that is commonly used in the industry is 'fabric handle'. This is an action verb that reflects the evaluation of fabric reaction to different modes of deformation at all levels of applied stress (low or high). In this case, fabric handle may imply different handling actions such as touching, folding, cutting, transporting, sewing, and pressing. In this chapter, we will use the two terms alternately to imply an integrated evaluation of fabric 'manipulability', or the extent of ease of response of a fabric sample through applying a multiplicity of unnecessarily organized manipulative actions. Our interest in fabric 'hand' stems from its relationship with the comfort phenomenon.

The fascination with fabric hand by researchers and technologists in the field has been a result of two basic facts. First, it represents one of the most important initial attractions that draw people's attention to fabrics and garments in the marketplace. Secondly, a great deal of complexity is associated with characterizing it as a result of the multiplicity of interactive factors influencing it.

The issue of fabric hand is commonly addressed in view of two types of perceptions: an active perception resulting from an initiative taken by humans to actually touch and feel (handle) a piece of fabric by hand, and a passive perception resulting from wearing a garment and unintentionally feeling its interaction with the skin and body movement. The significance of distinguishing these two types of fabric hand is that the first one primarily leads to an initial judgment of how the fabric feels, which may influence the appeal and the purchasing decision of a fabric or garment. In this regard, the person handling the fabric typically attempts to characterize his or her perception of fabric hand. At this point, it is often the case that verbal descriptors do not fully reflect the actual perception. This point often creates a problem to researchers analyzing the correlations between subjective hand scaling results and objective hand parameters. On the other hand, the passive fabric hand reflects a true experience with the fabric or garment after a period of wearing experience. In this regard, the information is essentially imposed on the skin, and the wearer has some justification for his or her decision.

Most investigators rely on active hand in establishing correlations between subjective and objective means of fabric evaluation. This approach is simple and very practicable. In addition, it reveals good information, particularly when fabrics of extreme hand characteristics are being compared. However, irreproducibility and unreliability can be of major concern, particularly when fabrics of small hand differences are being compared or when an inappropriate control sample is used.

In this chapter, we summarize some of the developments in fabric hand evaluation and introduce a new technique developed by two of the present authors that has received wide acceptance among researchers and industrial organizations in the US. In addition, we present some interesting hand results for woven and knit fabrics.

3.2 Subjectivity and objectivity in fabric hand

The key question that has been addressed in most hand studies is 'what constitutes fabric hand?'. Despite the extensive research in the area, a universal answer to this question is yet to be fully established. Indeed, every study on fabric handle, including some of the most recent studies, seems to aim at addressing this question using particular fabrics. As a result, and despite the significant developments in the field, a universal quantitative measure of fabric hand has not yet entered the textile database.

The main reason why a universal answer to the question of 'what constitutes fabric hand?' has not been fully established lies in the fact that the subjective aspect of fabric hand represents the driving force toward characterizing this critical phenomenon. Indeed, it is commonly agreed that it is necessary to examine the subjective assessment of hand before examining its relationship to fabric mechanical and surface properties. Since there is no standard format of subjective evaluation, no standard answer is provided. Until such a format is established, research on the subject will continue and many more attempts to address this question will be made.

Standardizing subjective hand evaluation requires translating various personal judgment criteria into reliable characterization categories that reflect true global mutual communication about fabric quality. The fact that personal judgment is typically of a continuous nature calls for utilization of advanced analytical techniques such as fuzzy logic to establish realistic membership functions of fabric hand characterization. This approach will provide many advantages over the traditional discrete psychological scaling. However, standard descriptors must be established first. More critically, a universal quantitative measure of fabric hand should be considered as the basis for developing reliable fuzzy membership functions [1, 2].

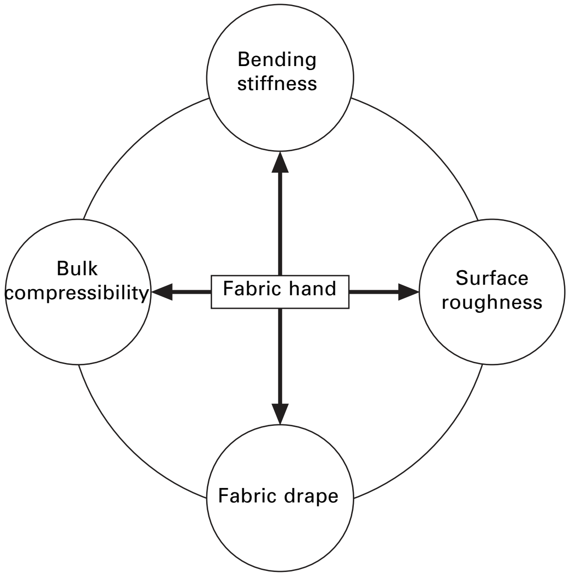
Perhaps the best and most acceptable answer to the question of what constitutes fabric hand was the one established by Peirce [3] in his classic paper in 1930. In this study, Peirce pointed out three basic determinants of fabric handle: bending stiffness, bulk compressibility, and surface friction. Fabric drape was added as another component of fabric hand by later studies. This is because it reflects the fabric's ability to conform to multiple curvatures. Figure 3.1 shows these components. Other parameters such as shear, crease recovery, and fabric thickness were also considered as determinants of fabric handle.

3.3 Developments in fabric hand objective evaluation

The interest in fabric hand (handle) has stimulated many researchers to develop objective ways for characterizing this important phenomenon. Our review of the different developments reveals two main categories of fabric hand (handle) evaluation systems:

- Indirect systems of fabric hand (handle) evaluation.
- Direct methods of fabric hand (handle) evaluation.

The difference between these two categories lies in the types of parameters produced by each category and their associated interpretations. Indirect systems do not characterize handle in a direct fashion. Instead, they produce instrumental parameters that are believed to represent basic determinants of fabric handle



3.1 Components of fabric hand.

such as fabric stiffness, fabric roughness, and compressibility. Only through parallel subjective assessment and cross-correlations are some parameters that are believed to simulate fabric handle estimated. The two common methods in this category are the Kawabata system (KES®) and the FAST (Fabric Assurance by Simple Testing) system. Direct methods of fabric hand (handle) evaluation represent creative techniques that are intended to simulate two or more aspects of hand evaluation and produce quantitative measures that are labeled as hand force or hand modulus. These methods include the ring method and the slot method. It should be pointed out that the term 'direct' does not necessarily mean more representative or more accurate in comparison with the indirect systems. These systems are discussed below.

3.3.1 Indirect handle evaluation systems: Kawabata and FAST

The Kawabata and FAST systems are commercial systems that are available in many fabric testing laboratories around the world. Reviews of these systems have been discussed in many papers [4–8]. Although the initial purposes of these systems were to replace subjective hand assessment with objective means, they relied heavily on subjective scaling to produce objective hand characteristics.

The Kawabata system is based on the general agreement that the stimuli leading to the psychological response to fabric handle are entirely determined by the physical and mechanical properties of fabrics [6, 7, 9]. In this regard, these properties are considered only at low loads and extensions and not at the level of load and extension at which fabric failure occurs.

In order to effectively use the Kawabata system, it is typically important to get experts to agree on what aspects of handle are important and the relative contribution of each aspect with respect to the fabric under consideration. In this regards, the Kawabata system establishes the so-called 'primary hand' as a measure characterized by properties such as stiffness, smoothness, fullness/softness, crispness, anti-drape stiffness, scrooping, flexibility with soft feeling, and soft touch. Given the fact that these descriptors may have interpretive differences, particularly when translated to other languages, Kawabata decided to use Japanese descriptors corresponding to these properties. In this regard, these properties were termed *Koshi*, *Numeri*, *Fukurami*, *Shari*, *Hari*, *Kishimi*, *Shinayakasa*, and *Sofutosa*, respectively.

Using the Kawabata system, the subjective assessment values of the primary hand properties are combined together to yield the so-called 'overall rating of fabric hand' of a given fabric category. This is achieved using empirical equations to yield the so-called 'total hand value', which is rated on a five-point scale where 5 is the best rating.

As can be seen from the above descriptors, the terms used exhibit a great deal of overlap and have their share of confusion. In addition, they are certain to be different from one fabric category to another. Indeed, it has been found [10] that there are differences between countries in their perception of what truly constitutes fabric handle with respect to a particular end use.

On the objective side, Kawabata developed a set of instruments to measure appropriate handle-related fabric properties. These include tensile and shearing, bending, compression, and surface friction and variation. The end result to assess fabric handle by the Kawabata system consists of a total of 16 objective mechanical and surface parameters measured all at low levels of force. These parameters are correlated with the subjective assessment of handle using linear regression equations.

It is important at this point to pay tribute and respect to the late Sueo Kawabata, who spent his life seeking objective ways of fabric evaluation and contributed immensely to this complex area. As I came to know him personally, he was a philosopher scientist and a pioneering thinker.

The FAST (Fabric Assurance by Simple Testing) system was designed with a more global view of fabric handle. It was developed by CSIRO for use by goods manufacturers to detect and diagnose problems associated with the process of conversion from fabric to garments. As a result, the system aims at distinguishing loosely constructed fabrics, which are easily deformable, from tightly constructed fabrics. The system consists of three instruments: compression meter, bending meter, and extension meter. The system also provides a method for measuring fabric dimensional stability.

One of the reasonable arguments against the above systems stems from the point that a phenomenon that can be characterized subjectively in a matter of minutes may take hours, if not days, to fully describe. This is particularly true in view of the time consumed to test, analyze, and interpret the results [10–13]. Another argument is associated with cost, which is considerable in view of price, labor, and the maintenance involved.

It is our opinion that the true merit of the Kawabata system is not necessarily in the subjective assessment of fabric handle, but rather in the objective means by which related parameters are instrumentally tested. The analytical approach to link subjective assessment with objective measures is not fully automated or systematic. In addition, there are great doubts associated with the use of multiple regression analysis to develop relationships that are essentially non-linear in nature. However, the systems can provide useful quantitative guidelines particularly in the area of fabric and garment design.

3.3.2 Direct handle evaluation systems: the ring and slot methods

The main purpose of developing direct handle evaluation methods was to provide quick and easy-to-use techniques to analyze fabric hand. The developers of these methods also claim that they are simulative since they are based on pulling a fabric sample through a ring (the ring method) or pushing a fabric sample through a slot (the slot method) and measure the resistances to the pull-through or push-through mechanisms. This in part simulates how a person tends to handle a piece of fabric when he or she is attempting to evaluate it.

As indicated above, the ring method is based on mechanically pulling a sample of fabric with pre-specified dimensions through a metallic ring. As simple as the method may seem, a great deal of argument about its source, and who initiated it, was apparent in the literature. Indeed, there were more arguments about the source of the method than its physical interpretation. With the principle being to measure the resistance to fabric pulling through a ring, different investigators used different sample shapes, sample dimensions and ring diameters [11–18]. Most investigators used circular fabric samples. But some used four radial cuts in addition to circular samples and compared the results to give better evaluation of the effect of the shear stiffness. Typical sample diameters used were 100 or 250 mm and typical ring diameters were 10 to 28 mm.

The key parameter typically obtained from the ring test is the maximum force required to pull the fabric through a ring. In addition, the initial slope of the profile obtained from a chart relating the force to the extraction distance was used as an index of the ease of pulling. In this regard, most studies indicated that the ease of pulling the fabric through the ring may vary depending on fabric variables such as yarn type, weave structure, finishes, and measurement conditions.

The slot method is another direct technique of handle evaluation in which a fabric, a paper, or a plastic film is pulled or pushed through a slot rather than a ring [19–24]. The slot or gap can be adjusted to any desired width between two plates. Examples of this method include the Handle-O-Meter, which was described in a TAPPI-proposed standard for 'softness' [23]. This tester operates with a blade on an arm which pushes the fabric into the slot. Because of the arm, this tester can be operated on-line, at least in principle. A similar test is the Handmeter which is a simple attachment for the Instron tester [24].

The fundamental difference between the ring and the slot test lies in the sample arrangement, which is essentially a 3-D arrangement in case of the ring method and a 2-D arrangement in case of the slot method. This makes interpretation of the slot test using the classic elasticity theory much easier than that of the 3-D ring test. The main parameter obtained from the slot test is the resultant resistance force on the center point of the fabric. The fabric weight and thickness are initially considered to be negligible. The initial slope of the load–deflection curve associated with the slot test was also used to indicate fabric stiffness or flexural rigidity. In addition, the ratio of maximum load to initial slope was used to indicate fabric friction.

3.4 The El Mogahzy–Kilinc hand method

As an integrated part of a larger study on fabric comfort [25, 26] sponsored by the National Textile Center of the USA, a new method of testing fabric hand was developed. This method is called the 'El Mogahzy–Kilinc hand method'. The underlying concept of this method was inspired by the theoretical and experimental efforts made by many of the previous outstanding investigations in the field. However, the method aims at overcoming many of the problems associated with statistical reproducibility and characterization parameters found in previous methods.

The El Mogahzy–Kilinc method shares some common features with previous direct methods including the methods of Grover *et al*. [13] and Alley and McHatton [29]. However, it exhibits distinct features in both the geometrical setup and the critical parameters produced. The uniqueness of this method stems from its simulative and interpretive capabilities. It is perhaps the first method that introduces a single hand index that reflects most of the constituents of fabric hand.

The main premises of the method are as follows:

- The issue of fabric hand is an issue of simulation and interpretation.
- A viable fabric hand evaluation technique should be reproducible and representative of the fabric being studied.

- A single fabric hand index that reflects most of the fundamental components of hand as established by Peirce and many other researchers will represent a major step toward incorporating fabric hand in the fabric quality database.
- The method should be inexpensive and very efficient (it takes only one minute to completely evaluate a fabric sample).

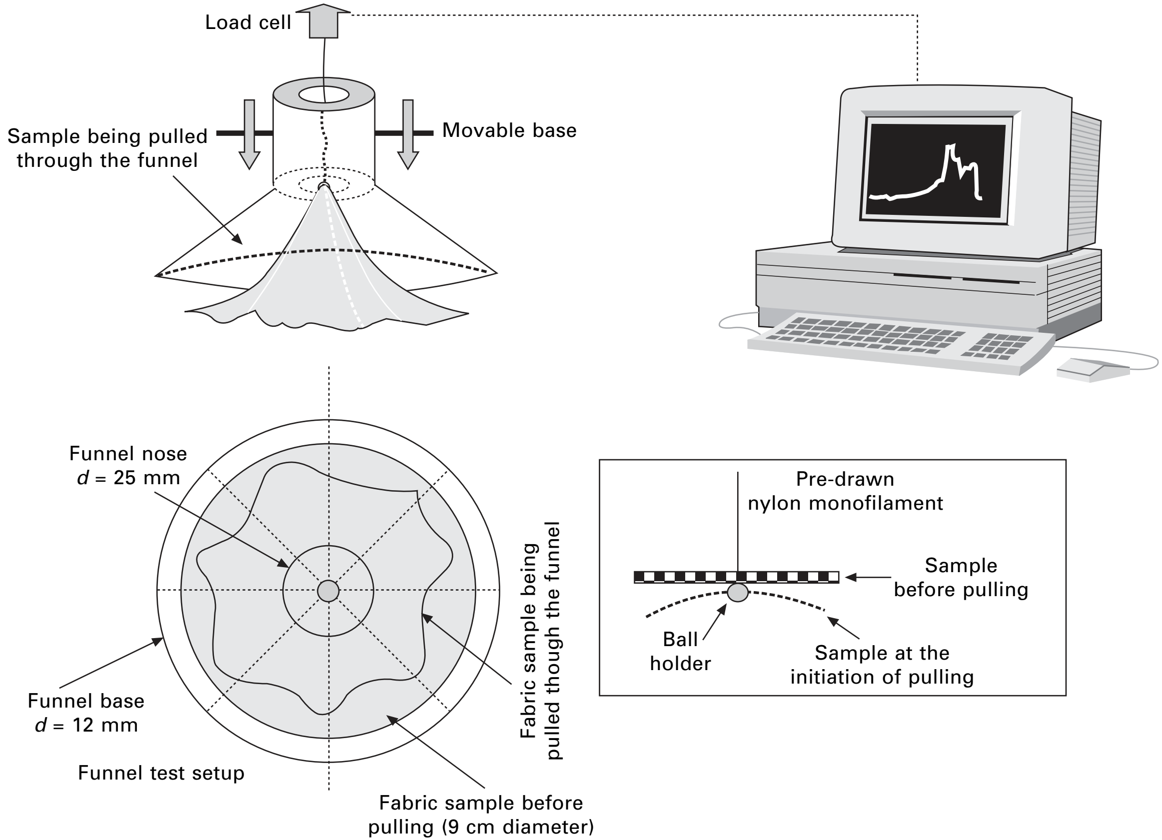
Figure 3.2 shows the basic components of the El Mogahzy–Kilinc hand method. A flexible light funnel is used to represent the medium through which the fabric sample is pulled. The idea of using a funnel medium instead of the ring or the slot arrangement is to provide better simulation of fabric hand. The contoured flexible surface of the light funnel simulates anticipated hand modes such as drapability, stretching, internal sample compression, lateral pressure, and surface friction. These modes are achieved both simultaneously and sequentially. In addition, the funnel medium allows both constrained and unconstrained fabric folding or unfolding, which simulates one of the mechanisms of fabric handle [25, 26].

Different funnel types and sizes can be used; however, funnel material should exhibit a great deal of flexibility (e.g. Teflon® plastic funnels). The funnel is rigidly suspended in a special horizontal attachment that is mounted rigidly on the movable head of the AU® mechanical tester. This machine was designed by El Mogahzy *et al.* [27, 28] for the purpose of performing low-deformation testing applications including tension, compression, stiffness, shear, and friction testing. The AU® mechanical tester is equipped with digital control and a host of software programs that allow monitoring, analyzing and profiling test results.

For the purpose of the hand test, fabric samples are cut circular at 9 cm diameter (smaller than the diameter of the funnel's wide base). However, the sample diameter may be changed if funnels of different dimensions are used as long as a ratio of 0.75 is maintained between the sample diameter and the base diameter. At this ratio, statistically reproducible results were obtained.

In general, as the movable head of the AU® mechanical tester moves downward, the funnel moves downward and the fabric sample is pulled through. During this process, the following sequence of sample behavior takes place:

- Initially, the sample is in a flat horizontal position.
- The initial downward movement of the funnel results in an upward movement of the fabric sample against its own weight and in a freely folding mode. Images taken of the sample at this initial step indicate an unconstrained folding leading to fabric drape. At this point, a very stiff sample will typically exhibit a simple one-dimensional folding similar to that of a piece of paper, and a flexible sample will exhibit multi-curvature drape.
- As the funnel continues to move downward, the sample begins to touch



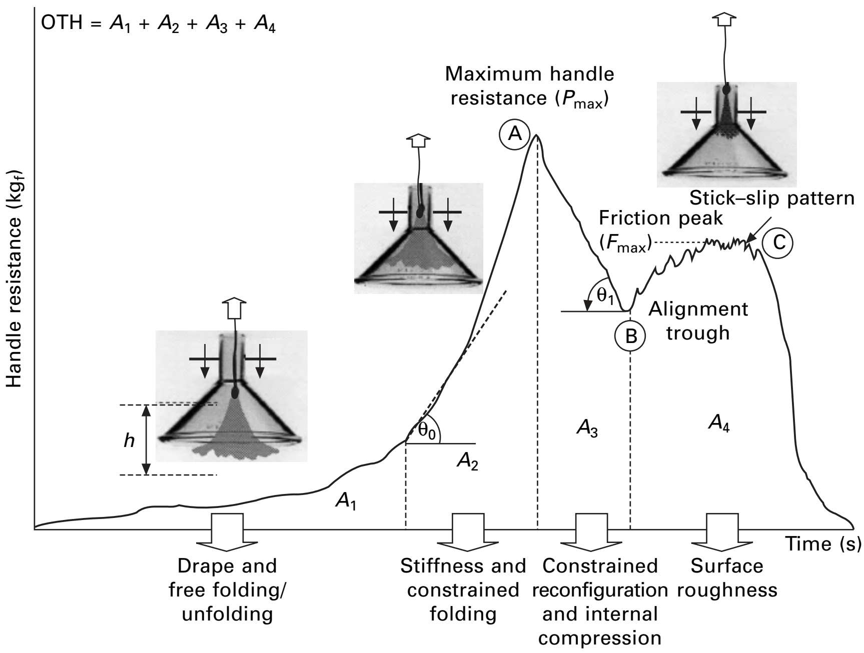
3.2 The El Mogahzy–Kilinc fabric hand method.

the inside wall of the conical part of the funnel at random points determined largely by the initial drape.

- The contact between the fabric sample and the inside wall of the conical part of the funnel initiates a constrained folding similar to that imposed by human hand compression of fabric during subjective evaluation. In addition, the conical shape of the funnel allows a great deal of reproducibility of this constrained folding. The extent of folding at this stage is largely determined by a combination of fabric stiffness and fabric inter-fold friction.
- As the sample attempts to enter the funnel's cylindrical nozzle, tension builds up as a result of a combination of stretching, compression, shear, and initial frictional effects. This tension reaches a peak at some point of the entering process at which the folded sample becomes aligned with the cylindrical nozzle of the funnel. At this point, the tension drops. The tension peak was found to typically occur when approximately two-thirds of the fabric length is inside the cylindrical nozzle. During this process, more constrained folding and surface reconfiguration is applied on the sample to accommodate its alignment with the cylindrical nozzle.
- The momentary tension drop lasts for about one to two seconds after which the tension begins to rise again. The extent of tension drop defined by the tension at the trough, or the difference between the peak tension and the trough tension, is expected to be largely a function of sample ease of reconfiguration, or fabric folding stiffness.
- Inside the cylindrical nozzle, the fabric sample undergoes internal compression, which depends on its folding status at the entrance point. In addition, sliding friction occurs between the points of the fabric that managed to remain on the surface during folding and the internal surface of the cylindrical nozzle. As a result, fabrics of different folding stiffness will exhibit different frictional stick–slip patterns. In addition, internal shear and elongation in the constrained sample is also expected, which increases with the increase in the length of the sample entering the cylindrical nozzle. As a result, another tension build-up occurs.
- The friction mechanism in the cylindrical nozzle is largely determined by the internal lateral pressure created by pressing the sample inside the nozzle and the extent of pre-folding. A stiff sample will result in high lateral pressure, and a flexible sample will result in low lateral pressure.
- The second tension build-up is typically smaller than the initial tension peak. However, for samples of extremely high folding resistance (stiff and rough samples), it can indeed exceed the first peak.
- As the fabric sample exits the cylindrical nozzle, a pressure release progressively occurs leading to a continuous reduction in tension. This pressure release results in internal stress relaxation, unfolding, and some form of crease recovery.

3.4.1 The hand profile

During the duration of the fabric pull through the funnel, a force–time profile is generated, termed the 'hand profile'. For most apparel fabrics, this profile takes the common shape shown in Fig. 3.3. The hand profile can be divided into four primary zones identified by the areas under the curve A_1, A_2, A_3, and A_4.The first zone expands from the starting point of the test to the point at which the fabric touches the inside wall of the conical part of the funnel. This zone represents a simple case of lifting a flat rounded sample off the base. The area under the curve of this zone, A_1, primarily reflects the work done to lift the sample (mainly a function of fabric weight and the vertical distance, h, to the touch point). However, the shape of the curve at this zone was found to reflect the extent of uniformity of sample drape behavior. In most cases, a smooth initial rise of this zone curve was witnessed. However, fabrics that exhibited a great deal of unbalance or spirality were associated with clear irregularity in the initial curve.



3.3 El Mogahzy–Kilinc fabric hand profile.

The second zone of the handle profile begins at the moment the fabric touches the inside wall of the conical part of the funnel and ends at the point of maximum handle resistance (point A). It reflects a combination of stretching, compression, shear, bending stiffness, and fabric inter-fold friction. The maximum resistance (point A) and the slope, θ_0, can be interpreted in a similar fashion to that used for the maximum handle peak and the handle modulus parameters considered in previous methods [13, 29]. In addition to these two parameters, we also considered the area under the curve of this zone, A_2. This area primarily reflects the work done to resist the constrained deflection and reconfiguration of the sample. Accordingly, this area is expected to be largely a function of a combination of stretching, compression, shear, bending stiffness, and fabric inter-fold friction.

The third zone of the handle profile begins at point A and ends at the point of tension trough (point B). The slope associated with the tension drop, θ_1, as well as the tension trough (point B) quantitatively characterizes the ease of reconfiguration, or fabric folding (alignment) flexibility. The area under the curve of this zone, A_3, primarily reflects the work done in reconfiguring and aligning the fabric sample under lateral deflection.

The fourth zone of the hand profile begins at point B and ends at the end of the test duration period. This zone is characterized by two parameters, the peak resistance of this zone, F_{max}, termed the 'friction peak', and the area under the zone curve, A_4. As indicated earlier, this zone entirely reflects a friction process determined by the internal lateral pressure created by pressing the sample inside the nozzle and the extent of pre-folding. A stiff and rough sample will result in high lateral pressure and high friction. A flexible and smooth sample will result in low lateral pressure and low friction. The progressively increasing tension in this zone is associated with the increase in the sample length entering the cylindrical zone. As was also indicated, this peak is typically smaller than the initial tension peak (point A). However, for samples of extremely high folding resistance (stiff and rough samples), it can indeed exceed the first peak. In this regard, the difference between the two peaks ($P_{max} - F_{max}$) is a useful parameter for characterizing the overall manipulability of fabric under a combination of constrained folding and rubbing action. In this regard, a positive difference would indicate a stiff but smooth fabric, and a negative difference would indicate a flexible but rough sample.

3.4.2 Single fabric hand index

As indicated above, the hand profile reflects most possible deformational modes involved in a hand trial. In addition, each zone of the profile reflects a specific mechanism of fabric hand. This point is important particularly when an enhancement of a particular hand-related parameter is required in the process of fabric design. If the goal is to establish a single fabric hand index, the total area under the El Mogahzy–Kilinc hand profile will provide an excellent quantitative parameter. This parameter is termed the 'Objective Total Hand', or OTH, and it is the sum of the four areas discussed above.

Detailed studies in which this parameter was evaluated [25, 26] proved that it is highly correlated to subjective hand assessments of tens of woven and knit fabrics considered in these studies and it is highly related to the different objective parameters constituting fabric hand. Some of these results are presented below.

3.4.3 Some experimental results of fabric hand

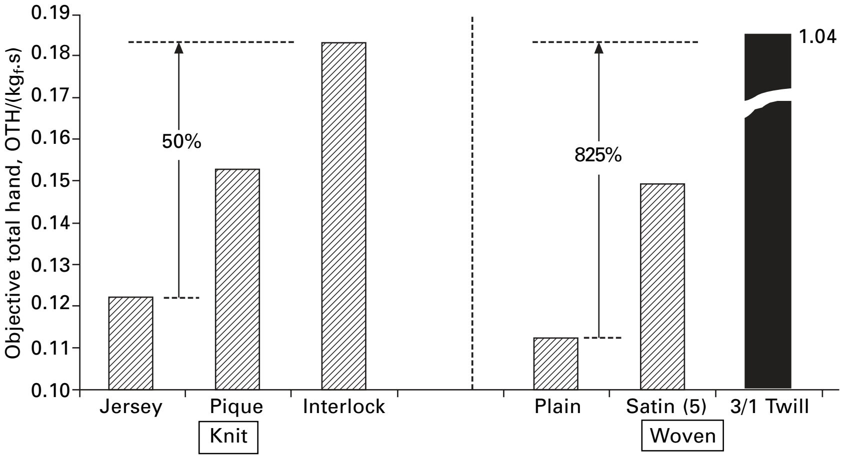
Merits of the hand test method discussed above were clearly realized from extensive testing of different fabrics. Some of the fabric types tested are listed in Table 3.1. These fabrics represent different fabric categories (woven and knit) and different patterns within each category. All fabrics were made from 100% cotton fibers.

Table 3.1 Average values of mechanical tactile parameters

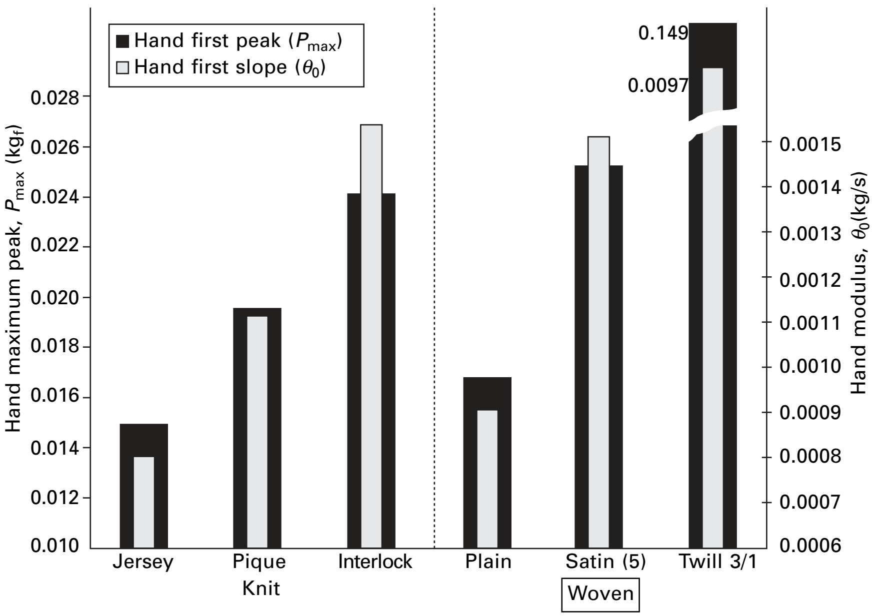
Fabric type	N_e (length-wise)	N_e (width-wise)	Thread count (length-wise)	Thread count (width-wise)	Fabric thickness (mm)	Fabric weight (g/m^2)
Plain	35	34	76	66	0.3048	104
Satin (5)	45	44	144	74	0.3302	124
3/1 Twill	7	20	79	65	0.705	290
Jersey	27	27	33	46	0.6215	157
Interlock	44	44	41	40	0.9400	177
Pique	26.5	26.5	26	40	0.793	193

Figures 3.4 and 3.5 show average values of some of the hand parameters described above for the different fabrics of Table 3.1. Among the woven fabrics, the twill fabric, which was made for durable heavy denim, exhibited the highest Objective Total Hand (OTH), the highest maximum peak, and the highest hand modulus. The plain weave, which represents lightweight dress shirt, exhibited the lowest OTH, the lowest maximum peak, and the lowest hand modulus.

Figure 3.6 shows the hand profiles produced for these two fabrics. The hand profile of the plain weave was enlarged (in a separate figure) to illustrate the details of the profile, which were masked by the high magnitude of the twill fabric. As can be seen in Fig. 3.6, the twill weave fabric required substantially higher hand force and hand work at different zones of the profile than the plain weave fabric. In addition, it exhibited a much higher resistance to hand, as demonstrated by the different slopes of the profile, than the plain weave sample. The hand profile of the plain weave sample also showed a tendency to exhibit an early drop in the hand resistance as illustrated by the dotted circles shown in the graph. This early drop is typically



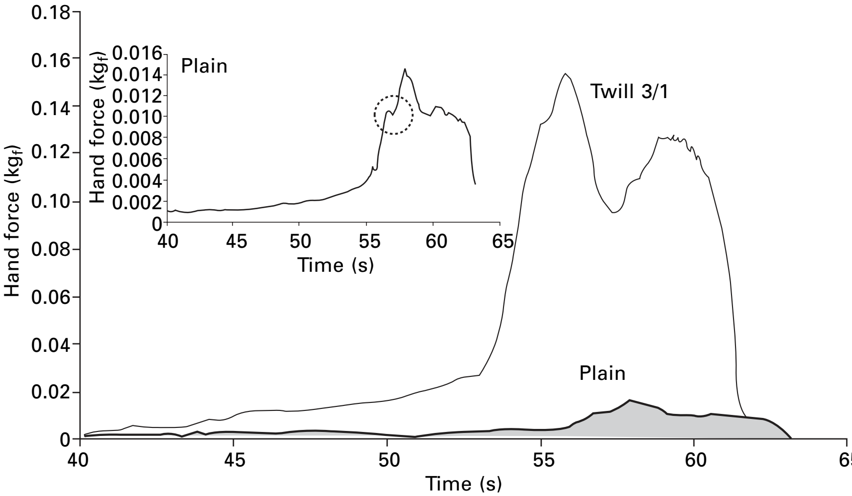
3.4 Objective total hand (OTH) of selected 100% cotton fabrics.



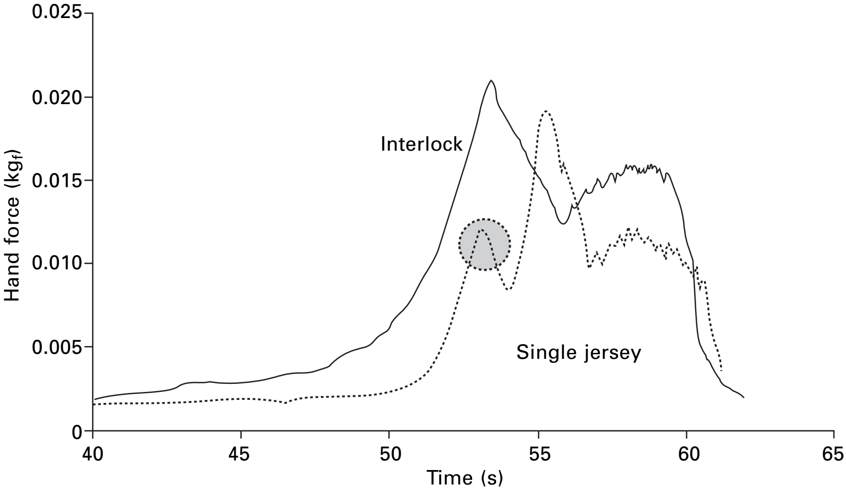
3.5 Hand peak and modulus of selected 100% cotton fabrics.

a result of a release in tension caused by some unfolding of the fabric at the transition stage from free folding to constrained folding.

Among the knit fabrics, Figs 3.4 and 3.5 clearly show that double-knit samples had higher total hand than the single-jersey sample. Figure 3.7 shows the hand profiles produced for the single-jersey and the interlock knit sample. As can be seen in this figure, the interlock double-knit sample required



3.6 Hand profiles of twill and plain weaves.

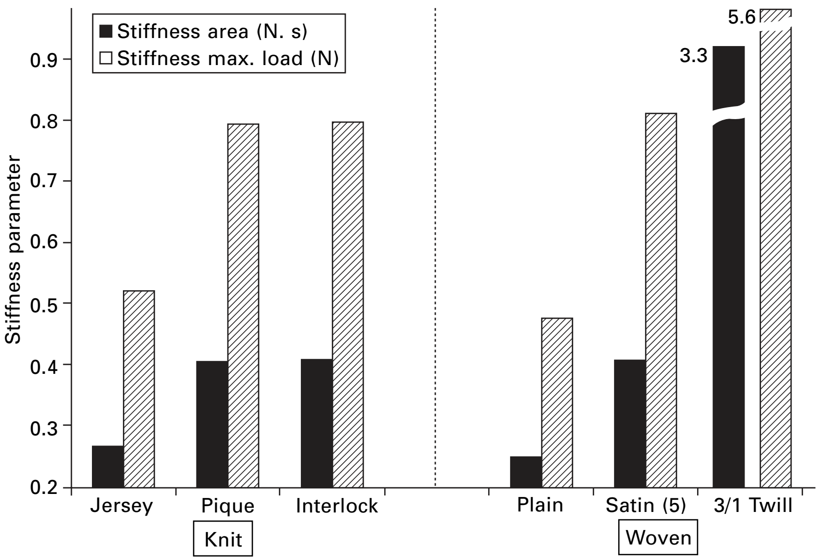


3.7 Hand profiles of jersey and interlock knits.

higher hand force and hand work at different zones of the profile than the single-jersey sample.

As indicated earlier, the El Mogahzy–Kilinc hand test method reflects most of the parameters constituting fabric hand. These include fabric stiffness, fabric drape, and fabric surface roughness. This point can be illustrated by examining the values of these parameters, tested independently, for the selected fabrics described in Table 3.1.

Figure 3.8 shows the values of fabric stiffness for these fabrics. Fabric



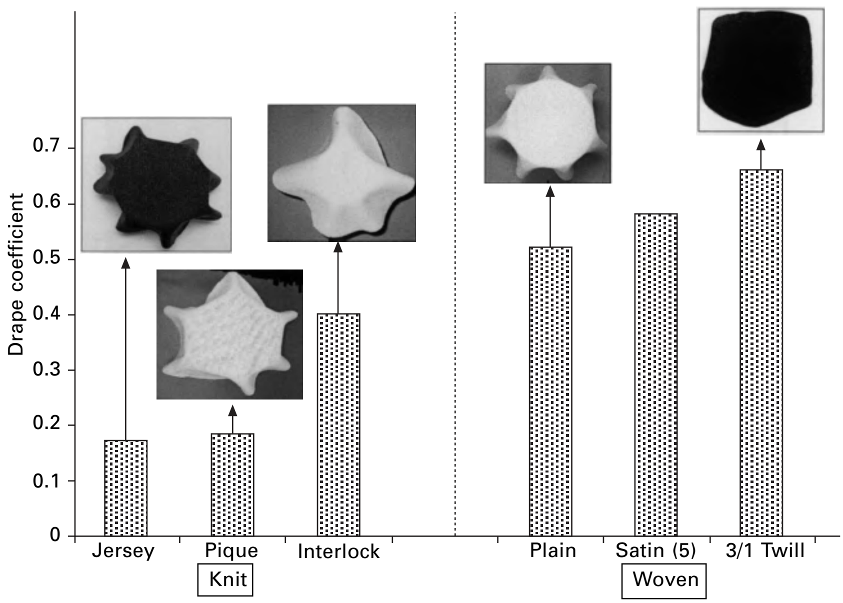
3.8 Stiffness area of selected 100% cotton fabrics.

stiffness was measured using ASTM D 4032–94 Standard Test Method for stiffness of fabric by the circular bend procedure. Additional effort was made to acquire the data during the test duration so that a stiffness profile can be obtained from which two basic measures can be determined: maximum stiffness load (newton), and the area (N.s) under the resistance force–time diagram (stiffness profile). These values reflect the ease of deformation under bending, which is a critical tactile comfort characteristic. This was made possible via the data acquisition program Labview.

As can be seen in Fig. 3.8, among the woven fabrics the twill weave sample exhibited the highest stiffness level and the plain weave sample exhibited the lowest stiffness. Among knit fabrics, the interlock double-knit sample had the highest stiffness and the single-jersey sample had the lowest. These results are in full agreement with the total hand results, the hand resistance values, and the hand modulus values of this set of fabrics.

Figure 3.9 shows the drape coefficient values of the same set of fabrics described in Table 3.1. As indicated earlier, drape is the term used to describe the way a fabric hangs down under its own weight in folds. It has an important bearing on how good a garment looks in use. In addition, it indicates the conformity of garments to body contours. In this study, we measured drape using the familiar BS5058 standard method in which drape is expressed by the so-called ‘drape coefficient’; the higher the drape coefficient, the lower the fabric drapability, or the lower the propensity to drape.

As can be seen in Fig. 3.9, knit fabric samples generally exhibited lower drape coefficients or higher propensity to drape than woven fabric samples.



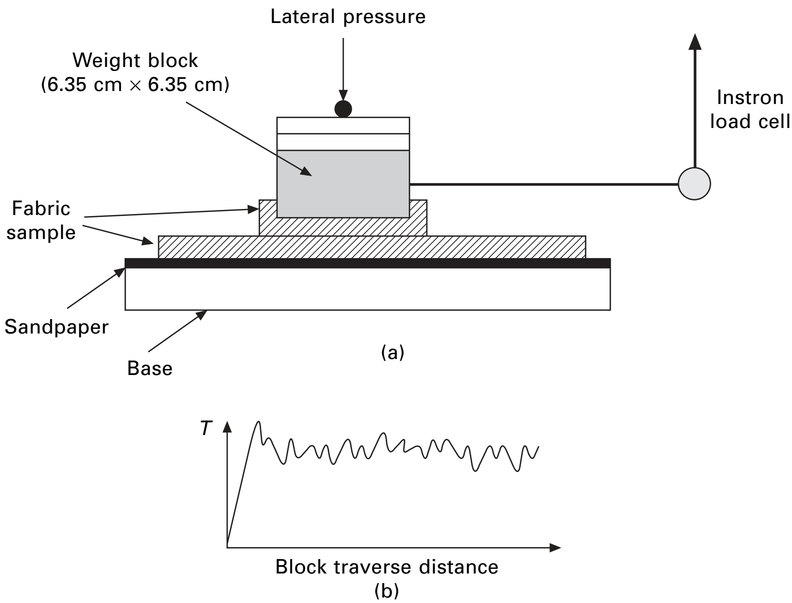
3.9 Drape coefficient of selected 100% cotton fabrics.

In general, it is well known that knitted fabrics are relatively floppy and garments made from them will tend to follow the body contours. Close examination of the values of drape coefficients of different fabrics will indicate a direct correspondence between these values and the initial area of the hand profiles.

Another important factor that contributes to the overall hand quality of fabric is surface roughness. This parameter was measured using geometrical surface image analysis and classic friction tests. In this chapter, we report the frictional results. Fabric friction was tested using the straightforward setup shown in Fig. 3.10 in which the apparent contact area is well defined. This method can be used for fabric-to-metal or fabric-to-fabric friction [25, 26].

The coefficient of friction, μ, was determined from the classical law of friction, $F_A = \mu \cdot P$ (where F_A is the frictional force per unit area, and P is the lateral pressure). This law typically assumes that the coefficient of friction, μ, is constant at all levels of lateral pressure and is independent of the area of contact. This assumption has been questioned in previous studies [e.g. 30, 31], and it was generally found to be inappropriate for materials deforming elastically or viscoelastically under lateral pressure. Fibers typically deform visco-elastically under lateral pressure. When the fibers are formed into fibrous structures or assemblies, the assumption of viscoelastic deformation should continue to hold as a result of the porous structure of fiber assemblies.

Many formulae have been developed to model the friction phenomenon



3.10 Sled friction method: (a) schematic of the friction device; (b) stick–slip profile.

of different materials. Gupta and El Mogahzy performed theoretical and experimental analyses aimed at evaluating different relationships between the frictional force F and the normal force N for fibrous materials [30, 31]. They concluded that the best expression that can characterize this relationship is:

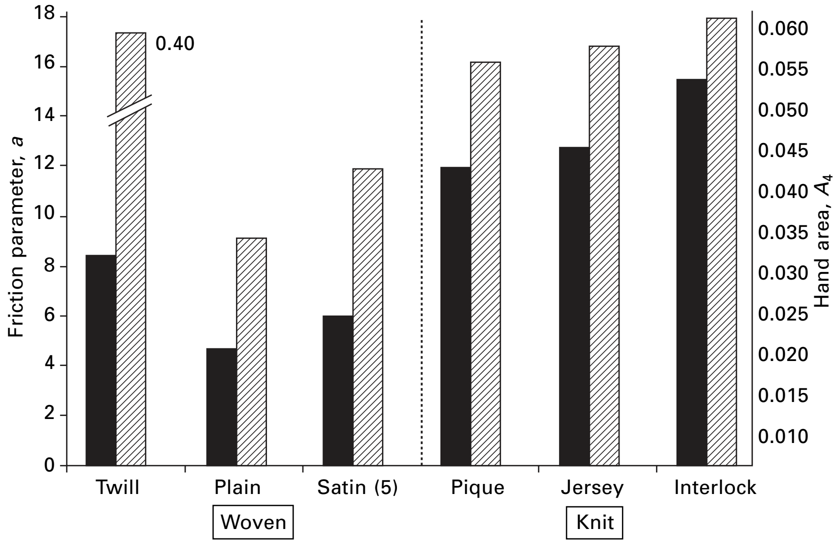
$$F_A = aP^n$$

The above relationship indicates that the frictional coefficient, defined by the ratio F/N, is not constant as suggested by the classic friction law. Instead, it is a function of the normal force, N, applied on the contacting area. This is revealed by the following equation:

$$\mu = \frac{F_A}{P} = aN^{n-1}$$

In this study, the parameters a and n were determined from the relationship between the coefficient of friction, as defined by the classical law ($\mu = F_A/P$), and the lateral pressure P.

Figure 3.11 illustrates the values of the friction parameter a and the hand area, A_4, for the different fabrics listed in Table 3.1. As can be seen in this figure, knit fabric samples generally exhibited higher a values (or higher friction) than woven fabric samples. The point of interest, however, is the relationship between the hand area A_4, which directly reflects the resistance



3.11 Fabric/sandpaper friction parameter *a* of selected 100% cotton fabrics.

to friction in the cylindrical nozzle zone, and the friction parameter *a*. This clearly indicates that the El Mogahzy–Kilinc hand test method is capable of detecting the mechanical hand effects associated with surface roughness.

We should point out that the El Mogahzy–Kilinc method has been used for evaluating fabrics of the same type under different treatments, including dyeing and finishing and washing treatments, and the results clearly showed its usefulness in design and performance enhancement applications [25, 26].

3.5 Conclusion

The phenomenon of fabric hand will continue to interest researchers in different sectors of the textile/apparel pipeline. The subjective nature of this important phenomenon will remain an essential aspect of research and implementation. This is primarily due to the critical importance of human judgment, which is highly variable and often psychologically driven. Unfortunately, subjective evaluation does not yield precise design guidelines except in extreme hand conditions. An objective hand evaluation coupled with subjective assessment seems to be the appropriate approach. In addition, a comprehensive database of hand parameters associated with human judgment scores will be very beneficial. We hope that this chapter will stimulate textile and apparel producers to establish a database of fabric hand of different products. Such a database will be extremely useful as we approach the era of complete Internet shopping in which little or no intimacy with fabrics will be involved in making purchasing decisions.

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4
Application of statistical methods in evaluation of fabric hand

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4.1 Introduction

The principles of textile production have been known for more than 6000 years. Over this long period manufacturing techniques have been optimized. However, the mechanisms affecting the psychophysical appearance of textiles leading to a pleasant feel during wearing are still not fully explained. One of the basic contact properties of textiles is 'hand'. The term 'hand' is difficult to define precisely. It relates to textile quality evaluation as one of the most important usability properties. It is possible to include hand among those subjective feelings evoked by measurable textile characteristics.

It is well known that hand plays an important role as the first characteristic encountered by the consumer. Evaluation is carried out by the consumer on the basis of his or her feeling of contact of the preceptors (fingers and palms) with the textile. With the development of new types of technologies and textile products, the objective characterization of hand becomes more important. The adoption of computer-oriented methods has led to the development of indirect but objective techniques for the prediction of subjective hand based on special regression models (multivariate calibration).

Multivariate calibration for subjective hand prediction is complicated, for the following reasons:

- Evaluation of subjective hand H_s is based on the categorization of respondent tactile sensation. The result is then an ordinal variable, and classical estimators of location (mean value) or variance cannot be directly used.
- Objective (measurable) properties (factors, regressors) connected with hand sensation $\boldsymbol{x} = (x_1, x_2, \ldots, x_m)$ are given in various scales and units. Their contribution to hand feeling is not direct but follows the stimulus response relation.
- Owing to strong interdependencies between regressors, regression-based models are often over-parameterized and the curse of multidimensionality appears.

- There are many methods for multivariate regression-type models predicting subjective hand based on assumptions about the characteristics of H_s. The classical least-squares method is frequently not optimal and more complex methods have to be used.

This chapter is devoted to a description of selected statistical methods capable of treating subjective hand data, checking the quality of potential regressors and creating prediction-type models. The techniques of univariate and multivariate data exploration are used for checking the assumptions about regressor (factor) distribution and dimension reduction.

The utilization of the well-known KES (Kawabata Evaluation System) for creation of regression-type models predicting the median subjective hand of protective fabrics is described. A set of properties correlated strongly with subjective hand is selected. A general methodology of subjective hand prediction based on mechanical and physical properties of textiles is proposed.

4.2 Subjective evaluation of fabric hand

Subjective hand is a result of the touching sensation and therefore is dependent on the mechanisms of human tactile sensation. The somatic senses are those nervous system mechanisms by which sensory information is collected from within the body. The somatic senses are classified in three groups:

1. Mechanoreceptors – stimulated by mechanical displacement of various tissues in the body.
2. Thermoreceptors – stimulated by temperature changes.
3. Nocioreceptors – representing the human pain sense.

The mechanoreceptors include the tactile sense, which includes touching pressure and vibration. The highest density of mechanoreceptors is in the glabrous skin on the palms and fingertips. Especially the thumb and index finger are used for tactile sensation.

Touch sensation results from stimulation of tactile sensors from the tissues immediately below the skin. The Meissner corpuscles and Merkels disks located in the upper layers of skin detect texture. These mechanoreceptors have spatial tactile stimulus. Hardness is identified by Pacinian corpuscles having temporal tactile stimulus. Light touch is detected by the free nerve endings having an amplitude of tactile stimulus [1]. Both these receptors are located deeper in the skin. Thermoreceptors are Rufini corpuscles, and receptors of coldness are Krause corpuscles.

Regarding tactile sensation there are rapidly reacting receptors (reaction time about a few hundred milliseconds) and two-phase reacting receptors (burst activity and then adaptation). The slowly adapting afferent receptors are Merkels disks and Rufini endings, and the rapidly adapting afferent receptors are Meissner and Pacinian corpuscles. The frequency range of these receptors is from 1 Hz (Merkels disks) to 500 Hz (Pacinian corpuscles).

Bolanowski [2] found that four distinct psychophysical channels contribute to tactation in the glabrous skin. From the sum of their complex responses humans can perceive and discriminate between textiles.

A detector's output R to a stimulus is a function of the product of its sensitivity S for that stimulus (the reciprocal of its threshold for the stimulus) and the stimulus intensity I [3]:

$$R = f\,(S \times I) \tag{4.1}$$

In the case of the transducer function, linearity gives $f = 1$ and $R = S \times I$.

The human observer's sensitivity to a stimulus is a nonlinear pooling of the sensitivities S_i of all detectors $i = 1, \ldots, m$:

$$S_{\text{ob}} = k\sqrt{\sum_{i=1}^{m} S_i^k} \tag{4.2}$$

For sensitivities S_i, the following is often valid:

$$S_i(x) = \exp\left(-\left(\frac{|x - x_i|}{K}\right)^Q\right) \tag{4.3}$$

where x_i is the best physical value for the ith detector and x is the physical value of the stimulus. Parameter K determines the bandwidth, and for a rounded sensitivity function, $Q = 3$.

It is then clear that subjective hand sensing is a combination of various receptors responsible for feelings of texture, pressure, stretching, thermal feedback, dynamic deformation and vibration (acceleration).

It has been empirically found that *subjectively evaluated hand* is connected especially with fabric surface, mechanical and thermal properties [4]. The first attempt at hand evaluation of textiles was published in 1926 [5]. Two basic procedures for subjective hand evaluation were proposed [6]:

1. The **Direct method** is based on the principle of sorting of individual textiles according to a subjectively defined ordinal grade scale (e.g., 0 – very poor, 1 – sufficient, 5 – very good, 6 – excellent).
2. The **comparative method** is based on sorting of textiles according to subjective criteria of evaluation (e.g., ordering from the textiles with the most pleasant hand to the textiles with the worst hand).

A wide range of expressions (words) is connected with the term hand, e.g., smooth, full, bulky, stiff, warm, cool, sharp, etc. These expressions are used for denoting *primary hand* (see below) [7]. For prediction of hand using any subjective method, it is necessary to solve the following problems [8]:

- Choice of respondents
- Choice of grade scale
- Definition of semantics.

Choice of respondents

The method of choice of respondents has a very strong influence on the data obtained and therefore also on the results of hand evaluation. It is obvious that subjective evaluation is based on the quality of the sensorial receptors of the individual respondents. Results of evaluation are also dependent on the physical and psychological state of the respondents and the state of the environment. Experts and consumers often give different results because of their different points of view concerning particular textiles. These problems show that it is very difficult to maintain reproducibility, and the choice of respondents has to be strongly defined. Significant differences exist between men and women, too. Men evaluate hand usually closer to the centre of the grade scale compared to women. A special problem is the size of the respondent group. The minimum size for expressing consumer feeling is 25–30 people, and for looking for relations with objective characteristics it is more than 200 people.

Choice of grade scale

If paired comparison is not applied, it is possible to choose the grade scale according to the actual criteria and needs. The size of the grade scale varies from five to 99. The 99-grade scale is more suitable for experts handling fabrics. For consumers, a grade scale length from 5 to 11 is preferred as they have less sensitivity to very small differences. The five-grade Likert scale (categories: strongly unfavourable, unfavourable, neutral, favourable, strongly favourable) is widely used. Generally, the neighbourhood of the grade scale centre is more frequently used than the neighbourhoods of the scale ends.

Definition of semantics

Evaluation of total hand is not sufficient when more precise results are required. Then, it is suitable to introduce primary hand values. Primary hand values are connected with surface, thermal and geometric properties. The following polar pairs are very often used for expressing primary hand values:

- Rough–smooth
- Stiff–flexible
- Open–compact
- Cold–warm.

Paired comparison of several samples is often carried out and then the ranks are obtained. This method is highly suitable for statistical data processing, but is valid only for small sets of textiles.

Influence of surface appearance on subjective judgements

During subjective hand evaluation, visual inspection of samples can influence the final decision. In this section, unpublished findings obtained from evaluation of subjective hand with and without 'visual inspection' are presented. Twenty-eight fabrics for men's suiting were chosen for subjective appearance evaluation and subjective hand evaluation with and without visual inspection. To achieve reproducibility of hand evaluation, two groups of respondents were selected, the first of 92 respondents and the second of 160. The ratio of ages of respondents, and the ratio of men to women, were similar in the two groups.

Consumers were used as respondents. Each of them was precisely informed about what and how to judge. The second group carried out evaluation of hand without visual inspection and appearance evaluation as well. The second group judged one year after the first. The first group rated their findings on a five-grade scale and the second group on an 11-grade scale. For comparison between judgements, Spearman's rank correlation coefficient was applied. The correlation between results of both groups was high (Spearman's rank correlation coefficient was 0.89). It can be said that, if respondents are well informed, it is possible to achieve reproducibility. On other hand, the five-grade scale is less sensitive to differences in judgement and this lower sensitivity leads to a higher loss of information. Correlation between the two types of subjective hand evaluation (with and without visual inspection) was also high (Spearman's rank correlation coefficient was 0.98), indicating that the well-informed respondent is able to restrain visual perception even though the majority of the respondents remarked on its influence through pattern (colour of textile). The correlation between hand and appearance was weaker (Spearman's rank correlation coefficient was 0.52 with visual inspection and 0.47 without). The results indicate that for well-prepared respondents, it is possible to ensure reproducibility of data concerning hand evaluation. Hand can be judged with visual inspection by well-informed respondents.

4.2.1 Statistical analysis of overall subjective hand

In this section the statistical treatment of subjective hand judgements, based on the ordinal nature of data, is discussed [9, 10]. This approach is used for overall subjective hand judgements. There is no problem in using this methodology for primary hand values as well. Generally, for the case of a categorized variable, the population of all events is divided into the categories $c_1, \ldots, c_k$. A special case of the categorized variable is the ordinal variable

[10]. For the ordinal variable, the categories $c_1, \ldots, c_k$ are sorted according to the external criterion (hand). It is assumed that the first category is the worst and the last category is the best, i.e. the category c_{i+1} is better than c_i for all $i = 1, \ldots, k$.

Let a fabric hand H_S be subjectively evaluated by N respondents (judges, raters). Each respondent R_i selects one from the k categories $c_1, \ldots, c_k$. Primary data can then be collected in an $N \times 1$ table containing numbers from 1 to k only. For M fabrics the primary table is $N \times M$. Primary data for subjective hand of TAMA and GOLEM fabrics ($M = 2$) graded to the five categories by 10 selected respondents ($N = 10$) are given in Table 4.1 [11]. This table is extracted from the primary table obtained from 30 respondents. For simplicity, it is used subsequently in this chapter to demonstrate the computations.

Table 4.1 Primary data for subjective hand grading of two fabrics by 10 respondents

Fabric	Respondent									
	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
TAMA	3	3	2	4	2	2	2	3	5	5
GOLEM	3	5	4	5	4	2	3	3	3	4

Let n_i respondents select the ith category, c_i. From the primary data table it is then simple to create a table of absolute frequencies for all categories having the general form (see Table 4.2). It is clear that $\sum_i^k n_i = N$. Absolute frequencies for the TAMA fabric example are given in Table 4.3.

Table 4.2 Absolute frequencies

Category	c_1	c_2	...	c_i	c_k
Overall grading	n_1	n_2	...	n_i	n_k

Table 4.3 Absolute frequencies of TAMA fabric

Category	c_1	c_2	c_3	c_4	c_5
Overall grading	0	4	3	1	2

Subjective hand H_S as a categorized (ordinal) variable can be modelled by the multinomial distribution $H_S \sim \text{Mult}(N, \boldsymbol{p})$ represented by the probability function [12]:

$$f(H_S, N, \boldsymbol{p}) = \frac{N!}{\prod_i n_i!} \times \prod_{i=1}^{k} p_i^{n_i} \tag{4.4}$$

The probability p_i is equal to the probability of selecting H_S to be in category c_i. For a full description of hand H_S, we need to know the vector of these probabilities, $\boldsymbol{p} = (p_1, p_2, \ldots, p_k)$. It is apparent that each category count n_i follows the binomial distribution $n_i \sim \text{bin}\,(N, p_i)$. Thus the expected value of the number of observations falling in the ith category is

$$E(n_i) = N \times p_i \tag{4.5}$$

while the variance is

$$V\,(n_i) = N \times p_i \times (1 - p_i) \tag{4.6}$$

Since the counts n_i must sum to N, they are negatively correlated with one another, and the correlation coefficient is given by

$$\text{corr}(n_i, n_j) = -\sqrt{\frac{p_i \times p_j}{(1 - p_i) \times (1 - p_j)}} \tag{4.7}$$

The estimators of p_i can be obtained by the maximization of the log likelihood function $L(\boldsymbol{p})$ which is simply equal to log $(f\,(H_S, N, \boldsymbol{p})$. [12, 13].

The maximum likelihood estimator of the probability of hand H_S falling in the ith category is the well-known frequency estimator

$$f_i = n_i/N \tag{4.8}$$

The approximate $100(1 - \alpha)\%$ confidence interval for p_i (sometimes called the Wald interval) is

$$f_i \pm u_{1-\alpha/2}\sqrt{f_i(1 - f_i)/N} \tag{4.9}$$

In this equation, $u_{1-\alpha/2}$ is the $(1 - \alpha/2)$ 100%th quantile of the standardized normal distribution. In most cases the 95% confidence intervals are created and then $\alpha = 0.05$, $(1 - \alpha/2) = 0.975$ and $u_{1-\alpha/2} = 1.98 \sim 2$.

A better confidence interval for the probability p_i based on the central limit theorem [1] has the form

$$f_i\left(\frac{N}{N + Z^2}\right) + 0.5\left(\frac{Z^2}{N + Z^2}\right) \pm \sqrt{\frac{f_i(1 - f_i)}{N} \times \frac{N^2 Z^2}{(N + Z^2)^2} + 0.25\left[\frac{Z^4}{(N + Z^2)^2}\right]} \tag{4.10}$$

where $Z = u_{1-\alpha/2}$. Because the categories are ordered from the worst (c_1) to the best (c_k), it is possible to define cumulative probabilities

$$C_i = \sum_{j=1}^{i} p_i \qquad C_1 = p_1 \qquad C_k = 1 \tag{4.11}$$

Estimates of these probabilities are the cumulative frequencies F_i defined by the relations

$$F_i = \sum_{j=1}^{i} f_i \qquad F_1 = f_1 \qquad F_k = 1 \tag{4.12}$$

The value C_i denotes the probability of subjective hand H_S occurrence in all categories up to the ith. The estimators f_i and F_i for the TAMA fabric are given in Table 4.4.

Table 4.4 Frequencies and cumulative frequencies for TAMA fabric

Category	c_1	c_2	c_3	c_4	c_5
f_i	0	0.4	0.3	0.1	0.2
F_i	0	0.4	0.7	0.8	1
S_i	1	2	3	4	5
R_i	0	0.2	0.55	0.75	0.9

Due to the ordinal character of the data, it is not possible to use standard characteristics of location such as mean value and scale as variance, because of the absence of the metric. It is not possible to say that the difference between the best and the worst is a number, $k - 1$, or that the difference between adjacent categories is 1. Numbers in Table 4.1 are symbols only and can be simply replaced, e.g. by letters. The problem is that probably the majority of the published work dealing with subjective hand avoids this fact and uses standard analysis, as in the case of cardinal continuous variables.

Because of the way the cumulative probability function is constructed, it is possible to use as a location estimator the **median** Mh defined as the 50% dividing point, so that 50% of H_S values are below Mh and 50% of values are above Mh. First, the median category Me is defined by inequalities

$$F_{\mathrm{Me}-1} < 0.5 \text{ and } F_{\mathrm{Me}} \geq 0.5 \tag{4.13}$$

The sample-rating median of the ordinal variable has the form

$$\mathrm{Mh} = \mathrm{Me} + 0.5 - \frac{F_{\mathrm{Me}} - 0.5}{f_{\mathrm{Me}}} \tag{4.14}$$

For characterization of mean hand grade, the sample rating median *Mh* is suitable. The characteristic Mh is an estimator of the population-rating median Med.

Subjective hand variance can be characterized by the **discrete ordinal variance**, dorvar, defined as [10]

$$\text{dorvar} = 2\sum_{l=1}^{k}[F_l(1 - F_l)] \tag{4.15}$$

The maximum value of dorvar is k – 1)/2 for the case when one half of the values are equal to 1 and the other half to k.

For practical purposes it is necessary to know the confidence interval for the population median estimator Med. In order to obtain the 100(1 – α)% confidence interval for Med, the following procedure was proposed [10]:

1. Computation of two cumulative frequencies (F_D^*, F_H^*):

$$(F_D^*, F_H^*) = 0.5 + 0.5\left(\frac{u_{1-\alpha/2}}{\sqrt{N}}\right) \tag{4.16}$$

2. Evaluation of categories D and H containing cumulative frequencies (F_D^*, F_H^*). For these categories it has to be valid that

$$F_{D-1} < F_D^* \quad F_D \geq F_D^* \quad \text{and} \quad F_{H-1} < F_H^* \quad F_H \geq F_H^*$$

3. Computation of correction terms:

$$d = \frac{F_D^* - F_{D-1}}{f_D} \qquad h = \frac{F_H^* - F_{H-1}}{f_H} \tag{4.17}$$

4. Creation of 100(1 – α)% confidence interval for Med (D – 0.5 + d, H – 0.5 + h).

This simplified procedure is applicable for the case when $N > 30$.

As an example of the use of this approach to characterize subjective hand, let us compute the median Mh and corresponding confidence interval for the TAMA fabric. It can be seen from Table 4.3 that the median category is equal to Me = 3 (category c_3). Substituting this in eqn. (4.14) leads to the following result:

$$\text{Mh} = 3 + 0.5 - \frac{0.7 - 0.5}{0.3} = 2.83$$

The value of dorvar = 1.22 is computed directly from eqn. (4.15). For the case of the 95% confidence interval and 10 respondents, cumulative frequencies (F_D^*, F_H^*) computed from eqn. (4.16) are equal to (0.1837, 0.8162). The corresponding categories are $D = 2$ and $H = 5$. Substitution eqn. (4.17) leads to correction factors $d = 0.4592$ and $h = 0.081$. Then the 95% confidence interval for the median is bounded by values (1.959, 4.581). Owing to the very small number of respondents this interval is very wide.

The proposed confidence interval can be simply used for *testing the hypotheses* about the statistical significance of subjective hand differences between fabrics. If the 95% confidence intervals of the grading median for two fabrics do not intersect, there is a significant difference in subjective hand grading.

For prediction of subjective hand from indirect measurements, it is possible to use a properly scaled median Mh in the interval (0, 1) i.e. Mp = Mh/k, directly. The second possibility is to use experimentally determined absolute frequencies n_i, $i = 1, \ldots, k$, directly. In the latter case there are problems with non-constant variance and mutual correlations. To avoid these problems, some non-linear transformations are often proposed. The so-called **arcsin transform** has the form

$$y_i = \arcsin\left(\sqrt{\frac{n_i}{N+1}}\right) + \arcsin\left(\sqrt{\frac{n_i+1}{N+1}}\right) \tag{4.18}$$

For higher N, the transformed variable y_i is approximately normally distributed with variance

$$D(y_i) = \frac{1}{N+0.5} \tag{4.19}$$

The empirical **logit transform** has the form

$$y_i = \ln\left(\frac{n_i + 0.5}{N - n_i + 0.5}\right) \tag{4.20}$$

The transformed variable y_i has estimator of variance

$$D(y_i) = \frac{(N+1)(n_i+1)}{N(n_i+1)(N-n_i+1)} \tag{4.21}$$

Some transformations are useful for conversion of categorical responses to numerical ones with the aim of converting a problem with ordinal data to a simpler problem with categorized cardinal data. The simplest possibility is to score the categories as the natural integers 1, 2, 3, …, k or a more suitable monotonic transformation of them. Yates [14] suggested the score for the ith category in the form

$$S_i = (2i - k - 1)/2 \quad i = 1, \ldots, k \tag{4.22}$$

The variable S_i is assumed to be continuous in the interval [(–(k – 1)/2, (k – 1)/2]. In some cases it is useful to use monotonic transformation in the interval (0, 1).

Scores are continuous representative values for categories, and the corresponding weights are f_i. Therefore the classical parametric procedures can be used. For example, the mean is equal to [15]

$$x_S = \sum_{j=1}^{k} S_j f_j \tag{4.23}$$

and the standard deviation is

$$S_S = \sqrt{\sum_{j=1}^{k} f_j S_j^2 - x_S^2} \tag{4.24}$$

The 100(1 – α)% confidence interval of the population mean is given by the well-known relation [15]

$$x_S \pm u_{1-\alpha/2} \times \frac{S_S}{\sqrt{N}} \tag{4.25}$$

where $u_{1-\alpha/2}$ is the quantile of standardized normal distribution as expressed before. For the TAMA fabric, natural scores and ridits (see below) are given in Table 4.4. The mean value is x_S = 3.1, the standard deviation is s_S = 1.1358, and the 95% confidence interval has bounds (2.381, 3.818). This interval is narrower than the interval for the grading median. Besides the fact that cardinalization by specifying scores is useful for some purposes, the narrower interval leads to avoiding the nature of categories and often offers too rough estimators. On the other hand, it is possible to use analysis of variance (ANOVA) and regression analysis in a very straightforward manner [14].

The very popular **ridit transformation** is defined as

$$R_i = F_{i-1} + 0.5f_i \tag{4.26}$$

For higher N, the transformed variable R_i is approximately normally distributed. **Ridits** are continuous variables defined in the interval (0, 1). Ridits are applicable to the situation when the goal is to compare a reference group with a treated group (e.g. finished and greige fabrics) [16].

It has been proved [17] that applying parametric procedures to ordered categorical data scored by the natural numbers is nothing more than using the ridit approach with the uniform distribution as a reference distribution.

The shifted version of the ridit transformation is the so-called **pridit** and is defined as

$$\mathrm{PR}_i = \sum_{j<i} f_j - \sum_{j>i} f_j \tag{4.27}$$

Pridits are continuous in the interval (–1, 1).

4.2.2 Evaluation of expert ratings quality

Quality of respondents (observers) is a key assumption for subjective hand evaluation. In practice there exist many techniques to facilitate subjective hand rating. One of the best is to use standards for each category and compare an unknown fabric with these standards. The aim of statistical analysis is to compare inter-respondent agreement [18]. Let us have, for simplicity, only two respondents. In this case the primary data in the form of an $M \times 2$ table contains numbers from 1 to k. Assume that the fabrics are randomly selected from the huge population of fabrics targeted for the same utilization area. For further treatment this table is converted to a $k \times k$ contingency table. In case of $k = 3$ categories the contingency table is shown in Table 4.5. Let A_i be a situation when respondent A selected category i and B_j be a situation when respondent B selected category j. The absolute frequency n_{ij} is equal to the number of cases when respondent A classified some fabrics in category i and respondent B classified the same fabrics in category j. The corresponding probability p_{ij} is estimated as the relative frequency f_{ij} defined as $f_{ij} = n_{ij}/n_c$.

Table 4.5 Contingency table for two respondents and three categories

	B_1	B_2	B_3	Subtotal
A_1	n_{11}	n_{12}	n_{13}	n_{r1}
A_2	n_{21}	n_{22}	n_{23}	n_{r2}
A_3	n_{31}	n_{32}	n_{33}	n_{r3}
Subtotal	n_{s1}	n_{s2}	n_{s3}	n_c

The symbol n_{ri} denotes the number of cases when respondent A classified fabrics in the selected category i and n_{sj} is the number of cases when respondent B classified fabrics in category j. The corresponding marginal probabilities are p_{ri} and p_{sj} estimated as relative frequencies $f_{ri} = n_{ri}/n_c$ and $f_{sj} = n_{sj}/n_c$. The value of n_c is equal to number of fabrics M. In addition to these probabilities, the so-called conditional probabilities can be computed as well. For example, the probability that respondent B classified a fabric in category j under the condition that respondent A classified the fabric in category i is $p_{j/i}$ estimated as $f_{j/i} = n_{ij}/n_{ri}$. From the elements of probability it is known that respondent A is independent of respondent B (total disagreement) in cases when:

- Conditional probabilities $p_{j/i}$ are independent of the conditions (i), i.e.

$$p_{j/i} = p_{j/l} \qquad i, l = 1, \ldots, k$$

- Conditional probabilities $p_{j/i}$ are equal to marginal probabilities: $p_{j/i} = p_{s/j}$
- The 'joint' probabilities p_{ij} are the products of marginal probabilities: $p_{ij} = p_{ri} p_{sj}$.

For practical purposes it is better to characterize agreement between raters as the degree of overall satisfaction of classification. A simple way is to use suitable scores for all categories and then calculate the classical correlation coefficient. Let us assume that categories A_i have scores d_i ($d_i < d_{i+1}$) and categories B_j have scores e_i ($e_i < e_{i+1}$). Correlation between observers A and B is then expressed in the form [15]

$$r = \frac{\sum_{i,j} d_i e_j n_{ij} - \left(\sum_i d_i n_{ri}\right)\left(\sum_j e_j n_{sj}\right)}{\sqrt{\left(\sum_i d_i^2 n_{ri} - q_r^2\right)\left(\sum_j e_j^2 n_{sj} - q_s^2\right)}} \tag{4.28}$$

where $q_r = \left(\sum_i d_i n_{ri}\right) \Big/ n_c$ and $q_s = \left(\sum_j e_j n_{sj}\right) \Big/ n_c$.

The test statistic MH = $(n_c - 1)r^2$ has a $\chi^2(1)$ distribution. The MH is known as the Mantel-Haenzsel test statistic. It is possible to choose integers, i.e. $d_i = i$, $i = 1, \ldots, k$ and $e_j = j$, $j = 1, \ldots, k$, as suitable scores. Another possibility is ridits or the so-called midranks defined by the relations

$$d_i = \sum_{l<i} n_{rl} + (n_{ri} + 1)/2 \qquad e_j = \sum_{l<j} n_{sl} + (n_{sj} + 1)/2 \tag{4.29}$$

In the case of nominal categories (this is not valid for hand categories) the agreement between two respondents A and B characterized by the Cohen kappa coefficient K_e is defined as

$$K_e = \frac{P_o - P_e}{1 - P_e} \tag{4.30}$$

where $P_o = \sum_{j=1}^{k} f_{jj}$ and $P_e = \sum_{j=1}^{k} f_{rj} f_{sj}$. The justification for this coefficient is described in [19]. The range of K_e is $-\infty < K_e \le 1$. The smallest possible value of K_e is equal to K_s where

$$K_s = 1 - \frac{n_c}{n_c - \sum_i f_{ii}} \tag{4.31}$$

The value of K_e is equal to zero if the probability of agreement is identical to the expected probability for independent raters (the case of complete disagreement between respondents). The relation $K_c = 1$ is valid only if the probability of disagreement is equal to zero (the case of complete agreement between respondents). Asymptotic variance of the kappa coefficient is estimated by the following relation:

$$D(K_e) \approx \frac{A + B - C}{n_c (1 - P_e)^2} \tag{4.32}$$

where

$$A = \sum_{j=1}^{k} f_{jj} [1 - (f_{rj} + f_{sj})(1 - K_e)]^2$$

$$B = (1 - K_e)^2 \sum_i \sum_{j \neq i} f_{ij} (f_{si} + f_{rj})^2 \tag{4.33}$$

and

$$C = [K_e - P_e(1 - K_e)]^2 \tag{4.34}$$

The $100(1 - \alpha)\%$ confidence limit for Cohen's kappa coefficient population has the form

$$K_e \pm u_{1-\alpha/2}\sqrt{D(K_e)} \tag{4.35}$$

For ordinal variables as in the case of subjective hand evaluation, it is necessary to introduce weights w_{ij} to allow each (i, j) cell to be weighted according to the degree of agreement between the ith and jth categories. Assigning weights $0 \leq w_{ij} \leq 1$ and $w_{ii} = 1$, Cohen's weighted kappa K_w can be defined by the following relation:

$$K_w = \frac{P_o(w) - P_e(w)}{1 - P_e(w)} \tag{4.36}$$

where $P_o(w) = \sum_{i}^{k}\sum_{j=1}^{k} w_{ij} f_{ij}$ and $P_e(w) = \sum_{i=1}^{k}\sum_{j=1}^{k} w_{ij} f_{ri} f_{sj}$.

In the case of integer scores it is useful to select weights according to the scheme [20]:

$$w_{ij} = 1 - \frac{(i-j)^2}{(k-1)^2} \tag{4.37}$$

After substituting eqn. (4.37) into eqn. (4.36), the weighted kappa reduces to the following form:

$$K_w = 1 - \frac{\sum_{i}\sum_{j=1}^{k}(i-j)^2 n_{ij}}{(1/n_c)\sum_{i}\sum_{j} n_{ri}\, n_{sj}\,(i-j)^2} \tag{4.38}$$

This form of K_w is equivalent to the concordance correlation coefficient used to measure the agreement between two continuous variables. The following relation defines the variance of K_w:

$$D(K_w) \approx \frac{\sum_{i}\sum_{j} f_{ij}[w_{ij} - (w_{ri} + w_{sj})(1 - K_w)]^2 - [K_w - P_e(w)(1 - K_w)]^2}{n_c[1 - P_e(w)]^2} \tag{4.39}$$

where

$$w_{ri} = \sum_{j} f_{sj}\, w_{ij} \quad \text{and} \quad w_{sj} = \sum_{i} f_{ri}\, w_{ij} \tag{4.40}$$

The $100(1 - \alpha)\%$ confidence limit for Cohen's weighted kappa coefficient population has the form

$$K_w \pm u_{1-\alpha/2}\sqrt{D(K_w)} \tag{4.41}$$

The coefficients K_w can also be defined in the case of multiple respondents [19].

Danoch and McCloud [18, 20] proposed an alternative coefficient:

$$D = 1 - \frac{2}{k(k-1)} \sum_{j=1}^{k-1} \sum_{l=j+1}^{k} \frac{f_{jl}\, f_{lj}}{f_{jj}\, f_{ll}} \tag{4.42}$$

The relation $D = 1$ is valid if all pairs of categories are completely distinguishable (total agreement) and $D = 0$ is valid in the case of independence (total disagreement), i.e. $p_{jl} = p_{rj}p_{sl}$.

In practice it is interesting to know respondents' bias as well. Bias refers to the tendency of a respondent to make ratings generally higher or lower than those of other respondents. Respondent bias for the ith respondent can be assessed by calculating the mean rating B_{Ri} of a respondent for all fabrics. For computation of the mean value B_{Ri} it is simple to define scores S_j for each category and use eqns (4.23) and (4.24) where f_j corresponds to the relative frequency of the selection for subjective hand rating the jth category by the ith respondent. High or low B_{Ri} relative to mean rating of all respondents $B_R = \left(\sum_i B_{Ri}\right)\Big/N$ indicates positive or negative respondent bias. This task is formally equal to identification of outliers in the case of a univariate sample. The sample is here composed of values B_{Ri}, $i = 1, \ldots, N$. Because there are B_{Ri} mean values, it is possible to assume normality. There are many different techniques for identifying outliers when a normal distribution of data can be assumed. One of the simplest and most efficient methods seems to be Hoaglin's modification of inner bounds I_L^* and I_U^* defined by relations

$$I_L^* = B_{R0.25} - K_I(B_{R0.75} - B_{R0.25})$$
$$I_U^* = B_{R0.75} + K_1(B_{R0.75} - B_{R0.25}) \tag{4.43}$$

where $B_{R0.75}$ and $B_{R0.25}$ are upper and lower quartiles computed from sample B_{Ri}, $i = 1, \ldots, N$. The value of parameter K_1 is selected such that the probability $P(N, K_1)$ that no observation from a sample of size N will lie outside the modified inner bounds $[I_L^*, I_U^*]$ is sufficiently high, for example $P(N, K_1) = 0.95$.

For $P(N, K_1) = 0.95$ and $8 \le n \le 100$, the following equation for calculation of K_1 can be used:

$$K_1 \approx 2.25 - 3.6/n \tag{4.44}$$

All respondents corresponding to B_{Ri} lying outside the modified inner bounds $[I_L^*, I_U^*]$ are considered to be biased. Another simple possibility is to use the ANOVA (analysis of variance) approach [19].

4.3 Analysis of factors affecting fabric hand

The subjective hand H_S (characterized by, e.g., the median Mh) is connected with various objectively measurable fabric properties. Peirce [21] identified a number of simply measured fabric properties such as bending length, flexural rigidity, hardness and compressibility that correlated well with subjective hand. Several other researchers proposed fabric properties suitable for subjective hand prediction [22–28]. The most widely known system for prediction of fabric hand is the Kawabata Evaluation System (KES) [7]. Kawabata's methodology assumes that fabric hand is derived from a combination of primary sensory factors such as softness, stiffness and roughness. A second assumption in Kawabata's approach is that the ultimate judgement of the hand of a fabric is dependent on the specification of the end use area. The unique feature of Kawabata's devices lies in their ability to measure fabric mechanical properties at small strains and to characterize energy loss in mechanical deformation and recovery processes.

Kawabata Evaluation System (KES)

Kawabata proposed a concept of the hand based on these hypotheses:

- One judges the hand mainly by the feel, which comes from the mechanical properties of the fabric.
- Criteria of hand judgement are based on whether or not the fabric possesses suitable properties for its use as a clothing material.

The KES systems of instrumentation for measuring the fundamental mechanical properties of fabric and the regression-type model for prediction of subjective hand are described in [7].

The properties being measured are grouped into seven blocks as follows: tensile, bending, shearing, compression, surface, weight, and thickness. The characteristic values that represent the property of each group have been decided so that the number of characteristic values should be as small as possible, but enough for expressing the property of its block sufficiently. These characteristics are collected in Table 4.6.

Details of the measurement principles, sample preparation and prediction of subjective hand are collected in [7]. Utilization of all 16 regressors (Table 4.6) for subjective hand prediction is often not necessary. Work done at NCSU using the Kawabata Evaluation System confirmed that the translations between subjective hand and fabric properties, measured using the KES, must be customized. The researchers proposed simple linear regression models for specific categories of woven or knitted fabrics:

- *Sheeting* [26]
  $\text{Hand} = 2.51 + 4.34 \log \text{WT} - 1.15 \log \text{MMD} + 1.31 \log \text{SMD} - 2.68 \log \text{W}$

Table 4.6 Basic properties for hand prediction

Property	Symbols		Characteristic value	Unit
Tensile	LT	x_1	Linearity	–
	WT	x_2	Tensile energy	gf.cm/cm^2
	RT	x_3	Resilience	%
Bending	B	x_4	Bending rigidity	gf.cm^2/cm
	2HB	x_5	Hysteresis	gf.cm^2/cm
Shearing	G	x_6	Shear stiffness	gf/cm.degree
	2HG	x_7	Hysteresis at $\varnothing$ = 0.50	gf/cm
	2HG5	x_8	Hysteresis at $\varnothing$ = 50	gf/cm
Compression	LC	x_9	Linearity	–
	WC	x_{10}	Compressional energy	gf.cm/cm^2
	RC	x_{11}	Resilience	%
Surface	MIU	x_{12}	Coefficient of friction	–
	MMD	x_{13}	Mean deviation of MIU	–
	SMD	x_{14}	Geometrical roughness	μm
Weight	W	x_{15}	Weight per unit area[a]	mg/cm^2
Thickness	T	x_{16}	Thickness at 0.5 gf/cm^2	mm

[a]Expressed in g/m^2 in our prediction equations.

Multiple correlation coefficient $R^2 = 0.98$

- *Men's suiting* [27]
  Hand = 7.87 – 14.61 LC + 0.02 RT
  Multiple correlation coefficient $R^2 = 0.97$
- *Single knits* [28]
  Hand = –8.4 + 20.9 MIU + 3.4 log W
  Multiple correlation coefficient $R^2 = 0.95$
- *Double knits* [28]
  Hand = –5.3 + 5.2 log SMD – 4.2 log B
  Multiple correlation coefficient $R^2 = 0.99$

(All symbols are explained in Table 4.6.) Subjective hand can therefore be predicted using simple linear regression models that incorporate as few as two KES measurements of properties [26–28]. The main problem is to select a suitable form of regression model and use good criteria for model quality evaluation. Another commercially proposed apparatus for evaluation of special properties connected with subjective hand is FAST [29].

Standard methods of measurements

There exist some attempts to replace KES measurements by the standard measurements in the same range of deformation. One of these systems was described by Raheel and Liu [30]. In the work of Militký and Bajzík [31], the prediction of subjective hand was made from eight objectively measurable characteristics selected from four basic groups of properties corresponding to the hand sensorial centres.

1. Fabric **surface roughness** is characterized by:
   - Coefficient of static friction $f_s \equiv x_6$ (dimensionless).
2. **Deformability** is characterized by:
   - Shear resistivity $G \equiv x_1$ (N)
   - Initial tensile modulus $Y \equiv x_8$ (MPa)
   - Stiffness $T \equiv x_7 (10^{-7}\ \mathrm{N\ m^{-2}})$.
3. **Bulk behaviour** is expressed by:
   - Area weight $T \equiv x_7$ ($\mathrm{gm^{-2}}$)
   - Compressibility $S \equiv x_5$ (dimensionless)
   - Thickness $t \equiv x_4$ (mm).
4. The **thermal part** of hand is characterized by:
   - Warm/cool feeling coefficient $b \equiv x_3$ ($\mathrm{W\ m^{-1}K^{-1}}$).

Generally, it is possible to select numerous other properties $\mathbf{x}$ connected with subjective hand. Before making any predictive model, H_S = function ($\mathbf{x}$), it is necessary to solve the following tasks:

- Inspection of individual factors (regressors) x_i, $i = 1, \ldots, m$, of quality with an aim of avoiding problems with outliers and spurious distributions
- Exploration of all variables $\mathbf{x}$ with an aim of dimensionality reduction, clustering, etc.
- Selection of suitable stimulus – response transformation.

Typically, inputs are m variables measured on the n various fabrics arranged in a matrix:

$$\mathbf{X} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ . & . & \cdots & . \\ . & . & \cdots & . \\ . & . & \cdots & . \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix} \tag{4.45}$$

Each element of this matrix is often the result of some repeated measurements. To demonstrate some statistical techniques, the data obtained from KES for 30 protective fabrics are used. Details of fabric manufacture and primary data are reported in [32]. For univariate data the resilience x_3 is used.

4.3.1 Response stimulus transformation

The objective properties **x** connected with hand are in various units and their contributions to tactile sensation follow the psychophysical rules [3, 33, 34]. Let the **stimulus** intensity I be expressed by the value of the measured variable x, and the **response** R corresponds to the tactile sensation.

Fechner derived that the sensation magnitude differential dR is connected with stimuli level I and just noticeable difference dI:

$$\mathrm{d}R = c \times \frac{\mathrm{d}I}{I} \tag{4.46}$$

Integration of eqn. (4.46) between I_o (absolute threshold) and I yields the so-called 'massformel':

$$R = c \ln\left(\frac{I}{I_o}\right) \tag{4.47}$$

Equation (4.47) is known as the Weber–Fechner psychophysical law. A Weber-Fechner type logarithmic transformation has often been used for treatment of hand results and creation of predictive models [25, 35, 36].

Guilford proposed that dI is proportional to I raised to the power d [33]:

$$\mathrm{d}I = c \times I^d \tag{4.48}$$

For $d = 1$ the Guilford law reduces to the Weber–Fechner law, and for $d = 0.5$ the Fullerton–Cattel law results.

Norwich entropy theory of perception is based on the assumption that more intensive stimuli contain more information (psychophysical entropy E). Sensation R is directly proportional to entropy [33]:

$$R = kE = k \ln(1 + k_1/I^c) \tag{4.49}$$

An alternative way to derive eqn. (4.46) is based on Link's wave theory of sensation. According to this theory, perception of an external stimulus is originated at the body surface by the quantized action of sensory receptors. The Poisson process models this situation. The output of the Poisson process is a similarity transformation of the intensity of the stimulus [33].

Based on the experimental evidence, Stevens proposed the following power function:

$$R = kI^d \tag{4.50}$$

The exponent d varies from much smaller (e.g. $d = 0.33$ for eye) to much greater than unity (intensity of electric current delivered to finger). In the work of Elder *et al.* [37], the Harper Stevens model

$$\log R = (1/b) \log (a + b \log I) + c \tag{4.51}$$

was used for modelling the stiffness psychophysical scale.

It is clear that the majority of these relations show non-linear stimulus–response dependence. Based on these models, the variable x is often replaced by the logarithmic transformation ln x. As is shown in section 4.3.5, the logarithmic transformation is optimal for data measured under conditions of relative error constancy as well.

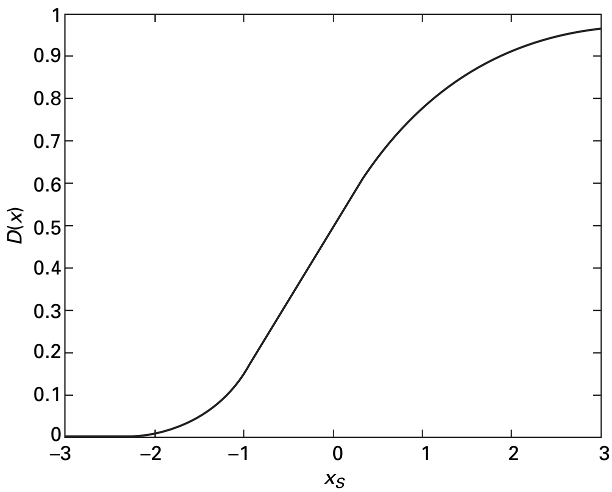
Instead of the stimulus-response relation an alternative possibility is to use the so-called concept of desirability proposed by Harrington [38]. For one-sided parameters, the Harrington function is defined by the relation

$$D(x) = \exp(-\exp(-x_S)) \tag{4.52}$$

where x_S is a properly scaled response of measurement x in physical units. One possibility is to use standardization:

$$x_S = \frac{x - \mathrm{mean}(x)}{\sqrt{\mathrm{variance}\ (x)}} + 0.3679 \tag{4.53}$$

The trace of the desirability function is given in Fig. 4.1. A better way is to use the knowledge about the just desirable and just undesirable values of x [38].



4.1 Harrington desirability function.

This concept is widely used in situations where it is necessary to combine various characteristics (properties) that have different units and different scales. The Harrington function allows converting physical parameters to the psychological scale of desirability. Desirability is defined in the range (0, 1) and corresponds to the interpretation given in Table 4.7.

The overall desirability function D for n properties is simply the weighted geometric mean of all $D(x_i)$:

Table 4.7 Harrington desirability interpretation

Desirability	Value on scale
Very good	1.0–0.8
Good	0.8–0.63
Fair	0.63–0.37
Poor	0.37–0.2
Very poor	0.2–0

$$D = \prod_{i=1}^{n} D(x_i)^{w_i} = \exp\left(\sum_{i=1}^{n} w_i \ln\left(D(x_i)\right)\right) \tag{4.54}$$

The desirability function D is a combination of all properties and is clearly defined in the interval (0, 1).

4.3.2 Utilization of fuzzy variables

Fuzzy theory has been frequently applied to subjective evaluation based on linguistic terms. The technique of fuzzy set theory introduced by Zadeh [39] is suitable for analysis of linguistic variables. The application of the fuzzy variables approach to rating and ranking of multiple alternatives is described in the work of Baas and Kwakernaak [40]. Rong and Slater [41] used a technique of fuzzy comprehensive evaluation for the assessment of comfort. Raheel and Liu published an application of fuzzy comprehensive evaluation to subjective hand evaluation [42] and prediction of hand from some objective characteristics [30]. Recently an application of fuzzy logic for evaluation and prediction of subjective hand was described by Zeng and Koehl [43]. The neural fuzzy technique for prediction of primary and total hand values was described by Stylios and Cheng [44].

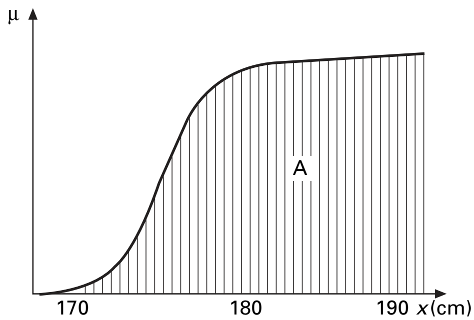
The main difference between the fuzzy approach and the probability approach to subjective hand evaluation based on the respondents' ratings lies in by the nature of primary data. The probability approach assumes that primary data are in fact ordinal random variables and statistical methods can be used for their treatment. The fuzzy approach is based on the concept of uncertainty, which is essentially not random but characterized by linguistic variables. Uncertainty is characterized by a membership function. Strictly speaking, the application of the fuzzy or probability approach is based on the technique of primary data retrieval. In the preceding paragraphs we used primary data H_S obtained from grading of subjective hand into prescribed categories. Typical data for fuzzy modelling are based on the degree of membership to some vague categories. In this paragraph, the main ideas of the fuzzy approach are described without giving details.

Fuzzy variables are characterized by numbers x_i and a membership function

μ_i defined in the interval $0 \le \mu_i \le 1$. This membership function describes the degree to which x_i belongs to a prescribed set (category). If a higher x_i is an indication of a higher degree of reaching the given category (e.g. the category of tall people) then the typical membership function is sigmoid and growing. An example of this function is shown in Fig. 4.2. It can be approximated by the empirical expression

$$\mu(x) = 1 - \exp\,(-|x - a|^2)/b^2 \tag{4.55}$$

where a and b are parameters describing the shape of the function. The general shape of the membership function for linguistic variables when excessively small and large values are indicated to be outside the given category can be simply approximated by a trapezoidal function. For linguistic variables there exist elementary logic operations such as logical summation, multiplication, etc.



4.2 Membership function for linguistic variable 'tall person'.

The model of fuzzy comprehensive evaluation is based on the grading level set $F_1, \ldots, F_M$ that is principally the same as for classical subjective hand evaluation. The second is a group of factors U (U_1, U_m) equivalent to properties connected with subjective hand. The core of fuzzy evaluation is the construction of the $(m \times k)$ membership matrix $\mathbf{R}$. The ith row R_i evaluates the contribution of factor i to the individual grading levels. Elements $R_{ij} = \mu(U_i, F_j)$ are membership functions of the contribution of factor i to the grading level F_j. For fuzzy comprehensive evaluation, for each factor it is necessary to define its relative importance characterized by the weight w_i, $i = 1, \ldots, m$. Let the weights be standardized, i.e. $w_i \ge 0$ and $\sum w_i = 1$. The fuzzy evaluation is then transformation from the weighting vector $\mathbf{w}$ to the comprehensive grading vector $\mathbf{b}$ by using the fuzzy transformation matrix R. The appropriate fuzzy transformation is in the form

$$b_j = \sum_{i=1}^{m} w_i R_{ij} \quad j = 1, \ldots, k \tag{4.56}$$

Raheel and Liu [30] used this approach to predict hand from five factors (mechanical properties), namely fabric weight, fabric thickness, flexural recovery, wrinkle recovery and 45° filling elongation. For each factor, the suitable membership function $\mu_i(x)$ has been selected. The hand value HV for the *j*th fabric was computed from the formula

$$\mathrm{HV}_j = \sum_{i=1}^{5} w_i \, \mu_i \, (x_{ij}) \tag{4.57}$$

where x_{ij} is the value of the *i*th factor for the *j*th fabric. Zeng and Koehl used a fuzzy controller to solve this task [43].

4.3.3 Exploration of univariate data quality

This chapter is devoted to exploration of individual variables potentially useful for prediction of subjective hand statistical peculiarities. Without loss of generality, the typical univariate sample x_i, $i = 1, \ldots, n$, is assumed. Here the index i corresponds to the individual fabric and then the sample corresponds to the *i*th column of the matrix shown in eqn. (4.45). The same approach can be used for treatment of data from repeated measurements on the same fabric. The differences between these tasks are given by the aim of analysis. For data from various fabrics, usability in the predictive regression model is the main goal. For repeated measurements, selection of the proper distribution for parameter estimation is needed. The system of exploratory data analysis based on the concept of quantile estimation can be used for both purposes [15].

From the classical statistical point of view, the analysis of measurement results leads to the identification of a probability model and the estimation of corresponding parameters. Due to the well-known fact that a lot of experimental data does not follow the normal distribution, the classical analysis based on the normality assumption cannot be automatically used. Frequently, textiles are strongly non-homogeneous and technological processes are influenced by many random events. The results of measurements are therefore often corrupted by the outliers (so-called dirty data). Techniques that allow isolating certain basic statistical features and patterns of data are collected under the name exploratory data analysis (EDA). According to Tukey [45], EDA is 'detective work'. It uses various descriptive and graphically oriented techniques as tools that are free of strict statistical assumptions. These techniques are based on the assumptions of the continuity and differentiability of underlying density only. The computationally assisted exploratory data analysis system is described in the book by Meloun *et al.* [15]. EDA techniques are one of the main parts of 'statistical methods mining', which is a collection of classical and modern parametric, non-parametric and function estimation methods for data treatment [46].

Some basic concepts

The EDA techniques for small and moderate samples are based on the so-called order statistics

$$x_{(1)} < x_{(2)} < \ldots < x_{(n)}$$

which are the sample values (assumed to be distinct) arranged in ascending order. Let $F_e(x)$ be the distribution function from which values x_i have been sampled. It is well known that the transformed random variable

$$z_{(i)} = F_e(x_{(i)}) \tag{4.58}$$

independently of the distribution function F_e follows the Beta distribution Be(i, $n - i + 1$). The corresponding mean value is

$$E(z_{(i)}) = \frac{i}{n+1} \tag{4.59}$$

where $E(.)$ is the operator of mathematical expectations. The elements V_{ij} of the covariance matrix $\boldsymbol{V}$ for all pairs $z_{(i)}$, $z_{(j)}$, i, $j = 1, \ldots, n$, are simple functions of i, j and N only. Using back transformations of $E(z_{(i)})$ the relation

$$E(x_{(i)}) = F_e^{-1}(z_{(i)}) = Q_e(P_i) \tag{4.60}$$

is obtained. In eqn. (4.60), $Q_e(P_i)$ denotes the quantile function and

$$P_i = \frac{i}{n+1} \tag{4.61}$$

is the cumulative probability.

Quantile function properties and their advantages for constructing empirical sample distributions are described in the papers of Parzen [46, 47]. From eqn. (4.60), it is obvious that the order statistic $x_{(i)}$ is a raw estimate of the quantile function $Q_e(P_i)$ in the position of P_i. For estimation of quantile $x_{(p)} = Q_e(P)$ at value $i/(n + 1) < P < (i + 1)/(n + 1)$ the piecewise linear interpolation

$$x_{(P)} = (n+1)\left(\frac{Pn + P - i}{n+1}\right)(x_{(i+1)} - x_{(i)}) + x_{(i)} \tag{4.62}$$

can be used. The interpolation (4.62) is useful for estimating sample quantiles x_{P_i} or x_{1-P_i} for $P_i = 2^{-i}$, $i = 1, \ldots, n$. These quantiles are called letter values [48]. All letter values except for $i = 1$ (median) are in pairs. For example, we can estimate lower quartile $x_{0.25}$ ($P_i = 0.25$) and upper quartile $x_{0.75}$ ($P_i = 0.75$), etc. Some proposals for definition of P_i are presented in Looney and Gulledge [49].

Checking of sample distribution

The most popular tool is the so-called quantile–quantile plot (Q–Q plot), having the quantiles $Q_s(P_i)$ along the x-axis and the order statistic $x_{(i)}$ along the y-axis.

Given a random sample, we often need to find whether the data can be regarded as a sample from a population with a given theoretical distribution. To look at the closeness of the sample distribution to a given theoretical distribution, the quantile–quantile plot (Q–Q plot) is suitable. The Q–Q plot allows comparison of the sample distribution being described by the empirical $Q_E(P_i)$ quantile function with the given theoretical one, with the theoretical $Q_T(P_i)$ quantile function. The empirical Q_E function is approximated by the sample order statistic $x_{(i)}$. If there is a close agreement between the sample and theoretical distributions, it must be true that

$$x_{(i)} \sim Q_T(P_i)$$

where P_i is the cumulative probability defined by eqn. (4.61).

When the empirical sample distribution is the same as the theoretical one, a straight line represents the resulting Q–Q plot. To construct this plot, the parameters of location and spread of the theoretical distribution (or their estimates) must be known. For many theoretical distributions, the standardized variable S may be used:

$$S = (x - Q)/R \tag{4.63}$$

where Q stands for a parameter of location or threshold and R for a parameter of spread. The standardized (theoretical) quantile function $Q_s(P_i)$ then contains only shape parameters (their magnitude may be systematically varied).

When there is agreement between the empirical sample and the theoretical distribution, the Q–Q plot is a straight line:

$$x_{(i)} = Q + R \times Q_s(P_i) \tag{4.64}$$

For selected theoretical distributions the x- and y-coordinates of the Q–Q graph are given in Table 4.8 [15]. The symbol $\Phi(s)$ defines the normal distribution function:

$$\Phi(s) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{s} \exp(-0.5 \times u^2)du$$

To calculate the inverse function $\Phi^{-1}(P_i)$, the following simple approximate expression may be used:

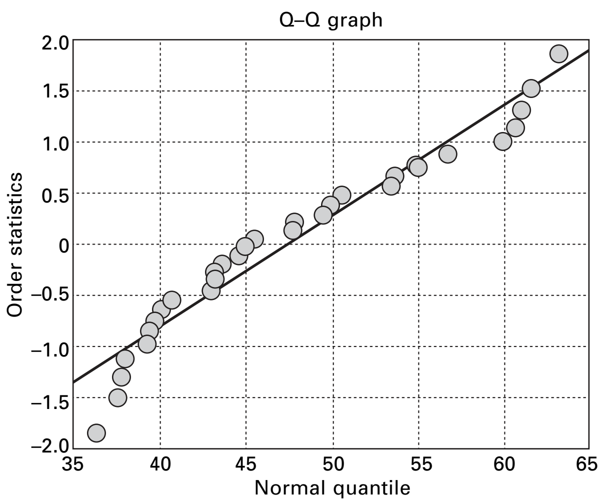
$$\Phi^{-1}(P_i) = u_{P_i} = \frac{-9.4\ln(1/P_i - 1)}{\text{abs}[\ln(1/P_i - 1)] + 14} \tag{4.65}$$

When it is desired to test whether a given random sample can be regarded as a sample from a normal (Gaussian) distribution, the resulting Q–Q plot is called the rankit plot or the normal probability plot (on the x-axis are the standardized normal quantile u_{P_i}). This plot enables classification of a sample

Table 4.8 Standardized frequency $f_T(s)$ and distribution functions $F_T(s)$ and corresponding coordinates (x, y) of the Q–Q plot

	Distribution			
	$F_T(s)$	$f_T(s)$	y	x
Rectangular	s	1	$x_{(i)}$	P_i
Exponential	$1 - \exp(-s)$	$\exp(s)$	$x_{(i)}$	$-\ln(1 - P_i)$
Normal	$\Phi(s)$	$(2\pi)^{-1/2}\exp(0.5s^2)$	$x_{(i)}$	$\Phi^{-1}(P_i)$
Laplace $x \leq Q$ for $P_i \leq 0.5$	$0.5\exp(s)$	$0.5\exp(s)$	$x_{(i)}$	$\ln(2P_i)$
Laplace $x > Q$ for $P_i > 0.5$	$0.5[2 - \exp(-s)]$	$0.5\exp(-s)$	$x_{(i)}$	$-\ln(2(1 - P_i))$
Log-normal	$\Phi[\ln(s)]$	$(2\pi)^{-1.2}\exp(-0.5\ln s^2)$	$x_{(i)}$	$\exp[\Phi^{-1}(P_i)]$

distribution according to its skewness, kurtosis and tail length. A convex or concave shape indicates a skewed sample distribution. A sigmoid shape indicates that the tail lengths of the sample distribution differ from those of the normal ones. The normal Q–Q plot for tensile resilience of 30 protective clothings [32] is given in Fig. 4.3. The moderate systematic deviation from normality is clearly visible.



4.3 Normal Q–Q plot for tensile resilience data of 30 protective clothings.

Data transformation

When exploratory data analysis proves that the sample distribution strongly differs from the normal one, we are faced with the problem of how to analyze the data. Raw data may require re-expression to produce an informative display, an effective summary, or a straightforward analysis. We may need to change not only the units in which the data are stated, but also the basic scale of the measurement. To change the shape of a data distribution, we must do more than change the origin and/or the unit of measurement. Changes of origin and scale mean linear transformations, and they do not change the shape. Non-linear transformations such as the logarithm and square root transformations are necessary to change shapes.

Data must be examined to find the proper transformation, which leads to symmetric distribution of data, stabilizes the variance, or makes the distribution closer to the normal. Such transformation of original data x to a new variable $y = g(x)$ is based on an assumption that the data represent a non-linear transformation of the normally distributed variable y, according to $x = g^{-1}(y)$.

Transformation for variance stabilization involves finding a transformation $y = g(x)$ in which the variance $\sigma^2(y)$ is a constant. If the variance of the original variable x is a function of type $\sigma^2(x) = f_1(x)$, the variance $\sigma^2(y)$ may be expressed by

$$\sigma^2(y) \approx \left(\frac{dg(x)}{dx}\right)^2 \times f_1(x) = C \tag{4.66}$$

where C is a constant. The variance stabilizing transformation $g(x)$ is the solution of the differential equation

$$g(x) \approx C \times \int \frac{dx}{\sqrt{f_1(x)}} \tag{4.67}$$

In some measuring devices, the relative standard deviation $\delta(x)$ (coefficient of variation) of the measured variable is a constant. This means that the variance $\sigma^2(x)$ is described by a function $\sigma^2(x) = f_1(x) = \delta^2(x) \times x^2 = \text{const} \times x^2$. Substitution of this into eqn. (4.67) leads to the logarithmic form $g(x) = \ln(x)$. Then the optimal form of transformation of these types of data is the logarithmic transformation. This transformation leads to the use of a geometric mean. When the dependence $\sigma^2(x) = f_1(x)$ is of a power nature, the optimal transformation will also be a power transformation. Since for a normal distribution the mean is not dependent on the variance, a transformation that stabilizes the variance makes the distribution closer to normal.

Transformation for symmetry is carried out by a simple power transformation [15]:

$$\begin{aligned} y &= g(x) = x^{\lambda} && \text{for parameter } \lambda > 0 \\ y &= g(x) = \ln(x) && \text{for parameter } \lambda = 0 \\ y &= g(x) = -x^{-\lambda} && \text{for parameter } \lambda < 0 \end{aligned} \tag{4.68}$$

which does not retain the scale, is not always continuous, and is suitable only for positive values of x. Optimal estimates of parameter λ are sought by minimizing the absolute values of particular characteristics of asymmetry. In addition to the classical estimate of skewness $g_1(y)$, the robust estimate $g_{1,R}(y)$ is used:

$$g_{1,R}(y) = \frac{(y_{0.75} - y_{0.5}) - (y_{0.5} - y_{0.25})}{y_{0.75} - y_{0.25}}$$

where $y_{0.25}$, $y_{0.5}$ and $y_{0.75}$ are the lower quantile, median and upper quantile respectively of the transformed data. The relative distance between the arithmetic mean y_a and the median $y_{0.5}$ may also be utilized, because for symmetrical distributions this is equal to zero.

The parameter λ may also be estimated from a rankit plot because for an optimal value of λ_o, the transformed quantiles $y_{(i)}$ will lie on the straight line.

An excellent diagnostic tool enabling estimation of parameter λ is represented by the Hines–Hines selection graph [50]. This graph has the ratio $x_{0.5}/x_{1-P_i}$, on the x-axis and the ratio $x_{P_i}/x_{0.5}$ on the y-axis. The Hines–Hines selection graph is based on an assumption of symmetry of individual quantiles around a median

$$\left(\frac{x_{P_i}}{x_{0.5}}\right)^{\lambda} + \left(\frac{x_{0.5}}{x_{1-P_i}}\right)^{-\lambda} = 2$$

where, for the cumulative probability $P_i = 2^{-i}$, the letter values F, E and D (i = 2, 3, 4) are usually chosen.

To compare the empirical dependence of the experimental points with the ideal one, patterns for various values of the parameter λ are drawn in a selection graph. These patterns represent a solution of the equation $y^{\lambda} + x^{-\lambda} = 2$ in the range $0 \le x \le 1$, $0 \le y \le 1$:

- For $\lambda = 0$ the solution is a straight line $y = x$
- For $\lambda \le 0$ the solution takes the form $y = (2 - x^{-\lambda})^{1/\lambda}$
- For $\lambda > 0$ the solution takes the form $x = (2 - y^{\lambda})^{-1/\lambda}$.

The estimate λ is guessed from a selection graph, according to the location of experimental points near to the various theoretical patterns.

Transformation to approximate normality can be achieved in many cases by use of the family of Box–Cox transformations defined as [51]

$$y = g(x) = \frac{(x^{\lambda} - 1)}{\lambda} \quad \text{for} \quad \lambda \neq 0$$

$$y = g(x) = \ln(x) \qquad \text{for } \lambda = 0 \tag{4.69}$$

where x is a positive variable and λ is real number. The Box–Cox transformation has the following properties [51]:

- The curves of transformation $g(x)$ are monotonic and continuous with respect to the parameter λ, because $\lim_{\lambda \to 0}(x^{\lambda} - 1)/\lambda = \ln(x)$. All transformation curves share one point $[y = 0, x = 1]$ for all values of λ. The curves nearly coincide at points close to [0, 1], that is, they share a common tangent line at that point.
- The power transformations with exponent –2, –3/2, –1, –1/2, 0, 1/2, 1, 3/2, 2 have equal spacing between curves in the family of Box–Cox transformation graphs.

The Box–Cox transformation defined by eqn. (4.69) can be applied only to positive data. To extend this transformation, x values are replaced by $(x - x_0)$ values, which are always positive. Here x_0 is the threshold value $x_0 < x_{(1)}$.

To estimate the parameter λ in the Box–Cox transformation, the method of maximum likelihood may be used, because for $\lambda_o = \lambda$, a distribution of the transformed variable y is considered to be normal, $N[\mu_y, \sigma^2(y)]$. The logarithm of the maximum likelihood function may be written as

$$\ln(L(\lambda)) = -\frac{n}{2}\ln(s^2(y)) + (\lambda - 1)\sum_{i=1}^{n}\ln(x_i) \tag{4.70}$$

where $s^2(y)$ is the sample variance of the transformed data y. The function $\ln L(\lambda) = f(\lambda)$ is expressed graphically for a suitable interval, for example $-3 \le \lambda \le 3$ (the log maximum likelihood plot). The maximum value on this curve represents the maximum likelihood estimate λ_o.

The asymptotic $100(1 - \alpha)\%$ confidence interval of the parameter λ is expressed by the following relation:

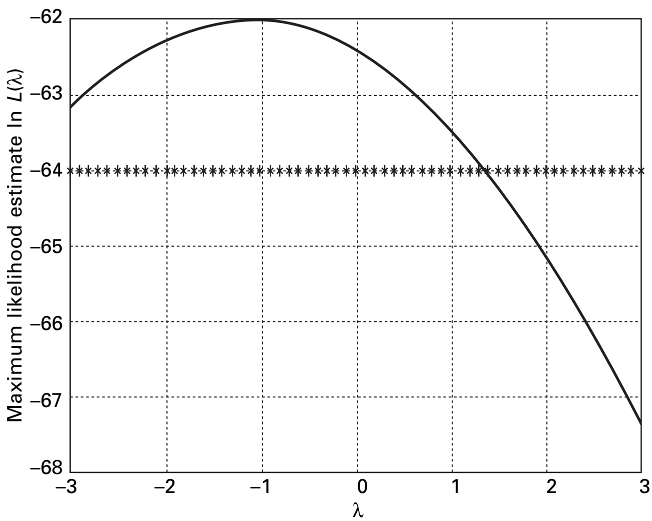
$$2[\ln(L(\lambda_o)) - \ln(L(\lambda))] \le \chi^2_{1-\alpha}(1) \tag{4.71}$$

where $\chi^2_{1-\alpha}(1)$ is the quantile of the χ^2 distribution with 1 degree of freedom. This interval contains all values λ for which it is true that:

$$\ln L(\lambda) \ge \ln L(\lambda_o) - 0.5\chi^2_{1-\alpha}(1) \tag{4.72}$$

The Box–Cox transformation is less suitable for wide confidence intervals. When the value $\lambda = 1$ is also covered by this confidence interval, the transformation is not efficient. The value of $\ln L(\lambda)$ as a function of λ in the range $-3 < \lambda < 3$ for tensile resilience of 30 protective clothings [32] is given in Fig. 4.4. The optimal value of λ is $\lambda_o = -1.08$, but the confidence interval covers value 0 and therefore the logarithmic transformation is acceptable as well. Due to this transformation skewness is reduced from 0.4519 to 0.070 and therefore the data are now symmetrically distributed.

After an appropriate transformation of the original data x, the transformed data gives an approximately normal symmetrical distribution with constant variance, and the statistical measures of location and spread for the transformed data (y) can be calculated. These include the sample arithmetic mean y_a the



4.4 Plot of ln $L(\lambda)$ as a function of λ for tensile resilience data of 30 protective clothings.

sample variance $s^2(y)$, and the confidence interval of the mean $y_a \pm t_{1-\alpha/2}(n-1)\, s(y)/\sqrt{n}$. These estimates must then be recalculated for the original data (x). Two different approaches for the re-expression of the statistics for the transformed data exist [15].

Rough re-expressions represent a single reverse transformation x_a, $R = g^{-1}(y)$. This re-expression for a simple power transformation leads to the general mean [15]

$$x_{a,R} = \left[\frac{\sum_{i=1}^{n} x_i^{\lambda}}{n}\right]^{1/\lambda} \quad \text{for } \lambda \neq 0 \quad \text{or}$$

$$x_{a,R} = \exp\left[\frac{\sum_{i=1}^{n} \ln(x_i)}{n}\right] \quad \text{for} \quad \lambda = 0 \tag{4.73}$$

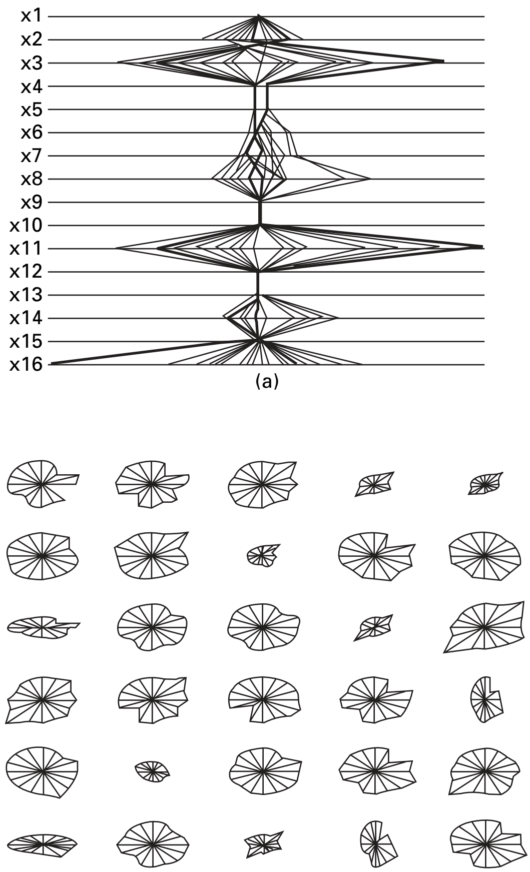
The re-expressed mean $x_{a,R} = x_{a,-1}$ stands for the harmonic mean, $x_{a,R} = x_{a,0}$ for the geometric mean, $x_{a,R} = x_{a,1}$ for the arithmetic mean and $x_{a,R} = x_{a,2}$ for the quadratic mean. More correct expressions based on the Taylor series expansion are presented in [15].

For the subsequent use of individual variables in regression models, transformation stabilizing variance is favourable. Especially, logarithmic transformation has a tendency to reduce the influence of gross errors and is often simple to apply to regression models.

4.3.4 Multivariate data exploration

Let the input data be given as the matrix defined by eqn. (4.45). The main aim of data exploration is investigation of outlying points or clusters of points and identification of various structures in data.

For graphical exploration, techniques based on symbols or scatter diagrams are used. Very simple representatives of symbol graphs are stars and profiles [52]. The profile and symbol graphs for 16 KES variables of 30 protective clothings are given in Fig. 4.5. Scatter graphs are represented by principal component (PC) graphs where original variables are replaced by latent variables with desired properties. PC graphs are useful in cases where the columns of matrix **X** in eqn. (4.45) are correlated. PCA is described in detail section in 4.3.5.



4.5 (a) Profile plot and (b) symbol plot for KES variables and protective clothings.

To identify the outliers, it is useful to define the Mahalanobis distance d_i as the distance of individual points from the centre (mean vector $\mathbf{x_A}$) weighted by the covariance matrix $\mathbf{C}$ [52]:

$$d_i = \sqrt{(x_i - x_\mathrm{A})^\mathrm{T} \mathbf{C}^{-1} (x_i - x_\mathrm{A})} \tag{4.74}$$

Outlying points have high Mahalanobis distance, i.e. $d_i > c(p, n, \alpha_N)$. For multivariate normal distribution and large samples $c(p, n, \alpha_N)$ is equal to the quantile of the χ^2 distribution:

$$c(p, n, \alpha_N) = \chi_p^2(1 - \alpha/n) \tag{4.75}$$

For small samples, it is better to use the modified coefficient

$$c(p, n, \alpha_n) = \frac{p(n-1)^2 F_{p,N-p-1}(1-\alpha/n)}{n(n-p-1+pF_{p,N-p-1}(1-\alpha/n))} \tag{4.76}$$

The main problem in using the Mahalanobis distance is to estimate the mean vector $\mathbf{x_A}$ and the covariance matrix $\mathbf{C}$. In the presence of outliers, the classical moment estimators are biased. The 'clean' estimates $\mathbf{x_A}$ and $\mathbf{C}$ are constructed by various robust methods [52]. A very simple method is the combination of trimming and identification of potential outliers. In the ith iteration the trimmed estimators x_{RC} and $\mathbf{C}_C$ are computed. About 30% of the points having maximum Mahalanobis distances d_{i-1}^2 computed in the $(i - 1)$th iteration are trimmed. From the trimmed estimators x_{RC} and $\mathbf{C}_C$, the corrected distances d_i^2 are computed and the iteration is finished.

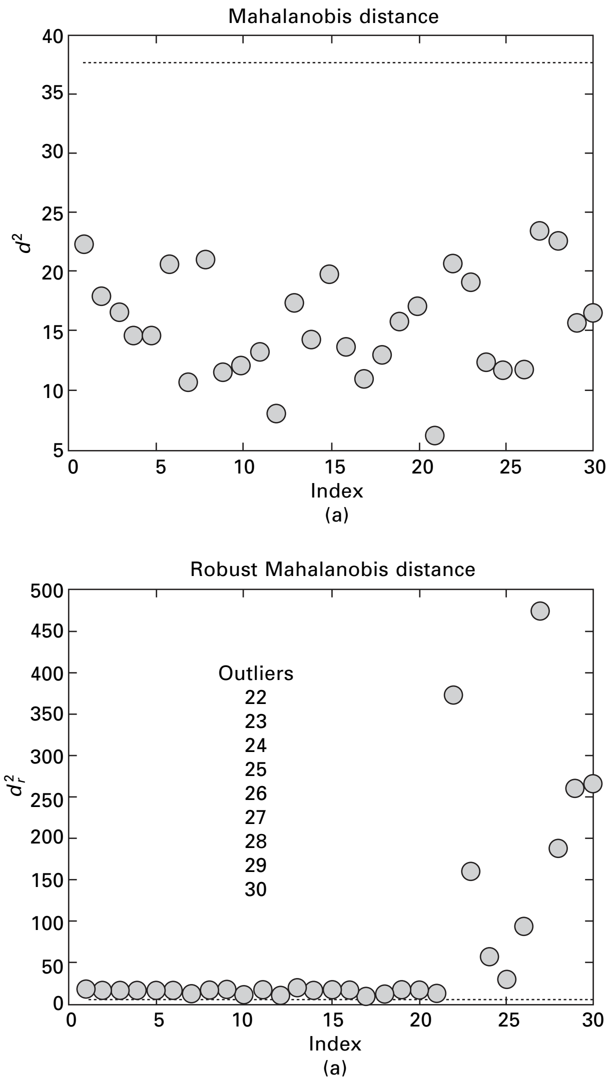
The Mahalanobis distance plot (dependent on the fabric index) and the robust Mahalanobis plot for 16 KES variables of 30 protective clothings are given in Fig. 4.6. It is clear that some fabrics appear to be far from the main group.

4.3.5 Dimension reduction

One of the main features of multivariate data is their dimension, which is a main source of complication in statistical analysis. Hence it is practical to make data reduction, which is acceptable in the following cases:

- The scatter of some variables is at the level of noise and therefore these variables do not convey useful information.
- There are strong linear dependencies (correlations between the columns of matrix $\mathbf{X}$) given by redundant variables or as a result of inherent dependencies between variables. These variables can be replaced by the reduced number of new variables or replaced by artificial ones without any loss of precision.

The main reason for dimension reduction is the curse of dimensionality [53],



4.6 (a) Mahalanobis distance plot and (b) robust Mahalanobis distance plot for KES variables of 30 protective clothings.

i.e. the number of points required to achieve the same precision of estimators is an exponentially growing function of the number of variables. For higher numbers of variables (e.g. in multivariate regression) it leads to parameter estimates with too wide confidence intervals, imprecise correlation coefficients, etc.

One of the simplest techniques enabling dimension reduction is principal component analysis (PCA) as a representative of the so-called linear projection methods [52]. The main aim of principal component analysis is the linear transformation of the original variables x_i, $i = 1, ..., m$, to a smaller group of latent variables (principal components) y_j. Latent variables are uncorrelated, explore major parts of data variability and their number is often very small. Latent variables are commonly called principal components. The first principal component y_1 is a linear combination of the original variables that describes the greatest possible part of overall data variability. The second principal component y_2 is perpendicular to y_1 and describes the maximum part of variability that is not contained in the first principal component. Further principal components are generated in the same way.

The basis of PCA is decomposition of the data covariance matrix **C** to eigenvectors and eigenvalues according to the relation [52]

$$\mathbf{C} = \mathbf{V}\,\boldsymbol{\Lambda}\,\mathbf{V}^{\mathbf{T}} \tag{4.77}$$

where **V** is an $(m \times m)$ matrix containing as columns eigenvectors $\mathbf{V}_j$ and $\boldsymbol{\Lambda}$ is an $(m \times m)$ diagonal matrix containing on the diagonal eigenvalues $\lambda_1 \le \lambda_2 \le \ldots \le \lambda_m$ of the covariance matrix. Matrix **V** is orthogonal, i.e. $\mathbf{V}^{\mathbf{T}}\mathbf{V} = \mathbf{E}$, where **E** is an identity matrix. The variance of the jth principal component $D(y_j) = \lambda_j$ is equal to the jth eigenvalue. The overall variance of all principal components is equal to

$$\mathrm{tr}\,\mathbf{C} = \sum_{i=1}^{m} \lambda_j \tag{4.78}$$

where tr (.) is the matrix trace. The relative variance explained by the jth principal component y_j is in the form

$$P_j = \frac{\lambda_j}{\sum_{i=1}^{m} \lambda_j} \tag{4.79}$$

If the sum of the first m_1 relative variances P_j is sufficiently high (near to 1, say 0.95), then it is possible to replace m original variables by the first m_1 principal components. Graphical selection of a suitable number of principal components is based on the Scree plot, which is a column diagram of ordered eigenvalues $\lambda_1 \le \lambda_2 \le \ldots \le \lambda_m$ independent of index i.

For a better interpretation of PCA it is suitable to quantify the contribution of the original variables to the principal components. It can be derived that the contribution of each original variable to the length of the jth principal component is proportional to the squared element V_{ij} of the eigenvector matrix **V**. The length of this vector is proportional to $\sqrt{\lambda_i}$. The importance of the ith original variable contribution to the jth principal component is then proportional to $V_{ij}^2\sqrt{\lambda}$.

The **contribution plot** is a grouped histogram, where each group corresponds to one principal component. Individual columns in groups have heights proportional to $V_{ij}^2\sqrt{\lambda}$. Individual heights are standardized in such a way that the sum of the relative portions is equal to 1. Based on the contribution plot, it is simple to select important original variables and remove parasite variables with variability at the level of noise.

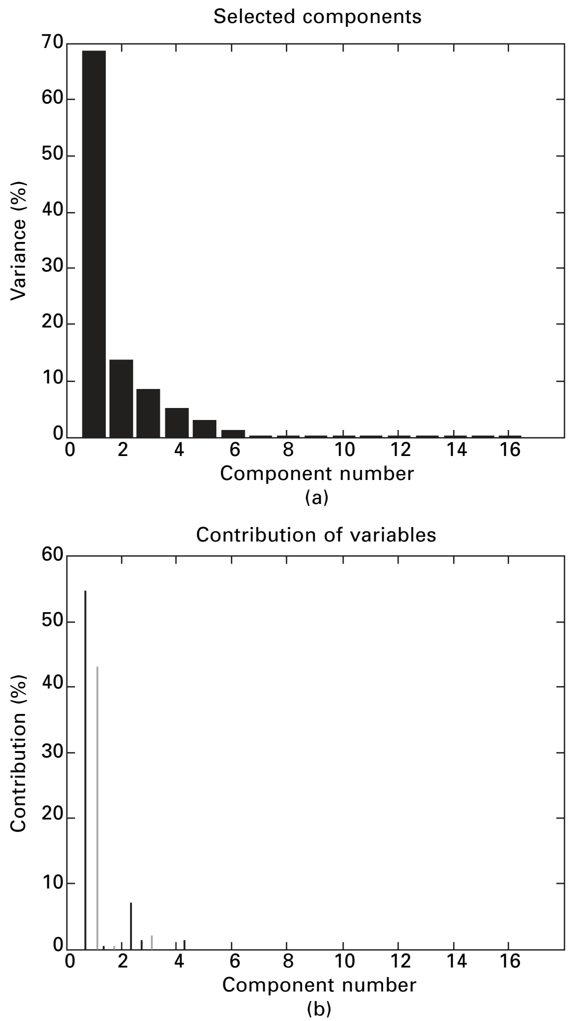
Apart from the linear projection methods such as PCA, there exist many non-linear projection methods [54]. Widely known are the Kohonen sell organized map (SOM), non-linear PCA and topographical mapping. The principle of SOM algorithms is projection to a smaller dimension space preserving approximate distances between points. When d_{ij}^* are the distances between the pairs of points in the original space and d_{ij} are the distances in the reduced space, the target function (reaching a minimum during solution) E takes the following form:

$$E = \frac{1}{\sum_{i<j} d_{ij}^*} \sum_{i<j} \frac{(d_{ij}^* - d_{ij})^2}{d_{ij}^*} \tag{4.80}$$

Minimization of the E function is realized by using Newtonian methods or by heuristic searching. A simple projection technique is the robust version of PCA, when the robust variant $\boldsymbol{S_R}$ replaces the covariance matrix $\boldsymbol{S}$. In this projection, it is simpler to identify point clusters or outliers [52]. The Scree plot and the contribution plot for 16 KES variables of 30 protective clothings are shown in Fig. 4.7. It is apparent from Fig. 4.7(a) that to describe the variability in the data, it is sufficient to use the first four principal components, which explain about 92% of overall variability. The contribution plot shows that only a few of the original variables contributed significantly to explaining the data variability. In Table 4.9 percentage contributions of the important original variables (coded according to Table 4.6) are listed for the first six most important principal components. Clearly, to explain the data variability, the six original variables are sufficient, namely WT (tensile energy), RT (tensile resilience), 2HG5 (shearing hysteresis), RC (compression resilience), SMD (geometrical roughness) and T (thickness). However, it is not possible to say that these variables are the best for subjective hand prediction (see [52]). The projections to the first two principal components and first two robust principal components for 16 KES variables of 30 protective clothings are shown in Fig. 4.8. It is clear that due to the presence of outlying points, the scatter plots are different, and strictly speaking the outlying points here play an important role.

4.3.6 Evaluation of interdependencies

For evaluation of interdependencies between regressors (factors), correlation or regression analysis is useful [52]. Correlation analysis is usually based on the comparison of paired correlation coefficients in the form of a correlation

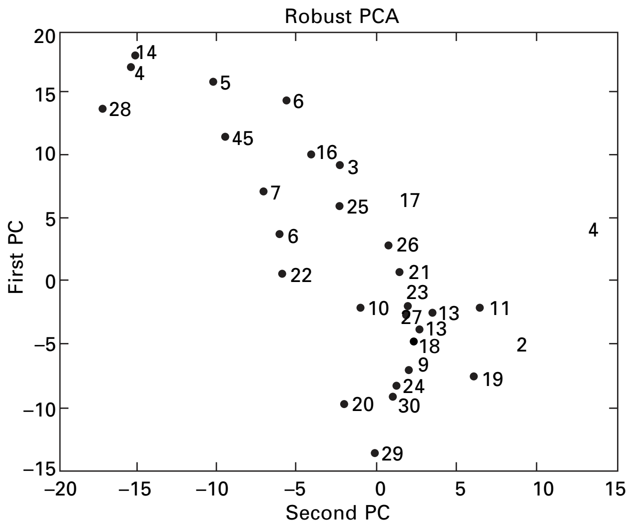


4.7 (a) Scree plot and (b) contribution plot for 16 KES variables of protective clothings.

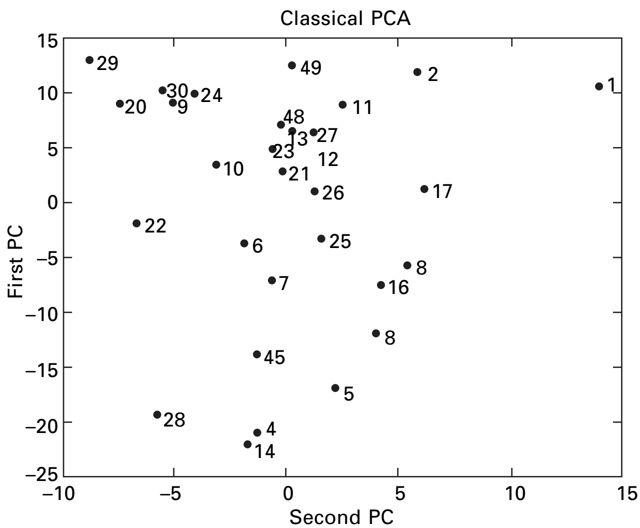
Table 4.9 Contribution of the most important KES variables (importance in %) for creation of first six principal components PC

KES variable	PC1	PC2	PC3	PC4	PC5	PC6
X2	1.3	0.012	0.19	0.043	0.056	0.16
X3	54.4	0.326	1.44	0.0023	0.0032	0.014
X8	0.176	0.758	0.124	0.3356	0.459	0.0052
X11	43.079	0.113	2.219	0.0025	0.0081	0.03
X14	0.0209	0.122	0.077	1.375	0.21	0.0098
X16	0.496	7.182	0.139	0.13	0.06	0.003

The most significant contribution for each principal component is shaded.



(a)



(b)

4.8 Projection into (a) first two robust principal components and (b) first two classical principal components for KES variables of protective clothings.

map. A typical correlation map for 16 KES variables of 30 protective clothings is given in section 4.4.1. It should be pointed out that it is better to use partial correlation coefficients for revealing the structure in data more correctly [52]. For finding interdependencies in the case when one variable is treated as the response and the other variables as explanatory variables, the standard method is to use regression analysis. Regression analysis is also a tool for creation of predictive models. In the case of investigation factors (regressors) indirectly influencing subjective hand feeling, the use of regression analysis is less frequent. It should be considered for replacing primary factors by their proper (non-linear) combinations. A general introduction to linear regression for regression model building is given here and its application to predicting subjective hand is presented in section 4.4.1.

Building of regression models

Creation of a multivariate calibration-type model as in the case of subjective hand prediction is a very complex task. Data-based models with good predictive capability are required. Data-based multiple linear and non-linear model building belongs generally to the most complex problems solved in practice. In many cases it is not possible to construct the mathematical form of the model based on the information about the system under investigation. In these cases, the interactive approach to regression-type model building could be attractive. The interactive approach to model building can be divided into the following four steps [52]:

1. Selection of provisional models
2. Analysis of assumptions about the model, the data and the regression methods used (regression diagnostic)
3. Extension and modification of the model, data and regression method
4. Testing of model validity, prediction capability of model, etc.

Some interactive strategy of multiple regression model building based on the above steps is described in [52]. In this strategy of regression model building, graphically oriented methods for estimation of model correctness and identification of spurious data are selected. These methods are based on special projections enabling the investigation of partial dependencies of response on the selected exploratory variable. Classical examples are partial regression graphs or partial residual graphs. Non-linear or special patterns in these graphs can be used to extend the regression model to include non-linear terms or interactions. For identification of spurious data, the so-called LR graphs can be used as well. For evaluation of model quality, the characteristics derived from the predictive capability are used. Some statistical tools for realization of the above-mentioned techniques are described in [52].

Summary of linear regression

A *linear* regression model is a model formed by a linear combination of explanatory variables $\mathbf{x}$ or their functions. For an additive model of measurement errors, the linear regression model has the form

$$\mathbf{y} = \mathbf{X}\boldsymbol{\beta} + \boldsymbol{\epsilon} \tag{4.81}$$

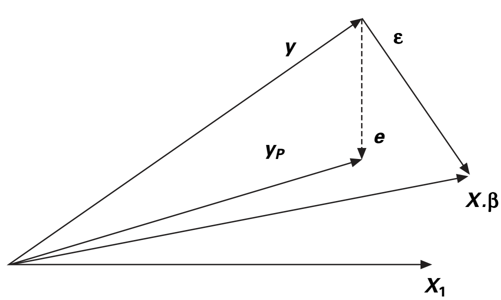
In eqn. (4.81), the $n \times m$ matrix $\mathbf{X}$ contains the values of m explanatory (predictor) variables at each of n observations, $\boldsymbol{\beta}$ is the $m \times 1$ vector of regression parameters, and $\boldsymbol{\epsilon}_i$ is the $n \times 1$ vector of experimental errors. The $\mathbf{y}$ is an $n \times 1$ vector of observed values of the dependent variable (response). Columns $\mathbf{x}_j$ i.e. individual explanatory variables, define geometrically the m-dimensional coordinate system or the hyperplane L in n-dimensional Euclidean space E^n. The vector $\mathbf{y}$ does not usually lie in this hyperplane L. Least squares is the most frequently used method in regression analysis. For linear regression, the parameter estimates $\mathbf{b}$ may be found by minimizing the distance between the vector $\mathbf{y}$ and the hyperplane L. This is equivalent to finding the minimum length of the residual vector $\mathbf{e} = \mathbf{y} - \mathbf{y}_\mathrm{P}$, where $\mathbf{y}_\mathrm{P} = \mathbf{Xb}$ is the *predictor vector*. This is equivalent to the requirement of minimal length of the residual vector $\mathbf{e} = \mathbf{y} - \mathbf{y}_\mathbf{P}$. In Euclidean space, the length of the residual vector is expressed as

$$d = \sqrt{\sum_{i=1}^{n} e_i^2} \tag{4.82}$$

The geometry of linear least squares is shown in Fig. 4.9. The classical least squares method is based on the following assumptions:

- Regression parameters $\boldsymbol{\beta}$ are not restricted,
- The regression model is linear in parameters and the additive model of measurements is valid (see eqn. (4.81)).
- The design matrix $\mathbf{X}$ has a rank equal to n.
- Errors ε_i are i.i.d. random variables with zero mean $E(\varepsilon_i) = 0$ and diagonal covariance matrix $D(\boldsymbol{\varepsilon}) = \sigma^2\mathbf{E}$, where $\sigma^2 < \infty$.

For testing purposes, it is assumed that errors ε_i have normal distribution $N(0, \sigma^2)$. When these four assumptions are valid, the parameter estimates $\mathbf{b}$ found by minimization of the least squares criterion



4.9 Geometry of linear least squares.

$$S(\mathbf{b}) = \sum_{i=1}^{n}\left[y_i - \sum_{j=1}^{m} x_{ij}b_j\right]^2 \tag{4.83}$$

are called best linear unbiased estimators (BLUE) [52]. The conventional least squares estimator $\mathbf{b}$ has the form

$$\mathbf{b} = (\mathbf{X}^{\mathbf{T}}\mathbf{X})^{-1}\mathbf{X}^{\mathbf{T}}\mathbf{y} \tag{4.84}$$

where $\mathbf{A}^{-1}$ denotes the inverse of matrix $\mathbf{A}$. The estimates $\mathbf{b}$ have an asymptotic multivariate normal distribution with covariance matrix $\mathrm{D}(\mathbf{b}) = \sigma^2 (\mathbf{X}^{\mathrm{T}}\mathbf{X})^{-1}$. The perpendicular projection of $\mathbf{y}$ into the hyperplane L can be made using the projection matrix $\mathbf{H}$ and may be expressed as

$$\mathbf{y}_{\mathbf{P}} = \mathbf{X}\mathbf{b} = \mathbf{X}(\mathbf{X}^{\mathbf{T}}\mathbf{X})^{-1}\mathbf{X}^{\mathrm{T}}\mathbf{y} \tag{4.85}$$

where $\mathbf{H}$ is the projection matrix. The residual vector $\mathbf{e} = \mathbf{y} - \mathbf{y}_{\mathrm{P}}$ is orthogonal to the subspace L and has the minimum length. The variance matrix corresponding to the prediction vector $\mathbf{y}_{\mathrm{P}}$ has the form $\mathrm{D}(\mathbf{y}_{\mathrm{P}}) = \sigma^2\mathbf{H}$ and the variance matrix for residuals is $\mathrm{D}(\mathbf{e}) = \sigma^2(\mathbf{E} - \mathbf{H})$. The residual sum of squares has the form $\mathrm{RSC} = S(\mathbf{b}) = \mathbf{e}^{\mathbf{T}}\mathbf{e} = \mathbf{y}^{\mathbf{T}}(\mathbf{E} - \mathbf{H})\mathbf{y} = \mathbf{y}^{\mathbf{T}}\mathbf{P}\mathbf{y}$, and its mean value is $E\,(\mathrm{RSC}) = \sigma^2\,(n - m)$. The unbiased estimator of the measurement variance σ^2 is equal to

$$s^2 = \frac{S(\mathbf{b})}{n - m} = \frac{\mathbf{e}^{\mathbf{T}}\mathbf{e}}{n - m} \tag{4.86}$$

The statistical analysis related to least squares is based on the normality of estimates $\mathbf{b}$. The quality of regression is often (not quite correctly) described by the multiple correlation coefficient R defined by the relation

$$R^2 = 1 - \frac{\mathrm{RSC}}{\Sigma(y_i - \Sigma y_i / n)^2} \tag{4.87}$$

For model building, the multiple correlation coefficient is not suitable. It is a non-decreasing function of the number of predictors and therefore the over-parameterized model results. The prediction ability of the regression model can be characterized by the quadratic error of prediction (MEP) defined for linear models by the relation

$$\mathrm{MEP} = \sum_{i=1}^{n}(y_i - x_i^{\mathrm{T}} b_{(i)})^2 / n \tag{4.88}$$

Here $\mathbf{b}_{(i)}$ is the estimate of regression model parameters when all points except the ith are used. The statistics MEP for linear models uses the prediction $y_{P_i} = \mathbf{x}_i^{\mathrm{T}}\mathbf{b}_{(i)}$ which was constructed without information about the ith point. The estimate $\mathbf{b}_{(i)}$ can be computed from the least squares estimate $\mathbf{b}$ as follows:

$$\mathbf{b}_{(i)} = \mathbf{b} - [(\mathbf{X}^T\mathbf{X})^{-1}\, \mathbf{x}_i\, e_i] \;/\; [1 - H_{ii}] \tag{4.89}$$

Here H_{ii} is a diagonal element of the projection matrix $\mathbf{H}$. An optimal model has a minimal value of MEP. The MEP can be used for definition of the predicted multiple correlation coefficient PR [52].

$$\mathrm{PR}^2 = 1 - \frac{n \times \mathrm{MEP}}{(\Sigma\, y_i - (1/n)\Sigma\, y_i)^2} \tag{4.90}$$

The PR is attractive especially for empirical model building. It is closely connected with the well-known method of cross-validation or single leave-out statistics. Analysis of various types of the regression residuals, or some transformation of the residuals, is very useful for detecting inadequacies in the model or problems in the data [52].

Graphical aids for model creation

In multiple regression one usually starts with the assumption that the response variable y is linearly related to each of the predictors. The aim of graphical analysis is to evaluate the type of non-linearity due to the function of predictors describing the experimental data well. The power-type function of predictors is suitable when the relation is monotonic. Several diagnostic plots have been proposed for detection of the curve between y and x_j [52]. Very useful for experiments designed without marked collinearities is the partial regression plot (PRL). This plot uses the residuals from the regression of y on the predictor x_j, graphed against the residuals from the regression of x_j on the other predictors. This graph is now a standard part of modern statistical packages and can be constructed without recalculating the least squares estimates. To discuss the properties of this plot, let us assume the regression model in the matrix notation

$$\mathbf{y} = \mathbf{X}_{(j)}\boldsymbol{\beta}^* + \mathbf{x}_j c + \varepsilon_i \tag{4.91}$$

Here $\mathbf{X}_{(j)}$ is a matrix formed by leaving out the jth column $\mathbf{x}_j$ from the matrix $\mathbf{X}$, β^* is an $(n - 1) \times 1$ parameter vector and c is a regression parameter corresponding to the jth variable $\mathbf{x}_j$. For the investigation of partial linearity between y and the jth variable $\mathbf{x}_j$, the projection into subspace L orthogonal to space defined by the columns of matrix $\mathbf{X}_{(j)}$ is used. The corresponding projection matrix into the space L has the form $\mathbf{P}_{(j)} = \mathbf{E} - \mathbf{X}_{(j)}(\mathbf{X}^T_{(j)}\mathbf{X}_{(j)})^{-1}\mathbf{X}^T_{(j)}$.

Applying this projection to both sides of eqn. (4.91), the following relation results:

$$\mathbf{P}_{(j)}\, \mathbf{y} = \mathbf{P}_{(j)}\, \mathbf{x}_j\, c + \mathbf{P}_{(j)}\, \boldsymbol{\epsilon} \tag{4.92}$$

The product $\mathbf{P}_{(j)}\, \mathbf{X}_{(j)}\, \boldsymbol{\beta}^*$ is equal to zero because the space spanned by $\mathbf{X}_{(j)}$ is orthogonal to the residuals' space. It is clear that the term $\mathbf{v}_j = \mathbf{P}_{(j)}\, \mathbf{x}_j$ is the residual vector of regression of the variable $\mathbf{x}_j$ on the other variables which form the columns of the matrix $\mathbf{X}_{(j)}$, and the term $\mathbf{u}_j = \mathbf{P}_{(j)}\,\mathbf{y}$ is the residual vector of regression of variable $\mathbf{y}$ on the other variables which form the columns of the matrix $\mathbf{X}_{(j)}$. The partial regression graph as dependence of vector $\mathbf{u}_j$ on vector $\mathbf{v}_j$ is created. If the term $\mathbf{x}_j$ is correctly specified the partial regression graph forms a straight line. Systematic non-linearity is an indication of the incorrect specification of $\mathbf{x}_j$. The random pattern shows the unimportance of $\mathbf{x}_j$ for explaining the variability of $\mathbf{y}$. The **partial regression graph (PRL)** has the following properties:

- The slope c in the PRL is identical with the estimate b_j in a full model.
- The correlation coefficient in the PRL is equal to the partial correlation coefficient R_{yxj}.
- Residuals in the PRL are identical with residuals for the full model.
- The influential points, non-linearities and violations of least squares assumptions are markedly visualized.

4.4 Prediction of subjective hand

Many methods are used for *indirect objective hand evaluation.* These techniques can be divided into three groups according to the instruments used:

1. **Special instruments**. Hand is the result of the measurement. Drawing a textile through a nozzle of defined shape and evaluating 'strength–displacement' dependence is the usual principle [5].
2. **Sets of special instruments** for measuring properties corresponding to hand. Kawabata's evaluation system (KES) belongs to this group.
3. **Standard instruments** for evaluation of fabric properties connected with hand [5].

Techniques of objective hand evaluation can be divided into two groups according to the way the data are processed:

1. The result is **a single number** characterizing hand. This number is very often obtained from multivariate calibration (for example in the regression model), where subjective hand is an endogenous variable and measured properties are exogenous ones [6].
2. The result is a **vector of numbers** characterizing hand. Comparison of hand is then carried out on the basis of multivariate statistical methods [7] (for example factor analysis, discrimination analysis and cluster analysis).

In this section, some methods for creation of models for prediction of subjective hand are described.

Because subjective hand, in fact, is an ordinal variable it is necessary to take this into account for building the model for predicting hand H_s based on continuous covariates (regressors). These covariates are selected from a set of measured properties on KES or from another set of properties.

There are two main categories of model:

I. Prediction of location characteristics only (typically scaled grading median M_p).
II. Information about probabilities or representatives in each category.

For **category I**, it is possible to use ordinary least squares. In this case, the main problems are due to the limited range of M_p and the unknown distribution of this variable. The corresponding variances of M_p will be non-constant and then weighted regression will be more correct.

A common approach to handling the data for **category II** models is to use just ordinary least squares regression with the category membership identifier as the target variable (response). This often works reasonably well, but there are some serious problems with using it:

1. An integer response variable is inconsistent with the assumption of continuous (normal) errors.
2. The ordinal variables exhibit less variability near the limits of their scale and the assumption of constant error variance is violated.
3. Prediction from ordinary regression models does not give integers, resulting in difficulties in interpretation.
4. Least squares regression implicitly assumes that the categories are equally distant from each other.

The solution of these problems is to generalize the well-known logistic regression for ordinal data. There exist several techniques to do this, leading to similar inferences about the ordinal structure of data [18, 55].

Because the models from **category I** are directly predictive models for subjective hand, we will discuss this approach in detail. Models from **category II** are only briefly mentioned. As a working example of regression-type models, we used data from subjective hand evaluation and KES measurement of 30 protective fabrics that are used frequently in the Czech Republic [56]. Protection against heat was realized by using a flame-retardant finish, special fibres (e.g. aramides) or blends of special fibres with properly finished classical ones (cotton). A classical cotton-type fabric was added for comparison as well. This set of fabrics covers the range of highly heat-protective textiles. Material characterization and basic construction parameters are given in [32].

In order to obtain the hand prediction equation, the characteristics measured on the KES system were selected. Raw data and total hand values THV are given in [32]. Subjective hand was judged by a group of 20 well-informed respondents. They classified hand into a $k = 12$ order grade scale (1 – very bad, …, 12 – excellent). The estimations of median values from subjective evaluation results were treated by means of the technique described in section 4.2.1. Results are given in [32]. For models from **category I** the median of the ordinal variable divided by 12 was used as *relative subjective hand* $M_{pi} = y_i = M_{hi}/12$.

4.4.1 Building of multiple linear regression models

The procedure of the regression-type predictive model for subjective hand is here demonstrated on the problem of protective clothing hand evaluation by using Kawabata measurements [56]. This procedure is general and can be used for any kind of cardinal factor (repressors). One example of the application of this approach (prediction of PET/cotton fabric hand for data from the usual devices) is given in [31]. Raw data are in the form $y_i, x_1, \ldots, x_{16i}$, $i = 1, 2, \ldots, 30$. The factors x_i are mean values computed from five repeated measurements. The median M_p is the response variable y_i.

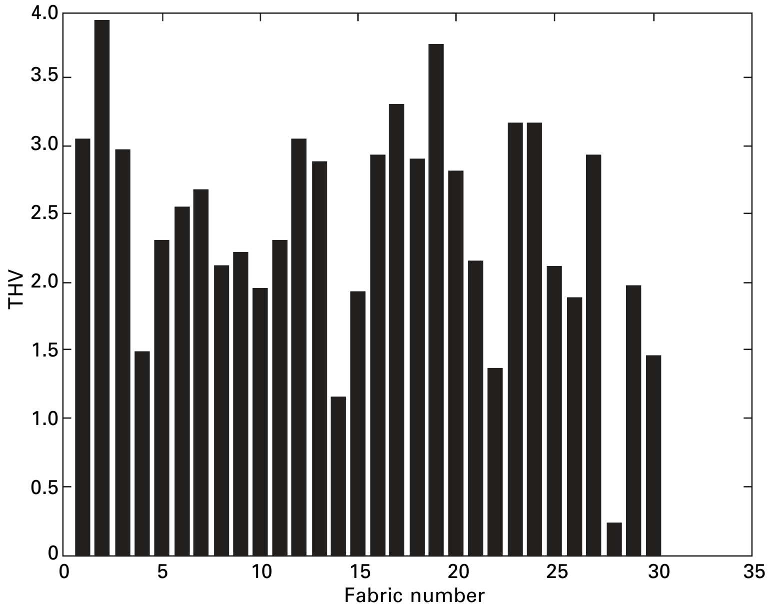
The procedure for the creation of a predictive model can be divided into the following parts:

- Selection of characteristics connected with subjective hand
- Data pretreatment
- Creation of regression model.

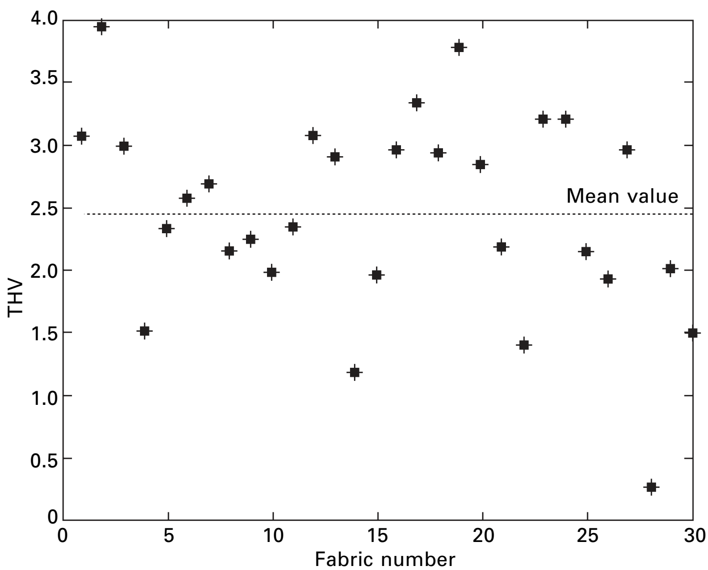
In KES these parts have been solved (see [7]) but only for clothing-type textiles. THVs for the investigated protective textiles computed from KES constants for men's winter suits are given in Fig. 4.10. In Fig. 4.11 the individual THVs for barrier fabric are compared with the mean value. It is seen that many fabrics have very poor hand and in some cases the THV values are near zero. The mean value of hand is comparatively small. The reason is the use of constants that are not valid for these textiles. A comparison of THV with relative subjective hand is given in Fig. 4.12. Moderate linearity is visible but the results are shifted in both intercept and slope. The main shortcoming is the huge number of characteristics (16) for computation of THV.

Selection of sufficient factors

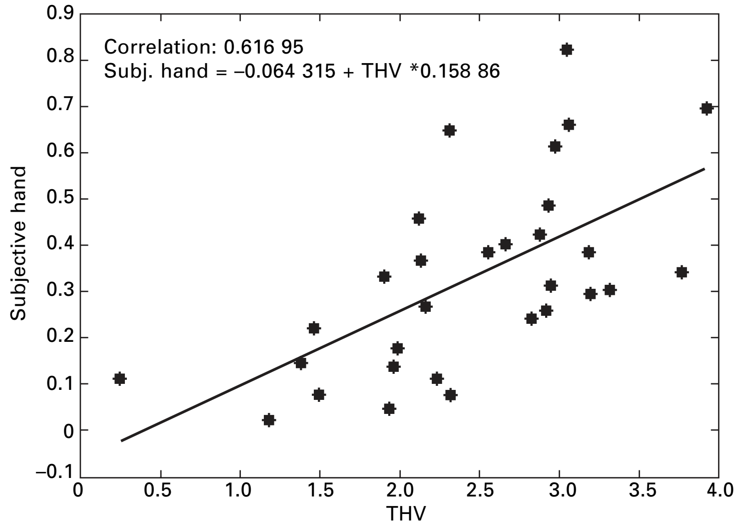
Because the results of KES are 16 factors, i.e. characteristics of mechanical and physical properties connected with hand, the aim is to inspect mutual correlations and correlation with subjective hand. The individual characteristics are numbered $x_1, \ldots, x_{16}$, and the median of subjective hand is x_{17} (see Table 4.6). The correlation map for all characteristics and relative subjective hand is shown in Fig. 4.13. The grey degree corresponds to the strength of correlation. The white indicates perfect correlation (paired correlation coefficient is equal to one) and the black is absence of correlation (paired correlation coefficient



4.10 THV computed from KES for men's winter suit parameters.



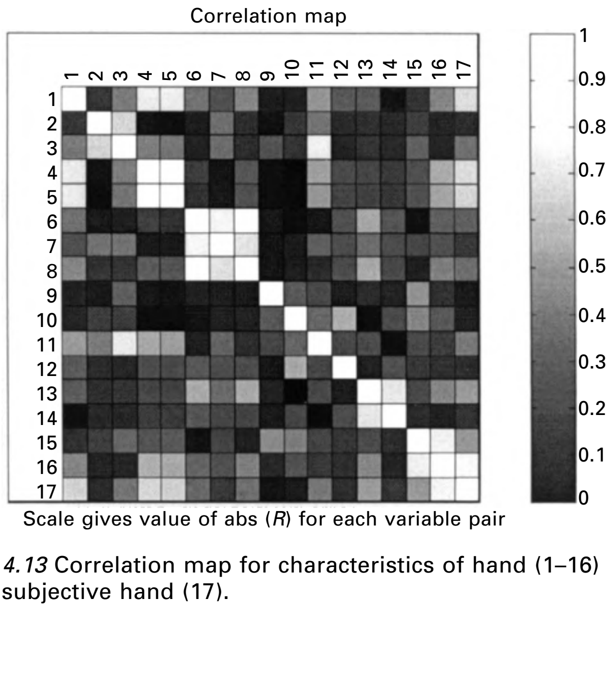
4.11 THV computed from KES for men's winter suit parameters and mean THV.



4.12. Comparison of relative subjective hand with THV.

is equal to zero). The following results can be simply obtained by inspection of Fig. 4.13:

- Subjective hand correlates strongly only with x_1, x_4, x_5 and x_{16}. There is moderate correlation with x_{13} and x_{15}.

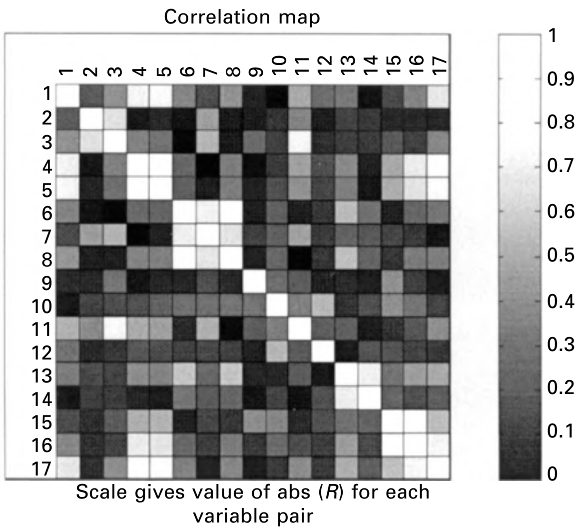


4.13 Correlation map for characteristics of hand (1–16) and relative subjective hand (17).

- There are a lot of very strong correlations between the characteristics, mainly in individual groups of properties.
- Correlations of properties with thickness (16) are very similar to correlations with subjective hand.

The properties LT, B, 2HB and T correlate highly with relative subjective hand (paired correlation coefficient is above 0.6).

In the KES some characteristics are transformed to the logarithmic scale to avoid problems with skew distribution. The correlation map for the transformed characteristics (see [7]) and the relative subjective hand is shown in Fig. 4.14. It is evident that the logarithmic transformation has very little influence on paired correlations between parameters and relative subjective hand.



4.14 Correlation map for transformed characteristics of hand (1–16) and relative subjective hand (17).

Data pretreatment

The main aim is data standardization and transformation to a suitable scale. Standardization is obtained by using the relation

$$u_{ji} = \frac{x_{ji} - x_j^*}{s_j} \tag{4.93}$$

where x_j^* is the sample mean and s_j is the corresponding standard deviation for the jth variable (characteristic). This standardization leads to dimensionless variables and is also realized in the Kawabata system. The logarithmic transformation for avoiding skewness was used by Kawabata. It limits the influence of extreme high values only. Because the meaning of hand comes from its psychophysical nature, it is preferable to use a non-linear transformation of the 'stimulus–response' type. The Harrington transformation was used here (see eqn. (4.52)). This transformation is able to constrain the influence of extremes from both sides. Its main advantage in use lies in the absence of extra parameters. The Harrington-type transformation combined with standardization has been used for all characteristics $x_1, \ldots, x_{16}$.

Creation of regression model

In the KES the quadratic-type regression model is used [7]. For flexibility and simplicity, the following **regression sub-models** were specified in this study:

$$\text{LIN} \qquad y_i = b_0 + \sum_{j=1}^{16} b_j w_{ji} + \varepsilon_i \tag{4.94}$$

$$\text{LINL} \qquad y_i = b_0 + \sum_{j=1}^{16} b_j \ln(w_{ji}) + \varepsilon_i \tag{4.95}$$

$$\text{LOGL} \qquad \ln(y_i) = b_0 + \sum_{j=1}^{16} b_j w_{ji} + \varepsilon_i \tag{4.96}$$

$$\text{GEOM} \qquad \ln(y_i) = \ln b_0 + \sum_{j=1}^{16} b_j \ln(w_{ji}) + \varepsilon_i \tag{4.97}$$

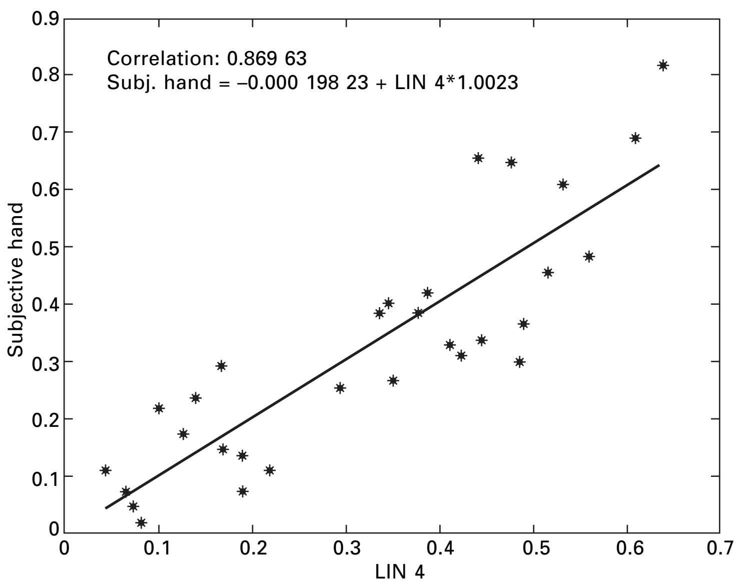
These models were used in the case of all variables ($x_1, \ldots, x_{15}$). For the six (x_1, x_4, x_5, x_{13}, x_{15} and x_{16}) and four (x_1, x_4, x_5 and x_{16}) statistically most important variables only the LIN model has been used. These cases are abbreviated, e.g. LIN6 or LIN4. The simple regression line for x_{16} (LIN1) was computed for comparative purposes as well. The predicted correlation coefficient R_p and mean quadratic error of prediction MEP were used to determine regression model quality. For the above-mentioned models, the characteristics R_p and MEP are shown in Table 4.10. It is evident that from the point of view of prediction ability, the LIN4 model is the best one. The model with all 16 characteristics is clearly over-parameterized. The simple line is surprisingly good (the correlation coefficient of 0.799 is slightly higher than the correlation coefficient for THV). The estimations of parameters $b_0, \ldots, b_4$ together with standard deviations are presented in Table 4.11. Figure 4.15 compares relative subjective hand and LIN4, i.e. hand predicted from the LIN4 model with parameters from Table 4.11. In comparison with Fig. 4.12 for THV values, higher correlation and absence of bias are visible. The higher prediction capability is bounded by the uncertainty in subjective hand prediction.

Table 4.10 Characteristics of regression model quality for various models

Model	R_p	MEP
LIN	0.787	0.0158
LINL	0.782	0.286
LOGL	0.790	0.0156
GEOM	0.794	0.271
LIN6	0.7964	0.0152
LIN4	0.8126	0.0141
LIN1	0.769	0.0169

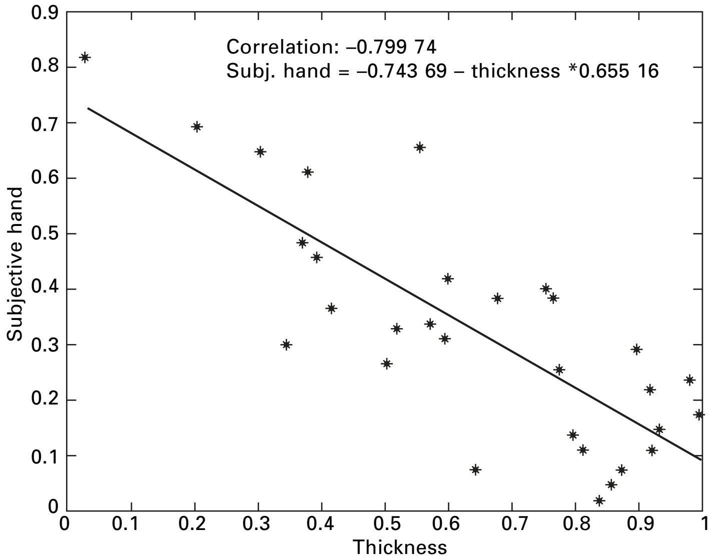
Table 4.11 Regression results for LIN4 model

Parameter	Estimate	Standard deviation of estimate
b_0	0.827	0.0617
b_1	–0.251	0.122
b_2	–0.439	0.725
b_3	0.302	0.721
b_4	–0.429	0.109



4.15 Comparison of relative subjective hand with hand predicted from the LIN4 model.

The regression line for dependence of subjective hand on normalized and transformed thickness of fabrics (x_{16}) is given in Fig. 4.16. From these results the following conclusions can be drawn:



4.16 Dependence of subjective hand on fabric thickness.

- The fabric thickness T (x_{16}) plays a very important role in the hand of protective textiles. The correlation coefficient of relative subjective hand with the transformed thickness is much higher in comparison with the THV.
- The linear model having only four characteristics, namely LT (x_1), B (x_4), 2HB (x_5) and T (x_{16}), is the best for prediction of subjective hand.
- MMD (x_{13}) and WC (x_{10}) have a moderate influence on hand.

The hand of protective fabric is therefore dependent on the *fabric geometry* (and weight), *tensile and bending properties* and variability of *surface friction*. These parameters can be modified in practice by using special softening agents (finishing) or by proper design of raw fabric.

Limitations

The methodology described is based on the assumptions of unbounded response and unbounded factors (explanatory variables). Strictly speaking, both variables are bounded and the bounds are known. The correct procedure in this case is to use the methodology described in the work of Oman [57]. This is based on checking the length of the parameter vector. For higher lengths, it is possible to derive optimal shrinking of parameters (in fact, this is so-called ridge regression). Where the parameter vector length is sufficiently small, the classical least squares estimators as used here are acceptable. These constraints should be imposed on the more precise estimation strategy. In the case presented above, there were no marked non-linearities and the degree of fit was very good, so the improved strategy was not applied. The second improvement is to use non-constant weights based on dorvar variance.

4.4.2 Logistic and polytomous models

The models from **category II** are created by logistic regression for ordinal data [18, 55]. The ordinal response Y_i takes values in k ordered categories; let F_{ij} be the estimate of cumulative probability that Y_i falls in the jth category or lower. There exist several techniques to do this, leading to similar inferences about the ordinal structure of the data [55]. For calculation of these models the special software in SAS, S Plus and STATA packages, is available [58]. As raw explanatory variables, for each fabric, it is necessary to use individual judgements (grades) or relative frequencies for each category [58].

The proportional odds model

The proportional odds model is based on the so-called **cumulative logits.** Consider a model with regressors $x = (x_i, \ldots, x_m)$ and target identifier T. Cumulative logit is defined by the relation

$$\mathrm{CL}_j(\mathbf{x}) = \mathrm{logit}(F_j(\mathbf{x})) = \log\left[\frac{F_j(\mathbf{x})}{1 - F_j(\mathbf{x})}\right] \quad j = 1, \ldots, k-1 \tag{4.98}$$

where $F_j(x) = P(T \leq j/x)$ is the cumulative probability for the jth category. The target identifier T takes values 1, 2, …, k. The $\mathrm{CL}_j(x)$ is then log odds of $Y \leq j$ versus $Y > j$. The proportional odds linear model has the form

$$\mathrm{CL}_l(\mathbf{x}) = a_{0,j} + \sum_{l=1}^{k-1} a_i x_l \quad j = 1, \ldots, k-1 \tag{4.99}$$

where a_{0j} ($j = 1, \ldots, k-1$) and a_l ($l = 1, \ldots, k-1$) are regression parameters. A positive value of a_l implies increasing probability of being in lower categories with increasing x_l. To avoid this problem the negative sign is often used in eqn. (4.99). This model is motivated by using a latent continuous response T^* of actual hand feelings. Then for class boundaries $-\infty \leq b_1 \leq \ldots \leq b_k \leq \infty$ the observed response T (category membership) is categorized according to the rule

$$T = j \text{ for } b_{j-1} < T^* < b_j \tag{4.100}$$

This is the so-called grouped continuous model.

If the latent variable $T^*(x)$ given the regressor setting x has the logistic distribution, the probabilities $p_j(x)$ satisfy the proportional odds model $\mathrm{CL}_j(x)$.

An alternative to the grouped continuous approach to modelling an ordinal variable is to focus directly on the specific probability relationship through the logits. *The adjacent categories logit* uses the following model:

$$\log\left(\frac{f_{j+1}}{f_j}\right) = a_{0j} + \sum_{l=1}^{k-1} a_l x_l \quad j = 1, \ldots, k-1 \tag{4.101}$$

This model is a special case of the multinomial logit model. The logit equations (4.101) can be re-expressed in terms of baseline category c_k using the identity

$$\log\left(\frac{f_{j+1}}{f_j}\right) = \log\left(\frac{f_{j+1}}{f_k}\right) - \log\left(\frac{f_j}{f_k}\right) \tag{4.102}$$

These logit models assume the existence of a continuous *latent* variable *T*. This is not correct for subjective hand, because categories here are truly discrete. For these cases it is better to use *stereotype models* based on the polytomous repression models [59].

One of the main advantages of the stereotype model is that it does not assume *a priori* ordering. The ordinality is built into it by imposing a structure on the regression coefficients. Starting from the stereotype model is similar to the adjacent category logit expressed in eqn. (4.101) for base category f_1:

$$\log\left(\frac{f_{j+1}}{f_1}\right) = a_{0j} + \sum_{l=1}^{k-1} a_{jl} x_l \quad j = 2, \ldots, k \tag{4.103}$$

From the model expressed in eqn. (4.103), it is clear that the ordinal nature of categories is not accounted for. The ordinality is reached by imposing a structure on the regression coefficients b_{jl} ($l = 1, \ldots, m$). One possibility is to use factorization:

$$b_{jl} = \phi_j b_l \quad i = 2, \ldots, k; \quad l = 1, \ldots, m \tag{4.104}$$

where b_l is a list of new parameters and ϕ_i can be thought of as scores S_i attached with category c_i. There are two constraints: $\phi_1 = 0$ and $\phi_k = 1$. After substitution of these into eqn. (4.103), the stereotype model results:

$$\log\left(\frac{f_{j+1}}{f_1}\right) = a_{0,j} + \phi_j \sum_{l=1}^{k-1} a_l x_l \tag{4.105}$$

The stereotype model contains a set of parameters ϕ_i and a single parameter b_l for each regressor. Weight parameters ϕ_i can be selected as *a priori* fixed scores or can be computed [60].

4.4.3 Neural network models

Lack of theoretical models for prediction of subjective hand is the main reason for utilization of soft models or non-parametric regression techniques such as neural networks. In these cases, the response is simply selected as the scaled sample grading median y = Mp, and as explanatory variables **x**, important measured characteristics can be used (see section 4.3).

Neural networks (NN) have recently received widespread application in many fields in which statistical methods are traditionally employed [61]. Recent possibilities for application of neural networks to textiles are described in [62]. From a statistical point of view NN are a wide class of flexible non-linear regression and discrimination models, data reduction models, and non-linear dynamic systems [63].

Basic ideas

Artificial neural networks have been developed as generalizations of mathematical models of human cognition or neural biology, based on the following assumptions:

1. Information processing occurs at many simple elements called neurons.
2. Signals are passed between neurons over connection links.
3. Each connection link has an associated weight, which in a typical neural net multiplies the signal transmitted.
4. Each neuron applies an activation function (usually non-linear) to its net input (sum of weighted input signals) to determine its output signal.

The use of neural networks offers the following useful properties and capabilities:

1. **Non-linearity**. A neuron is basically a non-linear device. Consequently, a neural network, made up of an interconnection of neurons, is itself non-linear. Moreover, the non-linearity is of a special kind in the sense that it is distributed throughout the network.
2. **Input-output mapping**. A popular paradigm of learning called supervised learning involves the modification of the synaptic weights of a neural network by applying a set of labelled training samples.

Neural network structure

A neural net consists of a large number of simple processing elements called neurons, units, cells, or nodes. Each neuron is connected to other neurons by means of directed communication links, each with an associated weight. The weights represent information being used by the net to solve a problem. Each neuron has an internal state, called its activation or activity level, which is a function of the inputs it has received. Typically, a neuron sends its activation as a signal to several other neurons. It is important to note that a neuron can send only one signal at a time, although that signal is broadcast to several other neurons.

For example, consider a neuron j, which receives inputs from neurons X_1, X_2, …, X_n. Input to this neuron is created as a weighted sum of signals from other neurons. This input is transformed to the scalar output y_j. The classical McCulloh and Pit neuron has an adjustable threshold μ_j. The output is then defined as

$$y_i = h\left[\sum_j (w_{ij}\, x_j - \mu_i\right] \quad h(x) = 1 \quad \text{for } x \geq 0, \quad h(x) = 0 \quad \text{for } x \leq 0 \tag{4.106}$$

The activation y_j of the neuron can be given by some function of its net input, $y = h(y_{\text{in}})$, e.g., the logistic sigmoid function (S-shaped curve).

The neurons are arranged in layers. The standard three-layer structure has one input layer, one output layer and one hidden layer. The signals go through the layers in one direction. After a set of inputs has been fed through the network, the difference between the true or the desired output and the computed output represents an error. The sum of squared errors ESS is a direct measure of performance of the network in mapping inputs to desired outputs. By minimizing ESS, it is possible to obtain the optimal weights and parameters of the activation function $h(.)$.

Radial basis functions and NN

The radial basis functions are a special kind of neuron activation. Their characteristic feature is that their response decreases (or increases) monotonically with distance from a central point. The centre, the distance scale and the precise shape of radial functions are adjustable parameters. A typical Gaussian radial function has the form

$$h(x) = \exp\left[-\frac{(x-c)^2}{r^2}\right] \tag{4.107}$$

where c is the centre and r is the radius. Radial basis functions are frequently used for creation of NN for regression-type problems. Traditionally, a single layer network with m neurons is expressed by the model

$$f(x) = \sum_{j=1}^{m} w_j h_j(x) \tag{4.108}$$

where w_j are weights. For the training set x_i, y_i, $i = 1, \ldots, p$, the computation of weights is based on the minimization of the criterion

$$S = \sum_p (y_p - f_p)^2 \tag{4.109}$$

If a weight penalty term is added to the sum of squared errors, the ridge regression criterion occurs:

$$C = \sum_p (y_p - f_p)^2 + \sum_{j=1}^{m} \lambda_j w_j^2 \tag{4.110}$$

where λ_j are regularization parameters. For fixed parameters of functions $h(x)$, weight estimation is a typical linear regression task.

Regularized forward selection

The basic algorithm (FS2) starts with a set of candidate RBFs with different positions but of the same size, and an empty network [64]. Candidates are selected and added to the network one at a time while keeping track of the estimated prediction error. At each step the candidate that most decreases the sum of squared errors and has not already been selected is chosen to be added to the network. Initially, predicted error decreases, but as the network becomes bigger, its complexity increases and it eventually begins to over-fit the data. At that point, the predicted error starts to increase and the algorithm stops adding RBFs. As an additional safeguard against over-fitting, the method uses ridge regression and the regularization parameter λ is re-estimated after each iteration. The locations of the candidate RBFs are determined by the inputs in the training set so there are as many candidates as there are cases. The nominal width in each dimension is equal to the total spread of input values and is the same for each candidate. The FS2 strategy is frequently used for creation of NN regression models.

The utilization of neural networks for creation of non-parametric models predicting subjective hand grading is relatively simple. The resulting fit is usually sufficient and there are no problems with multi-collinearities and non-linearities. On the other hand, the resulting model contains a relatively high number of parameters and it is not simple to distinguish between the important and unimportant variables.

4.5 Concluding remarks

The statistical analysis of hand data is not a simple task and there exist plenty of possibilities. The selection of strategy is based on the manner of primary data extraction and the creation of a model is based on the probability or other assumptions. There exist many good techniques but the overall quality of the results of such analysis is critically dependent on the amount and quality of the primary data. Statistical techniques are capable of revealing some problems in the data according to the aim of the application. Generally, it is not possible to improve bad data or add new information without new and properly designed relevant measurements.

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5
Comparison of fabric hand evaluation in different cultures

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5.1 Introduction

In recent years, international trade in textile products, and specifically in apparel, has shown a dramatic increase, mainly due to trade agreements such as NAFTA, WTO, and GATT. Globalization, turning the world into a village, has made communication among trading countries a potential problem area, involving such factors as differences in meanings and definitions and (in terms of comprehension in the field of fabric hand) across cultures. Such differences could influence consumers' selections of apparel and textiles. Many studies have highlighted the possibilities of cultural differences in response to fabric hand (e.g. Anttila [1], Behery [2], and Fritz *et al*. [3, 4]). Presently, there are data to confirm this, covering culture and language differences that may affect verbal responses to fabric hand.

In the last 40 years, progress in the design of textile machinery has been remarkable, especially with respect to improvement of efficiency, automation, and productivity. The machines have been designed largely for high-speed production of textile products which can be supplied to textile consumers at competitive prices. However, the quality of textile materials produced by modern high-production textile processing sequences is not necessarily as good as that produced by traditional machines; rather, the quality of our textile materials is becoming poorer in many cases. This general trend towards lower-quality textile products is of particular significance in the case of wool fabrics and garments, which traditionally occupy the 'up-market' end of the spectrum of textile products because of their superiority in the important quality features of fabric hand, garment appearance and comfort.

Over the years, and in most of the literature reported, assessment of fabric hand has been made subjectively by various experts within the textile and clothing industries, as well as by the ultimate consumers themselves. This has made it necessary to study the comparison of fabric hand assessment as a result of different cultures and other human factors.

This chapter presents studies of the comparison of fabric hand assessment, both subjective and objective, covering the effects of cultures, measuring techniques and instruments. Also, the effect of language differences, terminologies and definitions will be discussed for the following countries (in alphabetical order):

- Australia
- China
- Hong Kong
- India
- Japan
- Korea
- New Zealand
- Taiwan
- United Kingdom (UK)
- United States of America (USA)

In addition, a survey of an international fabric hand, together with the basic requirements of an international objective measurement program, will be outlined.

5.2 Effects of culture, language and male vs female on fabric hand evaluation and their interaction (USA and Korea)

A study was conducted by Kim and Winakor [5] to explore the possibility of developing comparable sets of unipolar adjectives for consumer evaluation of fabric hand in the United States and Korea. Untrained judges were selected because results were intended to apply to consumers, not to textile professionals; unipolar adjectives avoided problems inherent in use of bipolar adjectives, particularly when two languages are involved. The Judges were native English-speaking residents of the United States and native Korean-speaking residents of Korea. A scale of 11 points was chosen for its ease of use, the need to avoid fatigue when judging several fabrics, and theoretical concerns. As in making real-life choices, judges could both see and touch fabrics. Fabrics were limited to seven shirting fabrics. Tentative explanations of cultural and language differences were proposed.

Three hypotheses were developed in this study:

1. USA and Korean consumers do not differ in their responses to fabric hand.
2. Male and female consumers do not differ in their responses to fabric hand.
3. For a specific end use, consumers prefer the same fabrics for members of their own gender as they prefer for the other gender.

5.2.1 Experimental design of the study

The study included four phases:

1. Focus group interviews
2. Word list development
3. Training
4. Final correction.

Stimuli were selected to represent shirting fabrics that might be worn by USA and Korean consumers, both male and female. All fabric swatches were white to reduce color effects. An 11-point unipolar scale was used.

Focus group interviews were designed to collect hand descriptors of fabrics and to explore gender and cultural differences among natives of Korea and the USA. Following a trial focus group, four focus groups were conducted, each consisting of participants representing one gender and one language. Stimuli for focus group discussions were five white fabrics, cut into 44 × 44 cm swatches and selected for variety and familiarity to consumers so that respondents could give diverse and clear descriptions.

The list of unipolar adjectives was developed by collecting fabric hand descriptors from focus group interviews and literature review and by translating them into English or Korean. Textile experts who were fluent in both Korean and English reviewed the translations. Twenty-three adjectives and two preference statements were selected for the trial instrument. The six white shirting fabrics selected for the trial were cut into 20 × 20 cm swatches. Twenty each of native Korean-speaking males and females and 20 each of native English-speaking males and females participated in trial administrations. Reponses to the 25 items were translated to approximately normalized ranks, which could range from –8 to +8.

After analysis of responses, 18 adjectives and the two preference statements survived for final data collection. Seven white shirting fabrics were selected from retail stores in the USA and Korea; swatches were prepared as for the trial (Table 5.1). Korean data were collected in the summer, from 140 students at Seoul National University in Seoul, half males and half females. USA data were collected in the fall, from 155 students at Iowa State University in Ames, 87 males and 68 females. Of the 87 male students, 17 were ineligible because they were not native English speakers. Therefore, 70 male students were retained for analysis. The 11-point certainty scale and transformation of responses to approximately normalized ranks were used, as in the trial.

Plots of means and standard deviations of responses of US and Korean males and females compared response patterns by gender and country of respondents. Analyses of variance were performed separately for each item using the total data set and using sub-samples by country and gender. The model for the total sample is:

Table 5.1 Description of fabrics for the final data collection

Fabric	Fiber content	Symbol	Whiteness	Description
Carded blend twill	65% rayon 35% polyester	A	White with medium yellowish cast	Twill weave, spun yarn
Crash	100% linen	B	White with slight yellowish cast	Plain weave, spun yarn
Flat crêpe	100% polyester	C	White with slight yellowish cast	Crêpe weave, filament yarn
Moss crêpe	80% acetate 20% rayon	D	White with slight greenish cast	Granite weave, filament yarn
Balanced taffeta	100% polyester	E	White with slight greenish cast	Plain weave, filament yarn
Oxford cloth	60% cotton 40% polyester	F	White	Half basket weave, spun yarn
Crash	50% polyester 50% rayon	G	White with medium yellowish cast	Plain weave, spun yarn

Source: 'Fabric hand as perceived by US and Korean males and females', by H. Kim and G. Winakor, from *Clothing and Textiles Research Journal*, vol. 14, no. 2, p. 133, 1996. Copyright Sage Publications.

$$Y_{ijkl} = \mu + C_i + F_j + CF_{ij} + S_k + CS_{ik} + FS_{jk} + CFS_{ijk} + \varepsilon_{ikl} + \varepsilon_{ijkl} \quad (5.1)$$

where: C = country, i = USA or Korea
F = fabric, j = A, B, C, D, E, F, G
S = gender, k = male or female
I = 1, . . ., 70 or I = 1, . . ., 68 (respondents (R)
μ = population mean
ε_{ikl} = error term for country, gender, and their interactions; respondents within country and gender
ε_{ijkl} = error term for fabrics and their interactions.

The term ε_{ikl} represents the fact that subjects responded to the same items for each of the seven fabrics. Thus, the model could be described as a 'repeated measures' design. The model assumes that variances and correlations among fabrics are the same. To examine the possibility that this assumption was incorrect, the denominator degree of freedom for fabrics and interactions involving fabric was divided by 6, the degrees of freedom for fabric (that is, the denominator would be 324 rather than 1945). This did not change conclusions regarding significance.

Analysis of data separately by gender and country revealed differences in details, as compared with analysis of all data combined. However, no major new conclusions resulted from the analysis of data by sub-samples. For these data, observed differences in variances of means by gender or country seemed to have limited impact on the outcome of the analysis of variance and overall results.

5.2.2 Results of the study of fabric hand as perceived by US and Korean males and females

The results focused on the main effects of gender and country, plus the interaction of gender by country. Results are described as significant when the F-value exceeded the 5% level.

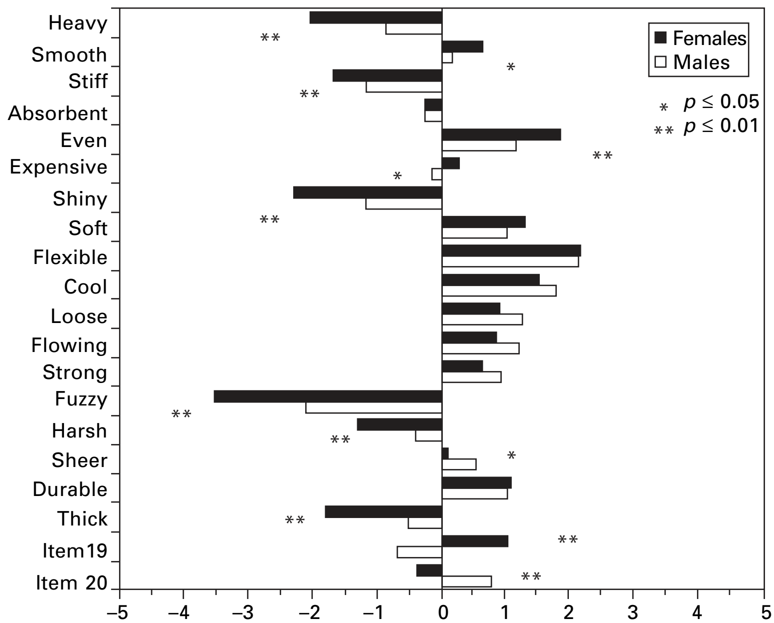
Effects of gender, country and their interactions

The main effects of gender and country, as well as the interaction of gender by country, are significant for two words: smooth and harsh (Table 5.2). Figure 5.1 indicates that females were more certain than males when the fabrics were smooth and not harsh. English-speaking judges were quite certain that the fabrics were smooth and not harsh; Korean-speaking judges were of the opposite opinion but not very certain (Fig. 5.2). Figure 5.3 illustrates the interaction of gender and country; for smooth, Korean males and females

Table 5.2 *F*-values for analysis of variance of transformed responses using total sample for 20 items

Item	Fabric	Sex	Country	S × F	C × F	C × S	S × C × F
Heavy	300.50**	31.31**	18.64**	2.48*	4.02**	0.34	2.68*
Smooth	243.73**	5.16*	64.37**	3.41**	6.40**	5.90*	0.62
Stiff	386.39**	8.19**	16.56**	8.80**	2.44*	0.03	3.63**
Absorbent	65.14**	0.00	0.06	6.95**	4.28**	2.87	3.40**
Even	129.08**	8.51**	0.34	2.28*	2.22*	0.26	0.48
Expensive	71.52**	5.00*	3.73	2.59*	5.48**	0.64	2.98**
Shiny	118.09**	19.34**	16.24**	1.78	3.88**	0.20	1.71
Soft	392.77**	2.47	4.32*	6.10**	11.42**	5.15*	0.53
Flexible	324.20**	0.03	22.04**	5.90**	9.29**	0.73	1.45
Cool	143.25**	1.81	28.53**	1.61	55.80**	15.76**	3.08**
Loose	75.19**	2.52	39.96**	2.28*	3.67**	5.74*	0.69
Flowing	258.13**	2.74	3.70	22.91**	2.49*	10.57*	1.38
String	97.23**	1.78	36.52**	1.63	0.36	0.09	1.37
Fuzzy	108.63**	28.25**	11.22**	3.15**	5.53**	1.63	1.51
Harsh	221.26**	18.64**	109.82**	4.82**	6.08**	11.83**	2.36*
Sheer	216.96**	3.93*	8.15**	3.58**	26.07**	0.11	3.69**
Durable	87.02**	0.06	12.54**	1.26	5.16**	0.01	1.08
Thick	266.8**	40.36**	0.26	2.96**	2.57*	0.22	1.68
Item 19	22.81**	41.96**	2.85	17.27**	21.74**	10.59**	6.30**
Item 20	22.00**	19.50**	0.43	70.43**	28.32**	0.05	2.93**

*$p < 0.05$
**$p < 0.01$
Source: 'Fabric hand as perceived by US and Korean males and females', by H. Kim and G. Winakor, from *Clothing and Textiles Research Journal*, vol. 14, no. 2, p. 133, 1996. Copyright Sage Publications.

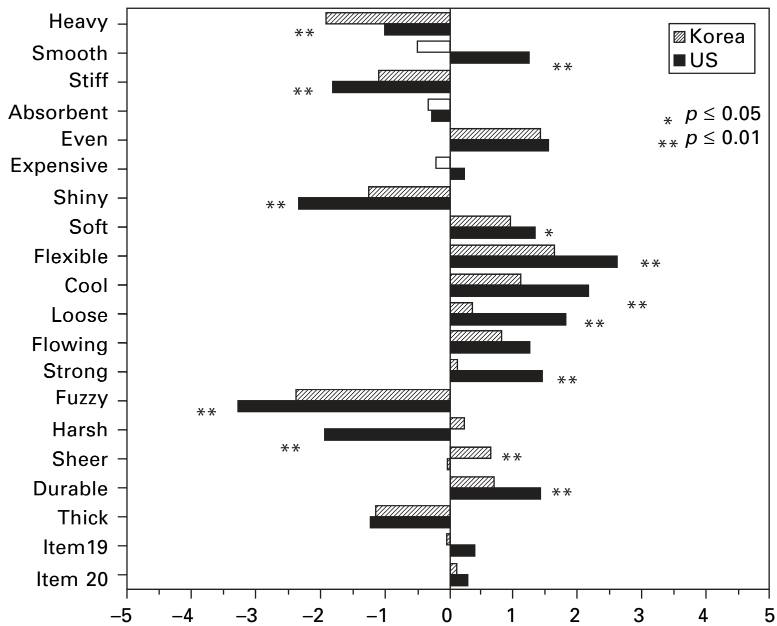


5.1 Means for male and female judges for 20 items for both countries across all fabrics. *Source:* 'Fabric hand as perceived by US and Korean males and females,' by H. Kim and G. Winakor, from *Clothing and Textiles Research Journal*, vol. 14, no. 2, p. 133, 1996. Copyright Sage Publications.

responded nearly identically that the fabrics were not smooth. US males and females were both certain that smooth described the fabrics, but females were more certain about this than males were. Thus, the significant main effect for gender resulted from the responses of US females. The pattern was similar for harsh, but in the opposite direction (i.e. not harsh).

The main effects of gender and country but not the interaction between them are significant for heavy, stiff, shiny, fuzzy, and sheer. For four of these adjectives – all but sheer – both Korean and US females were more certain than males of their own cultures that the words did not describe the fabrics (Fig. 5.3), Korean judges were more certain that the fabrics were not heavy, while US judges were more certain that the fabrics were not stiff, shiny or fuzzy. In contrast, males were more certain than females that sheer described the fabrics and Korean judges were more certain of this than US judges were; these differences, while significant, were moderate. Figure 5.3 shows that US males and Korean females responded nearly identically to sheer, while US females and Korean males responded in opposite directions.

The main effect of gender, but not of country nor the gender by country interaction, is significant for even, expensive and thick. Females were more certain than males that the fabrics were even and not thick. For both even

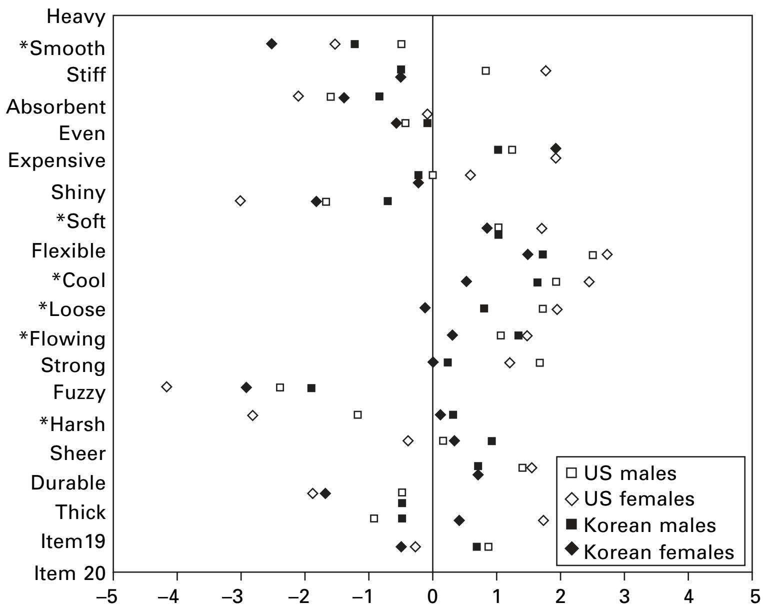


5.2 Means for US and Korean judges for 20 items for both genders across all fabrics. *Source:* 'Fabric hand as perceived by US and Korean males and females,' by H. Kim and G. Winakor, from *Clothing and Textiles Research Journal*, vol. 14, no. 2, p. 133, 1996. Copyright Sage Publications.

and thick, Korean and US males agreed, as did Korean and US females. According to Fig. 5.3, nobody was very certain that the fabrics were expensive; the only respondents who described them as even somewhat expensive were US females.

The main effect of country, but not of gender nor their interaction, is significant for flexible, strong, and durable. US judges were more certain that these words described the fabrics than were Korean judges. For all three adjectives, Fig. 5.3 shows that males and females within the same culture nearly agreed in their responses.

For three adjectives, country and gender by country are significant, but not the main effect of gender. These are soft, cool, and loose. For soft, US females were more certain than the rest of the judges; the country effect seemed to result from the distance between their responses and those of all other judges. US judges were more certain that cool and loose described the seven fabrics. For cool, the country effect is also rather misleading: Korean and US males differed a little, while Korean females were least certain and US females most certain that this adjective described the fabrics. Figure 5.3 reveals that the country effect is most meaningful for loose. Korean judges



5.3 Means for judges by gender and country for 20 items across all fabrics (asterisks indicate adjectives for which the gender by country interaction is significant at the 1% or 5% level). *Source:* 'Fabric hand as perceived by US and Korean males and females,' by H. Kim and G. Winakor, from *Clothing and Textiles Research Journal*, vol. 14, no. 2, p. 133, 1996. Copyright Sage Publications.

were considerably less certain than US judges about the appropriateness of this word. For flowing, only the gender by country interaction is significant. Korean females were least certain that flowing described these fabrics; all other judges agreed fairly closely.

5.2.3 Effects of fabric and its interactions

Selected examples of two- and three-way interactions involving fabric are discussed briefly, as they may clarify gender and country effects. Although fabrics were limited to shirtings in variations of white, the main effect for fabric is highly significant for every adjective (Table 5.2).

For six adjectives – heavy, stiff, absorbent, expensive, harsh, and sheer – both two-way interactions and the three-way interaction of gender by country by fabric are significant. Sheer and stiff have the highest F-values of any adjectives for the three-way interaction. Stiff also has the highest F-value for fabric. For two fabrics (C, flat crêpe, judged sheer; and F, oxford cloth, judged not sheer), Korean and USA male judges differed little in their responses, while US females were most certain. For fabrics B (linen crash), E (taffeta), and G (polyester–rayon crash), US judges agreed and Korean judges agreed, regardless of gender, but in all cases Korean judges were more certain of their responses – particularly in the case of *B*, which they judged to be sheer while US judges were uncertain. Fabric *E* was judged not sheer by Korean speakers, while US judges were divided – females, not sheer; males, sheer. All judges rated *G* as sheer. Fabric *A*, a twill, was judged not sheer by all, but females were more certain. Only Korean males thought that *D* (moss crêpe) was sheer; all others were uncertain.

5.2.4 Verification of the three developed hypotheses

Hypothesis 1

As mentioned earlier, the first hypothesis states that US and Korean consumers do not differ in their responses to fabric hand. A critical issue in investigating cultural differences in evaluation of fabric hand is differentiating whether the adjectives are equivalent in meaning in the two languages from whether fabric hand perceptions differ in the US and Korean cultures.

From the results obtained and illustrated in Table 5.2 and Fig. 5.3, this hypothesis was rejected. The significance of the main effect of country in Table 5.2 implies that a majority of the 18 adjectives may have a different central meaning in English and Korean. Also, cultural differences are implied in the main effect of country, as well as in the interactions of country by fabric.

Hypothesis 2

The second hypothesis states that male and female consumers do not differ in their responses to fabric hand. There is evidence to reject Hypothesis 2 for native English speakers. Females in both cultures were more certain of their responses, but the female–male difference was less consistent among Korean judges. Cultural differences were greater for females than for males, as shown by the gender by country interaction. Moreover, US judges of both genders were more certain of their responses than were Korean judges of the corresponding gender. Responses during the focus group sessions suggested that in Korea, more than in the US, fabric hand is seen as the female's topic, part of the female role; however, quantitative results offer little support for this supposition.

Hypothesis 3

The third hypothesis states that, for a specific end use, consumers prefer the same fabrics for their own gender and for the other gender. This hypothesis is rejected in part. For six of the seven fabrics, judges from the two cultures agreed in direction, although not in degree, about which fabrics were more appropriate for males and for females. Gender and cultural differences were evident, but there remained substantial agreement among respondents about preferences for these shirting fabrics for wearers of a specific gender.

5.2.5 Conclusions on the study of the effect of culture, language and male vs female on fabric hand evaluation and their interaction in USA and Korea

The results of this study suggested practical problems in international trade of apparel and textiles because of cultural differences among countries, as well as differences of meaning among languages. Information about cultural and semantic differences for fabric hand and subtle differences in perceptions between males and females in different countries should interest manufacturers and retailers in the international market. These differences in response to fabric hand also suggested a need to explore differences in subjective response to other properties of fabrics and clothing.

Parallel lists of descriptors in Korean and other languages could be used by textile manufacturers for evaluating textiles targeted for export markets. Standardized lists of textile hand descriptors in the languages of exporting and importing countries would be useful for manufacturers, consumers, and researchers. Given the continuing globalization of trade in fabrics and apparel, efforts to improve verbal communication are essential.

5.3 International comparison of fabric hand (Australia, China, Hong Kong, India, Japan, Korea, New Zealand, Taiwan, UK and USA)

Studies were conducted [6, 7] to investigate the levels of commonality and agreements between panels of judges from the different countries mentioned above in assessing fabric hand for both summer and winter men's suiting materials. The aims of the study were as follows:

- Establishing whether a panel of individuals assesses the hand of a series of men's outerwear fabrics in a consistent manner
- Ascertaining whether panels of expert judges from the different countries mentioned above ranked fabric hand in a similar manner
- Finding out the relationships between the experts' assessments of fabric hand and the primary hand characteristics outlined by Kawabata and Niwa [8].

5.3.1 Experimental design and procedure

Fabrics

A total of 214 winter-weight and 156 summer-weight outerwear suiting fabrics, produced from wool, wool-blend and synthetic fibers were used in the study. The fabrics were all commercially produced, and the details are given in Table 5.3.

Table 5.3 Commercially produced fabrics used in hand survey

Fabric weight range	No. of samples	
	Winter fabrics, 220–320 g/m^2	Summer fabrics, 160–220 g/m^2
Composition of sample		
100% wool worsted	157	76
Worsted synthetic blends	36	74
100% synthetic	15	6
Other[a]	6	0
	214	156
Fabric construction		
Plain weave	30	156
Twill	163	0
Hopsack	19	0
Other[b]	2	0
	214	156
Surface finish		
Clear surface	149	–
Semi-clear surface	61	–
Unclear surface	4	–

[a] Includes pure wool, pure cashmere, cashmere/wool, and cashmere/synthetic blends.
[b] Barathea and knitted constructions.
Source: 'Measuring and interpreting low stress fabric mechanical and surface properties. Part IV: Subjective evaluation of fabric hand', by T.J. Mahar and R. Postle from *Textile Research Journal*, vol. 59, no. 12, p. 721, 1989. Copyright Sage Publications.

Assessment of fabric hand

The panel of judges was given the following instructions when asked to assess the 370 fabrics:

1. Judge the fabrics following your country's base and following your own definition of 'good hand', but the effects of fashion, color and pattern must be excluded so that only fabric hand is judged.
2. The grading of 'good hand' is as shown in Table 5.4.

Table 5.4 Grading of good hand

Grade	Rating
Excellent	5
Good	4
Average	3
Below average	2
Poor	1
Not in use	0

Judging final panels

Independent sets of expert judges were selected from a variety of areas within the textile and clothing industries to represent each of the seven nominated countries. The 17 expert Australian judges were drawn from the following areas of these industries: fabric design (seven judges, including two with marketing and two with quality control responsibilities), finishing (two judges), clothing manufacture (three judges, including one with retaining responsibilities), merchandising (two judges), marketing (one judge) and fabric research and development (two judges). The six other sets of expert judges had a similar mix of background and experience, with the following total numbers: 123 from Japan, 13 from New Zealand, 15 from India, 15 from the USA, 16 from China (PRC), and 12 from Hong Kong/Taiwan. In the study, another set of judges were used, consisting of eight Australians with no particular experience in these industries (consumer judges) to establish how close to their ultimate consumers the expert judges were in their assessments of fabric hand.

The selection of a final panel of judges to represent the hand preferences of a particular country was made on the basis of the correlation of each judge's hand assessments with those of the mean assessments of his or her national panel. In this manner, seven national panels were assembled, each consisting of the eight judges whose hand preferences most closely matched the mean assessments of their national groups.

5.3.2 Results of comparison between the different countries and consumers

Within-group analysis

The level of agreement on fabric hand assessment within each of the eight (seven experts and one consumer) panels of judges was established using the following three-step procedure:

1. The mean fabric hand assessment was calculated within each panel for each fabric.

2. Correlation coefficients were obtained for the relationship between the hand assessments of each judge and the mean assessment of his or her national panel.
3. The mean of these correlation coefficients was calculated for each national panel.

The average correlation coefficients of all fabrics within a group are quoted in Table 5.5, which shows that each of the panels of judges had very good within-group agreement for winter-weight fabrics. Similarly, good but slightly lower within-group agreement was obtained for each panel for the summer-weight fabrics (Table 5.6). The Chinese expert judges showed similar within-group agreement to the other national panels for both men's winter and summer materials.

One reason that the within-group correlation coefficients for the New Zealand panel were lower than for the other panels might have been associated

Table 5.5 Correlations between mean hand assessments of national panels for 214 winter fabrics

	Australia	New Zealand	India	USA	PRC	Hong Kong/ Taiwan
Japan	0.85	0.76	0.82	0.80	0.62	0.84
Australia		0.86	0.91	0.87	0.58	0.87
New Zealand			0.83	0.83	0.71	0.83
India				0.86	0.82	0.85
USA					0.56	0.83
PRC						0.65

Source: 'Measuring and interpreting low stress fabric mechanical and surface properties. Part IV: Subjective evaluation of fabric hand', by T.J. Mahar and R. Postle from *Textile Research Journal*, vol. 59, no. 12, p. 721, 1989. Copyright Sage Publications.

Table 5.6 Correlations between mean hand assessments of national panels for 156 summer fabrics

	Australia	New Zealand	India	USA	PRC	Hong Kong/ Taiwan
Japan	–0.34	–0.30	–0.40	–0.33	0.75	–0.03
Australia		0.82	0.78	0.81	–0.15	0.72
New Zealand			0.76	0.74	–0.20	0.55
India				0.76	–0.26	0.55
USA					–0.13	0.63
PRC						0.13

Source: 'Measuring and interpreting low stress fabric mechanical and surface properties. Part IV: Subjective evaluation of fabric hand', by T.J. Mahar and R. Postle from *Textile Research Journal*, vol. 59, no. 12, p. 721, 1989. Copyright Sage Publications.

with the relatively strong (large fiber diameter) wool that is grown and processed in the New Zealand textile industry.

The high within-group correlation coefficients for the winter-weight fabrics indicated that judges with experience in the textile and/or clothing industries definitely agreed, within each national group, on the hand rating of these fabrics. The slightly lower correlations for the summer-weight materials signified that the judges had more difficulty in rating these samples.

Between-group analysis

The situation is quite different when comparing the between-group correlation coefficients for the summer-weight fabric hand assessments. In this case, there were high correlation coefficient values (0.74 to 0.82) for comparison between the Australian, New Zealand, Indian, and US judges. If the Hong Kong/Taiwan panel of judges were added to this group, there are moderate correlation values for this panel and with other panels (from 0.55 to 0.72).

However, the three between-group correlation coefficients involving the Japanese panels all have small negative values, indicating very little correlation between the Japanese panel of judges and any of the other three panels in the case of the summer fabrics. It is to be expected that these differences may be explained in terms of the different weightings given to the primary hand characteristics in the assessment of fabric hand by the different national panels of judges.

The between-group correlation coefficients involving the Japanese and Chinese panels on the one hand, and each of the other national panels on the other, averaged –0.28 and –0.1 for the Japanese and Chinese panels, respectively. Values of these correlations ranged from a low 0.13 to negative values as high as –0.40. The between-group correlation for the Japanese and Chinese panels was 0.75.

The analysis of summer fabric hand assessments indicates that at least two different, and somewhat opposite, assessments were made of the hand of men's summer fabrics as indicated by the size and signs of the correlation coefficients in Table 5.7. One consistent hand assessment was made in Australia, New Zealand, India, the USA and, to a slightly lesser extent, in Hong Kong and Taiwan. A second different, but again consistent, hand assessment was made in Japan and the PRC. There was also a significant level of direct disagreement between the Japanese/Chinese assessments and those of the other five national panels.

It is unclear whether these two different types of fabric hand preference are based on cultural or climatic differences or some combination of both. Certainly, Japan and parts of China experience annual periods of hot (>30 °C) and very humid (>90% relative humidity) weather. Similar conditions also apply in some coastal areas of Australia, India, the USA, and Taiwan, as

Table 5.7 Mean values[a] of the between-group correlation coefficients for the hand assessments of each national panel with the other six panels for the winter and summer fabrics

National panels	Winter fabrics (A)	Summer fabrics (B)
Japan	0.78	–0.28
Australia	0.82	0.78
New Zealand	0.80	0.74
India	0.80	0.71
USA	0.79	0.74
PRC	0.61	–0.19
Hong Kong/Taiwan	0.81	0.53

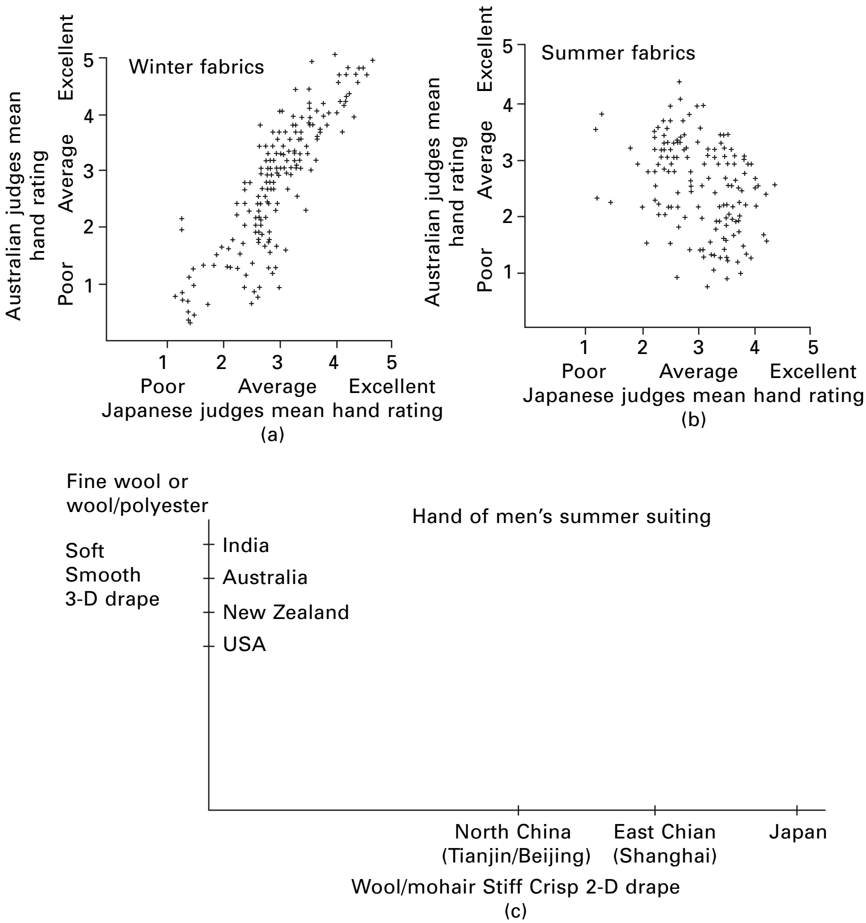
[a] Mean values taken only for the cases where the sign is constant.
Source: 'Measuring and interpreting low stress fabric mechanical and surface properties. Part IV: Subjective evaluation of fabric hand', by T.J. Mahar and R. Postle from *Textile Research Journal*, vol. 59, no. 12, p. 721, 1989. Copyright Sage Publications.

well as Hong Kong. One might also argue that of the seven countries investigated, Japan, the PRC, Hong Kong/Taiwan, and India have maintained their strong cultural identities, despite the obvious influence of Western culture, e.g. the wearing of Western-style suits.

Concerning between-group agreement for winter suiting materials (Table 5.7A), the two Chinese panels show slightly lower but still significant between-group agreement with the other national panels of expert judges for men's winter suiting materials. Between-group agreement is generally higher for the North China panel (Tianjin/Beijing) than for the East China panel (Shanghai).

Concerning between-group agreement for summer fabrics (Table 5.7B), the two Chinese panels show good between-group agreement only with the Japanese panel for the hand of men's summer suiting materials. The agreement with the Japanese panel is slightly stronger for the Shanghai panel than for the Tianjin/Beijing panel. There is no statistically significant between-group agreement for the two Chinese panels with the other national panels.

The hand of men's summer suiting materials may be represented on a two-dimensional chart according to market preference, as shown in Fig. 5.4(c). In Japan and to a slightly lesser extent China, the market preference is clearly for very lightweight, relatively stiff, crisp suiting materials having some relatively coarse fabrics, usually mohair, in the weft yarns. These fabrics tend to spread or bend in only two dimensions, thus giving a characteristic drape whereby the contact between the fabric and the skin is relatively small. These draping properties are particularly suited for hot tropical climatic conditions. In the other countries surveyed – Australia,



5.4 Graphical representation of the agreement between the mean hand ratings of eight Japanese judges and eight Australian judges for (a) 214 winter fabrics and (b) 156 summer fabrics. (c) Schematic representation of two axes for the hand for men's summer suiting material. *Source:* 'Fabric handle a comparison of Australian and Japanese assessments of suiting materials', by T.J. Mahar and R. Postle, from *Australian Textiles*, Jan–Feb. 1982. Reproduced with permission from *Australian Textiles*.

New Zealand, India, and the USA – the market preferences were for relatively smooth, fine, soft components of fabric hand for these summer suiting materials and appear to be very similar to those for the winter suiting materials, i.e. smoothness and softness. These fabrics would normally be made from fine wool or wool/polyester blend.

Correlation with subjectively assessed primary hand values

Besides the hand ratings previously discussed, each of these fabrics has been rated by the Japanese panel for the various subjective fabric characteristics previously noted as being the important primary components of fabric hand, namely *koshi* (stiffness), *numeri* (smoothness) and *fukurami* (fullness and softness) for the winter fabrics; and *koshi* (stiffness) and *shari* (crispness) for the summer fabrics. Average stiffness, smoothness, and fullness and softness ratings were calculated for each winter fabric, and similarly, stiffness and crispness ratings were calculated for each summer fabric. The average ratings of these subjective fabric characteristics (made by the Japanese panel of judges) were correlated with the mean total hand rating of each of the four panels of judges.

The results for the winter-weight fabrics are given in Table 5.8(a). From inspection it is clear that, in the hand assessment for the winter-weight

Table 5.8 Correlation between fabric hand ratings and subjectively assessed fabric characteristics
(a) Winter weight fabrics

Panel of judges	Smoothness (*numeri*)	Softness/fullness (*fukurami*)	Stiffness (*koshi*)
Japanese	0.87	0.84	–0.22
Australian	0.93	0.81	–0.40
New Zealand	0.79	0.72	–0.19
Indian	0.87	0.74	–0.39
United States	0.82	0.69	–0.39
Chinese			
Shanghai	0.54	0.62	0.31
Tianjin/Beijing	0.65	0.69	0.06
Consumers	0.67	0.64	0.01

(b) Summer weight fabrics

Panel of judges	Stiffness (*koshi*)	Crispness (*shari*)	Anti-drape stiffness (*hari*)	Softness/fullness (*fukurami*)
Japanese	0.51	0.74	0.43	0.25
Australian	–0.70	–0.74	–0.63	0.12
New Zealand	–0.60	–0.69	–0.52	0.32
Indian	–0.73	–0.75	–0.71	0.11
United States	–0.61	–0.65	–0.55	–0.02
Chinese				
Shanghai	0.32	0.53	0.27	0.15
Tianjin/Beijing	0.20	0.30	0.17	0.19
Consumers	–0.69	–0.68	–0.58	0.02

Source: International Fabric Hand Survey, by T.J. Mahar and R. Postle. Reproduced with permission from the Textile Machinery Society of Japan.

fabrics, each panel of judges rates fabric surface smoothness (*numeri*) as the most important of the three primary characteristics. Indeed, the high correlation coefficients (*ranging* from 0.79 for the New Zealand panel to 0.93 for the Australian panel) indicate that fabric smoothness has a very strong influence on the determination of overall fabric hand. Fabric fullness and softness (*fukurami*) is only slightly less important for each panel of judges, as evidenced by the slightly lower positive correlations (from 0.72 for the New Zealand panel to 0.84 for the Japanese panel).

The low negative correlation coefficients between winter fabric hand and fabric stiffness (from –0.40 for the Australian panel to –0.19 for the New Zealand panel) indicate that each panel of judges tends to prefer fabrics of lower stiffness (*koshi*), with the Australian and Indian judges showing a slightly stronger preference in this respect. Because the absolute value of the fabric stiffness correlations is much less than the fabric smoothness and fabric fullness and softness values, fabric stiffness appears to be by far the least important (though still a significant) factor in the assessment of winter fabric hand.

When considering the summer fabrics, the difference between the fabric hand assessments of the Japanese panel on the one hand, and the Australian, New Zealand, Indian and US panels on the other, are shown quite clearly by the correlation coefficients in Table 5.8(b). The Japanese panel shows a clear preference for summer fabrics of relatively high stiffness and crispness when rating overall fabric hand, as evidenced by the positive correlation coefficients, 0.51 and 0.74, with fabric stiffness and fabric crispness respectively. Conversely, the Australian, New Zealand and Indian panels have clearly rated fabric stiffness and fabric crispness as undesirable characteristics when assessing summer fabric hand, as evidenced by the relevant correlation coefficients (ranging from –0.74 for the Australian and Indian panels' correlation with fabric crispness to –0.60 for the New Zealand panel's correlation with fabric stiffness).

The correlation coefficients for the two Chinese panels between overall fabric hand assessments and the subjectively assessed primary components of fabric hand for both the winter and summer suiting materials are quoted in Table 5.8(a) and (b). The two Chinese panels are in agreement with the other national panels in placing most emphasis on the primary characteristics of fabric smoothness and fabric fullness when assessing the hand of men's winter suiting materials. For the summer fabrics, however, the correlation coefficients given in Table 5.8(b) show that the two Chinese panels assess the hand of men's suiting materials by weighting the primary hand components of stiffness, crispness, and fullness in a manner similar to the Japanese panel. The positive correlation coefficients for both the Chinese panels and the Japanese panel of judges indicate that fabric springy-stiffness, crispness and anti-drape stiffness are regarded as desirable characteristics in their summer fabric hand assessments. The opposite is true for the four other national panels.

5.3.3 Conclusions of the study of comparison of fabric hand assessments

A number of conclusions relevant to the overall concept of fabric hand and its measurement can be drawn from the results of this study.

1. It could be concluded with a high degree of confidence that a panel of judges from the textile and/or clothing industries of any one of the countries selected can produce a large measure of agreement when asked to assess the fabric hand of a very wide range of men's suiting materials. The agreement is better for winter-weight fabrics than for summer-weight fabrics.
2. As far as winter-weight fabrics are concerned, there is a very large measure of agreement for hand ratings between panels of Australian, Japanese, New Zealand, and Indian judges drawn from the textile and related industries in each of the four countries. Furthermore, it is scientifically possible to relate these judges' ratings of fabric hand to subjectively assessed measurements of fabric smoothness (*numeri*), fabric softness and fullness (*fukurami*) and, to a very much lesser extent, fabric stiffness (*koshi*). All judges placed a very high emphasis on fabric smoothness and to a slightly lesser extent on fabric softness and fullness, when assessing the hand of winter-weight materials. The same judges exhibited a slight tendency to prefer winter fabrics of lower stiffness in their assessments of hand, but much less emphasis was placed on fabric stiffness for winter fabrics than in the case of hand assessments for summer-weight fabrics. The judges seem to accept fairly readily that winter materials, being relatively thick, are fairly stiff, and accordingly, high levels of fabric stiffness were not severely penalized in their assessments of fabric hand for winter materials.
3. The situation is, however, very different for the summer-weight materials. Firstly, it is in this area that the Japanese panel of judges shows a marked difference in its assessment of fabric hand when compared to any of the other panels. The Japanese judges clearly prefer relatively stiff (*koshi*) and/or crisp (*shari*) fabrics in their assessments of lightweight fabric hand, but the exact opposite applied for the Australian, New Zealand, and Indian judges who showed a very clear preference for fabrics of relatively low stiffness and/or crispness when assessing lightweight fabric hand. The extension of the hand survey to include other Asian countries (e.g. Philippines, Taiwan, Hong Kong), as well as European countries (e.g. Germany, Italy, UK) may help to explain this apparently culturally based

difference in hand expectations between the Japanese judges and the other national panels of judges surveyed so far in this study.

4. The judges from both Chinese panels, in common with the judging panels from the other countries surveyed, placed high emphasis on fabric smoothness and fabric fullness when assessing the hand of winter-weight materials. For the summer suiting materials, the two Chinese judging panels were in reasonable agreement with the Japanese judging panel in their clear preference for relatively stiff and/or crisp fabrics in their assessments of lightweight fabric hand for men's summer suiting.

The differences in fabric hand preferences noted in this work may be traced to differences in cultural background and different fashion preferences between Eastern and Western nations.

5.4 Fabric hand equations for Australia, New Zealand, India and USA

A series of 10 equations for the translation of the Primary Hands (PHs) of men's suiting fabrics into Total Hand Values (THVs) is presented according to the model used by Kawabata [11]. These equations relate subjectively assessed PHs to fabric hand assessments (THVs) of expert judges drawn from the textile and clothing industries of Australia, New Zealand, India and the USA for both winter-weight and summer-weight suiting fabrics. Results based on the hand preferences of a group of consumers drawn from the Australian marketplace are also included.

An international survey [7] was undertaken involving fabric hand assessment of the same sets of fabrics as were studied before (Section 5.3.1), by similar panels of expert judges. The survey also included a panel of consumers or people with no textile expertise drawn from the Australian marketplace.

5.4.1 Experimental design and procedure

Each of the expert judges was asked to assess for fabric hand small (20 cm × 10 cm) samples of the 214 winter and 156 summer fabrics. In their assessments, the judges were requested to ignore the effect of fabric color and pattern. The judges were asked to assess subjectively, without reference to standard samples, the hand of each fabric according to the rating scale given before. Approximately 15 judges from each country completed the survey. The individual hand ratings of each judge were used to calculate the average hand assessment for each of the national panels of judges.

Each judge's individual rating was then correlated to the mean hand rating of his or her national group. The subgroup of eight judges from each country who showed the highest correlation with their group mean rating was then selected as the panel of expert judges who best represent the fabric hand preferences of their country. Besides the fabric hand ratings previously discussed, each of these fabrics was subjectively rated by the Japanese panel for the various primary hand expressions, or fabric characteristics, quoted by Kawabata [11] as being the important primary components of fabric hand. These primary components, which are given in Table 5.9, are *koshi* (stiffness), *numeri* (smoothness), *fukurami* (softness and fullness) for the winter fabrics; and *koshi* (stiffness), *shari* (crispness), *hari* (anti-drape stiffness), and *fukurami* (softness and fullness) for the summer fabrics.

Table 5.9 Fabric primary hand values

Winter	*Koshi*
	Numeri
	Fukurami
Summer	*Koshi*
	Shari
	Hari
	Fukurami

Source: 'Fabric handle equations for Australia, New Zealand, India and USA', by T.J. Mahar and R. Postle, from *Journal of The Textile Machinery Society of Japan*, vol. 31, no. 2, p. 35, 1985. Reproduced with permission from the Textile Machinery Society of Japan.

5.4.2 Results of fabric hand equations for Australia, New Zealand, India and USA

The primary hand ratings of the Japanese panel of judges have been used to predict the group mean hand ratings of each of the national panels of expert judges. The calculations followed the procedure adopted in the model proposed by Kawabata [11] to predict the hand preferences or total hand values of the Japanese panel of expert judges.

The general form of the mathematical model used to predict Japanese preferences for fabric hand is:

$$\text{Hand rating (or Total Hand Value, THV)} = C_0 + \sum_{i=1}^{k} Z_i \tag{5.2}$$

where $$Z_i = C_{i1}\left(\frac{Y_i - M_{i1}}{\sigma_{i1}}\right) + C_{i2}\left(\frac{Y_i^2 - M_{i2}}{\sigma_{i2}}\right) \tag{5.3}$$

Y_i are the handle characteristics given in Table 5.8; M_{i1}, M_{i2}, σ_{i1} and σ_{i2} are the mean values of Y and Y^2 and the standard deviations of Y and Y^2 respectively (see Table 5.10 for values); and C_0, C_{i1} and C_{i2} are constants.

Table 5.10 Values of the means and standard deviations for each of the PH and PH^2 defined by Kawabata as being necessary for the objective specification of fabric hand for 214 winter and 156 summer fabrics

	M_{i1}	M_{i2}	σ_{i1}	σ_{i2}
(a) Winter fabrics				
i = 1: *Koshi*	5.7093	33.9032	1.1434	12.1127
i = 2: *Numeri*	4.7537	25.0295	1.5594	15.5621
i = 3: *Fukurami*	4.9798	26.9720	1.4741	15.2341
(b) Summer fabrics				
i = 1: *Koshi*	4.6089	22.4220	1.0860	11.1468
i = 2: *Shari*	4.7480	24.8412	1.5156	14.9493
i = 3: *Fukurami*	4.9217	25.2704	1.0230	10.1442
i = 4: *Hari*	5.3929	30.7671	1.2975	14.1273

Source: 'Fabric handle equations for Australia, New Zealand, India and USA', by T.J. Mahar and R. Postle, from *Journal of The Textile Machinery Society of Japan*, vol. 31, no. 2, p. 35, 1985. Reproduced with permission from the Textile Machinery Society of Japan.

The values for the constants used in the model to determine the contribution to total hand value of the primary hand expressions have been published by Kawabata [11] for the case of the Japanese panel of expert judges. These values and the corresponding values for the non-Japanese expert and consumer sub-group panels of eight judges are given in Tables 5.11 and 5.12 for the winter and summer fabrics, respectively. The values of these constants were calculated with the aid of a standard multiple linear regression technique using the fabric hand ratings obtained in the international survey.

The values of the multiple correlation coefficients in Tables 5.11 and 5.12 with the exception of the US summer fabric assessments are high, ranging from 0.79 for the consumer summer fabric ratings to 0.94 for the Australian winter fabric ratings. High multiple correlation coefficients indicate that the model based on Japanese subjective assessments of the primary hand expressions can be used to predict the fabric hand preferences of the non-Japanese panels of expert and consumer judges to the level of accuracy applicable to the Japanese expert panel. In the case of the US summer fabric assessments the lower value of the multiple correlation coefficient (0.70) indicates less reliability when the Japanese model is applied. This effect may be related to the dominance of synthetic and cellulosic fibers in the men's suit market in the USA, particularly for summer fabrics. For the present international survey of fabric hand, the fabrics had been collected in Japan and are predominantly pure wool and wool/synthetic materials. The results shown in Table 5.12 indicate that, in order to achieve a higher level of reliability of prediction for US summer fabric hand, another primary hand expression (derived from lightweight synthetic and cellulosic materials) may be required.

Table 5.11 Constants and multiple correlation coefficients for the winter fabric HV-THV translation equations for each national judging panel

Constants for each judging panel	Winter Primary Hand (PH) expressions			Multiple correlation coefficient	C_0
	Stiffness (*koshi*)	Smoothness (*numeri*)	Softness and fullness (*fukurami*)		
Japanese					
C_1 (PH)	0.6750	–0.1887	0.9312	0.90	3.1466
C_2 (PH)^2	–0.5341	0.8041	–0.7703		
Australian					
C_1 (PH)	0.3810	1.2622	–0.0376	0.94	2.7768
C_2 (PH)^2	–0.3282	–0.1429	–0.0282		
New Zealand					
C_1 (PH)	0.4620	1.3449	–0.1562	0.86	3.1449
C_2 (PH)^2	–0.3644	–0.7663	0.2011		
Indian					
C_1 (PH)	0.7091	1.2617	–0.4972	0.88	3.0380
C_2 (PH)^2	–0.6818	–0.2446	0.3467		
United States					
C_1 (PH)	0.4146	1.4450	–0.2489	0.85	3.1351
C_2 (PH)^2	–0.4842	–0.6288	0.1343		
Consumers					
C_1 (PH)	1.2271	1.1203	0.4430	0.83	3.1483
C_2 (PH)^2	–0.9793	–0.4196	–0.3986		

Source: 'Fabric handle equations for Australia, New Zealand, India and USA', by T.J. Mahar and R. Postle, from *Journal of The Textile Machinery Society of Japan*, vol. 31, no. 2, p. 35, 1985. Reproduced with permission from the Textile Machinery Society of Japan.

The average hand rating for each national panel of the fullest of 214 winter fabrics, given by the value of the constant C_0, falls within a relatively narrow band, ranging from 2.78 for the Australian expert panel to 3.15 for the Japanese expert and Australian consumer panels. This result indicates that all panels had a similar average level of appreciation for the hand of the winter fabrics.

For the summer fabrics, it has been shown that although there is a good level of agreement among the non-Japanese panels of judges, there is a marked tendency for disagreement between the Japanese and each of the other national panels of judges. The Japanese judges show significant positive correlation coefficients with *koshi* (0.51), *shari* (0.74) and *hari* (0.43), whereas all the other judging panels show significant negative values for the correlation coefficients with these three summer fabric primary hand expressions, ranging from –0.52 to –0.75. Although there is a strong interaction between the three

Table 5.12 Constants and multiple correlation coefficients for the summer fabric HV-THV translation equations for each national judging panel

Constants for each judging panel	Primary Hand (PH) expressions				Multiple correlation coefficient	C_0
	Stiffness (*koshi*)	Crispness (*shari*)	Anti-drape Stiffness (*hari*)	Softness and Fullness (*fukurami*)		
Japanese						
C_1 (PH)	–0.0004	1.1368	0.3316	0.5309	0.85	3.2146
C_2 $(PH)^2$	0.0066	–0.5395	–0.4977	–0.3741		
Australian						
C_1 (PH)	–1.0332	–0.0542	1.0779	0.7032	0.83	2.5073
C_2 $(PH)^2$	0.8994	–0.3176	–1.2219	–0.6992		
New Zealand						
C_1 (PH)	–0.7082	0.2432	0.9902	0.4482	0.83	3.0825
C_2 $(PH)^2$	0.7945	–0.6296	–1.1357	–0.3373		
Indian						
C_1 (PH)	–0.3644	0.1152	0.1585	–0.0560	0.81	2.6489
C_2 $(PH)^2$	0.3135	–0.4730	–0.4308	–0.0982		
United States						
C_1 (PH)	–0.2250	–0.0460	0.5740	0.3452	0.70	2.8281
C_2 $(PH)^2$	0.2471	–0.3679	–0.7720	–0.4494		
Consumers						
C_1 (PH)	–0.9173	0.8220	0.6741	0.5958	0.79	3.1482
C_2 $(PH)^2$	0.7430	–1.1430	–0.8095	–0.6638		

Source: 'Fabric handle equations for Australia, New Zealand, India and USA', by T.J. Mahar and R. Postle, from *Journal of The Textile Machinery Society of Japan*, vol. 31, no. 2, p. 35, 1985. Reproduced with permission from the Textile Machinery Society of Japan.

Japanese summer primary hand expressions of *koshi*, *shari* and *hari*, the negative correlation coefficients for the non-Japanese judging panels is greatest for the case of *shari*. The difference in summer fabric hand expressions can be seen by inspection of Table 5.12, where the Japanese preference for a crisp summer fabric hand shows in the positive net contribution (i.e., the sum of the contribution to THV of the linear and squared terms for each of the primary hand expressions) of the PH and PH^2 constants for *shari*. The dislike shown for a very crisp fabric hand by each of the non-Japanese panels of judges is evidenced by the negative net contribution to summer fabric THV of the PH and PH^2 constants for *shari*. For the summer fabrics, the average hand ratings for each of the panels of judges ranged from 2.51 for the Australian expert panel to 3.21 for the Japanese panel. This result indicates a wider spread in the judges' overall appreciation of the summer fabrics than for the winter fabrics.

5.4.3 Conclusion of the study of the fabric hand equations for Australia, New Zealand, India and USA

It could be concluded that the international survey of the fabric hand preferences of judges drawn from the textile and clothing industries of Australia, New Zealand, India and the USA has provided the necessary data for a similar system of fabric hand specification in these countries. The separate specification of fabric hand on a national basis is necessary because, though there is broad overall agreement amongst the international panels of judges about winter fabric hand, there are subtle differences in hand preferences amongst the various national judging panels. These differences suggest that users of Kawabata's system for the objective measurement of fabric hand should consider the market for which a fabric is manufactured when evaluating the hand of winter-weight suiting fabrics.

Because of the much more readily defined differences in hand expectations between the Japanese and non-Japanese panels of judges when assessing summer fabric hand, it is imperative that users of this fabric hand specification system relate their measurements to the relevant national market when assessing the hand of summer-weight suiting fabric.

The values for the constants of the Kawabata hand specification equations given in Tables 5.10–5.12 for the Australian, New Zealand, Indian and US markets will enable users of these equations to specify fabric hand for these markets in a more confident manner.

5.5 Comparison between KES-FB and FAST systems in discrimination of characteristics of fabric hand

The differences in basic concept and application between the Kawabata system (KES) and fabric assurance by simple testing system (FAST) were discussed in Chapter 2.

In order to be able to compare the KES-FB and FAST systems in discrimination of fabric characteristics, Sang-Song *et al.* [12] applied discriminant analysis and neural network principles to the physical properties of fabrics measured by the KES-FB system and the FAST system. They established discriminant models for fabric characteristics. The KES-FB discriminant model, which applied fabric mechanical properties, appeared to have better classification ability than the FAST discriminant model. On the other hand, the discrimination model established by applying neural network principles appeared to have a better classification ability than that by applying discriminant analysis.

5.5.1 Experimental design and study methodology

The study included woven fabrics of cotton, linen, wool, and silk. Their basic properties are shown in Table 5.13. These fabrics are used mainly for summer outer garments, such as women's dresses and men's suiting. All samples were commercial fabrics that had not been processed through special finishes.

Table 5.13 The experimental fabrics

Fabric group	Yarn construction	Number of samples	Thickness (mm)	Weight (g/m^2)
Cotton	Spun	13	0.4–0.65	86–165
Linen	Spun	15	0.4–0.78	102–184
Wool	Spun	17	0.36–0.82	112–212
Silk	Filament	15	0.21–0.42	36–56

Source: Comparison between KES-FB and FAST in discrimination of fabric characterization, by Lai Sang-Song, Shyr Tien-Wei and Lin Jer-Yan, from *Journal of the Textile Machinery Society of Japan*, vol. 55, no. 7, p. 49, 2002. Reproduced with permission from the Textile Machinery Society of Japan.

5.5.2 Fabric physical properties

KES-FB system

Using Kawabata's system (KES-FB), 16 mechanical properties of fabrics were tested under standard conditions. These were given earlier (see page 22).

FAST system

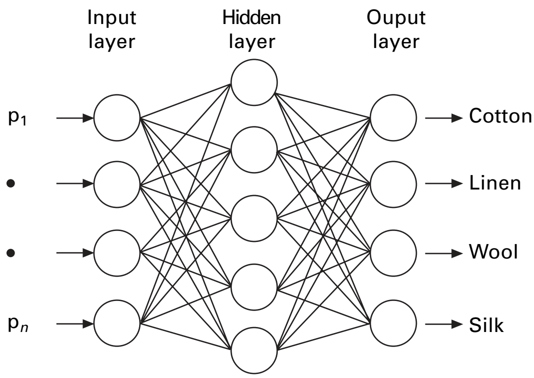
Only 10 independent variables of the fabric physical properties were measured by the FAST system. These were given earlier [13] and were selected to form the discrimination model.

5.5.3 Discrimination analysis

Based upon the presupposition of known group data, discrimination analysis can be applied to derive the 'Discrimination Function' for clear discrimination of group data. Then, discrimination of new group data can be carried out in accordance with the function. Using 60 fabrics of known fiber type and physical properties, discrimination analysis was applied to establish the discrimination function for fabric characteristics and types. The detailed step-by-step derivation of the effective discrimination is given in reference 12.

5.5.4 Neural network

Artificial neural networks are often applied to solve prediction and classification problems, especially in the prediction of nonlinear structural systems [14]. A back-propagation artificial neural network with an input layer, an output layer, and a hidden layer, was used by Sang-Song *et al.* [12]. Its configuration is shown in Fig. 5.5. Input variables included 16 mechanical properties measured by the KES-FB system (Method A), nine mechanical properties selected by applying the stepwise method (Method B), 10 physical properties measured by the FAST system (Method C), and five physical properties



5.5 Adopted neural network structure. *Source:* 'Comparison between KES-FB and FAST in discrimination of fabric characterization', by Lai Sang-Song, Shyr Tien-Wei and Lin Jer-Yan, from *Journal of Textile Engineering*, vol. 48, no. 2, 2002.

selected by applying the stepwise method (Method D). Characteristic discriminances of cotton, linen, wool and silk are used as the network target values in neural network training. The entire computation procedure is hidden. For nonlinear transformation, the sigmoid function, $f(x) = \dfrac{1}{1 + e^{-x}}$ was used, with a range of (0, 1). The related network conditions are presented in Table 5.14. For computation of the weight value variation between the hidden layer and the output layer, generalized delta learning rules were employed.

Table 5.14 Parameters of neural network

	Item	Parameter
Input layer	Normalization	Standard
	Number of units	16, 9, 10, or 5
Hidden layer	Transfer function	Sigmoid
	Number of units	5
Output layer	Normalization	Standard
	Number of units	4
Weights	Distribution	Uniform
	Range	0.1–1
Learning rule	Algorithm	Steepest descent
Training stages	Learning coefficient	0.5
	Momentum coefficient	0.3
	Maximum records	105
	Maximum updates	10000

Source: Comparison between KES-FB and FAST in discrimination of fabric characterization, by Lai Sang-Song, Shyr Tien-Wei and Lin Jer-Yan, from *Journal of the Textile Machinery Society of Japan*, vol. 55, no. 7, p. 49, 2002. Reproduced with permission from the Textile Machinery Society of Japan.

The learning network was aimed at reducing the margin between the target value and prediction output. The quality of learning was evaluated by the energy function $E = \frac{1}{2} \Sigma (T_j - Y_j)^2$, where T_j is the output layer target value and Y_j is the output layer prediction value. In order to minimize the value of the energy function, the steepest gradient descent entry method was implied. The optimal data convergence after network training was obtained under these conditions (see Table 5.14). In the supervised network learning process, the degree of convergence can be expressed as root-mean-square error:

$$\text{RMSE} = \left[\frac{1}{n} \Sigma (T_j - Y_j)^2\right]^{\frac{1}{2}} \tag{5.4}$$

where n is the number of units processed by the output layer. The RMSE values were in the range 0–1.0. If the RMSE converges to less than 0.1, a good result is obtained. Root-mean-square error, the confusion matrix, and the percentage of correct classification were used to evaluate the learning results of a supervised network [12].

5.5.5 Factor analysis

Factor analysis summarizes multiple variables into fewer groups of new factors, a kind of multiple analysis, and can be represented by vectors and matrices: $\mathbf{X} = \mathbf{Af} + \boldsymbol{\varepsilon}$, where $\mathbf{X} = [\mathbf{X}_1, \mathbf{X}_2, \ldots, X_p]$ is a $(p \times 1)$ observable random vector, $\mathbf{A} = [r_{ij}]$ is a $(p \times q)$ unknown matrix of factor loading where r_{ij} is the unknown parameter to represent the loading of the ith variable on the jth factor, $\mathbf{f} = [f_2, f_2, \ldots, f_q]$ is a $(q \times 1)$ unobservable error or so-called 'common factor', and $\varepsilon = [\varepsilon_1, \varepsilon_2, \ldots, \varepsilon_p]$ is a $(p \times 1)$ unobservable error or so-called 'specific factor' [15]. It is found after many tests that the principal component method provides a better reduction effect on the dimension of the variance–covariance matrix and, therefore, is used to estimate the model variance.

5.5.6 Results of the different analyses

Correlation analysis

As shown in Table 5.15, a significant correlation exists between every two of the fabric mechanical properties measured by the KES-FB system. This implies that they can be inter-replaced. Hence, the stepwise method was applied to select the mechanical properties that could affect discrimination of fabric characteristics most significantly. As shown in Table 5.16 a significant correlation also exists between every two of the fabric physical properties measured by the FAST system. Therefore, it was necessary to select those key variables that are non-collinear and can affect discriminating results most significantly before a simple, convenient and effective method for discrimination of fabric characteristics could be established.

Discriminant analysis

This section aims to use fabric physical properties measured by the KES-FB and FAST systems to establish a discriminant function for the characteristics of cotton, linen, wool, and silk. Correct percentages of the discriminant function obtained from discriminant analysis are shown in Table 5.17. In the KES-FB system, 100% correct discriminant percentage could be obtained when either the enter or the stepwise method was applied to measure fabric mechanical properties. When enter was applied in the FAST system, one piece of thin cotton twill fabric was wrongly discriminated as silk, three

Table 5.15 Mechanical properties and correlations for the KES-FB system

Property	Correlations
LT	WT*, 2HB*, G**, 2HG*, 2HG5**, MIU*, MMD*, T WW**
WT	RT*, SMD*, LC**, WC**, RC*, T***, W***
RT	2HB***, 2HG5*, MIU*, MMD***, SMD***, LC*, WC**, RC***, T**
B	2HB***, G**, 2HG**, 2HG5*, WC*, T**, W**
2HB	G**, 2HG***, 2HG5***, SMD**, WC***, RC**, T***, W***
G	2HG***, 2HG5***
2HG	2HG5***, WC*
2HG5	RC*
MIU	WC***
MMD	SMD***, RC**
SMD	LC*, RC***, T*
LC	RC***, T*, W*
WC	T***, W***
T	W***

*:$p < 0.05$
**:$p < 0.01$
***:$p < 0.001$
Source: Comparison between KES-FB and FAST in discrimination of fabric characterization, by Lai Sang-Song, Shyr Tien-Wei and Lin Jer-Yan, from *Journal of the Textile Machinery Society of Japan*, vol. 55, no. 7, p. 49, 2002. Reproduced with permission from the Textile Machinery Society of Japan.

Table 5.16 Physical properties and correlations for the FAST system

Property	Correlations
W	T2***, STR*, E100*, F***, RS*
T2	ST***, STR***, B**, E100***, F***
ST	STR***, B**, E100*
STR	B***, E100*
B	F*, G***, HE*
E100	F***
F	HE*

*:$p < 0.05$
**:$p < 0.01$
***:$p < 0.001$
Source: Comparison between KES-FB and FAST in discrimination of fabric characterization, by Lai Sang-Song, Shyr Tien-Wei and Lin Jer-Yan, from *Journal of the Textile Machinery Society of Japan*, vol. 55, no. 7, p. 49, 2002. Reproduced with permission from the Textile Machinery Society of Japan.

Table 5.17 Classification results and percentages discriminated for each system and method

Fabric	Predicted fabrics group of enter method				Predicted fabrics group of stepwise method			
	Cotton	Linen	Wool	Silk	Cotton	Linen	Wool	Silk
(a) KES-FB system								
Cotton	13	0	0	0	13	0	0	0
Linen	0	15	0	0	0	15	0	0
Wool	0	0	17	0	0	0	17	0
Silk	0	0	0	15	0	0	0	15
Correct % discriminated		100				100		
(b) FAST system								
Cotton	12	0	0	1	8	3	1	1
Linen	2	12	1	0	3	9	2	1
Wool	0	1	16	0	0	0	17	0
Silk	0	0	0	15	0	0	0	15
Correct % discriminated		91.67				81.67		

Source: Comparison between KES-FB and FAST in discrimination of fabric characterization, by Lai Sang-Song, Shyr Tien-Wei and Lin Jer-Yan, from *Journal of the Textile Machinery Society of Japan*, vol. 55, no. 7, p. 49, 2002. Reproduced with permission from the Textile Machinery Society of Japan.

pieces of linen were wrongly discriminated as two cotton and one wool piece, and one piece of wool was wrongly discriminated as linen, to give a correct discriminant percentage of 91.67%. When the stepwise method was applied, five pieces of cotton were wrongly discriminated as linen (three), wool and silk, and six pieces of linen were wrongly discriminated as cotton (three), wool (two) and silk. Therefore, it is feasible to use fabric physical properties measured by the KES-FB or the FAST system to establish a discriminant function for the characterization of cotton, linen, wool and silk, but the KES-FB discriminant function gives much more reliable discrimination than the FAST discriminant function.

The KES-FB (stepwise) or FAST (enter) canonical discriminant function formed by the fabric physical properties can be expressed as:

$$D_{n(\mathrm{K\ or\ F})} = \beta_{n0} + \beta_{n1}X_{i1} + \beta_{n2}X_{i2} + \beta_{n3}X_{i3} + \ldots + \beta_{np}X_{ip} \qquad (5.5)$$

where $D_{n\mathrm{K}}$ is the KES-FB canonical discriminant function and $D_{n\mathrm{F}}$ is the FAST canonical discriminant function. Function coefficients are shown in Table 5.18. Both $D_{n\mathrm{K}}$ and $D_{n\mathrm{F}}$ have good discrimination ability but $D_{n\mathrm{K}}$ has fewer variables than $D_{n\mathrm{F}}$.

Table 5.18 Canonical discrimination function coefficients

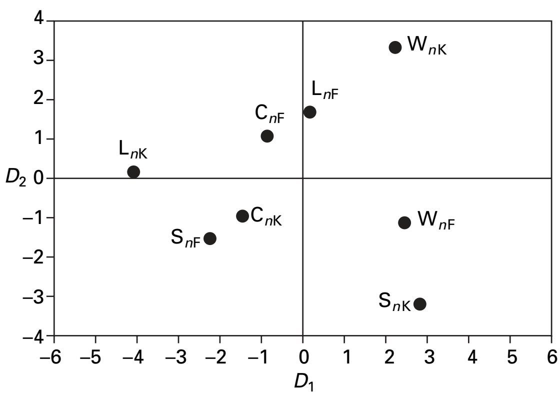
Coefficients	$D_{n\mathrm{K}}$			$D_{n\mathrm{F}}$		
	X	$n = 1$	$n = 2$	X	$n = 1$	$n = 2$
β_0	–	–5.2550	–1.7013	–	–4.4500	–1.6000
β_1	LT	–9.5944	1.1271	W	0.0201	–0.0029
β_2	RT	0.1187	–0.0284	T2	2.6658	2.9972
β_3	2HB	1.9286	–33.7060	ST	51.1094	15.3248
β_4	2HG	0.0420	0.6208	STR	–51.2280	–20.5250
β_5	SMD	–0.2927	–0.1012	B	–0.0813	0.1922
β_6	WC	–3.6143	–17.1370	E100	0.2514	0.5218
β_7	RC	0.1306	–0.0369	F	0.1658	–3.8234
β_8	T	3.6741	8.7783	G	0.0315	–0.0690
β_9	W	–0.1328	0.2824	RS	–0.0347	–0.0061
β_{10}	–	–	–	HE	0.2713	–0.1239

Source: Comparison between KES-FB and FAST in discrimination of fabric characterization, by Lai Sang-Song, Shyr Tien-Wei and Lin Jer-Yan, from *Journal of the Textile Machinery Society of Japan*, vol. 55, no. 7, p. 49, 2002. Reproduced with permission from the Textile Machinery Society of Japan.

The results of significance tests on $D_{n\mathrm{K}}$ and $D_{n\mathrm{F}}$ discriminant functions were as follows. Respectively, for KES-FB canonical discriminant functions D_1 and D_2, eigenvalues were 8.55 and 6.25, canonical correlation coefficients were 0.9462 and 0.9284, and Wilks' Lambda values were 0.0075 and 0.0718. Their cumulative variance percentages were more than 94.15% and their p values were <0.001. Respectively, for FAST canonical discriminant functions

D_1 and D_2, eigenvalues were 3.34 and 1.92, canonical correlation coefficients were 0.8771 and 0.8108, and Wilks' Lambda values were 0.0503 and 0.2178. Their cumulative variance percentages were more than 90.17% and their p values were <0.001. Therefore, it is necessary only to find the two functions D_1 and D_2 to achieve good interpretation ability. Also, finding the two functions will help visual observation when a two-dimensional scatter diagram is used to indicate fabric characteristics.

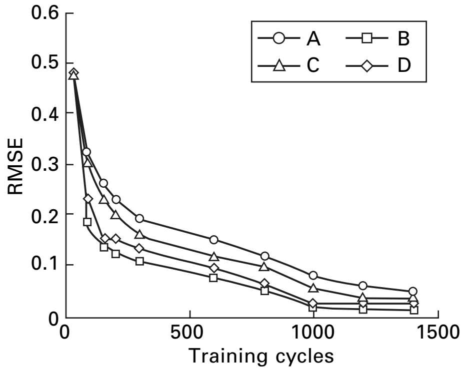
Figure 5.6 is the scatter diagram of D_{nK} and D_{nF}. For D_{nK}, coordinates of centurions for the characteristics of linen, cotton, silk and wool are (–1.46, –0.94), (–4.07, 0.19), (2.23, 3.33) and (2.80, –3.16), respectively. For D_{nF}, coordinates of centurions for the characteristics of linen, cotton, silk and wool are (0.18, 1.67) (in the first quadrant), (–0.84, 1.09) (in the second quadrant), (–2.23, –1.48) (in the third quadrant) and (2.45, –1.09) (in the fourth quadrant), respectively. For both D_{nK} and $D_{nF,}$ centurions for the characteristics of the four fabrics can be classified in different quadrants of a two-dimensional plane. D_{nK} consists of nine mechanical properties of fabric and has 100% correct discriminant percentage. Variables in the discriminant function established by using FAST fabric physical properties and applying the stepwise method include W, E100, B, F and G. The correct discriminant percentage is 81.67%. Indeed, the stepwise method possesses the characteristics of simplicity, convenience and effectiveness for discrimination.



5.6 Centurions of cotton (c), linen (L), wool (W) and silk (S) fabrics (nK: D_{nK}, nF: D_{nF}). *Source:* 'Comparison between KES-FB and FAST in discrimination of fabric characterization', by Lai Sang-Song, Shyr Tien-Wei and Lin Jer-Yan, from *Journal of Textile Engineering*, vol. 48, no. 2, 2002.

Neural network

In Fig. 5.7, the RMSE of method A decreases along with the increase in the number of network training cycles. When the number of training cycles



5.7 Convergence of RMSE. *Source:* 'Comparison between KES-FB and FAST in discrimination of fabric characterization', by Lai Sang-Song, Shyr Tien-Wei and Lin Jer-Yan, from *Journal of Textile Engineering*, vol. 48, no. 2, 2002.

reaches 950, the RMSE become 0.028, indicating that convergence has been reached. Methods B, C and D all have the same tendency of convergence as method A. The number of cycles for convergence and the RMSE are 1150 and 0.014 respectively for method B, 1250 and 0.037 for method C, and 1325 and 0.051 for method D. These results indicate that all four neural network models established in this study have a good training effect. Table 5.19 shows the confusion matrices for the four neural network models. Factors on the diagonals of the matrices are larger than the other values, indicating that the models have good training and discrimination effects. Confusion coefficients of methods A and B were both 0, indicating that the four natural fiber fabrics had been correctly discriminated. The confusion coefficient of method C was 0.017, because one piece of linen was wrongly discriminated as cotton. The confusion coefficient of method D was 0.60, because one piece of cotton was wrongly discriminated as wool, four pieces of linen were wrongly discriminated as cotton, and one piece of silk was wrongly discriminated as wool.

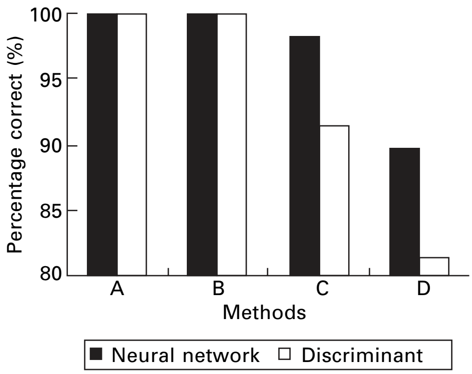
Figure 5.8 compares the KES-FB and FAST systems in characteristic discrimination of natural fiber fabrics. Regardless of whether discriminant analysis or neural network is applied, all the discriminant models established by the KES-FB system give 100% correct discrimination. Although the discriminant models established by the FAST system can also discriminate cotton, linen, wool and silk, they give a slightly lower correct percentage than those established by the KES-FB system. In terms of discrimination ability, discriminant models established by applying neural networks are better than those established by applying discriminant analysis, and method C is better than method D.

In other words, a discriminant model could also be established by the

Table 5.19 Confusion matrices for neural network output (60 samples)

True		Predicted of method A		
	1	1.6	2.6	3.4
1	13	0	0	0
1.6	0	15	0	0
2.6	0	0	17	0
3.4	0	0	0	15
True		Predicted of method B		
	1	1.6	2.6	3.4
1	13	0	0	0
1.6	0	15	0	0
2.6	0	0	17	0
3.4	0	0	0	15
True		Predicted of method C		
	1	1.6	2.6	3.4
1	13	0	0	0
1.6	1	14	0	0
2.6	0	0	17	0
3.4	0	0	0	15
True		Predicted of method D		
	1	1.6	2.6	3.4
1	12	0	1	0
1.6	4	11	0	0
2.6	0	0	17	0
3.4	0	0	1	14

Source: Comparison between KES-FB and FAST in discrimination of fabric characterization, by Lai Sang-Song, Shyr Tien-Wei and Lin Jer-Yan, from *Journal of the Textile Machinery Society of Japan*, vol. 55, no. 7, p. 49, 2002. Reproduced with permission from the Textile Machinery Society of Japan.



5.8 Comparison between the KES-FB system and the FAST system in percentage correct. *Source:* 'Comparison between KES-FB and FAST in discrimination of fabric characterization', by Lai Sang-Song, Shyr Tien-Wei and Lin Jer-Yan, from *Journal of Textile Engineering*, vol. 48, no. 2, 2002.

parameters in the FAST system. For either statistical method used (method A or B), the discriminant percentage of the model established by the KES-FB system's variables is 100%. In addition, the discriminant percentage under method B (only using nine variables in the KES-FB system) is higher than that under method C (using 10 variables in the FAST system). The study showed that the higher number of model variables did not imply higher discriminant percentage. Only through finding the key variables that affect the characteristics of the four kinds of fabrics would the discriminant percentage be improved.

Factor analysis

Factor analysis indicated that the four natural fiber fabrics possessed their own characteristics when correctly discriminated in accordance with their physical properties as described in the previous section. In order to know the characteristic combinations of the four fabrics, the principal component method of factor analysis was applied. Under the condition that the eigenvalue is greater than 1, physical properties measured by the KES-FB and FAST systems were transformed into four new factors. Cumulative variance percentages of the factors in the KES-FB and FAST systems were 75.09% and 79.34% respectively, as shown in Table 5.20.

Table 5.20 Eigenvalues and cumulative variances

Factor	KES-FB system			FAST system		
	Eigenvalue	Variance (%)	Cum. variance (%)	Eigenvalue	Variance (%)	Cum. variance (%)
1	5.09	31.81	31.81	2.91	29.13	29.13
2	3.28	20.53	52.34	2.22	22.19	51.32
3	2.39	14.91	67.25	1.60	16.02	67.34
4	1.26	7.84	75.09	1.20	12.0	79.34

Source: Comparison between KES-FB and FAST in discrimination of fabric characterization, by Lai Sang-Song, Shyr Tien-Wei and Lin Jer-Yan, from *Journal of the Textile Machinery Society of Japan*, vol. 55, no. 7, p. 49, 2002. Reproduced with permission from the Textile Machinery Society of Japan.

New combinations of the 16 mechanical properties measured by the KES-FB system were as follows:

- Factor 1: G, 2HG, 2HGS, 2HB, B and LT. Since there are three shear properties having a communality of more than 0.95 when 2HB, B and LT are 0.74, 0.48 and 0.40 respectively, shear properties can affect Factor 1 significantly. Factor 1 is defined as 'shear stiffness'.

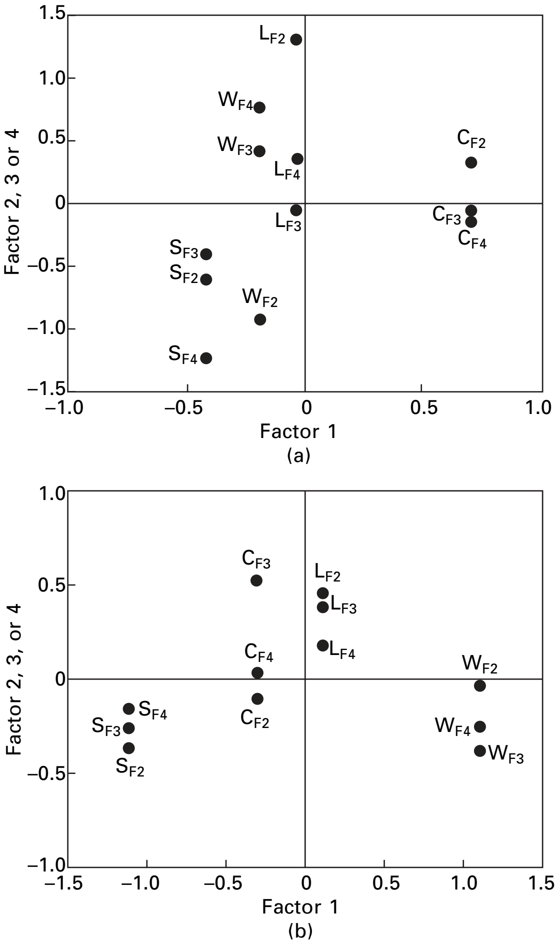
- Factor 2: SMD, MMD, RT and RC. Since surface property has a high communality and is significantly correlated with RT and RC, Factor 2 is defined as 'surface roughness'.
- Factor 3: W, MIU and T. Since WC has a high communality and is significantly correlated with MIU and T, Factor 3 is defined as 'compression energy'.
- Factor 4: WC, LC and WT. Since W is significantly correlated with LC and WT, Factor 4 is defined as 'weight'.

New combinations of the 10 mechanical properties measured by the FAST system were as follows:

- Factor 1: F, T2, W and E100. Since thickness and weight are correlated with fabric formability, Factor 1 is defined as 'formability'.
- Factor 2: ST and STR. Factor 2 is defined as 'thickness'.
- Factor 3: G and B. Factor 3 is defined as 'rigidity'.
- Factor 4: RS and HE. Factor 4 is defined as 'dimensional stability'.

Transforming a large number of variables that can affect discrimination of fabric characteristics into a small number of factors helps to observe the characteristics of the four natural fiber fabrics. Figure 5.9(a) shows the distribution for the average factor scores of cotton, linen, wool and silk samples in the four factor spaces of the KES-FB system. From the characteristic space formed by Factor 1 and Factor 2, the following can be noted. Cotton tends to have extremely high shear stiffness and medium surface roughness. Linen tends to have extremely high surface roughness and medium shear stiffness. Wool tends to have extremely low surface roughness and slightly low shear stiffness. Silk tends to have low shear stiffness and surface roughness. From the characteristic space formed by Factor 1 and Factor 3, the following can be noted. Cotton and linen tend to have medium compression energy. Wool tends to have high compression energy. Silk tends to have slightly low compression energy. From the characteristic space formed by Factor 1 and Factor 4, the following can be noted. Cotton tends to have medium weight. Linen and wool tend to be heavy in weight. Silk tends to be light in weight.

As shown in Fig. 5.9(b), for the FAST system, the characteristics of silk appear to cluster in four factor spaces (F1, F2, F3 and F4). The same applies to wool and linen. Cotton tends to have slightly low formability, low thickness, medium dimensional stability and high rigidity. Linen tends to have slightly high formability, high rigidity and thickness and slightly high dimensional stability. Wool tends to have extremely high formability, medium thickness, and slightly low rigidity and dimensional stability. Silk tends to have extremely low formability, low thickness, and slightly low rigidity and dimensional stability. In the new factor space of either the KES-FB system or the FAST system, the characteristics of the four natural fiber fabrics do not overlap. In



5.9 Distribution of fabric average factor scores in the characteristic spaces: (a) KES-FB; (b) FAST. *Source:* 'Comparison between KES-FB and FAST in discrimination of fabric characterization', by Lai Sang-Song, Shyr Tien-Wei and Lin Jer-Yan, from *Journal of Textile Engineering*, vol. 48, no. 2, 2002.

other words, each of cotton, linen, wool and silk has its own unique characteristics.

5.5.7 Conclusion of the comparison between KES-FB and FAST systems

Discriminant analysis and neural network were used successfully to apply fabric physical properties measured by the KES-FB or the FAST system to establish discriminant models for characteristics of cotton, linen, wool and silk. The discriminant model established by the KES-FB system gave 100% correct discrimination and is apparently a better discriminant model than the one established by the FAST system. Only nine mechanical properties for KES-FB (LT, RT, 2HB, 2HG, SMD, WC, RC, T and W) and five physical properties for FAST (W, E100, B, F and G) needed to be applied in methods B and D, respectively, to effectively discriminate the characteristics of the four natural fiber fabrics. Therefore, for simplicity and convenience, methods B and D are surely better than those discriminant models established previously [16, 17]. Also, discriminant models can help in understanding the characteristic distribution of the four natural fiber fabrics and improving the effectiveness of man-made fabrics in imitating natural fabrics.

5.6 English version (translation) of the Japanese description of primary hand values

The task of providing accurate translations from one language to another of the meaning of words, in particular words which describe abstract concepts, is extremely difficult. Each culture develops words in its language in order to communicate concepts that are considered relevant to that culture. Although, in the case of describing the characteristics of the 'hand' of fabrics in either Japanese or English, the basic cloths themselves are the same, or very similar, each of the two cultural groups represented by the two languages employs different concepts in its description. The Japanese terminology, e.g. *numeri, koshi*, etc., does not equate exactly with any single word in the English language. The use of any 'best', or most appropriate, single word descriptor for one of the Japanese PHVs represents, then, an imperfect substitution which may well be misleading, since this 'best' word really describes a fabric quality attribute which is different from the Japanese PHV.

An international team [18] conducted a study with two objectives:

1. To propose a series of single-word descriptors considered to best characterize each of the five PHVs nominated by the HESC as being necessary to describe the hand of men's suiting fabrics.
2. To describe the concepts identified by these PHVs.

5.6.1 Procedure

For the English-speaking world, the origins of the traditional worsted menswear fabric industry lay in the West Riding area of Yorkshire, England. One of the research team (P. Wheelwright) gained his technical training and early experience of the worsted menswear industry in the region. During his subsequent working experience in the textile industry of other countries, Mr Wheelwright found the vocabulary used in these countries to describe aspects of fabric quality to be in common with that used in the United Kingdom.

An extensive search was undertaken of literature relating to the terminology used traditionally by the worsted manufacturing industry in Yorkshire to characterize fabric hand, quality and finish. The combination of Mr Wheelwright's experience and the literature survey ensured that there was a comprehensive list of fabric descriptors from which to draw in order to assign an English terminology to the Japanese PHVs.

In order to obtain a strong grasp of the concepts identified by the Japanese PHVs, detailed examinations were made of both the fabric samples and the mechanical property data contained in the PHV standards [11] published by the HESC. Discussions were held with English-speaking Japanese (especially S. Sukigara, a member of the research team), who were involved with the textile and/or clothing industries and thus acquainted with the terminology.

5.6.2 Results and discussions

Numeri

Standards were first established for winter suitings. A summary of the fabric quality attributes which characterize the PHV *numeri* is provided in Table 5.21. Of the English expressions used to describe the hand of a fabric with high *numeri*, 'sleekness' is considered to be the most appropriate. 'Smoothness',

Table 5.21 English description of the Japanese primary hand expression, *numeri*

HESC:	Smoothness 'A mixed feeling come from smooth, limber and soft feeling. The fabric woven from cashmere fiber gives this feeling strongly'
Preferred word:	*Numeri* = Sleekness
Other words:	Silkiness Softness Smoothness
Characteristic fabric:	Traditional, fine, high quality velour in very fine wool. (Twill weave, raised, cut both ways)
Opposite characteristics:	Rawness* (underdone) Harshness Wiriness Threadiness
	*Rawness could be due to overtwisting component yarn of underscouring fabric in finishing.

Source: 'Quality attributes and primary hand expressions for wool fabric – English versions of the Japanese descriptions', by P. Wheelwright, T.J. Mahar, R. Postle and S. Sukigara, from *Proc. Third Japan–Australia Joint Symposium on Objective Measurement: Applications to Product Design and Process Control*, 1985. Reproduced with permission from the Textile Machinery Society of Japan.

'silkiness' and 'slipperiness' are also included as examples of feelings associated with high-*numeri* fabric.

Fukurami

The results for the English description of the PHV *fukurami* are summarized in Table 5.22. *Fukurami* is used to characterize both winter and summer fabric hand. 'Fullness' has been chosen as the preferred descriptor for this PHV. Another word which might be used within the textile and clothing industries to characterize this Japanese concept is 'loftiness'. Examples of fabrics which might be expected to display strong *fukurami* are:

- a half-milled flannel (acid milling in fulling stocks) in a twill weave, weighing approximately 280 g/m^2, resultant count of yarn 37 tex/2, and made from 80s quality wool;
- an all-wool heavyweight, woolen split-pick Crombie (double cloth).

Fabric characteristics of 'thinness', 'sponginess' and 'paperiness' are the opposite of *fukurami*.

Table 5.22 English description of the Japanese primary hand expression *fukurami*

HESC:	Fullness and softness 'A feeling come from bulky, rich and well formed feeling. Springy property in compression and thickness accompanied by warm feeling are closely related with this feeling (Fukurami means swelling)'
Preferred word:	*Fukurami* = Fullness
Other word:	Loftiness
Characteristic fabric:	Traditionally achieved by acid milling a cloth made from 'fine' wool in fulling stocks 2/48^s w.c. yarn, lightweight (12 oz/yd), halfmilled flannel in 80^s quality wool twill; all wool heavyweight, woolen split-pick Crombie (double cloth)
Opposite characteristics:	Thinness Sponginess* Paperiness *Sponginess may be the result of overworking a gaberdine repp or fresco in the wet processing – or by refinishing (including rescouring) any firmly set cloth.

Source: 'Quality attributes and primary hand expressions for wool fabric – English versions of the Japanese descriptions', by P. Wheelwright, T.J. Mahar, R. Postle and S. Sukigara, from *Proc. Third Japan–Australia Joint Symposium on Objective Measurement: Applications to Product Design and Process Control*, 1985. Reproduced with permission from the Textile Machinery Society of Japan.

Koshi

As in the case of *fukurami*, *koshi* is a PHV which is used by the HESC to assess the hand of both winter and summer suiting fabrics. The preferred single-word translation of this fabric characteristic, which is described in Table 5.23, is 'firmness'. The complexity of the concept which the Japanese describe as *koshi* can be gauged by the list of 'other (descriptor) words', including 'resilience', 'springiness' and 'solidarity'.

Table 5.23 English description of the Japanese primary hand expression *koshi*

HESC:	*Stiffness* 'A feeling related with bending stiffness. Spring property promotes this feeling. The fabric having compact weaving density and woven by springy and elastic yarn makes this feeling strong'
Preferred word:	*Koshi* = Firmness
Other words:	Resilience Springiness Solidity
Characteristic fabric:	Typified by plain weave, worsted warp $2/40^s$ w.c. yarn of 64^s, $1/18^s$ w.c. mohair weft yarn, overset in loom weft way, and tensioned in finishing to bring weft on to fabric face, singed
Opposite characteristics:	Limpness Slackness Underset Sleaziness

Source: 'Quality attributes and primary hand expressions for wool fabric – English versions of the Japanese descriptions', by P. Wheelwright, T.J. Mahar, R. Postle and S. Sukigara, from *Proc. Third Japan–Australia Joint Symposium on Objective Measurement: Applications to Product Design and Process Control*, 1985. Reproduced with permission from the Textile Machinery Society of Japan.

A fabric which displays the *koshi* PHV strongly is a plain weave; worsted warp yarn-resultant yarn count 44 tex/2 in 21.5 μ wool; mohair weft yarn, single 49 tex/1 overset in loom weft way, tensioned during finishing to bring the weft yarns to the fabric face. The fabric would be singed during finishing.

'Limpness', 'slackness' and 'sleaziness' are fabric characteristics which are opposite to *koshi*. An 'underset' fabric would behave in a manner opposite to a fabric with a strong *koshi* feeling.

Shari

Shari is a PHV which is considered by the HESC to be extremely important to the characterization of the hand of summer suitings in Japan. Neither *shari* nor the final PHV to be considered, *hari*, is considered necessary for the description of the fabric hand of winter suitings. Both are uniquely (for menswear) required to characterize summer fabric hand. As indicated in Table 5.24, the preferred translation of *shari* is 'crispness'.

Table 5.24 English description of the Japanese primary hand expression *shari*

HESC:	*Crispness* 'A feeling that comes from crisp and rough surface of fabric. This feeling is brought by hard and strongly twisted yarn. This feeling brings us a cool feeling (this word means a crisp dry and sharp sound arisen by that the fabric is rubbed with itself'
Preferred word:	*Shari* = Crispness
Characteristic fabric:	A characteristic of the traditional 'Frescoe' as patented by Ganier (pre-WWII) or heavier 'thornproof' Border Tweeds (Reid and Taylor, Kynoch, Scotland)
Opposite characteristic:	Softness

Source: 'Quality attributes and primary hand expressions for wool fabric – English versions of the Japanese descriptions', by P. Wheelwright, T.J. Mahar, R. Postle and S. Sukigara, from *Proc. Third Japan–Australia Joint Symposium on Objective Measurement: Applications to Product Design and Process Control*, 1985. Reproduced with permission from the Textile Machinery Society of Japan.

The traditional 'frescoe' fabrics and the heavier 'thornproof' Scottish Border Tweeds are examples of fabrics whose hand is characterized by strong *shari*. 'Softness' is the opposite fabric attribute to shari.

Hari

The final PHV for men's suiting fabrics is *hari*, described in Table 5.25. The most appropriate single word for *hari* is 'boardiness'.

The traditional Bradford (UK) 'hair' cloths, e.g. 'Orleans', 'Brilliantines' and 'Sicilians', typify a strong *hari*. These fabrics are generally made with a worsted warp yarn and a coarser hair or blended wool coarse hair weft, and are firmly set. Similar strong *hari* hand can be obtained in fabrics by using coarse crossbred wools. A 'soft', 'clothy' fabric hand is the opposite of a strong *hari*.

5.6.3 Conclusion

The dedication and skill of the HESC in publishing standards for fabric hand have provided an opportunity to improve the level of communication about the aesthetic qualities of fabrics on an international basis, both within and between the textile and clothing industries.

Table 5.25 English description of the Japanese primary hand expression *hari*

HESC:	*Anti-drape stiffness* 'Anti-drape stiffness, no matter whether the fabric is springy or not'
Preferred word:	*Hari* = Hardness
Other word:	Boardiness
Characteristic fabric	Traditional Bradford (UK) 'hair' cloths (i.e. worsted warp, single, coarser hair or blended weft), firm sett, such as 'Orleans', 'Brilliantines', 'Sicilians', etc. Currently produced by oversett crossbred cloths with various proofing treatments
Opposite characteristics:	Softness Clothiness

Source: 'Quality attributes and primary hand expressions for wool fabric – English versions of the Japanese descriptions', by P. Wheelwright, T.J. Mahar, R. Postle and S. Sukigara, from *Proc. Third Japan–Australia Joint Symposium on Objective Measurement: Applications to Product Design and Process Control*, 1985. Reproduced with permission from the Textile Machinery Society of Japan.

The English versions of the Japanese primary hand expressions presented in this study are, of course, not unique. Indeed, in most cases, the word considered as the single most appropriate descriptor of a given primary hand expression has been nominated together with a group of words that have similar, but not the same, meaning.

The translations and descriptions presented here represent an educated attempt to build upon the work of the HESC in order to establish a sounder international basis for the assessment of the aesthetic qualities of fabrics both within and between the textile, clothing and fabric and garment merchandising and retailing industries. If agreement can be reached on acceptable English translations of the Japanese terminology with respect to the primary hand values, the English-speaking world will be better placed to take advantage of the unique opportunity provided by the HESC. A Japanese translation of English words is given in Table 5.26.

5.7 Measurement of fabric hand by different methods

In this comparison between the USA and Japan, a comprehensive study was designed to obtain results showing the effect of the following different procedures used [2]:

- commercial fabric from both countries
- type of yarns in the fabric and the raw material
- evaluation of primary hand value
- physical and mechanical properties and their relation to fabric hand

Table 5.26 Japanese translations of English words

List I	
Silkiness:	Kinu no youna hyoomen no utsukushisa
Softness:	Yawarakasa (Nuno o osaeta tokino)
Smoothness:	Namerakasa
Rawness:	Shiage no fujuubunsa
Harshness:	Araku, zarazara shita kankaku
Wiriness:	Harigane de kousei sareta you na nuno
Threadiness:	Fujuunun na shiage no tame, ito ga yoku wakaru (e.g. kibata)
List II	
Loftiness:	Koushyo, kedakai
Thinness:	Ususa
Sponginess:	Yawaraka ku pan o yaku mae no kigi o netta you na danryoku sei
Paperiness:	Kami no you
List III	
Resilience:	Danryoku sei
Springiness:	Hanekaeru chikara
Solidity:	Kataku mitsu de aru
Limpness:	Shinayakasa
Slackness:	Shimari ga nai
Undersett:	Shiage ga fujuubun de orikozo ga so de aru
Sleaziness:	Usuppera de orikouzou ga yowai
List IV	
Boardiness:	Ita no youna danryoku sei
Clothiness:	Yawarakaku, drape ga aru nuno. Ita no you dewa nai

Source: 'Quality attributes and primary hand expressions for wool fabric – English versions of the Japanese descriptions', by P. Wheelwright, T.J. Mahar, R. Postle and S. Sukigara, from *Proc. Third Japan–Australia Joint Symposium on Objective Measurement: Applications to Product Design and Process Control*, 1985. Reproduced with permission from the Textile Machinery Society of Japan.

- nozzle measurement or engineering evaluation of fabric hand
- subjective assessments by panels of judges from the two countries.

The 145 fabrics evaluated in the study were commercially available and mainly used for career uniforms. Woven fabric constructions of 100% polyester, 100% wool, and five polyester/wool blends were analyzed. Fabric weights ranged from 270 to 478 g/m on a 142.2 cm width basis. Polyester yarn types included 100% spun staple, 100% texturized continuous filament, and a combination of staple and texturized filament yarns.

5.7.1 Primary hand values

The fabrics were judged with standard samples for men's winter suits and also with standards for men's summer suits by Kawabata and Niwa. Primary hand values of *koshi*, *numeri*, and *fukurami* were obtained when fabrics were compared with the men's winter suiting assessments, and *koshi*, *shari*, *fukurami*, and *hari* were determined for the fabric samples from a comparison with men's summer suit standards.

5.7.2 Mechanical properties and total hand values

Measurements for selected mechanical properties of the fabrics were conducted by Kawabata and Niwa on the KES system. These tests are described in Appendix A and include tensile linearity, tensile energy, tensile resilience, bending rigidity, bending hysteresis, shear stiffness, shear at $\theta = 0.5°$, shear hysteresis at $\theta = 5.0°$, compression linearity, compression energy, compression resilience, coefficient of friction, mean deviation of coefficient of friction, geometrical roughness, fabric weight, and fabric thickness. Kawabata and Niwa calculated total hand values for summer and winter men's suit fabrics as given in detail in references 11, 19 and 20.

5.7.3 Nozzle measurements

Fabric samples were tested by the nozzle quantitative measure of hand developed by Alley and McHatton [21]. Hand modulus was calculated using the revised theory [22].

5.7.4 Subjective assessment

A panel of four experts from the textile industry [20, 23, 24] made a qualitative assessment of the fabrics. The end use of the materials was established as career uniforms. Fabric samples were judged in reference to a standard fabric. Ratings of the fabrics were established according to the scale given earlier (Table 5.4).

5.7.5 Physical tests related to fabric hand

Physical tests considered relevant to fabric hand were performed on the fabrics, including (a) cantilever bending: (1) bending length and (2) flexural rigidity; (b) compressibility; (c) cyclic bending: (1) coercive couple and (2) elastic flexural rigidity; (d) initial tensile; and (e) percent drape coefficient.

5.8 Results of fabric hand evaluation by different methods

5.8.1 Primary hand value

Statistical analyses were made by calculating the Spearman rank correlation coefficients to compare the various means of assessing fabric hand. Significance tests were conducted on these correlation coefficients at the 0.01 and 0.05 levels. The results of the significance tests of Kawabata's primary hand values compared with other tests are shown in Table 5.27.

Table 5.27 Results of significance tests of the correlation coefficients for primary hand values versus results of tests conducted

Tests conducted	*Koshi* (winter)	*Numeri* (winter)	*Fukurami* (winter)	*Koshi* (summer)	*Shari* (summer)
1. Subjective hand	*				
2. Hand modulus	**	**	**	**	**
3. Cantilever bending length	**	**	*	**	**
4. Cantilever flexural rigidity	**	*		**	**
5. Compressibility	**	*	**	**	
6. Cyclic bending – coercive couple	**			**	
7. Cyclic bending – elastic flexural rigidity	**			**	*
8. Initial tensile modulus	*			*	
9. Percent drape coefficient	**	**	**	**	**
10. Fabric weight	**	**	**	**	
11. Fabric thickness	*	**	**		*
12. Tensile linearity	**	**	*	**	**
13. Tensile energy	**				
14. Tensile resilience		**	**		
15. Bending rigidity	**	**		**	**
16. Bending hysteresis	**			**	**
17. Coefficient of friction	**			**	
18. Mean div. of coeff. of friction		**	**		**
19. Geometric roughness		**	*		**
20. Shear stiffness	**	**	**	**	**
21. Shear hysteresis, 0.5°	**	**	**	**	**
22. Shear hysteresis, 5.0°	**	**	**	**	**
23. Compression linearity					
24. Compression energy	**	**	**	**	*
25. Compression resilience		*			*
26. Thickness	**	**	**	**	**
27. Fabric weight	**	**	**	**	
28. Total hand value – winter	**	**	**		
29. Total hand value – summer				**	**

*Significant at 0.5 level.
**Significant at 0.01 level.
Source: 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.

5.8.2 Subjective hand assessment

Subjective hand assessment conducted in the previous study [24] was significantly correlated at the 0.01 level to the primary hand value *hari* (summer) and *koshi* (winter) at the 0.05 level. This indicated that stiffness properties as measured by the primary hand values in both *hari* (summer) and *koshi* (winter) were reflected in the other subjective evaluation, which shows a consistency in the US panel in response to the fabric stiffness.

5.8.3 Nozzle measurement or engineering evaluations of fabric hand

Hand modulus calculated from the nozzle measurement correlated significantly at the 0.01 level to all of the primary hand values with the exception of *fukurami*-summer (fullness and softness). This could be because most of the fabrics used tend toward the stiffer side. Also, the mechanics of flow through the nozzle might be influenced by fabric stiffness. The hand modulus also correlated significantly to *fukurami*-winter, perhaps because of the effect of the fabric weight. The negative correlations found between hand modulus and *numeri*-winter, as well as *fukurami*-winter, indicated that as the hand modulus increased, the primary hand values for both *numeri* and *fukurami*-winter decreased.

5.8.4 Effect of physical and mechanical properties on primary hand value

Table 5.28 sums up the correlation between primary hand value and physical properties 3–11 in Table 5.27 tested in the study by Behery [24]. The table shows the five physical properties with the highest significant correlations to each primary hand value. The percent drape coefficient and cantilever bending length were among the top five physical measurements correlated to every primary hand value. Cantilever flexural rigidity was correlated to all the primary hand values with the exception of *fukurami*-winter. A significant correlation between compressibility and each primary hand value was observed except for *shari*-summer. The cyclic bending measurement of the coercive couple was significantly correlated to *koshi*-winter, *koshi*-summer, and *shari*-summer, indicating the test detects stiffness. Significant correlations were noted between cyclic bending–elastic flexural rigidity and primary hand values, with the exception of *numeri*-winter and *fukurami*-winter.

Table 5.29 shows the mechanical properties that were most highly correlated to the primary hand values as measured by Kawabata's system (KES). Shearing and bending properties were reflected in the *koshi*-winter values, which

Table 5.28 The five most highly correlated physical test values for each primary hand value

Primary hand value	Physical test	Correlation
Koshi-winter	Percent drape coefficient	0.699
	Cantilever flexural rigidity	0.674
	Cantilever bending length	0.599
	Coercive couple	0.395
	Elastic flexural rigidity	0.371
Numeri-winter	Fabric thickness	0.418
	Percent drape coefficient	–0.368
	Cantilever bending length	–0.341
	Fabric weight	0.254
	Cantilever flexural rigidity	0.234
Fukurami-winter	Fabric thickness	0.554
	Compressibility	0.375
	Fabric weight	0.306
	Percent drape coefficient	–0.303
	Cantilever bending length	–0.234
Koshi-summer	Cantilever flexural rigidity	0.772
	Percent drape coefficient	0.756
	Cantilever bending length	0.737
	Elastic flexural rigidity	0.470
	Coercive couple	0.418
Shari-summer	Percent drape coefficient	0.444
	Cantilever bending length	0.404
	Cantilever flexural rigidity	0.361
	Fabric thickness	–0.193
	Elastic flexural rigidity	0.180
Fukurami-summer	Cantilever bending length	–0.526
	Fabric weight	0.418
	Percent drape coefficient	–0.320
	Elastic flexural rigidity	–0.319
	Cantilever flexural rigidity	–0.314
Hari-summer	Percent drape coefficient	0.723
	Cantilever flexural rigidity	0.699
	Cantilever bending length	0.658
	Coercive couple	0.496
	Elastic flexural rigidity	0.355

Source: 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.

represent fabric stiffness. Figure 5.10 shows the correlation between *koshi*-winter and the shear hysteresis at $\theta = 5.0°$.

Numeri-winter, which represents the fabric smoothness, was most highly correlated to surface properties. Fullness and softness as judged in the *fukurami*-

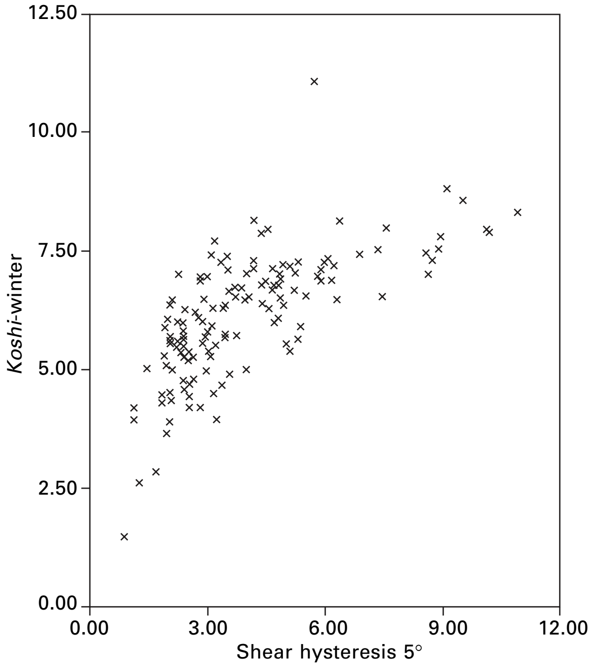
Table 5.29 The five most highly correlated mechanical tests of Kawabata for each primary hand value

Primary hand value	Kawabata's mechanical test	Correlation
Koshi-winter	Shear hysteresis, 5.0°	0.759
	Shear stiffness	0.747
	Shear hysteresis, 0.5°	0.684
	Bending rigidity	0.681
	Bending hysteresis	0.615
Numeri-winter	Mean deviation coefficient of friction	–0.786
	Fabric thickness	0.568
	Compression energy	0.502
	Geometric roughness	–0.465
	Shear hysteresis, 5.0°	–0.422
Fukurami-winter	Fabric thickness	0.835
	Compression energy	0.797
	Mean deviation coefficient of friction	–0.561
	Shear hysteresis, 5.0°	–0.369
	Tensile resilience	–0.357
Koshi-summer	Bending rigidity	0.770
	Shear hysteresis, 5.0°	0.744
	Shear hysteresis, 0.5°	0.721
	Bending hysteresis	0.698
	Shear stiffness	0.689
Shari-summer	Geometric roughness	0.732
	Mean deviation coefficient of friction	0.628
	Bending rigidity	0.370
	Tensile linearity	0.346
	Shear stiffness	0.338
Fukurami-summer	Tensile linearity	0.534
	Tensile energy	–0.510
	Fabric weight	0.426
	Compression resilience	0.410
	Bending rigidity	–0.374
Hari-summer	Shear hysteresis, 5.0°	0.792
	Bending hysteresis	0.751
	Shear stiffness	0.735
	Shear hysteresis, 0.5°	0.723
	Bending rigidity	0.647

Source: 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.

winter values were correlated to a variety of mechanical properties, including thickness and compression, reflecting the fullness and softness of fabrics.

The correlation between *fukurami*-winter and fabric thickness is shown in Fig. 5.11. *Koshi*-summer was correlated most highly to bending and shear characteristics in magnitudes similar to that of *koshi*-winter.



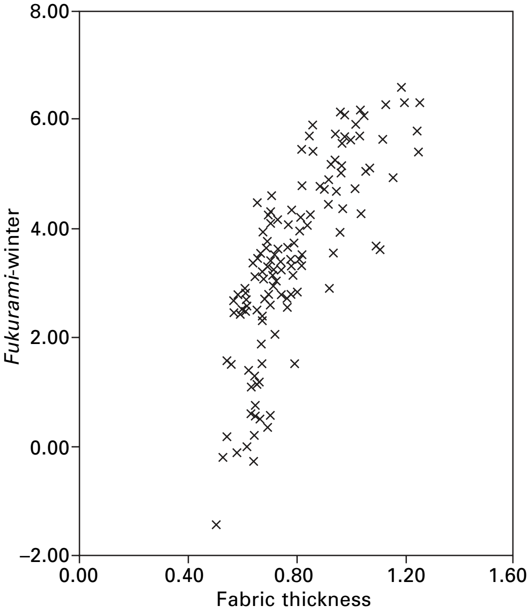
5.10 Correlation between *koshi*-winter and shear hysteresis at θ = 5.0°. *Source:* 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.

Crispness properties of *shari*-summer were related most to the surface qualities of geometric roughness and mean deviation of the coefficient of friction, as shown in Fig. 5.12.

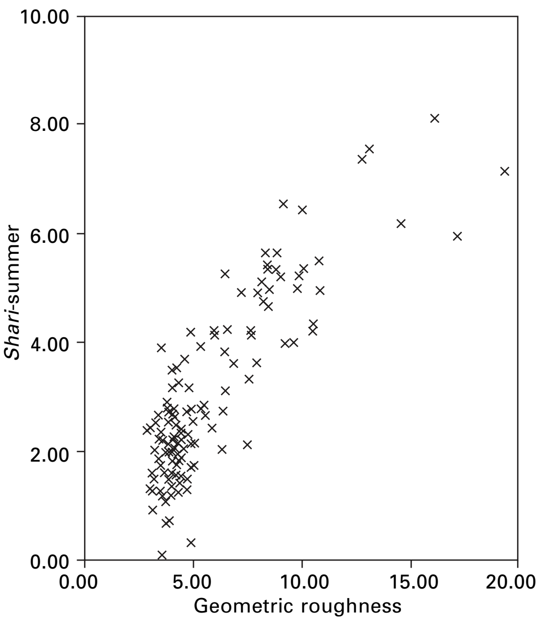
Significant correlations were noted between *fukurami*-summer and tensile properties as given in Fig. 5.13. *Hari*-summer was best represented by shearing and bending properties.

Figure 5.14 shows the correlation between *hari*-summer and the shear hysteresis at $\theta = 5.0°$. There are great similarities between both correlations shown in Figs 5.10 and 5.14.

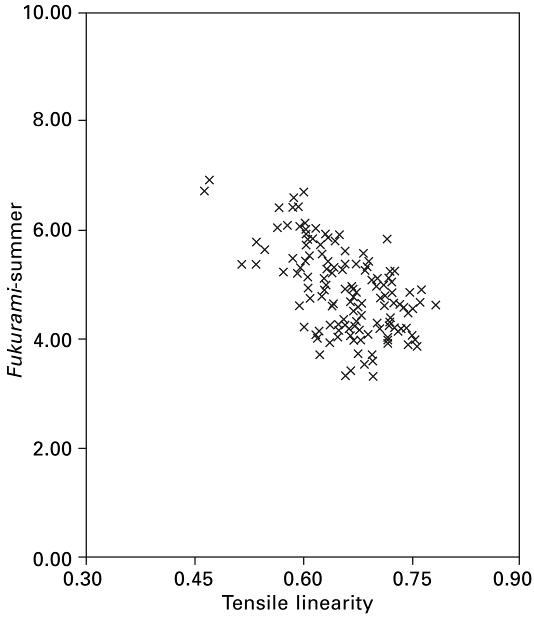
Correlations between the primary hand values were studied in the same fashion as Kawabata and Niwa [8] and are given in Table 5.30. High correlations were observed for *koshi*-winter versus *koshi*-summer, *koshi*-summer versus *hari*-summer, *koshi*-winter versus *hari*-summer, and *numeri*-winter versus *fukurami*-winter. Stiffness properties of a fabric were judged to be similar when compared to standards of *koshi* for summer or winter suits. Anti-drape stiffness as characterized in *hari* ratings was related to *koshi* (stiffness) for both winter and summer suiting. Properties of softness and fullness for men's



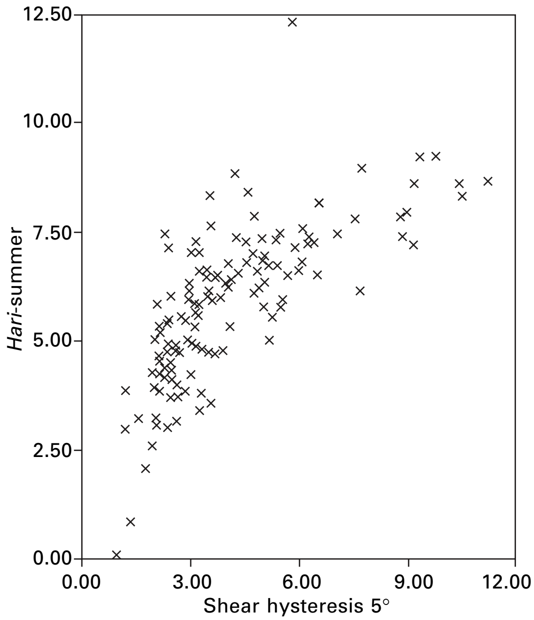
5.11 Correlation between *fukurami*-winter and fabric thickness. *Source:* 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.



5.12 Correlation between *shari*-summer and geometric roughness. *Source:* 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.



5.13 Correlation between *fukurami*-summer and tensile linearity. *Source:* 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.



5.14 Correlation between *hari*-summar and shear hysteresis at $\theta = 5.0°$. *Source:* 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.

Table 5.30 Correlation between primary hand values

	Koshi (winter)	*Numeri* (winter)	*Fukurami* (winter)	*Koshi* (summer)	*Shari* (summer)	*Fukurami* (summer)	*Hari* (summer)
Koshi-winter		–0.494**	–0.482**	0.944**	0.467**	–0.198*	0.921**
Numeri-winter			0.867**	–0.504**	–0.755**	0.476**	–0.426**
Fukurami-winter				–0.414**	–0.537**	0.394**	–0.372**
Koshi-summer					0.584**	–0.367**	0.927**
Shari-summer						–0.442**	0.497**
Fukurami-summer							–0.142
Hari-summer							

*Significant at 0.05 level.
**Significant at 0.01 level.
Source: 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.

suits were found in many fabrics that had a smoothness desirable for winter suiting.

No correlation at the 0.05 level existed for the relationship of anti-drape stiffness to fullness and softness. Kawabata's study of fabrics [19] reported a positive correlation for the relation between *fukurami*-summer and *hari*-summer, but this correlation was found to be negative for fabrics in Behery's study [24]. Positive correlations were observed in Kawabata's work, as well as our investigation, for *numeri*-winter versus *fukurami*-winter, *koshi*-summer versus *shari*-summer, *koshi*-summer versus *hari*-summer, and *shari*-summer versus *hari*-summer.

5.8.5 Total hand value and its interaction with other factors

Total hand values for winter suiting were most highly correlated to the primary hand values of *numeri* and *fukurami* as shown in Table 5.30. This indicated that smoothness, fullness, and softness were the fabric properties best represented by the total hand values. All three primary hand values were significantly correlated at the 0.01 level to the total hand value for winter suits. A negative correlation existed for the *koshi* (stiffness) primary hand value.

According to Kawabata's hand evaluation and standardization committee, koshi was more important than *fukurami* in the judgment of hand for winter suiting; however, in the study, a high correlation to total hand value was found with *fukurami* than *koshi*.

Summer suit total hand values were significantly correlated to primary hand values and expressions of *koshi*, *shari*, and *fukurami* at the 0.01 level. Significant correlations were found at the 0.05 level between the summer total hand values and *hari* (anti-drape stiffness). *Fukurami* (fullness and softness) was negatively correlated to the summer total hand value. Kawabata's work [19] found positive correlations for all the primary hand values as related to total hand value for summer. Total hand value for summer suiting was most highly correlated to *shari* (crispness).

A negative correlation was observed between THV-winter and THV-summer in Table 5.31, which shows correlations for the total hand values versus the subjective hand and hand modulus. Hand modulus was significantly correlated to the total hand value for men's winter suiting at the 0.05 level.

5.8.6 Comparison between conventional physical and mechanical properties and those measured by Kawabata's system

Correlations were examined between conventional physical tests conducted on the fabrics and similar tests performed by Kawabata's system; the results

Table 5.31 Correlation coefficients for total hand values versus subjective hand and hand modulus

	Total hand value: winter	Total hand value: summer
Subjective hand	–0.071	0.011
Hand modulus	–0.234*	0.089
Total hand value: winter		–0.420**

*Significant at 0.05 level.
**Significant at 0.01 level.
Source: 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.

are shown in Table 5.32). Significant correlations at the 0.01 level were observed for all these comparisons. A negative correlation occurred between the coefficient of friction values. The coefficient of friction measurements by Behery and Monson [23] used the inclined plane method under the fabric's own weight. Kawabata's method of determining the coefficient of friction was more representative of the surface roughness under a standard weight, so this method gives a higher value for rough surfaces and a lower value for smooth surfaces. The coefficient of friction as measured by the inclined plane method gives higher values for a smooth surface and vice versa for a rough surface. This is in agreement with previous findings by Bradbury and

Table 5.32 Correlation coefficients for Kawabata's KES measurements versus physical tests

Kawabata's KES measurements		Physical tests	Coefficient
Bending hysteresis	vs.	cyclic bending coercive couple	0.696**
Bending rigidity	vs.	cyclic bending elastic flexural rigidity	0.786**
Compression energy	vs.	compressibility	0.584**
Coefficient of friction	vs.	coefficient of friction	–0.342**
Fabric weight	vs.	fabric weight	0.991**
Fabric thickness	vs.	fabric thickness	0.759**
Tensile work recovery – W	vs.	tensile work recovery – W	0.615**
Tensile work recovery – F	vs.	tensile work recovery – F	0.543**

** Significant at 0.01 level.
Source: 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.

Reicher [25], in which they indicated that the yarn coefficient of friction is associated with the true area of contact.

Hand modulus values are significantly correlated at the 0.01 level to several of Kawabata's mechanical tests as indicated in Table 5.33. The highest significant correlations were noted between hand modulus and bending and shearing properties. Tensile linearity, tensile energy, coefficient of friction, and fabric weight were also significantly correlated at the 0.01 level. This indicates that the mechanics of the flow of the fabric through the nozzle are affected by most of the properties measured by Kawabata.

Table 5.33 Results of significance tests of the correlation coefficients for Kawabata's mechanical tests versus hand modulus and subjective hand values

Kawabata's KES measurements	Hand modulus	Subjective hand
Tensile linearity	**	*
Tensile energy	**	**
Tensile resilience		**
Bending rigidity	**	
Bending hysteresis	**	*
Coefficient of friction	**	**
Mean deviation of the coefficient of friction		
Geometric roughness		
Shear stiffness	**	**
Shear hysteresis at $\theta = 0.5°$	**	**
Shear hysteresis at $\theta = 5.0°$	**	**
Compression linearity		**
Compression energy	*	
Compression resilience		**
Thickness	*	*
Weight	**	*

* Significant at 0.05 level.
**Significant at 0.01 level.
Source: 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.

The tensile resilience was not significantly related to the hand modulus, as this property relates to the recovery of the material, which is a post-action to the passage of the fabric through the nozzle. The same explanation could also be provided for the non-significance of the correlation between the hand modulus and the compression resilience property.

The non-significance of the correlation between the geometric roughness, the coefficient of friction mean deviation, and the hand modulus could be explained as being due to the difference between the action of the material rubbing against the nozzle and the principle of the measurement of both the friction coefficient and surface roughness in the Kawabata system.

Correlations between the subjective assessment as measured by the US panel and Kawabata's (KES) measurements are also reported in Table 5.33. Subjective hand values were correlated most highly to shear properties, compression linearity, and tensile energy. Properties of tensile resilience and compression resilience were also noted to be significantly correlated at the 0.01 level. These properties seem to reflect the action of the hands and the responses to the tactile qualities of the fabrics.

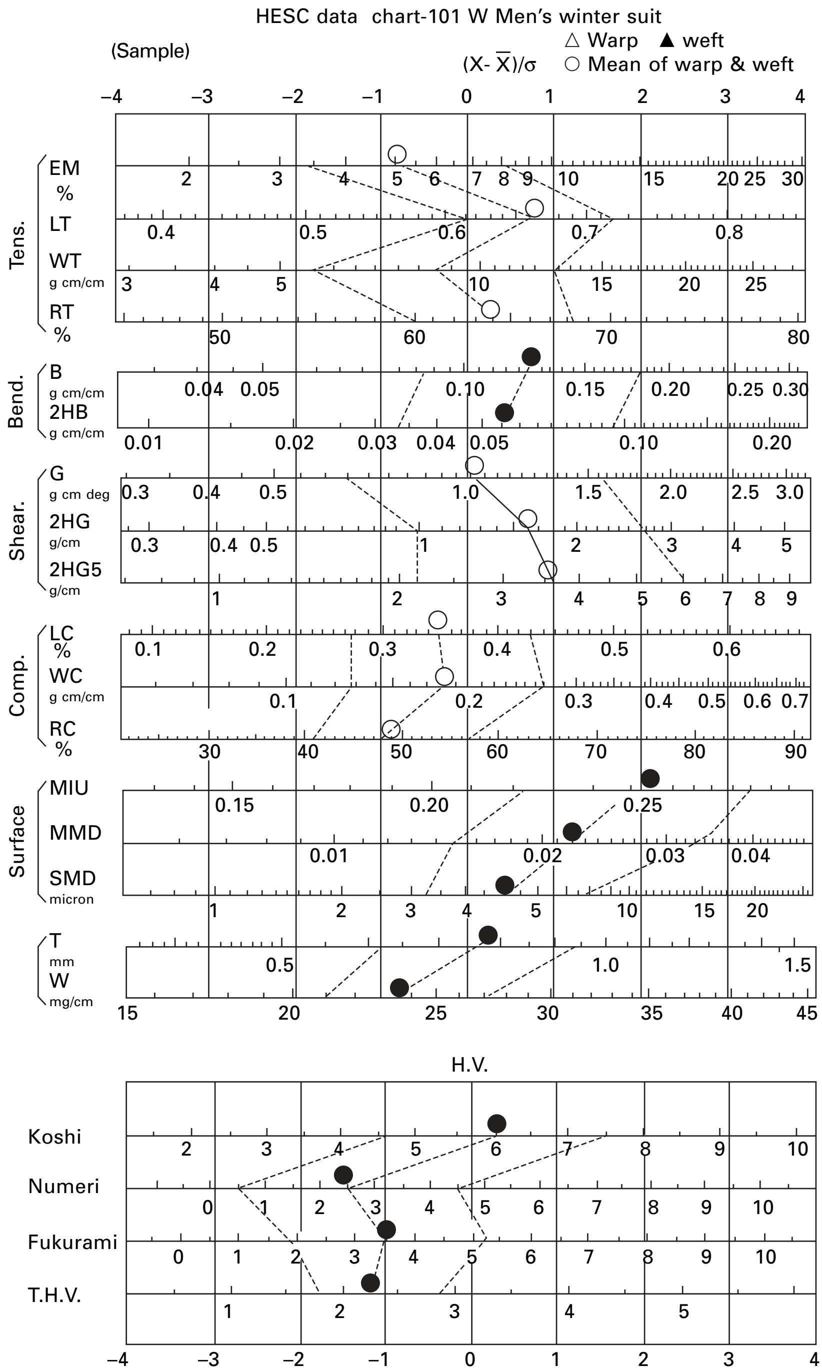
5.8.7 Comparison between US and Japanese fabrics

The study was further extended and a comparison made between fabrics produced in Japan similar to those used in the study. This analysis was done by Kawabata and Niwa [8] using a total of 214 samples for Japanese men's suiting versus the 145 US fabrics used in this study. The Japanese fabrics also included different types of fiber blends, yarns, and fabric constructions. For the summer men's suiting, the comparisons were made with 186 Japanese fabrics.

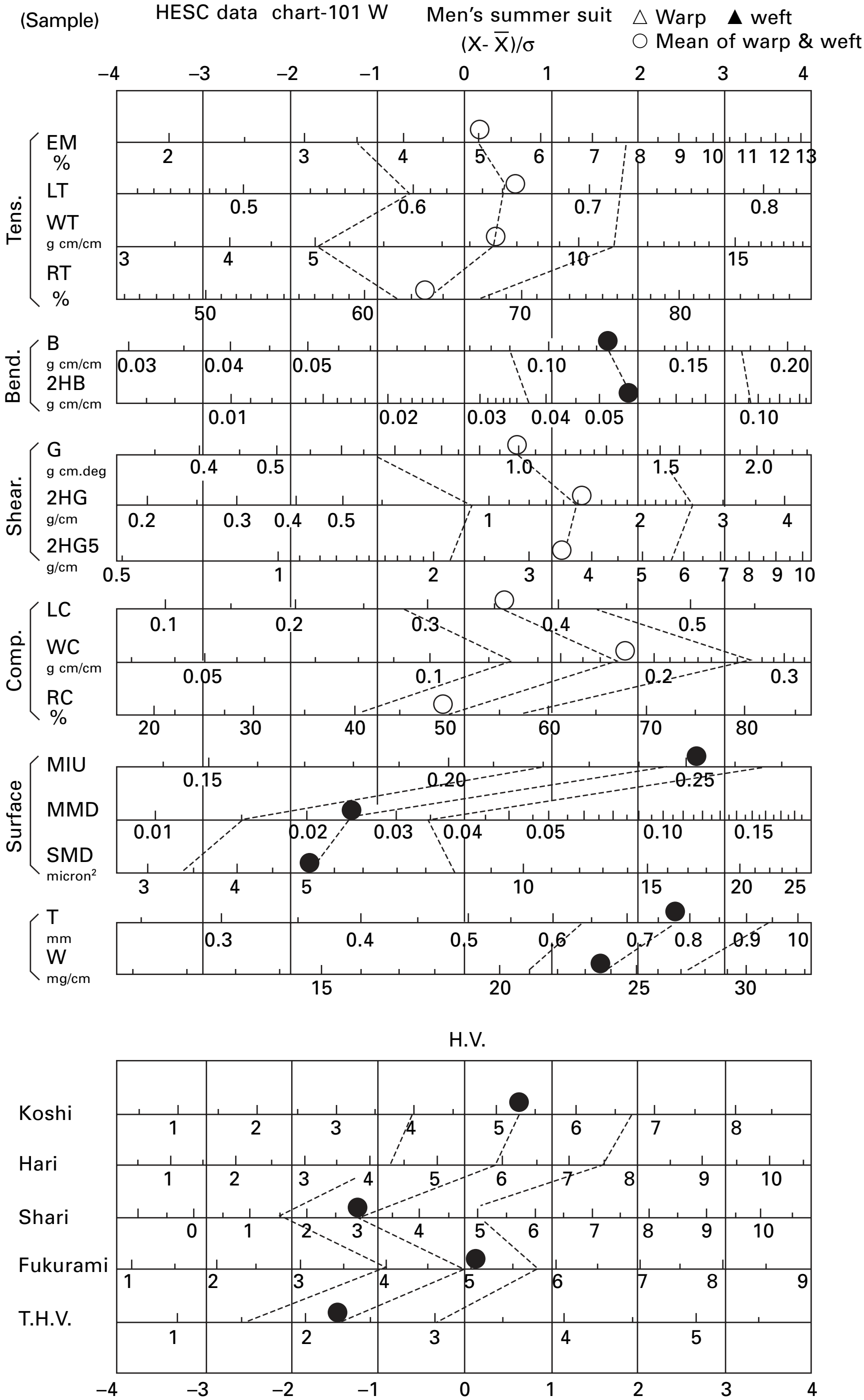
The HESC chart shown in Fig. 5.15 illustrates the deviation of the mean values of the different properties of the US winter suiting fabrics from the Japanese winter fabrics. The center line of value zero used as the reference value for the comparison represented the average of the properties of the Japanese fabrics. It is quite clear that the US fabrics had higher values in tensile, bending, and shear properties, as well as higher values of surface characteristics. The compression properties of the US fabrics were lower than the values for the Japanese fabrics except for the compressional energy, which was equal. This explains the difference of the hand values. Because of the higher tensile properties, the *koshi* value (stiffness) of the US fabrics was higher than that of the Japanese fabrics. On the other hand, the higher surface friction and roughness of the US fabrics showed lower hand values of *numeri* (smoothness) and *fukurami* (fullness and softness) for these fabrics. Also the total hand value for the US fabrics was lower than for the Japanese fabrics.

Figure 5.16 shows a similar comparison of US and Japanese summer suitings. Similar findings were obtained as in the case of winter men's suiting of Japanese fabrics. Note that the 145 US fabrics had weights ranging from 190 to 360 g/m, even though all the fabrics were chosen from those commercially available for career uniforms.

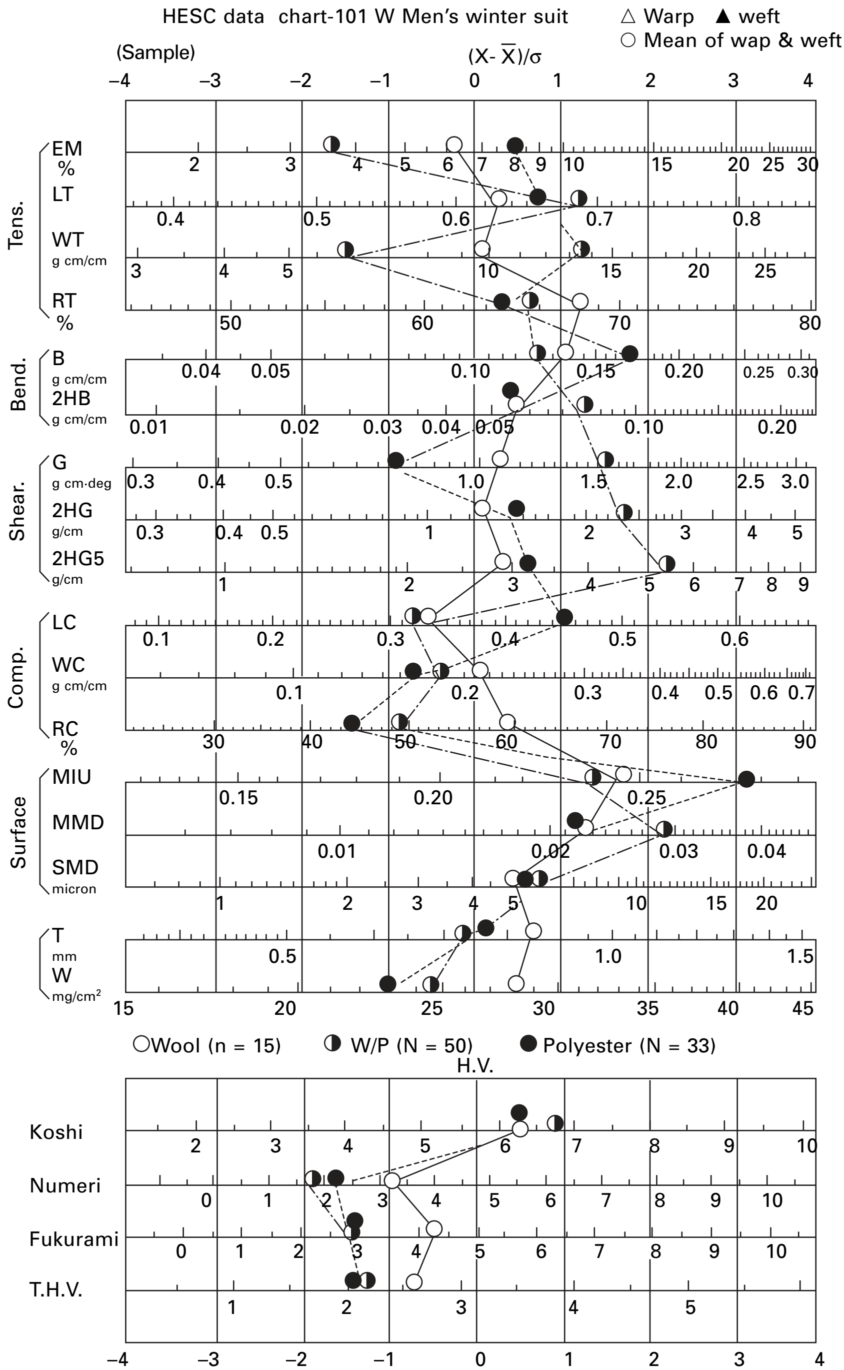
Three groups were chosen from the US fabrics and compared with similar fabrics from Japan: (a) 100% wool – 15 fabrics, (b) polyester/wool blends – 50 fabrics, and (c) textured polyester – 33 fabrics. The results of the comparison are shown in Fig. 5.17. One striking feature is that all the groups show the same trend: the US fabric properties are higher than those of the Japanese fabrics, resulting in lower hand values for *numeri*, *fukurami*, and total hand value, but higher hand value for *koshi*. This is also in full agreement with the



5.15 Comparison of properties measured by KES system and hand values between US and Japanese fabrics (men's winter suiting). *Source*: 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.



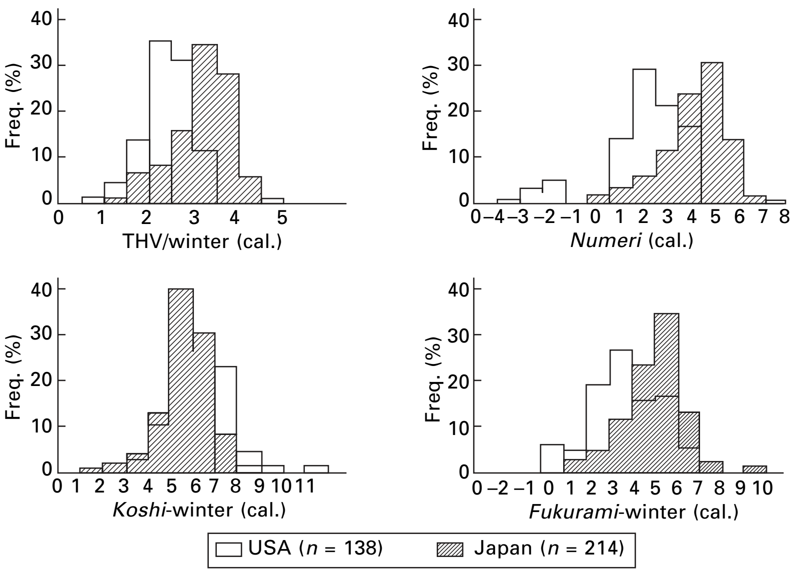
5.16 Comparison of properties measured by KES system and hand values between US and Japanese fabrics (men's summer suiting). *Source:* 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.



5.17 Comparison between 100% wool/polyester blends and 100% polyester fabrics made in USA and Japan. *Source:* 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.

comparison made when all the samples were taken together regardless of fiber type.

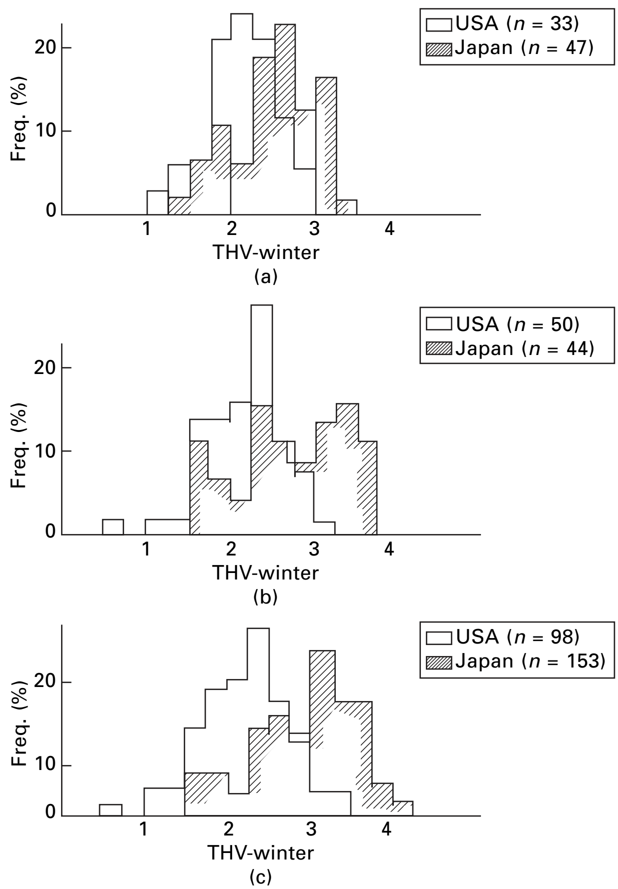
Figure 5.18 shows the distribution of primary hand values as calculated for *koshi*, *numeri*, and *fukurami*, as well as the distribution of total hand values for fabrics from the USA and Japan. These were calculated for winter men's suiting. The distribution indicated that there was good agreement in the fabrics evaluated with *koshi* (stiffness) for both US and Japanese fabrics, probably because the feel of stiffness was more or less consistent. For the other two primary hand values, *numeri* and *fukurami*, the Japanese fabrics tended to have more hand values in these categories than the US fabrics. For total hand value, the Japanese fabrics were distinctly different from and higher than the US fabrics.



5.18 Distribution of primary and total hand values for US and Japanese fabrics. *Source:* 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.

The distribution of total hand values for the fabrics, when divided into the three groups indicated previously, is shown in Fig. 5.19. The differences in the total hand values (winter) for fabrics made of textured polyester and wool/polyester blends were relatively small between US fabrics and Japanese fabrics. The Japanese fabrics tended to have higher total hand values than the US fabrics (Fig. 5.19(a) and b)).

When studying the fabrics of the three groups as a whole, the distribution

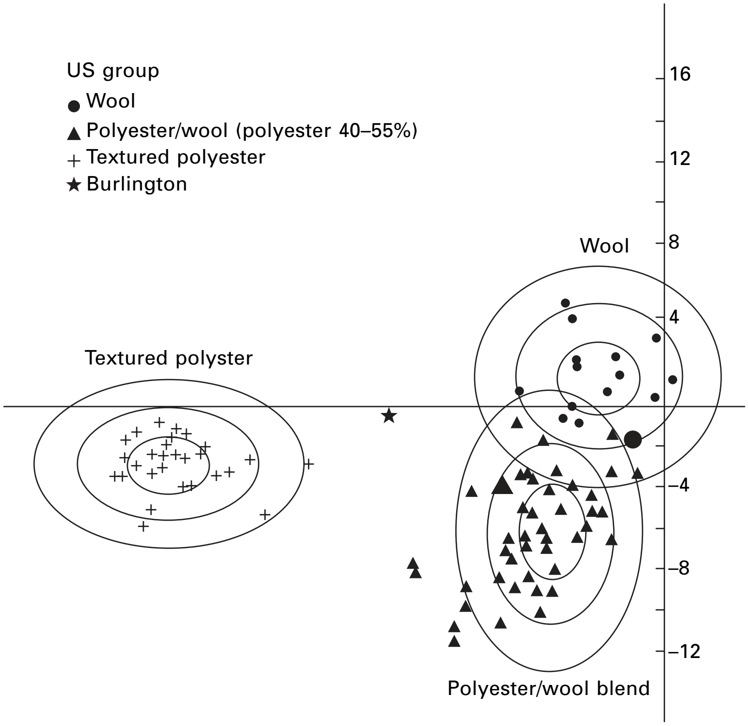


5.19 Distribution of total hand values (THV-winter) of (a) textured polyester; (b) polyester/wool; and (c) wool + polyester/wool + polyester. *Source:* 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.

of the total hand values is shown in Fig. 5.19(c). The difference between US fabrics and Japanese fabrics is very distinct, with the Japanese fabrics showing higher total hand values.

A discrimination analysis was conducted following the same procedure adopted by Kawabata and Niwa [20]. The results are shown in Figs 5.20 through 5.23. The fabrics used in the analysis were those identified by the three groups mentioned before: wool, wool/polyester blends, and textured polyester. The values of Z_1 and Z_2 were calculated from the following equations:

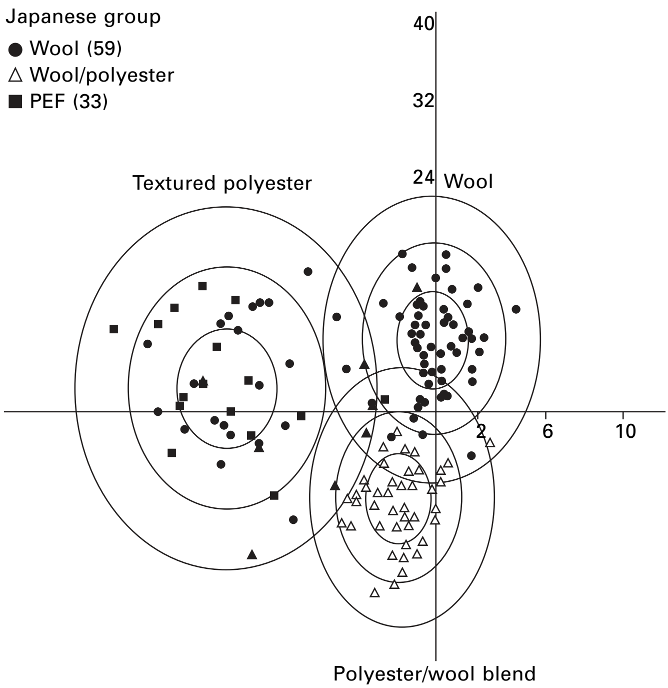
$$Z_1 = \sum_{i=1}^{16} \lambda_{1i} \left(\frac{X_i - \overline{X}_i}{\sigma_i} \right) \tag{5.6}$$



5.20 Two-dimensional discrimination mapping of three US fabrics. *Source:* 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.

$$Z_2 = \sum_{i=1}^{16} \lambda_{2i} \left(\frac{X_i - \overline{X}_i}{\sigma_i} \right) \tag{5.7}$$

where X_i represents the 16 different parameters measured by the KES system. The values for the discrimination analysis shown in Fig. 5.20 are given in Table 5.34. The graphs in Fig. 5.20 show a two-dimensional discrimination mapping of the three types of material. The values of Z_1 and Z_2 from equations (5.6) and (5.7) can separate the generic hands of the different materials. The graphs show the overlap between the wool and wool/polyester hands, while the textured polyester fabrics have a separate sort of hand that seems to be characteristic of these fabrics. The center point of each graph is shown in Table 5.35.

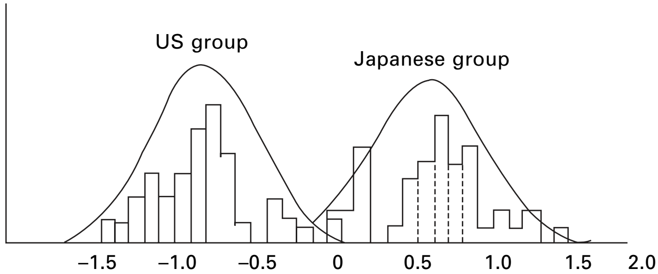


5.21 Two-dimensional discrimination mapping of three Japanese fabrics. *Source:* 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.

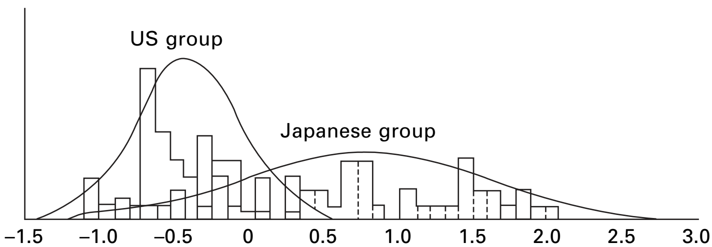
5.9 Conclusions from the comparison of fabric hand assessments between the USA and Japan measured by different methods

This study included the following five different methods and/or data by which the fabric hand could be assessed: hand modulus (by the nozzle method), subjective evaluation by a US panel of experts, testing of several mechanical properties (Behery [24], Kawabata's (KES) system (primary hand value), and Kawabata's (KES) system (total hand value)). It was concluded that there was a fairly good agreement between the quantitative approaches used in this study. There were few overlaps between the data obtained from these methods as shown by this discrimination analysis. This resulted in some differences in the hand evaluation.

The other conclusion worth pointing out is the difference in the hand of fabrics in the USA and Japan. The striking feature is the consistency and the degree of the differences, though the fabrics were obtained from various producers in the two countries. The mechanical properties of the fabrics were also different and this resulted in different assessments of



5.22 Comparison of discrimination analysis of textured polyester fabrics from US and Japanese groups. *Source:* 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.



5.23 Comparison of discrimination analysis of US and Japanese fabrics for properties relating to bending only. *Source:* 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.

tailorability, with the USA fabrics showing better tailorability than the Japanese fabrics.

5.10 Fabric hand globalization interaction in the textile industry

5.10.1 Standards for fabric hand

The question arises as to whether it is feasible to construct an internationally acceptable scale of fabric hand standards development. Clearly, in view of the results summarized before, this task is more difficult for lightweight summer fabrics than for winter-weight fabric where the level of agreement is very good for all countries considered so far in the international hand survey. Such fabric hand standards could then be specified in objective terms through the 16 fabric mechanical parameters quoted in Table 5.33. This procedure could prove a scientific basis for an objective system of measuring overall fabric quality as shown in Fig. 5.19.

Table 5.34 Values of λ_{1i} and λ_{2i} for determination of Z_1 and Z_2 for wool, polyester/wool blend, and polyester textured fabrics for the 16 parameters

X_i^a	λ_{1i}	λ_{2i}
1. LT	–0.0645	–0.6482
2. log WT	–0.2054	1.4229
3. RT	0.0484	–0.2881
4. log B	–1.0524	2.5218
5. log 2HB	0.5424	–2.0117
6. log G	1.2462	1.9681
7. log 2HG	0.1557	1.5406
8. log 2HG5	–1.4999	–3.5823
9. LC	–0.2823	–1.5067
10. log WC	–0.2628	0.3235
11. RC	–0.0858	0.7927
12. MIU	–0.4003	0.0687
13. log MMD	–0.0043	–0.3112
14. log SMD	0.3144	0.2236
15. log T	–0.1846	–1.5543
16. log W	1.0000	1.0000

[a] The key to these abbreviations is given in Appendix A.
Source: 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.

Table 5.35 Center points of discrimination charts for wool, wool/polyester, and textured fabric

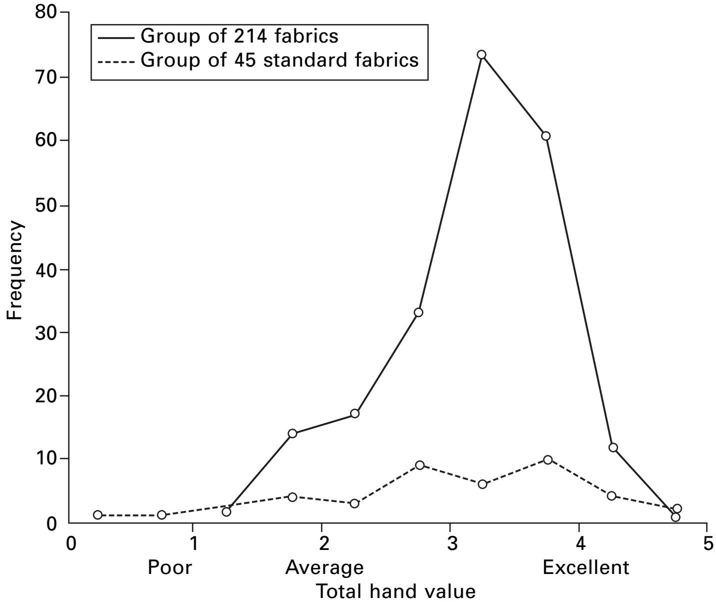
Center point for discrimination graphs	Z_1		Z_2	
	$\breve{Z}_1$	σ_1	$\breve{Z}_2$	σ_2
Wool	–0.8153	0.5022	1.4355	1.8214
Wool/polyester blend	–1.4250	0.3723	–6.1878	2.3432
Textured polyester	–6.1017	0.5520	–2.8378	1.3756

Source: 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.

A frequency distribution for a series of 40 winter fabric hand standards, prepared jointly from Japanese and Australian fabric hand assessments, is shown by the dashed line in Fig. 5.24. The full line shows the frequency distribution for the population of 214 men's winter suiting fabrics from which the hand standards were derived.

5.10.2 Management of fabric hand property

It is significant to realize that substantial technological developments have been achieved in past years by chemical and physical modification of both



5.24 Frequency distribution for a series of forty winter fabric hand standards from Japanese and Australian fabric hand assessments. *Source:* 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.

natural and synthetic fibers in order to improve specific performance characteristics of the resultant fabrics. Relatively little emphasis has been placed until now on the fabric engineering approach whereby the use of different fiber qualities or varieties is combined with the optimization of yarn and fabric construction in order to produce superior fabrics and garments for specific end uses and with the hand that renders the product appealing, attractive and marketable.

5.11 References

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