9—
Micromeasurement of the Mechanical Properties of Single Fibers

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I—
Introduction

There is a strong anisotropy in the mechanical properties and strength of fibers. This is caused by the strong orientation of molecular chains along the direction of the fiber's axis. Clarification of the details of these fiber properties is necessary for both the science of oriented polymers and the engineering needed to apply these fibers to various fibrous structures and fiber-composite materials. Because of the difficulty in directly measuring single fibers due to the very small size of the fibers, fiber mechanical properties are usually estimated by an indirect method such as the measurement of a fiber bundle or fiber/resin composites. Even though this difficulty exists, direct measurement is desirable and necessary for more precise research on fibers and fiber assembly bodies.

The single-fiber measurement eliminates the uncertainty of measurement caused by the indirect method. One difficulty in direct measurement is, however, the measurement of the very small force and deformation caused by the small size of the fiber. Recently, a system of directly measuring the mechanical properties of single fibers was developed [1], and the anisotropy in the mechanical properties and the strength of various fibers have been clarified using this system [1,3,4,7–16]. This new measurement was named *micromeasurement* by the author and is introduced in this chapter.

II—
Anisotropy in Mechanical Properties

Consider an elastic body, being referred to an orthogonal set of cartesian axes X_1, X_2, X_3 as shown in Figure 1, whose mechanical properties are represented by the following linear equations [2]:

$$\sigma_i = \sum_{j=1}^{6} C_{ij} e_j \quad (1)$$

or

$$e_i = \sum_{j=1}^{6} S_{ij} \sigma_j \quad (2)$$

where σ_i(i = 1–6) is the engineering component of stress and ei (i = 1–6) is the engineering component of strain. The terms σ_1, σ_2, and σ_3 correspond to the normal components of the stress acting on the X_1, X_2, and X_3 planes, respectively, and σ_4, σ_5, and σ_6 are the shear stress components of the stress acting on these planes, respectively. The terms e_1, e_2, and e_3 are the normal strains along the X_1, X_2, and X_3 axes, respectively and e_4, e_5, and e_6 are the shear strain on the X_1, X_2, and X_3 planes, respectively. The terms C_{ij} and S_{ij} (i,j = 1–6) are elastic constants representing material properties and are called the stiffness constants and compliance constants, respectively. This relationship, Eq. (1) or (2), is called the generalized Hooke's law. When the body is isotropic, S_{ij} is represented by the following matrix, where S_{ij} is the value of the compliance of the ith row and jth column:

$$S_{ij} = \begin{bmatrix} S_{11} & S_{12} & S_{12} & 0 & 0 & 0 \\ S_{12} & S_{11} & S_{12} & 0 & 0 & 0 \\ S_{12} & S_{12} & S_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & 2(S_{11} - S_{12}) & 0 & 0 \\ 0 & 0 & 0 & 0 & 2(S_{11} - S_{12}) & 0 \\ 0 & 0 & 0 & 0 & 0 & 2(S_{11} - S_{12}) \end{bmatrix} \quad (3)$$

There are only two independent parameters among the S_{ij}, S_{11} and S_{12}. In the case of uniaxial extension along the X_1 axis ($\sigma_2 = \sigma_3 = 0$) in Fig. 1, we have

$$e_1 = S_{11}\sigma_1 \quad (4)$$

Hooke's law is expressed as

$$e_1 = (1/E)\sigma_1 \quad (5)$$

From Eqs. (4) and (5),

$$S_{11} = 1/E \quad (6)$$

where E is Young's modulus.

Poisson's ratio ν is defined by the strain ratio under the uniaxial extension along the X_1 axis ($\sigma_2 = \sigma_3 = 0$) as follows:

$$\nu = -e_2/e_1 \quad (7)$$

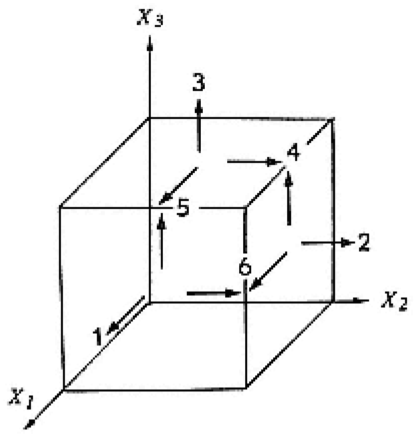

Figure 1
Coordinate system and the suffix numbers indicating the engineering components of stress and strain.

From Eqs. (2), (3), and (5),

$$S_{12} = -\nu/E \tag{8}$$

The term $2(S_{11} - S_{12})$ is equal to 1/G where G is the shear modulus and, from Eqs. (6) and (8), there is a relationship such that

$$G = E/[2(1 + \nu)] \tag{9}$$

In the case of the isotropic body, there are two independent mechanical constants, any two of E, G, and ν.

Because of the molecular orientation along the fiber axis (the X_3 axis in the coordinates in Figure 2), fibers have strongly anisotropic mechanical properties, Young's modulus along the fiber axis is different from that in the direction transversing the fiber axis. In the fiber cross-sectional plane the X_1–X_2 plane, the property is isotropic because of the symmetric structure of the fiber about its axis. Such an anisotropy is called *fiber symmetry*; the modulus along the fiber axis is normally higher than the modulus along the transverse direction.

The compliance constants S_{ij} of the fiber symmetric body are shown by Eq. (10). This matrix form may be derived by the symmetric condition

$$S_{ij} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & 0 & 0 & 0 \\ S_{12} & S_{11} & S_{13} & 0 & 0 & 0 \\ S_{13} & S_{13} & S_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & S_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & S_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & 2(S_{11} - S_{12}) \end{bmatrix} \tag{10}$$

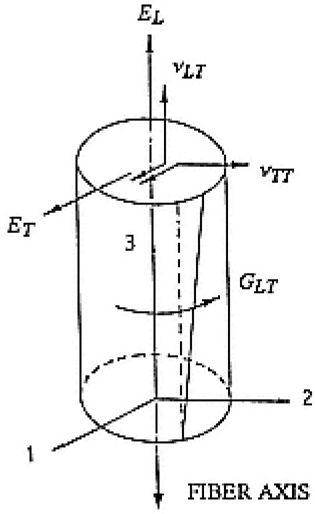

Figure 2
Fiber symmetric
anisotropy of fiber.

The S_{ij} of Eq. (10) may be expressed with moduli as follows.

$$S_{ij} = \begin{bmatrix} 1/E_T & -\nu_{TT}/E_T & -\nu_{LT}/E_L & 0 & 0 & 0 \\ 0 & 1/E_T & -\nu_{LT}/E_L & 0 & 0 & 0 \\ & & 1/E_L & 0 & 0 & 0 \\ & & & 1/G_{LT} & 0 & 0 \\ & \text{(Symmetric)} & & & 1/G_{LT} & 0 \\ & & & & & 2(1+\nu_{TT})/E_T \end{bmatrix} \quad (11)$$

There are five independent elastic constants that represent the material property of the fiber symmetry body. They are

E_L, longitudinal modulus (= $1/S_{33}$)

E_T, transverse modulus (= $1/S_{22} = 1/S_{11}$)

G_{LT}, longitudinal shear modulus (= $1/S_{44}$)

ν_{LT}, longitudinal Poisson's ratio (= $-S_{13}E_L$)

ν_{TT}, transverse Poisson's ratio (= $-S_{12}E_T$)

The terms E_L and E_T are the modulus along the fiber axis and its transverse direction, respectively, and G_{LT} is the shear modulus related to the torsion of the fiber about the fiber axis. The longitudinal Poisson's ratio ν_{LT} is defined by $-e_1/e_3$ (or $-e_2/e_3$) in the uniaxial extension of the fiber in the longitudinal direction—the X_3 axis direction in Fig. 2. The transverse Poisson's ratio ν_{TT} is the Poisson's ratio in the fiber cross-sectional plane and defined by the strain ratio $-e_2/e_1$ in the uniaxial extension in the X_1 direction, or $-e_1/e_2$ in the uniaxial extension in the X_2 direction. It is necessary to measure these five constants for the characterization of fiber mechanical property even if the linear elasticity of the fiber is assumed. When a fiber has nonlinearity in its mechanical behavior, we have to measure these nonlinearities for at least the three deformation modes: the longitudinal, transverse, and torsional deformation modes. The in-plane shear deformation in the cross-sectional plane corresponds to the shear modulus G_{TT} (= $1/S_{66}$), and this modulus may be replaced by $2(S_{11} - S_{12})$ in the linear case as shown in Fq. (10). However, this relation is not valid in the nonlinear case. When the fiber property is viscoelastic, we have to characterize it for each of these deformation modes. These characterizations of the fiber properties are important, The mechanical anisotropy of the fiber strictly reflects the microstructure of the fiber. In the research on the micromechanics of fiber/resin composites, all of the compliance constants in Eq. (10) are necessary for the stress analysis of the composite, especially the matrix/fiber in the interface region. In this chapter, this micromeasurement of single fibers is introduced.

III— Micromeasurement

A— The Longitudinal Modulus E_L

The mechanical noise of the tensile tester must be kept to a minimum [1]. A single fiber approximately 5–10 cm in length is reinforced at both ends by gluing pieces of paper with adhesive so that it can be clamped by a chuck in a tensile tester as shown in Figure 3.

The E_L is measured from the slope of the stress—strain curve of, for example, a constant rate of extension. The E_L of a fiber in the longitudinal compression mode is not necessarily the same as that in the extension mode. The tensile E_L of most organic fibers is normally larger than the compressional E_L. The measurement of the longitudinal compression property was carried out for Kevlar 29 (aramid fiber) using a microcomposite method [3,4,17]. A uniaxially oriented fiber composite of Kevlar 29 and epoxy resin, 5 mm in length, 1 mm in diameter, was prepared and compressed in its fiber direction as shown in Figure 4. The compression modulus of the composite was converted into a fiber modulus by applying the simple mixture law as follows:

$$E_c = V_f E_f + V_m E_m \qquad (12)$$

where E_c, E_f, and E_m are the compression modulus of the composite, fiber, and matrix resin respectively, and V_f and V_m are the volume fraction of the fiber and matrix, respectively, where $V_f + V_m = 1$.

This simple equation is reliable with a high-volume fraction of fiber. The V_f of the specimen used in this experiment was around 0.85–0.9. This small size of

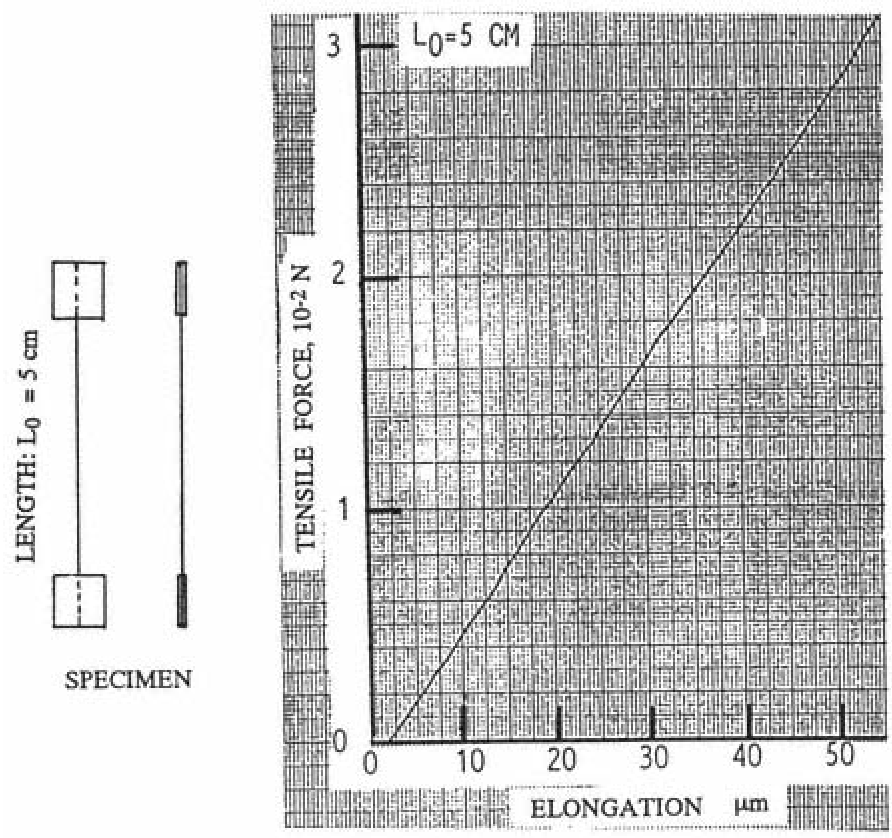

Figure 3
Specimen of a single fiber for the tensile testing and the initial region of a loadelongation curve of Kevlar 29 single fiber measured by a low-mechanical-noise tensile tester.
(From Ref. 1.)

the composite enables such a high fraction. The complete longitudinal property of the Kevlar 29 fiber is shown in Figure 5. The tensile region was measured by the single-fiber extension measurement, and the compression region was measured by the microcomposite method. Note that both curves are smoothly connected to each other even though they were measured separately. As seen in this curve, the compression strength is much weaker than the tensile strength.

B—
Transverse Modulus E_T

In order to investigate the fiber transverse property, the transverse compression method of single fiber was applied, and a new tester was built as shown in Fig-

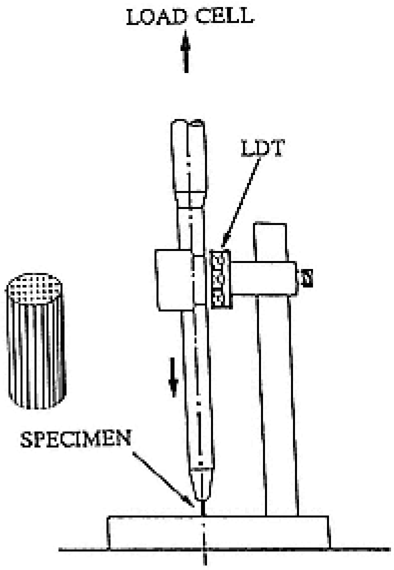

Figure 4
Longitudinal compression testing
of fiber using the microcomposite
method.
(From Refs. 3, 4 and 17)

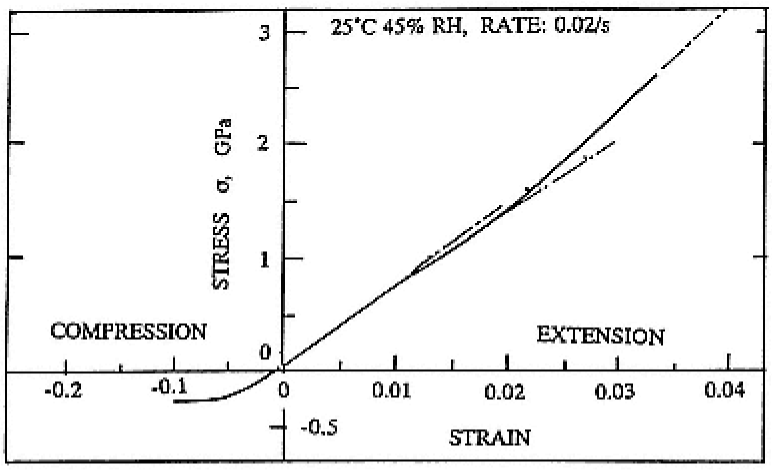

Figure 5
The longitudinal property of Kevlar 29 fiber.
(From Refs. 3, 4 and 17)

ures 6 and 7 [1,7]. A single fiber is placed on a flat steel bed that has a mirror-finish surface. The fiber is compressed by a hard steel compression rod. The tip of the rod has a contact plane of 0.2 × 0.2 mm^2. Its surface is also given the same type of mirror finish as the bottom plane. The compression rod is connected to an electromagnetic power driver with a load capacity of 50 N. A force transducer connected to the compression rod detects the compressional force. The linear differential transformer (LDT), which is also connected to the compression rod, directly detects very small changes in the diameter of the fiber without error arising from the compliance of the force transducer, as the transducer is mounted outside the deformation-detecting system. The resolution of the LDT is 0.05 µm.

An equation that describes the diametral change U in a fiber with a circular cross section as a function of the transverse compressional force per unit length of fiber F has been derived for an anisotropic body by Ward et al. [2,5,6] and is based on the equation derived by McEwan in 1949 for an isotropic body as a solution to the contact problem. The equation derived by Ward is as follows:

$$U = (4F/\pi)[(1/E_T) - (\nu^2_{LT}/E_L)][0.19 + \sinh^{-1}(R/b)] \quad (13)$$

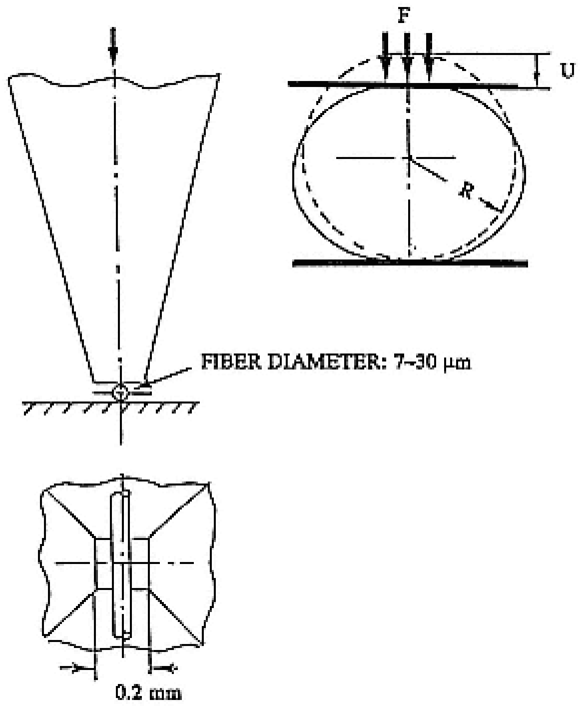

Figure 6
Compression of a single fiber
in the transverse direction.

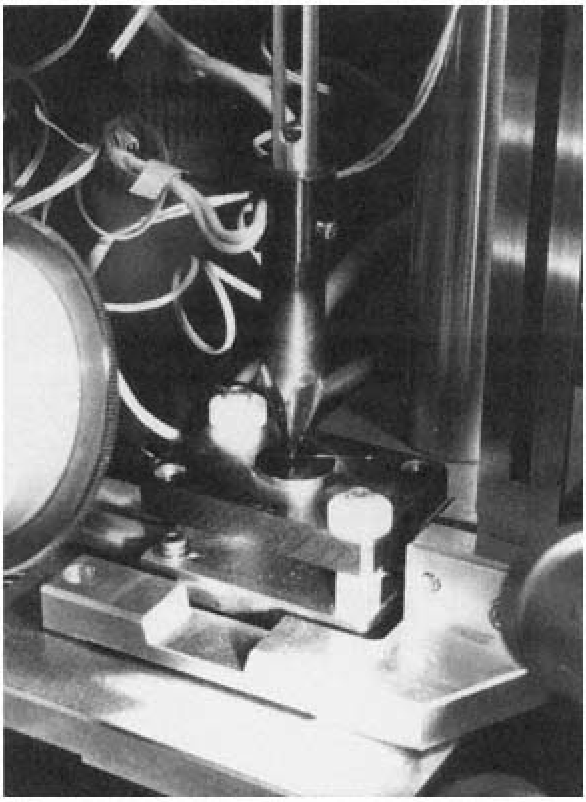

Figure 7
Transverse compression tester.

where b is given by

$$b^2 = (4FR/\pi)[(1/E_T) - (\nu_{LT}^2/E_L)] \quad (14)$$

and R radius of the fiber. When $\nu_{LT}^2/E_L \ll 1/E_T$, the term ν_{LT}^2/E_L in Eqs. (13) and (14) may be eliminated and these equations become simpler. From our investigation [6], it was found that the degree of error caused by this equation simplification is about 1% of the exact value of E_T. From these equations, E_T is obtained by measuring the relation between F and U by transverse compression and solving Eq. (13).

The transverse compression curves of Kevlar 149, Kevlar 49, and Kevlar 29 are shown in Figure 8 [6].

As seen in this figure, the Kevlar fibers have a clearly ductile property in their transverse direction, while the yielding does not appear in the tensile property of these Kevlar fibers in the longitudinal direction. Also, the yielding stress is much

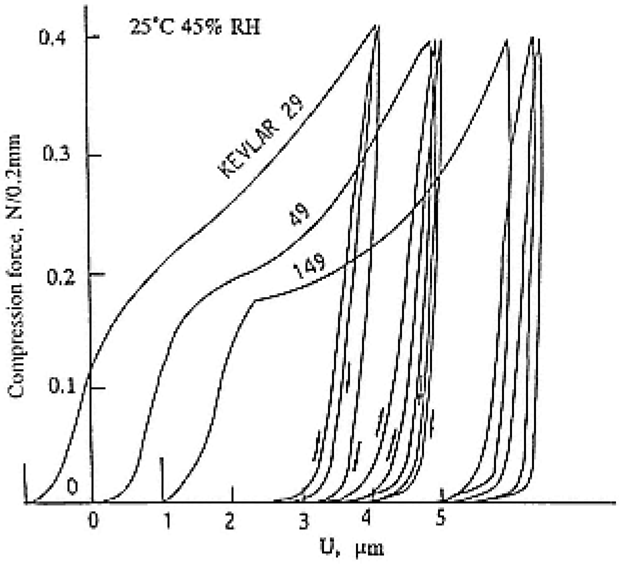

Figure 8
Transverse compression properties of the Kevlar fibers.
(From Ref. 6.)

lower than the longitudinal tensile strength, as shown later for Kevlar 29 in Table 1. Carbon fibers and ceramic fibers, however, do not exhibit a behavior of yielding in the transverse compression property, and show a tendency for brittle fracture as well in their longitudinal properties. Also, their transverse strength is much higher than that of organic fibers, as shown in Figure 9. The relationships between E_L and E_T for various fibers and between E_T and breaking stress or yielding stress of the same fibers are shown in Figures 10 and 11, respectively [6].

C—
Shear Modulus G_{LT}

The shear modulus G_{LT} is obtained from the torsion of the fiber (Fig. 12) about the fiber axis. For a cylindrical rod, the G_{LT} is obtained as follows:

$$G_{LT} = TL/(\theta I_p) \qquad (15)$$

where T is torque, L is length of specimen, θ is torsional angle (rad), and I_p is torsional moment of inertia of area, given for a cylindrical rod of diameter D by

$$I_p = \pi D^4/32 \qquad (16)$$

The shear strain at the fiber skin is $\gamma = \theta D/(2L)$ and the skin stress is $\sigma = \theta D G_{LT}(2L)$.

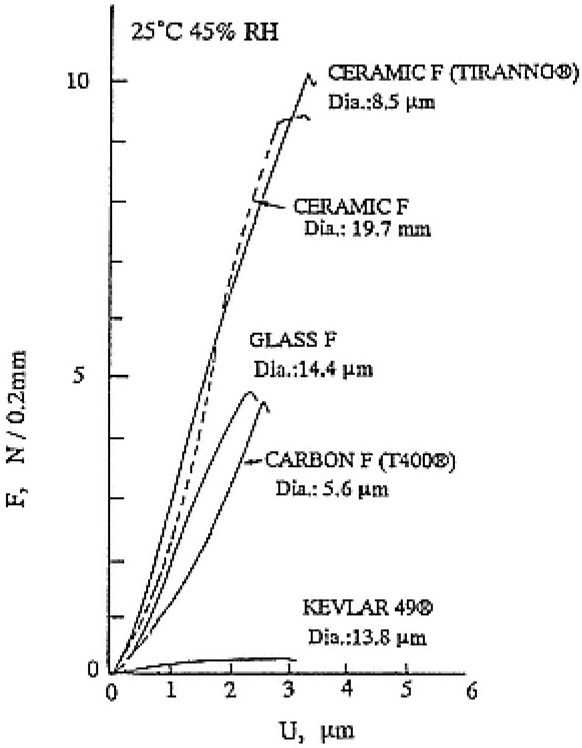

Figure 9
Transverse compression property of carbon
and ceramic fibers.
(From Ref. 6.)

When the torsion of a single fiber of D = 14 µm, L = 5 mm, and G_{LT} = 2 GP_a is measured, the torque T is approximately 70 nN m (0.7 mg cm) at torsion angle $\theta/L = 6\pi \times 10^3$ rad/m, which is the torsion angle range normally measured. This small torque is caused by the small diameter of a single fiber. A highly sensitive torque transducer for this torque range has been developed [1]. The mechanism of the torsion tester is shown in Figure 13 and the tester is shown in Figure 14 [1].

A typical torque—torsional angle relation is shown in Figure 15 for a Kevlar 49 single fiber. A constant rate of torsion was applied at a rate of 0.53.π rad/s. The shear modulus was obtained from the initial slope of the curve.

As seen from this figure, yielding is observed also in the torsional property. In the region larger than the yielding torque, optical microscopy observation of the fiber surface reveals diagonal lines. After repeated torsion, many such lines are observed and fiber splitting along the fiber axis is initiated from these lines that leads the fiber to a state of reduced shear stiffness, and then fiber failure [8].

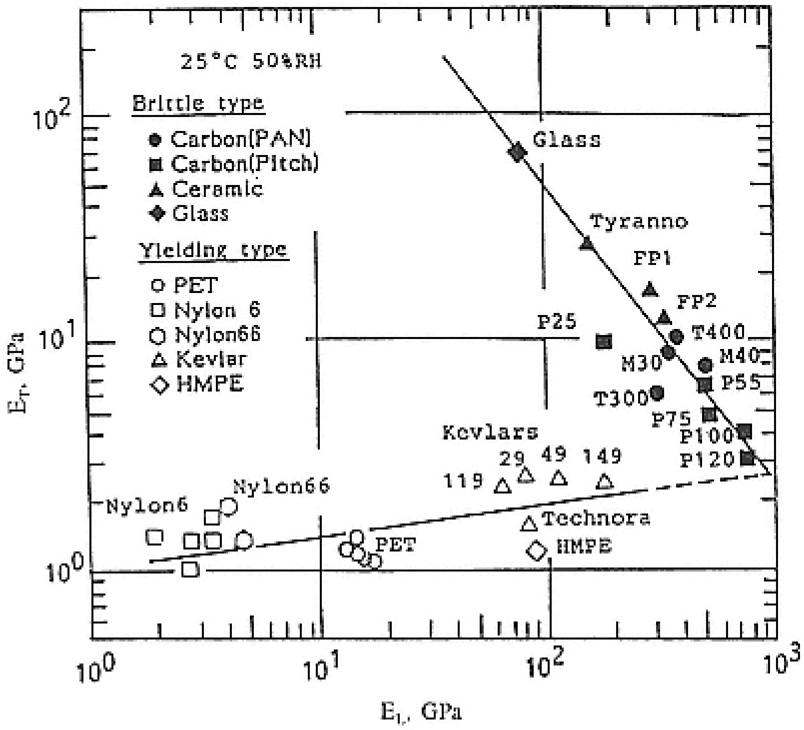

Figure 10
Relation between E_L and E_T. The brittle type group and ductile group meet where E_L is approximately 1000 GPa, which is near the modulus of diamond, the ultimate material.
(From Ref. 6.)

D— Measurement of Poisson's Ratios, ν_{LT} and ν_{TT}

The ν_{LT} may be measured by measuring the change in fiber diameter that occurs with fiber longitudinal extension. A special tester with a resolution of 0.01 µm was designed for detecting fiber diameter change as shown in Figure 16 [15]. The ν_{LT} is measured from the slope of the e_L-e_T relation curve as shown in Figure 17 [15]. A single-fiber measurement for ν_{TT} is not possible at present. We have estimated this parameter from ν_{TT} by measuring the Poisson's ratio of a unidirectional fiber composite plate by the ordinary strain gauge method.

E— Anisotropy in the Mechanical Properties of Fibers

Table 1 lists a full set of elastic constants for Kevlar 29 fiber [3]. These constants were measured in an atmospheric condition of 25°C, 45% RH. The G_{LT} values of some fibers are shown with their E_L and E_T in Table 2 [3,4,7,10–13,16].

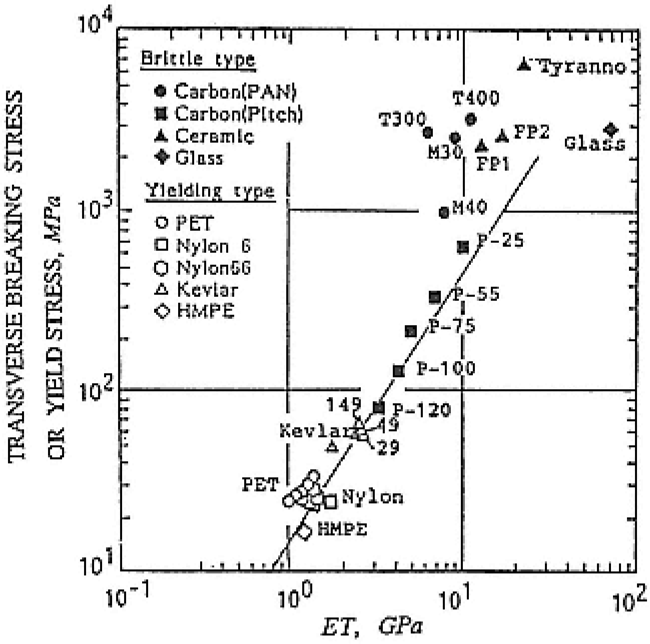

Figure 11
Correlation of breaking stress or yield stress and E_T.
(From Ref. 6.)

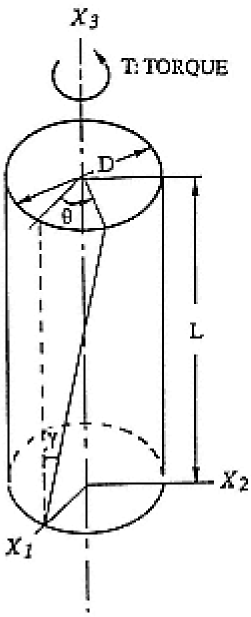

Figure 12
Torsion of fiber.

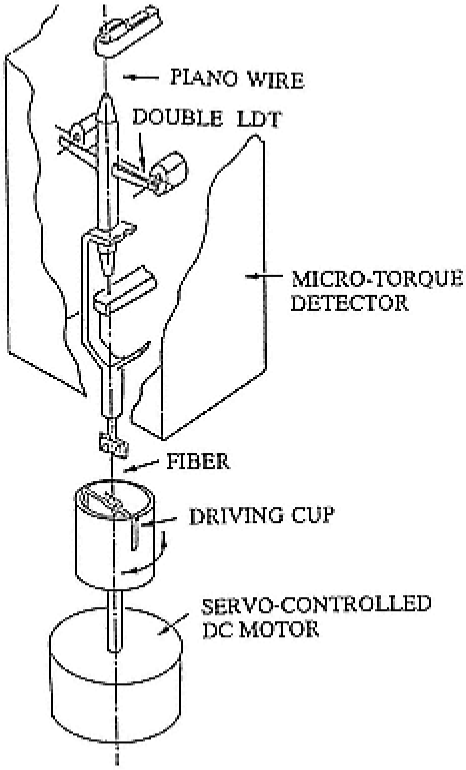

Figure 13
Mechanism of the torsion tester.
(From Ref. 1.)

III—
Concluding Remarks

As seen from Figures 10 and 11 and Table 2, apparel fibers [16] as well as highstrength fibers exhibit strong anisotropy in their mechanical properties. These mechanical properties are closely related to the mechanical properties of fiber assembly bodies. It is important for textile scientists and engineers to have a good understanding of these fiber properties for future advanced research on fibers and textiles.

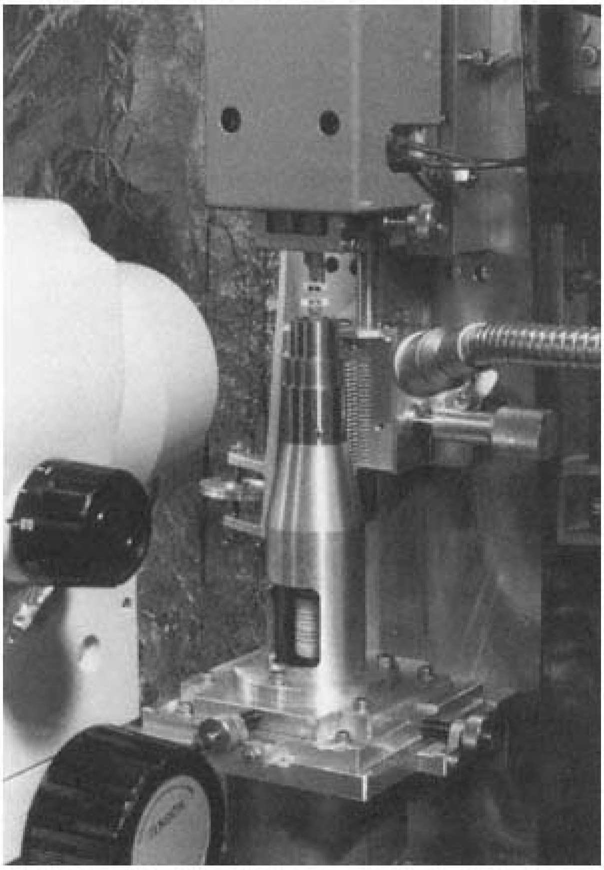

Figure 14
Torsion tester.

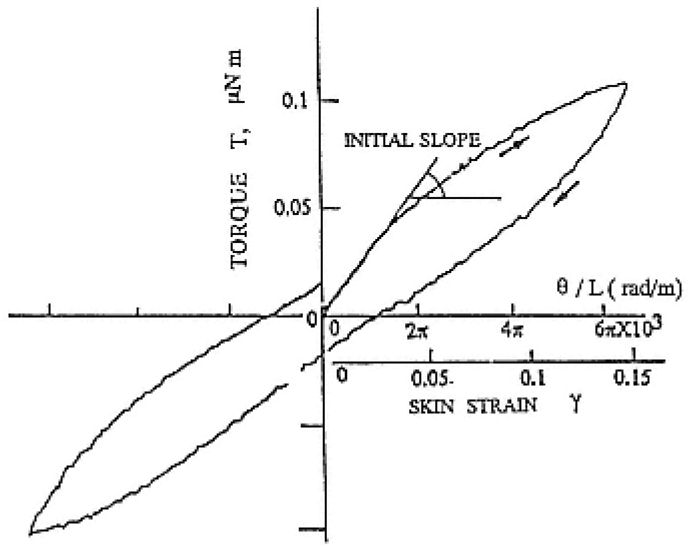

Figure 15
Torsion property of a Kevlar 29 fiber.

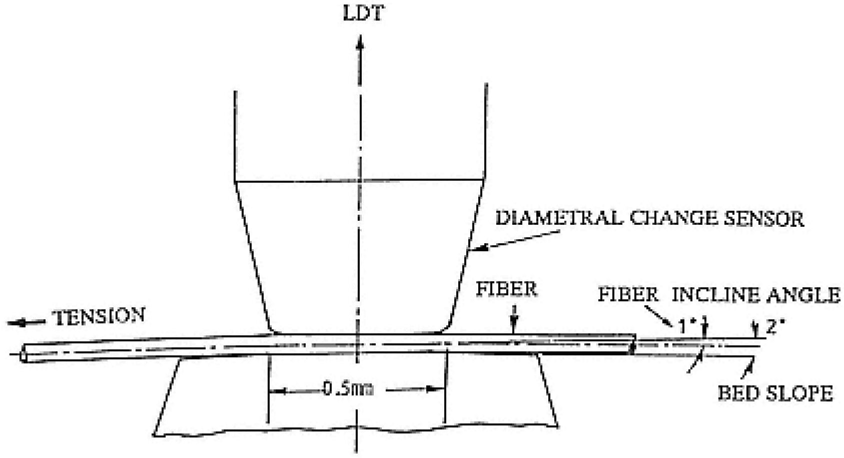

Figure 16
Tester measuring Poisson's ratio ν_{LT}.
(From Ref. 15.

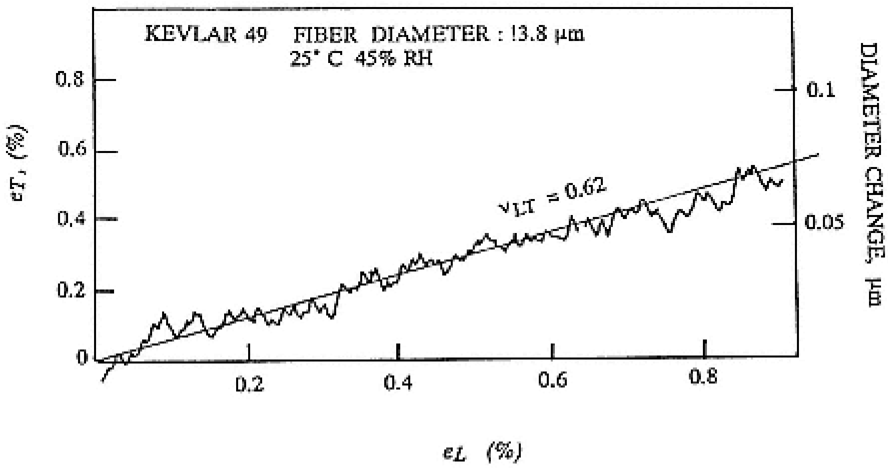

Figure 17
The e_L-e_T curve of a Kevlar 49 single fiber.

Table 1 Mechanical Properties of Kevlar 29 in 25°C, 45% RH

Elastic constants		
E_L(GPa)		
Tensile	79.8	Strain at 0.005
	69.5	Strain at 0.02
	98.4	Breaking strain region
Compression	60.0	Strain at -0.001
	45.0	Breaking strain region
E_T (GPa)	2.59	
G_{LT} (GPa)	2.17	
ν_{LT}	0.63	
ν_{TT}	0.43	
Strength	Stress (GPa)	Strain
Longitudinal		
Tensile	2.55	0.037
compression	0.31 (yielding)	0.091
Transverse		
compression	0.056 (yielding)	0.007
Torsion	0.101 (yielding)	0.047

Table 2 E_L, E_T, and G_{LT} of Fibers

Fiber	E_L(GPa)	E_T (GPa)	G_{LT} (GPa)
Carbon (T-300, PAN)	234.6 (308.1)*	6.03	18.2
Ceramic (Tiranno)	159.7	26.5	45.80
Kevlar 49	113.4 (129.6)*	2.49	2.01
HMPE	89.3	1.21	1.90
Kevlar 29	79.8 (98.4)*	2.59	2.17
Glass	77.4	67.9	42.5
PET	15.6	1.09	0.63
Nylon	2.76	1.37	0.55
Wool	3.33	1.09	1.47

Source: Data accumulated from Kawabata's experiments [3].
*The value in the breaking region is shown in parentheses.

References

1. S. Kawabata, Proc. 4th US-Japan Conf. on Composite Materials at Washington DC, June 27–29, 1988, Technomic, Lancaster, Pa., 1989, 99. 253–262.

2. I. M. Ward, *Mechanical Properties of Solid Polymers*, 2nd ed., John Wiley & Sons, Chichester, New York, 1985.

3. S. Kawabata, Annual Report of the Research Institute, for Chemical Fibers, Department of Polymer Chemistry, Kyoto University, Kyoto, Japan (Japanese ed.), 1992, pp. 17–24.

4. T. Kotani and S. Kawabata, Proc. 15th Composite Materials Symposium, Society for Composite Materials, Japan, 1990, pp. 113–116.

5. D. W. Hadley, I. M. Ward, and J. Ward, *Proc. R, Soc. A285*:275 (1965).

6. P.R. Pinnock, I. M. Ward, and J. M. Wolfe, *Proc. R. Soc. A291*:267, 1966.

7. S. Kawabata, J. Textile Inst. 81:432 (1990).

8. S. Kawabata, and M. Niwa, Proc. 9th ICCM, Madrid, Vol. 6, 1993, pp. 671–677.

9. S. Kawabata and M. Sera, Proc. Advanced Composites, Woolongong, Australia, 1993, pp. 797–802.

10. S. Kawabata and K. Katsuma, Proc. 21st Textile Res. Symp. at Mt. Fuji, August 1992, pp. 1–4

11. C. Muraki, M. Niwa, and S. Kawabata, Proc. 21st Textile Res. Symp. at Mt. Fuji, August 1992, pp. 10–13.

12. C. Muraki, M. Niwa, and S. Kawabata, *J. Textile Inst. 85*:12 (1994).

13. S. Kawabata, Abstract 2nd Inst. Conf. on Advanced Materials & Technology, Hyogo Pref., Kobe, 1991, pp. 51–58.

14. S. Kawabata, N. Amino, K. Katsuma, M. Sera, T. Kotani, and M. Kakiuti, Proc. 22nd Textile Res. Symp. at Mt. Fuji, August 1993, pp. 54–60.

15. S. Kawabata, Proc. 18th Textile Res. Symp. at Mt. Fuji, August 1989, pp. 1–6.

16. S. Kawabata, C. Muraki, and M. Niwa, 18th Textile Res. Symp. at Mt. Fuji, August 1989, pp. 7–12.

17. S. Kawabata, T. Kotani, and Y. Yamashita, *J. Textile Inst. 86*:347 (1995).

10—
Objective Measurement of Fabric Hand

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I—
Introduction

There are two types of clothing fabric performance. One type is utility performance, such as strength, color durability, shrinkage resistance, etc. While this type of performance is, of course, very important for clothing materials, consumers are generally satisfied with fabrics that meet these criteria to a certain extent. Beyond this the consumers' attention turns to higher level performance factors, such as improved quality from the standpoint of garment appearance and comfort. This second factor of fabric quality-type performance factors is related to the idea of "better fit" to the human body, and is also an essential requirement in clothing material. The evaluation of fabric quality performance is, however, more difficult than the evaluation of utility performance [1].

The quality of clothing fabric with regard to the second type of performance has been evaluated by consumers and textile producers subjectively by means of the hand touch of fabric from the mechanical-comfort viewpoint. This evaluation is called *hand evaluation* and the fabric property relating to this evaluation is *fabric hand* ("handle" in England). The subjective judgment of fabric hand is based on human sensitivity and experience. It is true that this subjective method is the most direct method for evaluating fabric mechanical comfort, as the human body and sensitivity feel the comfort of clothing.

This subjective evaluation is essential and becomes highly refined with the accumulation of experience. However, a problem exists in that it is a subjective method, which restricts the scientific understanding of fabric hand for those who wish to design high-quality fabrics by engineering means. Because of the importance of the scientific understanding of fabric hand, many trials for replacing the subjective method with an objective method have been carried out by many researchers in the textile field, beginning with the trials by Peirce in 1930 [2]. Peirce proposed a correlation between fabric hand and fabric mechanical properties. Many textile scientists conducted research in this field after Peirce. Because of the difficulty in linking human sensitivity to fabric properties, progress in this field has been slow. However, the importance of the understanding of fabric hand has been considered throughout.

Kawabata and his co-workers began researching fabric hand around 1969 based on their concepts of fabric hand and on the work of many of their predecessors in this field. The research focused on the analysis of the judgment of fabric hand as carried out by experts in textile mills, especially finishing mills for wool textiles. The first step of the research was to standardize the fabric hand expressions that were traditionally used by the experts in wool textile mills. Based on this standard, a numerical expression of fabric hand became possible; then subjective hand judgment was transferred to an objective evaluation system based on fabric mechanical properties [3]. In this chapter, we take a look at the objective evaluation system of fabric hand.

II—
Subjective Hand Judgment

When we touch a clothing fabric and inspect its hand by finger sensitivity, we not only enjoy the fabric touch itself, but we also think about the performance of the fabric as a clothing fabric on the basis of our experience. In the end, we must determine if the fabric is good for clothing from the viewpoint of the second performance type described in the preceding section. The criterion in this judgment is therefore not simply a like or dislike of the feeling, but rather judgment based on the comfort and beautiful appearance of the clothing.

Professionals working in textile mills must daily produce good fabrics for consumers, and by doing so have accumulated many years of knowledge about consumer fabric preference; this information is passed and transferred from professionals to professionals by means of their professional hand judgment. Although the basis for the criteria is consumer preference, the individual consumer is not necessarily a good judge, and his or her criteria for good fabric are not necessarily reliable or consistent due to lack of experience. Experts in textile mills have come to understand many consumer preferences and use semi-objective criteria although making a subjective judgment. This is a major advantage in asking the advice of experts. This research on fabric hand focused on the analysis of the experts' subjective hand judgments, men's suiting materials in particular (Fig. 1).

In order to develop an objective hand evaluation system, in 1972 Kawabata organized the Hand Evaluation and Standardization Committee in Japan, and 12 experts were invited to join the committee. Progress toward an objective evaluation system has been made possible by the cooperation of this group of experts.

Figure 1
Hand touch in suiting.

A— Analysis of Expert Hand Judgment

When experts touch a fabric, they primarily inspect the mechanical properties including surface properties. Then they summarize these properties with hand expressions such as "smoothness," "stiffness," etc. Each of these expressions summarizes a fabric property that is closely related to the fabric performance with respect to comfort and beautiful appearance, we call this the essential performance as garment material. Next, the experts again summarize these fabric properties to evaluate the overall hand in terms of an expression, as good or poor, or a grade with quality rank. Thus, there are two steps in performing the hand evaluation.

1. Evaluation of the fabric hand, which summarizes the specific fabric properties that express fabric characteristics in relation to fabric quality.

2. Evaluation of the overall hand expressing the fabric quality with regard to the essential fabric performance of the garment or clothing that will be made from the fabric.

There are not many hand expressions for type 1. Among these, three for winter/autumn-use suiting and four for summer-use suiting have been selected as

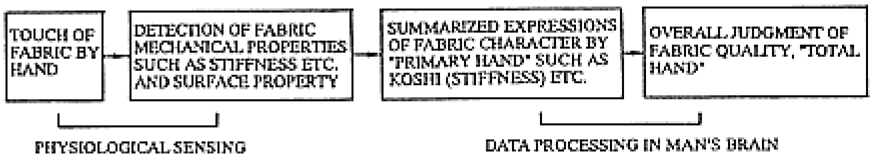

Figure 2
Subjective judgment of fabric hand by experts.

important hand expressions, called "primary hand". The hand of type 2 is an overall hand called "total hand". Figure 2 shows the experts' hand-evaulation process.

B—
Primary Hand and Its Grading

The three primary hands for winter/autumn suiting and the four for summer suiting have been defined by the experts as follows.

For winter/autumn suiting:

Stiffness (*koshi*): A feeling related mainly to bending stiffness. A springy property promotes this feeling. A fabric having a compact weave density and made from springy and elastic yarn gives a high value.

Smoothness (*numeri*): A mixed feeling coming from a combination of smooth, supple, and soft feelings. A fabric woven from a cashmere fiber gives a high value.

Fullness (*fukurami*): A feeling coming from a combination of bulky, rich, and wellformed impressions. A springy property in compression and thickness, accompanied by a warm feeling, is closely related with this property. (The Japanese word literally means "swelling.")

For summer (meaning midsummer) suiting:

Stiffness (*koshi*): The same as *koshi* in winter/autumn suiting.

Crispness (*shari*): A feeling coming from a crisp and ridged fabric surface. This is found in a woven fabric made from a hard and strongly twisted yam. This gives a cool feeling. (The Japanese word means crisp, dry, and a sharp sound caused by rubbing the fabric surface with itself.)

Fullness (*fukurami*): The same as fullness in winter/autumn suiting.

Antidrape (*hari*): The opposite of limp conformability, whether the fabric is springy or not. (The Japanese word means "spread.")

One primary hand, stiffness, is related to a moderate space between the human body and the outer garment to allow freer body movements. A moderate stiffness also brings a beautiful drape of the garment. Smoothness is the hand most important to fabric quality. In general, consumers like the strong feeling of smoothness and get a sense of quality from this feeling. This is due to the smooth contact of fabric with human skin. This smooth contact is necessary to prevent skin injury; by instinct people defend themselves from injury. This instinct is related to a feeling of comfort. On the other hand, the smooth fabrics stick to sweaty skin in tropical climates. Consumers prefer a rough rather than smooth surface in hot climates because of the comfortable feel in this situation. This is the crispness hand. Although the crispness hand is essential in tropical climates, most western countries have temperate climates, and as such do not traditionally prefer this hand. Only the consumers in Japan and a few other Asian countries such as China, Korea, etc. prefer this hand for midsummer suiting. This is one of their traditional hands. Accordingly, only winter/autumn primary hands may be applicable to western country consumers.

The grading of feeling intensity was applied to each of these Primary hands. Standard samples were selected for each grade and expressed numerically on a scale of 1–10. This number was named "primary hand value," or hand value (HV) for short, as shown in Table 1.

C—
Total Hand and Its Grading

The total hand was also standardized by the group of experts for the fabric categories winter/autumn and midsummer. Standard samples that express the grade of total hand were selected and graded as shown in Table 2 [4–7].

Fabric characteristics are expressed by the hand values of the three primary hands, and its quality by a total hand value (THV). Fabric hand is clearly expressed by these hand values. For example, the hand of a worsted suiting is expressed by values such as stiffness = 3.6, smoothness = 6.7, fullness = 5.3, and THV = 3.7.

D—
Extension to Other Types of Fabrics

The first trial for the standardization of fabric hand was conducted primarily with suiting materials, regardless of fiber kind. Worsted fabrics are traditionally a major material used in suits due to a preference for wool from the standpoint of suit

Table 1 Hand Value of the Primary Hand

Hand value	Feeling grade
10	The strongest
•	
•	
•	
5	Medium
•	
•	
•	
1	The weakest
0	No feeling

Table 2 Total Hand Value (THV)

Grade	THV

Excellent	5
Good	4
Average	3
Fair	2
Poor	1
Not useful	0

quality. The hand of a suit is traditionally based on the hand of worsted fabrics, and precise criteria have been derived from the worsted-base fabrics. We must therefore consider whether the traditional hand criteria may be applicable to other fabrics of suiting regardless of fiber kind. With this in mind, we included fabric specimens woven from various kinds of fibers in the hand assessment. The only condition for the assessment was that the specimen be a material used in suits.

A similar procedure for hand assessment was carried out for women's garment fabrics, and it was discovered that the criteria for the hand of women's suiting had much in common with that of men's suiting. We could apply the standard of men's suiting hand to the women's suitings as shown in Section III.B. Women's thin dress fabrics, however, have a little different hand from that of suitings. We had to add two more primary hands, as follows [3,4,5,6,7]:

Stiffness (*koshi*): The same definition as stiffness of men's suiting.
Antidrape (*hari*): The same definition as antidrape of men's suiting.
Crispness (*shari*): The same definition as crispness of men's suiting
Fullness (*fukurarni*): The same definition as fullness of men's suiting.
Scrooping feeling (*kishimi*): Silk fabric possesses this feeling strongly.
Flexibility with soft feeling (*shinayakasa*): Soft, flexible, and smooth feeling.

Standard samples for each primary hand were selected, and the feeling intensity of each primary hand was graded using a scale of 1–10 in the same manner as men's suiting. It was unfortunately difficult to find experts to conduct the THV evaluation for this fabric category. We are still continuing the assessment at present.

III—
Objective Evaluation of Hand Value and Total Hand Value [1, 3]

As seen in Fig. 1, human fingers can detect the fabric bending stiffness, surface properties, compression property, and shearing property of a fabric. In addition, another important action of the inspection is streching of fabric at low strain levels. The mechanical response of the fabric is transferred to the person's brain, where the fabric hand properties are evaluated as previously mentioned, based on the person's experience. The concept of the objective evaluation system is as follows. Instead of using the touch of a fabric by a hand or finger, we measure fabric

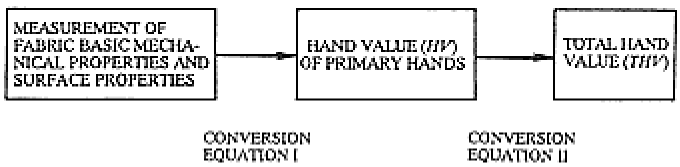

Figure 3
Objective system for hand evaluation.

mechanical properties and express them with mechanical parameters. Then these parameters are converted into the hand values with a conversion equation (equation type I). Next, these hand values are converted into a total hand value with the second conversion equation (equation type II) as shown in Fig. 3.

A—
Mechanical Parameters

Based on our preliminary investigation, fabric mechanical properties and surface properties related to fabric hand and applicable to this objective system were selected. Deformation modes selected here were the basic deformations of fabric and the complex modes were avoided, considering the future application of a system to the design and control of fabric hand. As is well known, fabric mechanical properties in a low-load region possess a peculiar nonlinearity in their properties. These properties must be measured exactly and expressed by parameters. One example of the nonlinearity is hysteresis behavior in the load-deformation relation. This hysteresis plays an important part in objective evaluation of fabric hand. The selected properties and parameters are introduced in this section. Fabric samples of 20 cm × 20 cm were used for all measurements. The standard measuring condition is shown here. There are some other conditions, such as nonwoven conditions [11], high sensitivity condition for thin fabrics, etc. [15].

1—
Tensile Property

As shown in the top of Fig. 4, a 20 cm × 5 cm sample is cramped and extension is applied along the 5 cm direction up to a maximum load 500 N/m. Rate of tensile strain is $4.00 \times 10^{-3/s}$. This is a type of biaxial extension called *strip biaxial extension*. This deformation mode is much easier to use than simple uniaxial extension for theoretical property prediction. This simplicity is important for further fabric design for controlling the fabric hand. There are three parameters expressing this nonlinear property in the warp direction, and another set of three is necessary for the weft direction. For hand value derivation, these two directional values are averaged.

2—
Bending Property

Pure bending (Fig. 5) is applied to a fabric 1 cm in length with a constant rate of curvature, 5.0×10^{-3} $m^{-1/s}$. The stiffness (slope) and hysteresis are measured.

3—
Shearing Property

A rate of shear strain of $8.34 \times 10^{-3/s}$ (shear deformation 1.46×10^{-4} degrees/s), is applied under a constant extension load 10N/m up to a maximum shear angle of 8 degrees (Fig. 6). The stiffness (slope) and hysteresis are measured.

4—
Compression Property

A fabric specimen is compressed in the direction of thickness to a maximum pressure of 5 KN/m^2 (50 gf/cm^2), at a constant velocity, 20 µm/s (Fig. 7). The shape

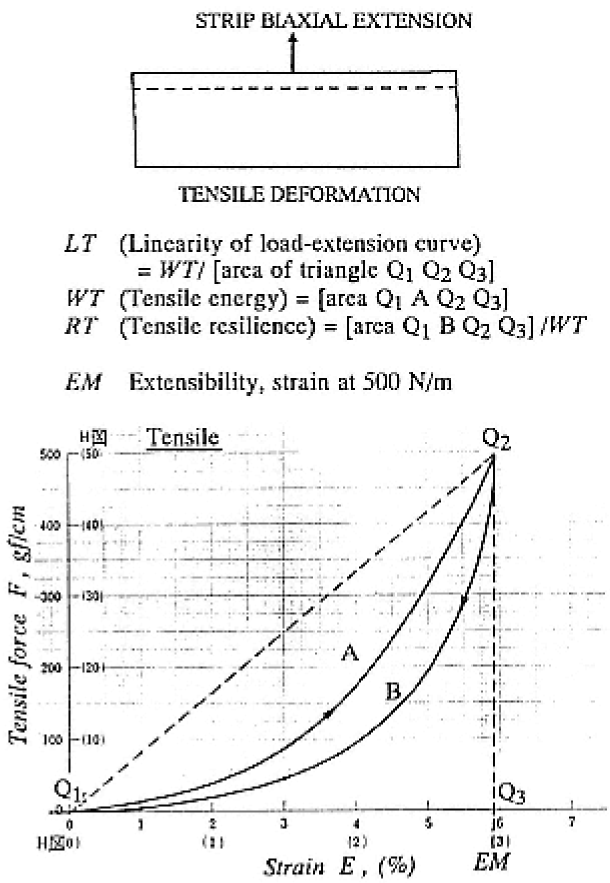

Figure 4
Tensile property. The standard measuring condition is shown. Scale in parenthesis is the high-sensitivity condition for thin fabrics. Curve A is extension process and B is recovery process. Linearity of curve A is defined by the ratio of WT to the area of a triangle shown by additional dotted lines.

of the load thickness is similar to the shape of the tensile property curve, and the same parameters are used with the identification C(LC, etc.).

5—
Surface Property

Surface geometrical smoothness and frictional smoothness are measured. The sensors for these measurements are shown in Fig. 8(a) and (b), respectively. The contact surface of the frictional sensor is 10 parallel piano wires 0.5 mm in diameter, and the surface shape is similar to that of a human fingerprint, as shown in Fig. 8(c). A weight is used to apply 0.5N (50 gf) contact force during measurement. The rough surface of the fingerprint shape is sensitive to fabric surface roughness.

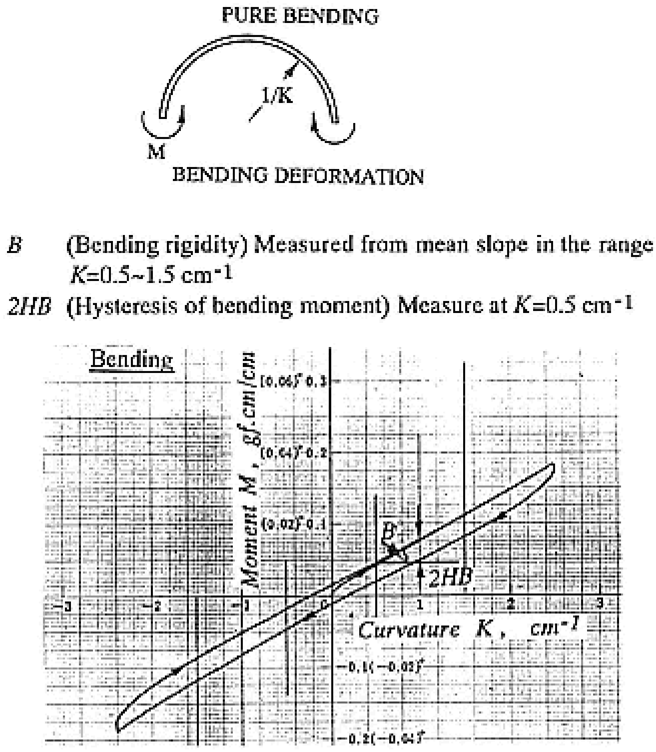

Figure 5
Bending property. The standard measuring condition
is shown. Scale in parenthesis is applied to the
high-sensitivitycondition for thin fabrics.

For the geometrical smoothness sensor, a single wire of the same diameter is used to measure geometry more accurately. The signals from these sensors pass a frequency filter with a second-order high-pass response. The frequency response is shown in Fig. 9. The sweep velocity is 1 mm/s. When we touch a fabric and sweep our finger across the fabric surface, the sweep velocity is normally 5 cm/s; that is, the 1 Hz in the measurement corresponds to about 50 Hz in an actual sweep. A frequency component higher than about 250 Hz in an actual sweep is naturally eliminated by the fingerprint surface and the transducer mechanism. The most sensitive frequency range of human sensation is 50–200 Hz [8], and a filter is used to detect only this range, eliminating the noise component from surface sensing.

The parameters representing surface properties are MIU, MMD, and SMD, which are measured for a 2-cm return sweep. They are defined as

MIU, mean frictional coefficient (for a 2-ctu return sweep)
MMD, mean deviation of frictional coefficient
SMD, mean deviation of surface contour

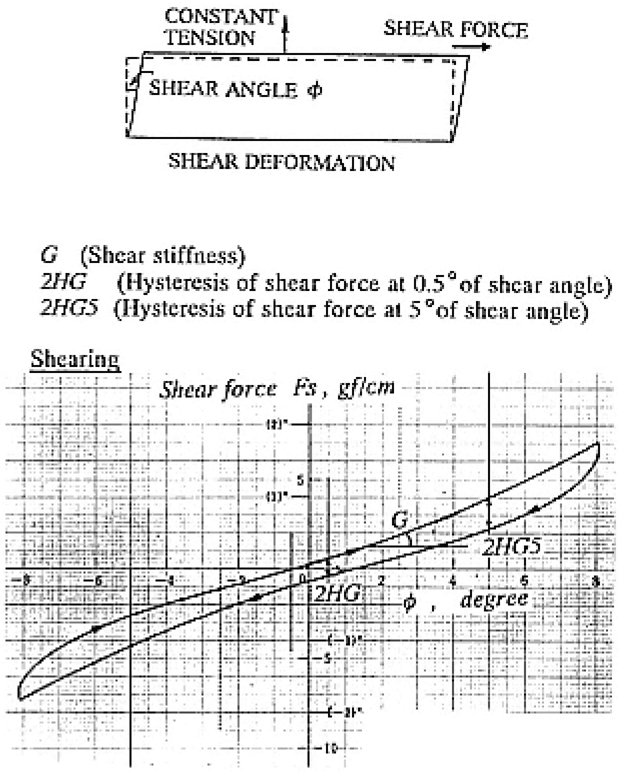

Figure 6
Sheafing property. The Standard measuring-condition
is shown Scale in parenthesis is applied to the High
Sensitivity condition for thin fabrics

The mechanical and surface parameters are shown in Table 3.

In the beginning of the development of the objective system, a system of four machines was used to measure these parameters (Fig. 10). A fabric specimen of 20 cm × 20 cm was used consistently throughout the system. This system was later named KESF 1, 2, 3, and 4, or simply, the KESF System. Recently, an automatic system was developed; however, the principle of the measurement is the same as with the original machines, with all measurement operations fully automated.

B—
Equations for the Calculation of Hand Values

The equation used to derive primaryhand values was assumed to be linear. The equation for THV was also assumed to be nonlinear, considering the existence of the optimum value of HV contributing to the highest value of THV. The HV equation is as follows:

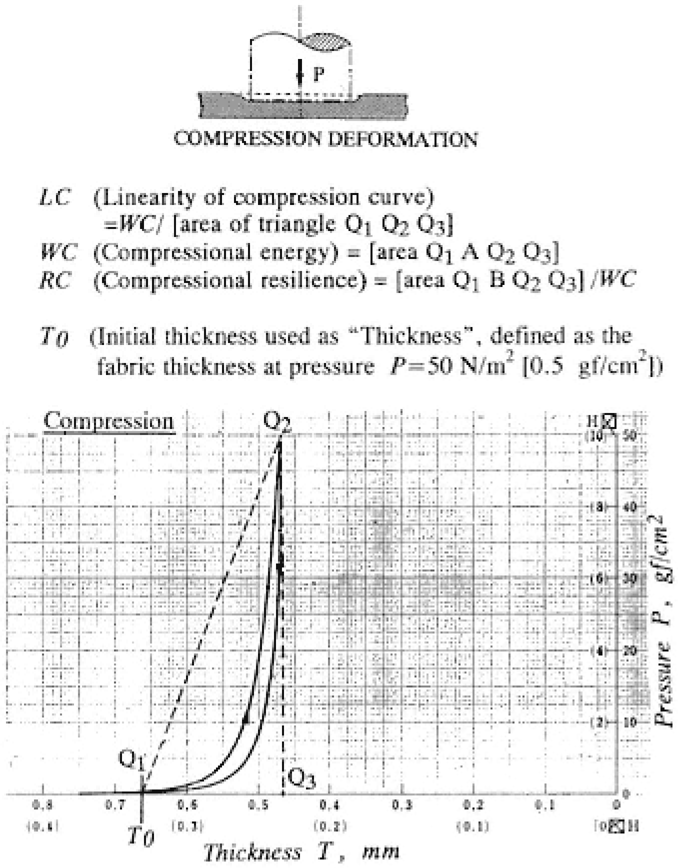

Figure 7
Compression property. The Standardmeasuring-condition is shown.
Scale in parenthesis is applied to the High Sensitivity
condition for thin fabrics.

$$Y_k = C_0 + \Sigma C_{ki} x_i \qquad (1)$$

where Y_k is the kth hand value such that, k = 1 is stiffness, k = 2 is smoothness, and k = 3 is fullness for winter/autumn suiting, and k = 1 is stiffness, k = 2 is crispness, k = 3 is fullness, and k = 4 is antidrape stiffness for summer suiting. The term x_i is the normalized ith (i = 1–16) mechanical parameter, normalized as

$$x_i = (X_i - M_i)/\sigma_i \qquad (2)$$

where X_i is the mechanical parameter shown in Table 4. Note that a logarithm is used for some parameters. M_i and σ_i are the mean and standard deviation of X_i for

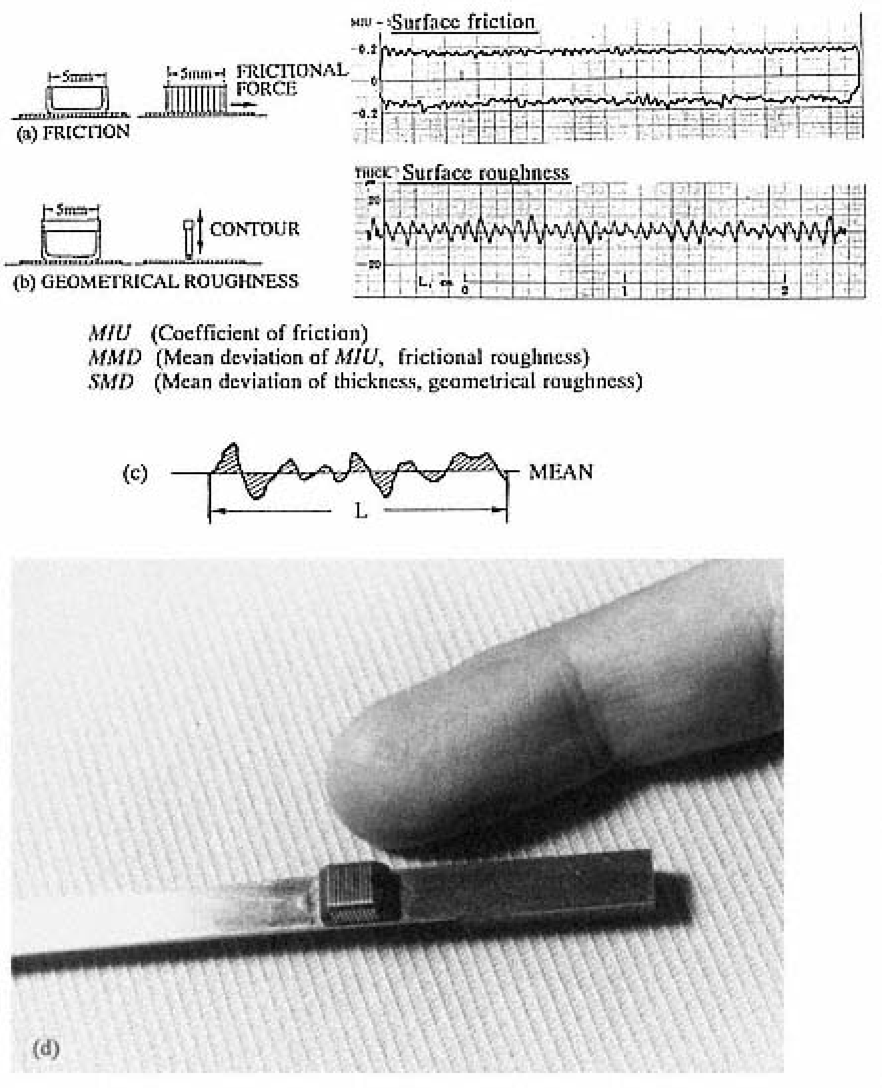

Figure 8
Surface properties: (a) measurement of surface friction, (b) Surface geometry measurement, (c) mean deviation (MD) = [hatched area/L], and (d) the appearance of the contact surface of friction detector.

the men's suiting population. C_0 and C_{ki} are constant coefficients, shown in Table 4 with M_i and σ_i.

The value of THV value is derived by substituting Y_k that are derived from Eq. (1) into Eq. (3) as follows:

$$THV = C_0 + \Sigma Z_k \qquad (3)$$

where

$$Z_k = C_{k1}(Y_k - M_{k1}) / \sigma_{k1} + C_{k2}(Y_k^2 - M_{k2}) / \sigma_{k2} \qquad (4)$$

Thus Z_k is the contribution of the kth primary hand to THV. The constants M_{k1} and σ_{k1} are population means and standard deviations of Y_k, and M_{k2} and σ_{k2} are population means and standard deviations of Y_{k2}, respectively, shown in Table 4 with the constant coefficients C_{k1} and C_{k2}, and the constant C_0.

The primary hand equations have been derived on the basis of experts' judgment for the men's suiting population and were later named KN-101-Winter and KN-101-Summer for the primary hand of winter/autumn and summer suiting respectively, and the THV equations were KN-301-Winter and KN-301-Summer, respectively.

C—
Extension to a New Object Population

The equations introduced in the preceding sections are applicable to the men's suiting population, and the coefficients in the equations were derived by correlat-

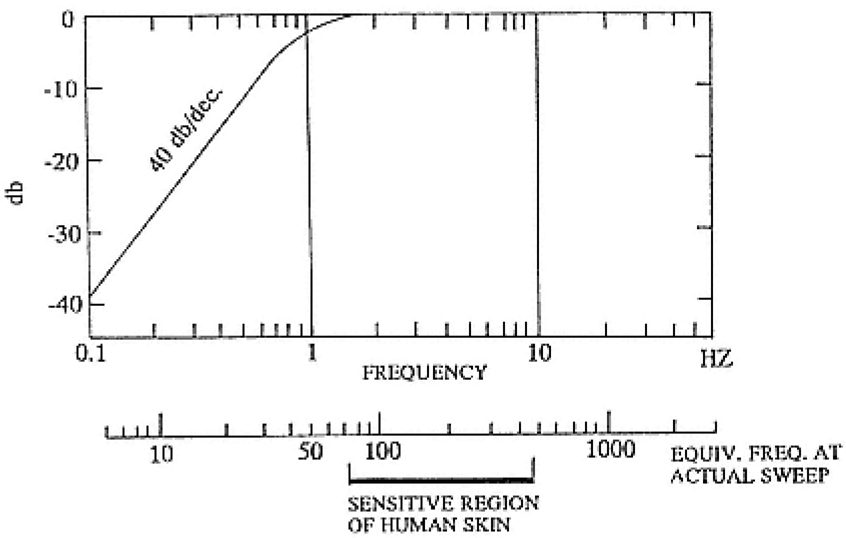

Figure 9
Frequency response of the filter.

Table 3 Mechanical and Surface Properties

Parameters	Description	Unit
Tensile[a]		
LT	Linearity of Load/extension curve	None
WT	Tensile energy	N/m (gf cm/cm2)
RT	Tensile resilience	%
EM[b]	Extensibility, strain at 500 N/m (gf/cm of tensile load)	None
Bending[a]		
B	Bending rigidity	10^{-4} Nm (gf cm^2/cm)
2HB	Hysteresis of bending moment	10^{-2} N (gf cm/cm)
Shearing[a]		
G	Shear stiffness	N/m deg. (gf/cm degree)
2HG	Hysteresis of shear force at 0.5 degrees of shear angle	N/m (gf/cm)
2HG5	Hysteresis of shear force at 5 degrees of Shear angle	N/m (gf/cm)
Compression		
LC	Linearity of compression/thickness curve	None
WC	Compressional energy	N/m (gf cm/cm2)
RC	Compressional resilience	%
Surface[a]		
MIU	Coefficient of friction	None
MMD	Mean deviation of coefficient of friction (frictional roughness)	None
SMD	Geometrical roughness	µm
Construction		
T	Fabric thickness	mm
W	Fabric weight/unit area	10 g/m$_2$ (mg/cm^2)

[a]Average of the values in warp and weft directions is applied. The warp and weft directional values are identified by 1 and 2, respectively, such as MMD-1, B-2, etc.
[b]EM is not used for the conversion equation to HV.
Source: Refs. 1 and 2.

ing subjective judgment by the experts with the mechanical parameters of fabric. If a new population is the goal of the objective measurement, a similar procedure to that described earlier is necessary, to derive the coefficients for the new population. However, the construction of new equations is not necessary in some cases. It may be possible to apply the men's suiting equation to other categories of fabrics. This is based on the fact that primary hand may be applied commonly to many

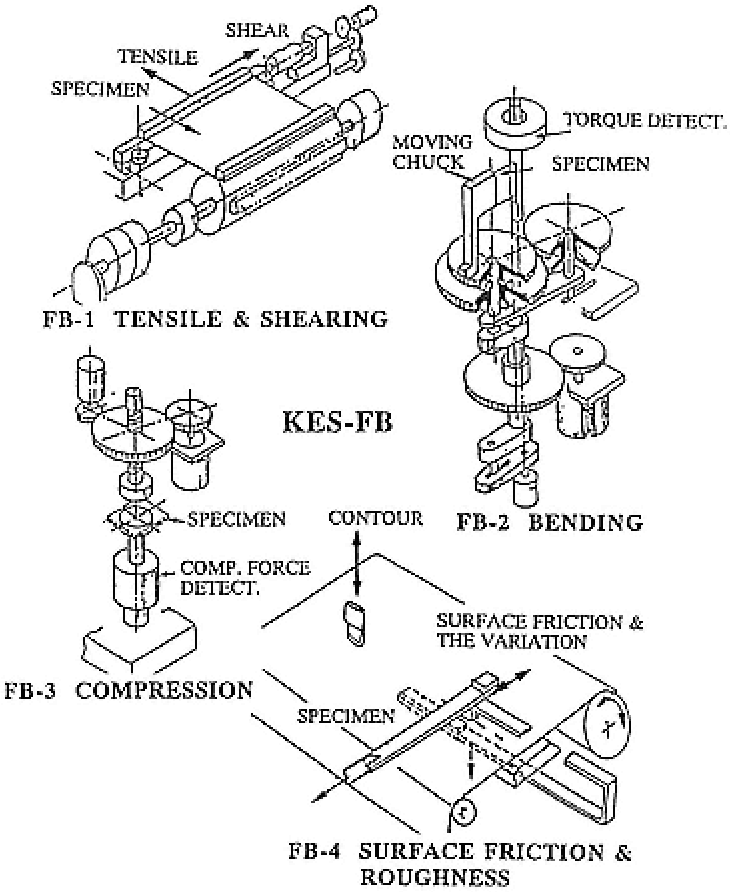

Figure 10
The KESF system.

different categories of fabrics. Even in the case of total hand, it may be possible to apply the men's suiting equation for THV. This is because there is a possibility ofa common criterion in human interactive materials.

An example is the application of men's suiting equations to women's suiting. We use the same coefficients as the coefficients of men's suiting equations for both HV and THV equations, and apply a minor modification as follows. The mechanical parameters X_i are normalized by Eq. (5) with the M_i' and σ_i', the population mean and standard deviation of women's suiting, where

$$x_i = (X_i - M_i') / \sigma_i' \quad (5)$$

Table 4 Equations Converting Mechanical Parameters into HV of Primary Hand and THV of Total Hand

A. HV equation for evaluating the primary hand value of suiting (Equation KN101-W-Series) for men's winter suiting

	Ci				
	Smoothness (*numeri*)	Stiffness (*koshi*)	Fullness (*fukurami*)	Population parameters men's winter suitings	
Mechanical				(*n* = 214)	
parameters	C_0 = 4.7533	C_0 = 5.7093	C_0 = 4.9799	M_i	σ_i
Tensile	(5)	(4)	(3)		
LT	-0.0686	-0.0317	-0.1558	0.6082	0.0611
log WT	0.0735	-0.1345	0.2241	0.9621	0.1270
RT	-0.1619	0.0676	-0.0897	62.1894	4.4380
Bending	(4)	(1)	(6)		
log B	-0.1658	0.8459	-0.0337	-0.8673	0.1267
log 2HB	0.1083	-0.2104	0.0848	-1.2065	0.1801
Shear	(3)	(2)	(4)		
log G	-0.0263	0.4268	0.0960	-0.0143	0.1287
log 2HG	0.0667	-0.0793	-0.0538	0.0807	0.1642
log 2HG5	-0.3702	0.0625	-0.0657	0.4094	0.1441
Compression	(2)	(5)	(1)		
LC	-0.1703	0.0073	-0.2042	0.3703	0.0745
log WC	0.5278	-0.0646	0.8845	-0.7080	0.1427
RC	0.0972	-0.0041	0.1879	56.2709	8.7927
Surface	(1)	(6)	(2)		
MIU	-0.1539	-0.0254	-0.0569	0.2085	0.0215
log MMD	-0.9270	0.0307	-0.5964	-1.8105	0.1233
log SMD	-0.3031	0.0009	-0.1702	0.6037	0.2063
Construction	(6)	(3)	(5)		
log T	-0.1358	-0.1714	0.0837	-0.1272	0.0797
log W	-0.0122	0.2232	-0.1810	1.4208	0.0591

[a]Order of importance.

B. Suiting THV equation parameters (Equation KN301-W) for men's winter suiting, where C_{00} = 3.1466

k	Y_k	C_{k1}	C_{k2}	M_{k1}	M_{k2}	σ_{k1}	σ_{k2}
1	Smoothness	-0.1887	0.8041	4.75372	5.0295	1.5594	15.5621

2	Stiffness	0.6750	-0.5341	5.7093	33.9032	1.1434	12.1127
3	Fullness	0.9312	-0.7703	4.9798	26.9720	1.4741	15.2341

(Continued)

Table 4

C. HV equation for evaluating the primary hand values of suiting (Equation KN101-S-Series) for men's summer suiting

	Ci					
	Crispness (*shari*)	Stiffness (*koshi*)	Fullness (*fukurami*)	Antidrape stiffness (*hari*)	Population parameters men's summer suiting (*n* = 156)	
Mechanical parameters	C_0 = 4.7480	C_0 = 4.6089	C_0 = 4.9217	C_0 = 5.3929	M_i	σ_i
Tensile	(3)[a]	(5)	(1)	(6)		
LT	0.2012	-0.0031	-0.4652	0.0156	0.6286	0.0496
log WT	0.1632	0.1154	-0.1793	-0.1115	0.8713	0.0977
RT	0.1385	0.0955	0.0852	0.0194	66.4557	5.4242
Bending	(2)	(1)	(6)	(1)		
log B	0.4260	0.7727	-0.0209	0.8702	-0.9641	0.1081
log 2HB	-0.1917	0.0610	0.0201	0.1494	-1.4150	0.1635
Shear	(5)	(2)	(3)	(3)		
log G	0.0400	0.2802	0.0567	0.0643	-0.0662	0.1079
log 2HG	-0.0573	-0.1172	0.0361	-0.0938	-0.0533	0.1769
log 2HG5	0.1237	0.1110	-0.0944	0.2345	0.3536	0.1678
Compression	(4)	(4)	(5)	(4)		
LC	0.0828	-0.0193	-0.0388	-0.1153	0.3271	0.0660
log WC	-0.0486	-0.1139	0.1411	-0.0846	-0.9552	0.1163
RC	-0.2252	-0.1164	0.0440	-0.0506	51.5427	8.8275
Surface	(1)	(3)	(4)	(2)		
MIU	-0.2712	-0.2272	-0.1157	-0.3662	0.2033	0.0181
log MMD	0.1304	0.0472	-0.0635	0.1592	-1.3923	0.1707
log SMD	0.9162	0.1208	-0.0560	0.1347	0.9155	0.1208
Construction	(6)	(6)	(2)	(5)		
log T	0.0001	0.0245	-0.0591	0.0067	-0.3042	0.0791
log W	0.0824	0.0549	0.2770	0.0918	1.2757	0.0615

[a]Order of importance.

D. Suiting THV equation parameters (Equation KN301-S) for men's mid-summer suiting, where C_{00} = 3.2146

k	Y_k	C_{k1}	C_{k2}	M_{k1}	M_{k2}	σ_{k1}	σ_{k2}
1	Crispness	1.1368	–0.5395	4.7480	24.8412	1.5156	14.9493

2	Stiffness	–0.0004	0.0066	4.6089	22.4220	1.0860	11.1468
3	Fullness	0.5309	–0.3741	4.9217	25.2704	1.0230	10.1442
4	Antidrape stiffness	0.3316	–0.4977	5.3929	30.7671	1.2975	14.1273

The M_i' and σ_i' for the women's suiting population are shown in Table 5. The equation for the THV derivation of women's suiting is exactly the same as that of the men's THV equation. In the case of women's suiting, one additional hand, "soft feeling," is also important. This is not a primary hand, but rather one segment of the total hand value, and is used frequently. This hand is derived from mechanical parameters in the same manner as primary hand. The coefficient for the conversion equation is shown in Table 6.

We may apply the basic men's equation to a very wide range of fabric categories. The inspection of the validity of this extension method is continuing as of this writing.

Table 5 M_i' and σ_i' of Women's Suiting Population (Equation KN201-MDY-Series)

	Population parameters of women's suitings (n = 220)	
Mechanical parameters	M_i'	σ_i'
Tensile		
LT	0.6177	0.0823
log WT	1.1511	0.2166
RT	42.0564	6.9586
Bending		
log B	–0.8722	0.2565
log 2HB	–1.1444	0.3473
Shear		
log G	–0.0745	0.2099
log 2HG	0.1312	0.2966
log 2HG5	0.4217	0.2596
Compression		
LC	0.4070	0.1061
log WC	-0.6211	0.2380
RC	52.2626	9.1288
Surface		
MIU	0.2416	0.0431
log MMD	–1.7248	0.1926
log SMD	0.5696	0.3521
Construction		
log T	–0.0446	0.1693
log W	1.3550	0.1270

Source: Ref. 90

Table 6 Coefficients for the Converting Equation for Soft Feeling of Women's Suiting (Equation KN201-MDY-Series)

Mechanical parameters	Soft feeling (*sofutosa*), C_i for $C_0 = 3.2881$
Tensile	(4)[a]
LT	–0.1783
log WT	0.0102
RT	–0.3573
Bending	(5)
log B	–0.3073
log 2HB	0.0159
Shear	(3)
log G	–0.4214
log 2HG	0.0146
log 2HG5	–0.0326
Compression	(2)
LC	–0.0472
log WC	0.5641
RC	0.4741
Surface	(1)
MIU	–0.2159
log MMD	–0.9211
log SMD	0.3479
Construction	(6)
log T	–0.0657
log W	0.0340

[a]The order of importance.

Table 7 Mechanical Parameters of Samples 1, 2, and 3

		Sample		
i	X_i	1	2	3
Tensile				
1	LT	0.526	0.565	0.653
2	*log* WT	1.058	1.017	0.826
3	RT	66.9	74.4	59.9
Bending				
4	*log* B	-1.096	-1.177	-0.733
5	*log* 2HB	-1.529	-1.699	-1.076
Shearing				
6	*log* G	-0.158	-0.213	0.224
7	*log* 2HG	-0.105	-0.398	0.151
8	*log* 2HG5	0.227	-0.034	0.614
Compression				
9	LC	0.312	0.293	0.242
10	*log* WC	-0.682	-0.821	-0.780
11	RC	59.1	54.5	51.2
Surface				
12	MIU	0.182	0.174	0.220
13	*log* MMD	-2.027	-1.879	-1.747
14	*log* SMD	0.389	0.344	0.632
Construction				
15	*log* T	-0.122	-0.233	-0.284
16	*log* W	1.406	1.307	1.400

D—
HV and THV Derivation Example

The mechanical parameters of a fabric specimen are measured as shown in Table 7. We then substitute these parameters into Eqs. (1) and (2) to obtain the HV of the three (or four) primary hands, then substitute these HV values into Eqs. (3) and (4) to obtain THV. Samples 1, 2, and 3 are suiting for winter/autumn use. Mechanical parameters are shown in Table 7.

This fabric is for winter/autumn suiting. We then obtain the HV and THV of these specimen as shown in Table 8.

E—
Analysis of Fabric Hand and Quality

It is useful to plot the HV of the primary hand and the THV on a hand chart, as shown in Fig. 11. The shaded area is the high-quality zone, derived from statistical survey of commercial suitings. When the hand values of a sample fall into this zone, the sample is evaluated as a high-quality fabric. Figure 12 is the same chart

Table 8 The Primary Hand and THV

k	Primary hand	Y_k(= HV) and THV for sample 1	2	3
1	Stiffness (*koshi*)	4.00	3.61	7.67
2	Smoothness (*humeri*)	7.65	6.57	3.70
3	Fullness *fukurami*)	6.94	5.35	4.09
	Total hand value (THV)	4.47	3.70	2.70

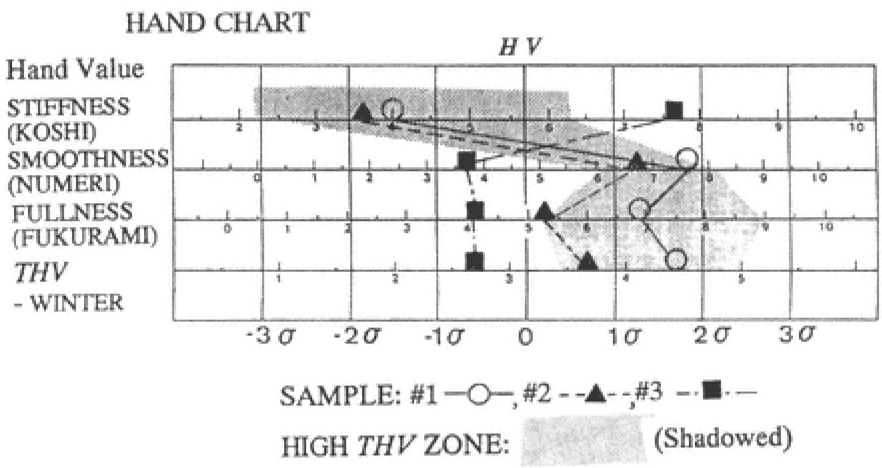

Figure 11
Hand chart for winter/autumn suiting.

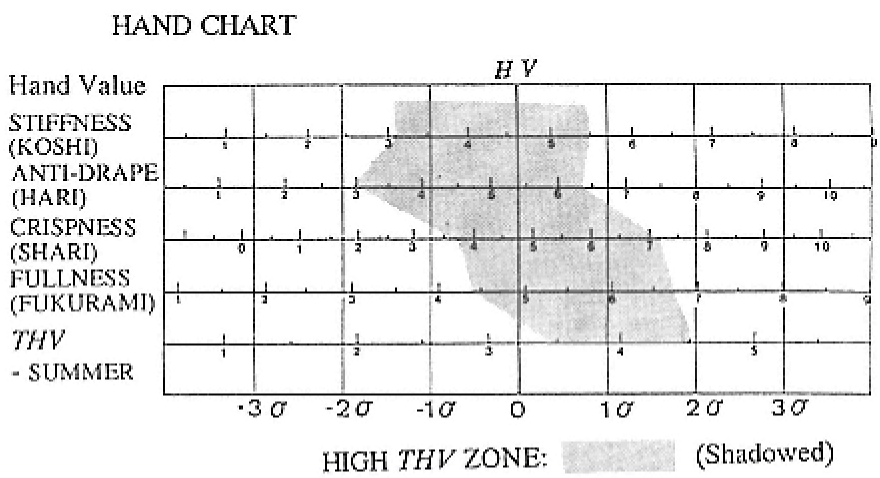

Figure 12
Hand chart for summer suiting.

for summer suiting. Plotting a hand chart is a convenient and simple method of fabric hand analysis. In order to relate the analysis to fabric design, it is important to cover all mechanical parameters on the mechanical parameter chart shown in Fig. 13. The parameters of samples 1, 2, and 3 are plotted on this chart. The shaded area is a good fabric zone that is derived statistically. The scales on the horizontal axes are normalized x_i axes. For convenience, the raw value is also scaled on each axis. This chart can be used to find extremely abnormal mechanical properties.

F— How to Construct the Equations

The coefficient C in the conversion equations was derived on the basis of the experts' subjective judgments. When one wants to create a new equation for any object population, one must locate reliable judges to perform the subjective judgments. The physical parameters that are the basis of an objective evaluation must be those that express the related fabric properties as accurately as possible. For example, if the number of parameters used for creating an equation is 10, the number of samples correlating to the subjective values must be at least 10 times the number of parameters—more than 100 in this example.

When the subjective data matrix $[Y_i]$ (i = 1-n, n = number of samples) and the mechanical parameter matrix $[X_{ij}]$ (i = 1-n, j = 1-m, m = number of parameters) are correlated with the linear equation, the constant coefficients C_j are obtained by solving Eq. (6) for C_j in the condition so that the regression error is kept to a minimum.

$$[Yi] = [Cj]\,[Xij] \qquad (6)$$

$$\sum_{i=1}^{n} (Y_i - Y_i')^2 = \text{minimum} \qquad (7)$$

where Y_i' is the regressed value calculated from X_{ij} and a known C_j. This procedure is a regular multivariable regression, which is common in statistics [10].

In the application of multivariable regression, however, it is necessary to use the regression method most suitable to the circumstances. In the case of fabric hand, there are strong correlations between some of the parameters and hand values. When two variables have a strong correlation, we usually eliminate one of them. However, even though B and 2HB may have a strong mutual correlation, for example, we can not eliminate either one because both parameters are important to fabric design in characterizing fabric bending property. We considered them both necessary unless a perfect correlation exists between them. In the case of primary hand, for example, smoothness and fullness have a strong correlation. From a statistical standpoint, we may eliminate one of them; however, both have been used by many experts for a long time. Even though a strong correlation exists between them, they each make a different, important contribution to fabric quality.

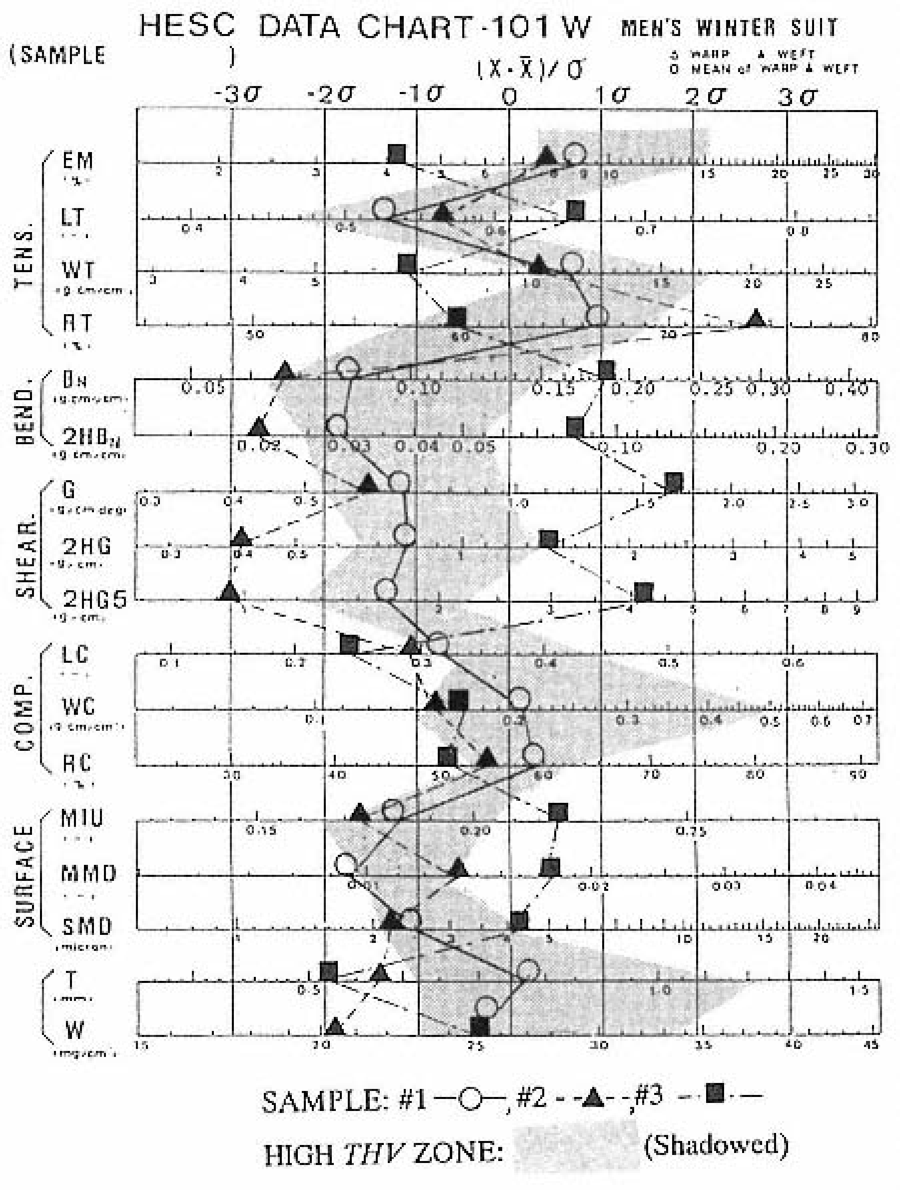

Figure 13
Mechanical parameter chart for winter suiting.

Another situation is when two or three mechanical parameters represent the same property of a fabric—for example, when B and 2HB both represent the bending property. From a fabric design point of view, these two are not separate parameters but are considered to be one group. From these considerations for correlation between parameters and the group concept, the following "block stepwise regression" was used for the regression of primary hand, the KN-101 series [3, 11]. This block stepwise regression is a modification [12] of the step-wise regression.

Variables are grouped into six blocks, with each block corresponding to a fabric property, such as tensile, bending, etc. In the first step, each variable group is regressed separately with Y and the block with the highest regression accuracy is chosen. The resulting regression error is then regressed with each of the remaining blocks in the same manner. The first and second regression equations are added to form a new regression equation in which the two blocks are regressed. The same procedure is repeated until the last block is completed. The rank of the step also gives us information on the ranking of the importance of the blocks to the Y value. After the regression equation is complete, we again apply stepwise regression to variables in the first block to reconstruct the regression equation for the first block; then the variables of the second block are regressed stepwise, and the new regression equations of the first and second blocks are added. This procedure continues, following the order of the block already determined by the first stepwise block regression. In this stepwise method, a significance inspection was done at every step to determine if the new step was necessary. In this case, we did not eliminate any blocks and used all parameters.

For the derivation of the THV equation, we have no blocks, and the ordinary multivariable regression method was applied to constructing the KN-301 series equation, where the square-term variables are included as shown in Eqs. (3) and (4).

IV—
Direct Applications of the Mechanical Parameters

The mechanical parameters used for the objective evaluation of fabric hand are useful not only for the fabric hand evaluation but also for evaluating the fabric performance from different viewpoints. One example is the application to tailoring process control in suit manufacturing [1, 13]. The control chart is shown in Fig. 14. The mechanical parameters used in this control are those of the tensile and shearing properties of fabric. When the parameters of a fabric fall into the central zone indicated as the "noncontrol" zone, the tailoring of this fabric does not require any control on the suit manufacturing line. When only some of the parameters fall into this zone, tailoring control is necessary, for example, careful handling of the fabric during sewing, the use of reinforcement tape, etc., as indicated.

While using this chart, it was discovered empirically that the parameters of high-quality suiting from the mechanical comfort viewpoint in wearing fall into

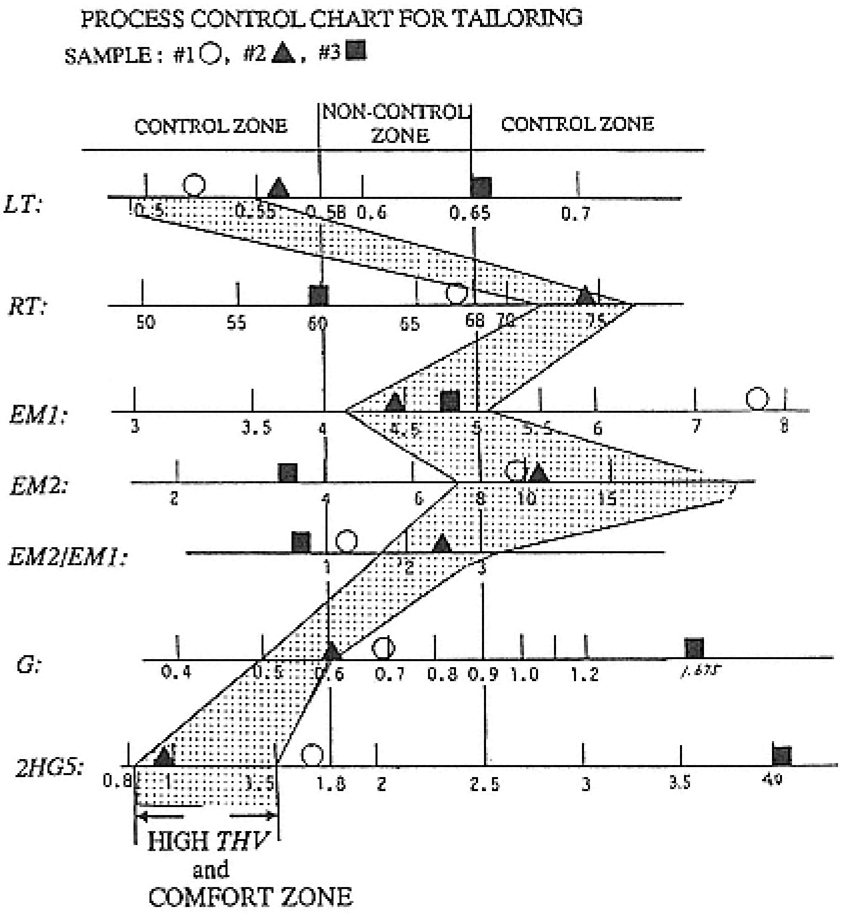

Figure 14

Process control chart for tailoring and comfortable suit zone. Sample # 2 (▲) satisfies the comfort condition. Sample # 1 (O) satisfies almost the comfort zone except for warp directional extensibility, *EM1*, which is too high.

the snake-shaped zone shaded on this chart. We call this zone the "comfortable suit zone."

V—
Concluding Remarks

In this chapter, we introduced the objective hand evaluation method. This method was developed for the objective measurement of fabric hand; however, the method may be applied to other materials that interact with the human senses, such as leather, artificial leather [14], and even to study the effects of cosmetics on human hair softness, food technology, etc. The authors have named these materials "human interactive materials." Some actual applications have been reported.

The mechanical parameters used in this analysis have been applied not only to the objective hand evaluation system but also to many other fields such as tailoring process control, the prediction of the making up of a suit, the prediction of comfort wearing properties based on these parameters, etc. The delicate nonlinear mechanical properties in the low-load region are important for the characterization of human interactive materials.

References

1. S. Kawabata and M. Niwa, Fabric performance in clothing and clothing manufacture, *J. Textile Inst. 80*:19–50 (1989).

2. F. T. Peirce, The "handle" of cloth as a measurable quantity, *J. Textile Inst. 21*:T377–416 (1930).

3. S. Kawabata, *The Standardization and Analysis of Hand Evaluation*, 2nd ed., Hand Evaluation and Standardization Committee, Textile Machinery Society of Japan, Osaka, 1980.

4. S. Kawabata, ed., *HESC Standard of Hand Evaluation* (*HV Standard for Men's Suiting*), HESC, Textile Machinery Society of Japan, Osaka, 1975.

5. S. Kawabata, ed., *HESC Standard of Hand Evaluation*, Vol. 1, *HV Standard for Men's Suiting*, 2nd ed., HESC, Textile Machinery Society of Japan, Osaka, 1980.

6. S. Kawabata, ed., *HESC Standard of Hand Evaluation*, Vol. 2, *HV Standard for Women's Thin Dress Fabric*, HESC, Textile Machinery Society of Japan, Osaka, 1980.

7. S. Kawabata, ed., *HESC Standard of Hand Evaluation*, Vol. 3, *HV Standard for Men's Winter Suiting*, HESC, Textile Machinery Society of Japan, Osaka, 1982.

8. V. B. Mountcastle, R. H. LaMotte, and G. Carli, Detection thresholds for vibratory stimuli in humans and monkeys: Comparison with threshold events in mechanoreceptive afferent nerve fibers innervating the monkey hand, *J. Neurophysiol. 35*:122–136 (1972).

9. M. Niwa, Analysis of Fabric Hand of High-Quality Apparel Fabrics on the Basis of Objective Evaluation Technique and the Design and Development of the High-Performance Fabrics, Report of Research Project, Grant-in-Aid for Co-operative Research in Japan, 1988, pp. 125–155.

10. P. G. Hoel, *Introduction to Mathematical Statistics*, 4th ed., John Wiley and Sons, New York, 1971.

11. S. Kawabata, M. Niwa, and W. Fumei, Objective hand measurement of nonwoven fabrics, Part I: Development of the equations, *Textile Res. J. 64*:597–610 (1994).

12. N. R. Draper and H. Smith, *Applied Regression Analysis*, John Wiley and Sons, New York, 1966.

13. S. Kawabata, K. Ito, and M. Niwa, Tailoring process control, *J. Textile Inst. 83*:361–373 (1992).

14. M. Niwa, C. Liu, and S. Kawabata, Application of the objective fabric-hand evalua-tion technology to the other materials such as artificial leather, foam and tissue paper,

Proc. 18th Textile Technology Symposium at Mount Fuji, Textile Machinery Society of Japan, Osaka, 1989, pp. 167–173.

15. S. Kawabata, and M. Niwa, A Proposal of the Standardized Measuring Condition for Mechanical Property of Apparel Fabrics, *Proc. Third Japan-Australia Symposium on Objective Measurement*, Textile machinery Society of Japan, Osaka, 1985, pp. 825–835.