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Analysis of the Physical Fundamentals of an Objective Integral Measuring System for the Determination of the Handle of Knitted Fabrics

Abstract
In this paper, an objective measuring method was devised to determine the handle of knitted fabrics. A test was performed using a special pulling device consisting of two horizontal plates: a base plate with a hole in the centre and a distance plate placed at a specified distance from the base plate. The device is mounted on a tensile testing machine. Since there is no standard method of assessing the handle of summer T-shirt knits, a mathematical method (Weighted Euclidean Distance method) was applied which highly correlates with the results of the KES-F system. The correlation analysis revealed that the features of the pull-through curve corresponded to the result of the Weighted Euclidean Distance method (WD-values). The pulling-through method with a distance plate could be a useful quantitative method of determining fabric handle during product development, quality control and consumer preference studies.

Key words: *fabric handle, pulling-through method, mechanical and surface properties, knitted fabric.*

Introduction

Several attempts have been made to measure fabric handle properties objectively, and also a number of items of equipment have been introduced for this purpose. The Kawabata Evaluation System [1] is the primary method of objectively characterising fabric handle. The precision and wide coverage of the fabric properties of this system is unprecedented, although for most industrial applications this system seems too expensive in terms of purchasing and operating costs. Another remaining problem in this approach has to do with establishing the relationship between the properties measured and handle preference, which has proven very complex and frustrating. On the other hand, because the system is based on the preferences of Japanese judges, the unsuitability of the results for markets other than Japan is inevitable, owing to the background-related nature of tactile sensory assessment [2].

Pan and Yen [3] commented on this problem and introduced a new approach for calculating the handle value from objective measurements without any recourse to subjective evaluations. This objective measure is described as the “Weighted Euclidean Distance”. Pan reported a high correlation between calculated handle values (WD-values) and total handle values obtained from Kawabata’s equations. However, as all the mechanical and surface properties of fabrics should be measured by Kawabata’s instruments, the application of this method becomes expensive, as with the KES method.

Tester and De Boos [4] reported: “For routine measurements and application of fabric objective properties particularly relevant to industry, only a fraction of the information obtained from previously available systems (such as Kawabata’s system) was required”. It is from this consideration that CSIRO in Australia developed its own routine fabric measurement system, named FAST. This system is specially designed for use by tailors and fabric finishers and has the advantage of simplicity. Despite the fact that the FAST system is much less expensive than Kawabata’s system, it is still not readily affordable for most textile laboratories. In order to overcome these limitations, several studies have been conducted to generate simpler measurement techniques. Several groups of workers [5 - 8] have described methods for evaluating fabric handle that depend on the analysis of the force-displacement curve obtained when a circular fabric sample, held at its centre, is pulled through a nozzle using an Instron Tensile Tester. Grover, Sultan and Spivak [9] used this method to determine the handle of many fabrics and reported: “The variation in the pulling force is high as a result of variation in the folding configuration formed by the fabric passing through the nozzle. This variation may necessitate increasing the number of tests”. In order to reduce the variation in results as well as the control of the folding configuration during the withdrawing, a novel technique [10 - 13] was developed, which is basically similar to the conventional pulling-through method.

In this study, the principles of this objective measuring method as a simple method will be investigated to determine fabric handle for industrial applications, especially in the case of small-scale apparel and textile products. Moreover, most of the studies relating handle and mechanical properties have involved woven fabrics, but more research is required on knitted fabrics.

Measurement technique

In this technique (PDP method[1]), a test is performed by a special pulling device mounted on a tensile testing machine consisting of two horizontal plates: a replaceable base plate with a hole in the centre and a distance plate placed at a specified distance from the base plate (***Figure 1***). The distance between the

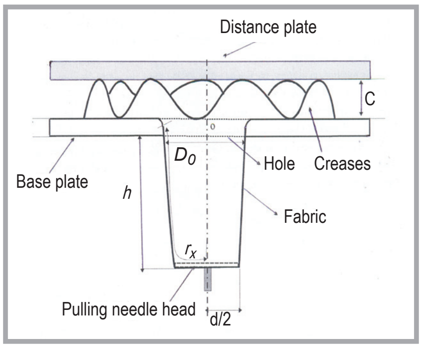

Figure 1. *Principle of the PDP method.*

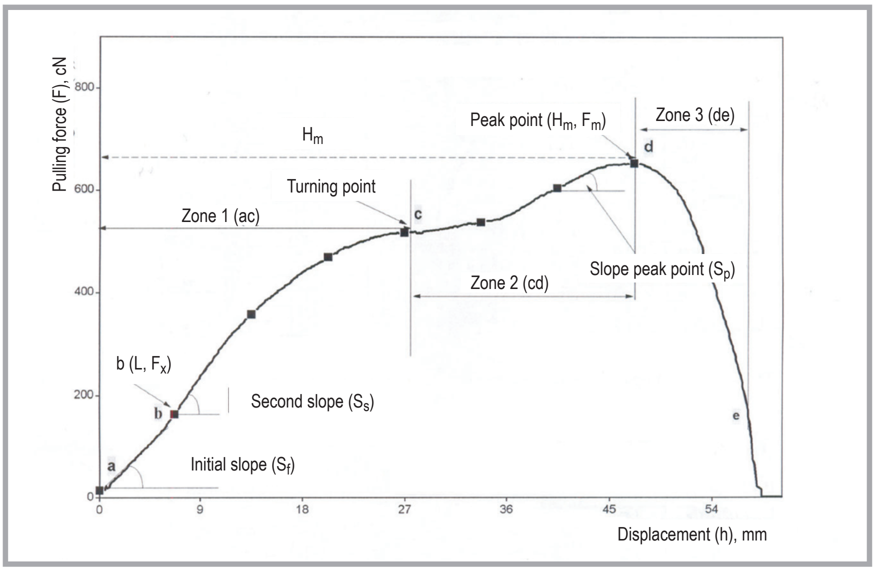

Figure 2. *Force-displacement curve obtained by PDP method.*

base plate and distance plate is adjustable in the range of 0.5 - 6 mm. The hole's diameter can be changed in the range of 10 - 30 mm. A rounded sample is pulled through the hole; the pulling force required is measured with respect to the displacement of the specimen, which is recorded as a force-displacement curve.

A careful examination of the fabric's behaviour during withdrawing reveals a three-stage deformation process. A typical pull-through curve (force-displacement curve) obtained by the PDP method is shown in ***Figure 2***. In the first stage of the pulling-through process, the specimen starts to wrinkle, and the pulling force changes linearly with respect to the fabric displacement. The pulling force is required to overcome the bending and shearing forces. The round sample is not fully in contact with the hole's wall. The curve slope changes when the hole is filled by the specimen (point *b*). In this case, the force needed to pull the specimen through the hole changes proportionally to the packing ratio of the specimen, which is defined as follows:

$$\psi = \frac{2\pi r_x \sigma}{\pi (\frac{D_0}{2})^2} , \qquad (1)$$

where D_0 and σ are the hole diameter and the fabric thickness, respectively. The term $2\pi r_x \sigma$ is the premier of the specimen at a specified point of the withdrawing. The packing ratio of the specimen in the hole and, consequently, the force needed to withdraw the fabric will increase as more and more of the specimen is introduced into the hole.

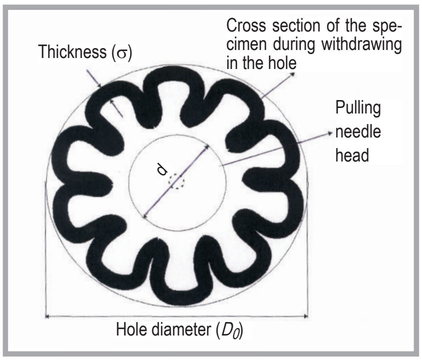

Figure 3. *Cross section of the specimen during the pulling-through process in the hole at a specified point of the withdrawing (r_x).*

Continuing the pulling-through process, the specimen deviates from a circular (initial shape) to another shape, which happens because the number of creases in the specimen's stiffer direction is different from the stiffer direction. This can cause a slight decrease in the curve slope. The endpoint of this stage is termed the "turning point" (point *c*). In the next stage of the pulling process (zone 2), the contact surface of the fabric with the base plate and the distance plate decreases gradually, and the packing ratio of the fabric in the hole increases synchronously. Consequently, the slope of the curve increases significantly once again. The force needed to withdraw the fabric will increase more and more as it continues to a peak point (F_m, H_m). The slope of the pull-through curve at the peak point (S_p) shows the resistance of the fabric when pulled through the hole. A maximum value of the pulling force is achieved when the entire specimen has nearly passed through the hole. In the last stage of the pulling process (zone 3), the whole fabric passes through the hole, and the pulling force decreases. The change in some geometrical parameters greatly affects the results of the pulling-through technique as well as the shape of the pull-through curve. The following parameters can be changed depending on the characteristics of the fabric tested:

1. Hole diameter (D_0): According to formula (1), the packing ratio of the specimen is inversely proportional to the square of the hole diameter. Therefore, an increase in the hole diameter remarkably reduces the packing ratio as well as the fabric resistance and pulling force during withdrawing.
2. Distance between the base plate and distance plate (*C*): the distance between these two plates influences the number of creases of the specimen as well as the contact surface of the fabric as a result the pulling force.
3. Diameter of the pulling needle's head (*d*): Pulling the specimen with a greater pulling needle head provides more contact with the hole and consequently increases the pulling force.

In order to determine the distance between the base plate and distance plate (*C*) as well as the hole diameter of the base plate (D_0) for each fabric, two conditions can be defined for this test [11]:

1. Pulling of the fabric through the base plate's hole without any jamming.
2. Pulling of the fabric from the space between the base plate and distance plate.

A closer look at ***Figures 3*** & ***4*** and the definition of the fabric packing ratio in the hole with the following assumption can help to define conditions which prevent the fabric jamming in the two cases mentioned above: $r_x = R_m$.

The fabric can be pulled through the base plate's hole without any jamming if the

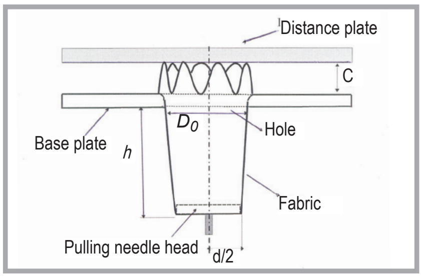

Figure 4. *Side view of the specimen at the end of the pulling-through process.*

volume of the hole is greater than that of the specimen. This condition can be defined as follows:

$$\pi \frac{D_0^{\,2}}{4} L > 2\pi R_m \sigma L k . \qquad (2)$$

Fabric jamming will not occur in the space between the base plate and distance plate if:

$$\pi D_0 C > 2\pi R_m \sigma k . \qquad (3)$$

Where R_m is the radius of the round specimen (R_m = 56.5 mm), and σ is the fabric thickness in mm. The behaviour of a knitted fabric is far from that of a solid body. Hence, a correcting factor (k) was added to the conditions above. In this case, from experience, the value of this factor was assumed to be $k = 0.7$.

These conditions can be calculated based on the fabric weight (w). Calculation of the fabric weight based on the nominal thickness (σ) is very imprecise. On this account, the calculation must be based on the effective thickness of the fabric, which is defined as follows:

$$\textit{Effective thickness } (\sigma_e) = \frac{\textit{True volume}}{\textit{Area}} \qquad (4)$$

Alley and Halton [5] applied a special instrument to measure the effective thickness and reported that the ratio of the effective thickness and nominal thickness (σ) for knitted fabrics is $\sigma_e/\sigma \approx 0.1$. It is assumed that this ratio is constant for all knitted fabrics. Thus, the approximate fabric weight can be calculated based on this equation. The optimal testing conditions based on the fabric thickness are as follows:

- If $0 < w < 0.40\,\rho \rightarrow D_0 = 10$ mm & $C > (6.77\,w)/\,\rho$ mm
- If $0.40\,\rho < w < 0.55\,\rho \rightarrow D_0 = 12$ mm & $C > (5.64\,w)/\,\rho$ mm
- If $0.55\,\rho < w < 0.75\,\rho \rightarrow D_0 = 14$ mm & $C > (4.84\,w)/\,\rho$ mm
- If $0.75\,\rho < w < 0.95\,\rho \rightarrow D_0 = 16$ mm & $C > (4.23\,w)/\,\rho$ mm
- If $0.95\,\rho < w < 1.20\,\rho \rightarrow D_0 = 18$ mm & $C > (3.76\,w)/\,\rho$ mm
- If $1.20\,\rho < w < 1.50\,\rho \rightarrow D_0 = 20$ mm & $C > (3.38\,w)/\,\rho$ mm
- If $1.50\,\rho < w < 1.80\,\rho \rightarrow D_0 = 22$ mm & $C > (3.08\,w)/\,\rho$ mm.

Where w is the fabric weight in g/100 cm^2, and ρ is the density in g/cm^3 of the material tested.

Table 1. *Specifications of the knitted fabrics; * I.B: Intensive bleaching (bleaching at 80 °C, 30 minutes with 1.5% H_2O_2), N.B: Normal bleaching (bleaching at 98 °C, 60 minutes with 15% H_2O_2), S_1: First softener (Tubingal 220), S_2: Second softener (Tubingal MSQ), S_3: Third softener (Tubingal KRE).*

Fabric code	Material and yarn specifications	Spinning system	Fabric structure	Knit density, loop/cm^2	Finishing stage
C001	Cotton/Nm68/Carded	Ring	1x1 Rib	112	Dyed
C002		Vortex		45	
V001	Viscose/Nm68/Carded	Ring		84	
V002		Vortex		60	
C01	Cotton/Nm50/750TPM/Combed	Vortex	Plain single jersey	349	I.B*
C02		Open-end		357	
C03		Compact		352	
C05	Cotton/Nm50/750TPM/Carded	Compact		352	
C10		Ring		333	
C04				344	
C06	Cotton/Nm50/850TPM/Combed		Double cross tuck	192	
C07			Plain single jersey	341	
C08			Double cross miss	168	
C09	Cotton/Nm50/650TPM/Combed		Double cross tuck	186	
C10			Plain single jersey	338	
C11			Double cross miss	161	
C12	Cotton/Nm50/750TPM/Combed		Double cross tuck	208	
C13			Plain single jersey	195	
C14			Double cross miss	145	
C15			Plain single jersey	285	
C16				352	
A01				247	Scoured
A02				300	I.B
A03				320	I.B+ S_1*(2%)
A04				320	I.B+ S_2*(2%)
A05				320	I.B+ S_2 (4%)
A06				320	I.B+ S_3*(2%)
A07				300	N.B*
A08				310	N.B+ S_1 (2%)
A09				310	N.B+ S_2 (2%)
A10				310	N.B+ S_2 (4%)
A11				310	N.B+ S_3 (2%)
A12				315	Dyed
A13				315	N.B+Dyed
A14				315	N.B+Dyed+S_1

Table 2. *Range of mechanical and surface properties of the fabrics.*

Mechanical and surface properties	Maximum value	Minimum value	Average value
Shear rigidity (G), g/(cm·1°)	0.762	0.291	0.526
Hysteresis of shear force at 0.5 grad (2HG), g/cm	3.877	1.00	2.430
Hysteresis of shear force at 5.0 grad (2HG5), g/cm	4.28	1.43	2.855
Bending rigidity (B), g·cm^2/cm	20.76	0.88	10.82
Hysteresis of bending moment (2HB), g·cm/cm	36.51	1.60	19.05
Energy in extending fabric to 5 N/cm (WT), g·cm/cm^2	162	73.03	117.51
Tensile resilience (RT), %	30.7	17.00	23.80
Linearity of load extension curve (LT), (max 1)	0.744	0.594	0.669
Energy in compressing under 5 kPa (WC), g·cm/cm^2	5.44	3.52	4.48
Compressional Resilience (RC), %	48.09	28.05	38.07
Linearity of compression (LC), (max 1)	0.33	0.423	0.376
Coefficient of steel/fabric friction (MIU), (max 1)	0.3	0.21	0.255
Mean deviation of *MIU* (MMD), (max 1)	0.02	0.012	0.016
Geometric Roughness (SMD) µm	18.50	4.90	11.70
Fabric thickness (T), mm	1.23	0.89	1.06
Fabric mass per unit area (W), g/m^2	197.4	118	157.7

Experimental design

In this study thirty six fabric specimens were knitted on a circular knitting machine. The specimens were produced with different fibres, yarns, fabrics and finishing specifications that can be used for a summer T-shirt. The specification of the knitted fabrics is shown in ***Table 1***. The mechanical properties of the knits were measured using a KES instrument. Sixteen properties were measured under standard conditions, including tensile, bending, shear, compression and surface properties, as well as the thickness and weight of the knitted fabrics. Because

Table 3. *Eigenvalues (C_i) of the covariance matrix and their corresponding ratios.*

i	eigenvalues (C_i)	W_i^2	$\sum W_i^2$
1	6.7620	4.2262	0.4226
2	2.7092	1.6932	0,5919
3	2.2188	1.3867	0.7306
4	1.4779	0.9236	0.8230
5	0.9560	0.0597	0.8827
6	0.5513	0.0344	0.9171
7	0.5037	0.0314	0.9485
8	0.1762	0.0110	0.9595
9	0.1655	0.0103	0.9698
10	0.1012	0.0063	0.9761
11	0.0946	0.0059	0.9820
12	0.0668	0.0041	0.9861
13	0.0434	0.0027	0.9888
14	0.0295	0.0018	0.9906
15	0.0186	0.0011	0.9917
16	0.0039	0.0002	0.9919

anisotropy is a consideration in knitted fabrics, eleven of the tests (tensile, bending, shear and surface properties) were conducted in both the wale and coarse directions, and mean values were used in the data analysis. Furthermore, the fabrics were tested by the PDP method, and the pull-through curves were analysed. The range of mechanical properties of the specimens tested is shown in ***Table 2*** (see page 65).

The Weighted Euclidean Distance method [3] was implemented to assess the fabric handle. In addition, to evaluate the results of the PDP method, features of the pulling-through curve were compared with the results of the mathematical method. The processing of the original data to calculate the handle values of knitted fabrics by the Weighted Euclidean Distance method is introduced in this section. An original data matrix was created from the mechanical parameters of the fabric samples according to the Kahunen-Loeve theory [14]. Data are measured using the KES-FB instrument system, with 16 variables for each sample. The original matrix is formed as equation 5.

The method is sensitive to the unit in which the original variables are measured [15]. Consequently, before further calculation, the original matrix X must be standardised. Then the covariance matrix V of X is calculated as:

$$V = (V_{i,j}),\ i = 1, 2, ..., n \qquad (6)$$

The eigenvalues2) n (C_i) and eigenvectors2) R_i ($i = 1, 2, ..., n$) of the covariance matrix V are easily obtained by means of the Jacobi algorithm [16, 17]. Ranking C_i in the sequence of their values and selecting p prior values $C_1 \geq C_2 \geq ... \geq C_p$ $(p < n)$ satisfies the following condition:

$$\sum_{i=1}^{p} C_i \big/ trV \geq 0.85. \qquad (7)$$

The eigenvalues (C_i, i = 1, 2, …, 5) of the covariance matrix with their corresponding ratios, $W_i^2 = C_i/trV$, are listed in ***Table 3***. Hence, from ***Table 3***, p = 5 is chosen as the number of prior eigenvalues justified in condition (7). The original matrix (X) can be replaced by the orthonormal vector Y through a matrix transformation - equation (8), where *R[1]*, *R[2]*, …, *R[5]* are the five eigenvectors corresponding to the five prior eigenvalues of the covariance matrix V of ***X.*** Thus the ratio

$$W_i^2 = \frac{C_i}{\sum_{k=1}^{n} C_k} = \frac{C_i}{trV}, \qquad (9)$$

where $trV = \sum_{k=1}^{n} C_k$ is the trace of covariance matrix V, which can be defined as the weight of component *Y[i]*. Transformation matrix Y is then composed of $p = 5$ eigenvectors. Therefore, the weighted Euclidean distance method is a mathematical transformation of the data from a higher dimensional space to a lower one by eliminating superfluous components so as to condense the information and reduce the dimensions of the original data. The definition of the weighted Euclidean distance between fabrics [8] is:

$$WD = \sqrt{\sum_{i=1}^{5} \left(W_i \left(Y_{1i} - Y_{2i} \right)^2 \right)}. \qquad (10)$$

where Y_{1i} and Y_{2i} are the components of the transformation matrix for the specimen and standard fabric, respectively. The fabric which presented the lowest pulling-through features was selected as standard fabric. The value of *WD* can reflect the degree of fabric handle. The higher the *WD* value, the further away from the standard sample and the worse the fabric handle is.

In order to compare the results of the weighted Euclidean Distance method (*WD* values) and PDP method, a simple approach was used to examine the shape of the curve. Six characteristics of the pull-through curve (***Figure 2***) were chosen as follows:

1. Initial slope of the pull-through curve (S_f): This slope is taken out at the starting point of the curve.
2. Second slope of the pull-through curve (S_s): It must be calculated when the sample is in full contact with the hole's wall. This occurs when the sample is pulled more than 5 mm (the height of the hole) downwards.

$$X = (X_{37,16}) = \begin{array}{cccccc}
\text{1‘st property} & \text{2‘st property} & \text{3‘st property} & & \text{16‘st property} & \\
\Downarrow & \Downarrow & \Downarrow & & \Downarrow & \\
X_{1,1}, & X_{1,2}, & X_{1,3}, & \ldots\ldots, & X_{1,16} & \Rightarrow \text{1‘st sample} \\
X_{2,1}, & X_{2,2}, & X_{2,3}, & \ldots\ldots, & X_{2,16} & \Rightarrow \text{2‘st sample} \\
X_{3,1}, & X_{3,2}, & X_{3,3}, & \ldots\ldots, & X_{3,16} & \Rightarrow \text{3‘st sample} \\
\ldots, & \ldots, & \ldots, & \ldots\ldots, & \ldots & \\
\ldots, & \ldots, & \ldots, & \ldots\ldots, & \ldots & \\
\ldots, & \ldots, & \ldots, & \ldots\ldots, & \ldots & \\
X_{36,1}, & X_{36,2}, & X_{36,3}, & \ldots\ldots, & X_{36,16} & \Rightarrow \text{36‘st sample}
\end{array} \qquad (5)$$

$$Y = X \cdot R \qquad (8)$$

$$\begin{array}{ccc}
Y[1] & Y[2] & Y[5] \\
\Downarrow & \Downarrow & \Downarrow \\
Y_{1,1}, & Y_{1,2},\ldots, & Y_{1,5} \\
Y_{2,1}, & Y_{2,2},\ldots, & Y_{2,5} \\
Y_{3,1}, & Y_{3,2},\ldots, & Y_{3,5} \\
\ldots, & \ldots, & \ldots \\
\ldots, & \ldots, & \ldots \\
\ldots, & \ldots, & \ldots \\
Y_{16,1} & Y_{16,2},\ldots, & Y_{16,5}
\end{array}
=
\begin{bmatrix}
X_{1,1}, & X_{1,2}, & X_{1,3},\ldots\ldots, & X_{1,16} \\
X_{2,1}, & X_{2,2}, & X_{2,3},\ldots\ldots, & X_{2,16} \\
X_{3,1}, & X_{3,2}, & X_{3,3},\ldots\ldots, & X_{3,16} \\
\ldots, & \ldots, & \ldots,\ldots\ldots, & \ldots \\
\ldots, & \ldots, & \ldots,\ldots\ldots, & \ldots \\
\ldots, & \ldots, & \ldots,\ldots\ldots, & \ldots \\
X_{36,1}, & X_{36,2}, & X_{36,3},\ldots\ldots, & X_{36,16}
\end{bmatrix}
\cdot
\begin{array}{ccc}
R[1] & R[2] & R[5] \\
\Downarrow & \Downarrow & \Downarrow \\
R_{1,1}, & R_{1,2},\ldots, & R_{1,5} \\
R_{2,1}, & R_{2,2},\ldots, & R_{2,5} \\
R_{3,1}, & R_{3,2},\ldots, & R_{3,5} \\
\ldots, & \ldots, & \ldots \\
\ldots, & \ldots, & \ldots \\
\ldots, & \ldots, & \ldots \\
R_{16,1}, & R_{16,2},\ldots, & R_{16,5}
\end{array}$$

Equations: 5 and 8; *The dependences of $X = (X_{37,16})$ and $Y = X \cdot R$.*

3. Initial slope of the pull-through curve (S_p): This slope is taken out at the peak point of the curve.
4. Maximum pulling force (F_m)
5. Area under the pull-through curve (A)
6. Peak location (H_m).

These features can be easily extracted from the pull-through curves.

Results and discussions

The matrix *Y* is orthonormal, meaning that all its Components are uncorrelated with each other, each component reflecting one aspect of the fabric hand, which differs from those by other components. Hence, the components of matrix *Y* (*Y[1]*, *Y[2]*,…,*Y[5]*) can be called primary hand values. On the other hand, sixteen mechanical parameters measured by KES-FB instruments reflect five different primary hand features for summer knitted T-shirts.

Because there is neither a clear definition nor an objective and reliable calibration for primary hand values, it is difficult to determine the physical meaning of these features directly. As an expedient choice, however, correlation analysis is used in this paper to relate these features to the mechanical and surface properties of knitted fabrics. The correlation coefficients between five primary hand features(*Y[i], i* = 1, 2, …, 5) and the sixteen original mechanical and surface parameters are calculated and listed in ***Table 4***. According to the results of this Table and Bishop [18], the features can be named as follows:

1. *Y[1]* is highly correlated with shear, bending and compression properties; condensed results of these parameters are called “firmness”.
2. *Y[2]* is highly correlated with compression properties and thickness; the condensed results of these parameters can be called “fullness”.
3. *Y[3]* is significantly correlated with surface properties, weight, shear, tensile and stiffness; condensed results of these parameters can be termed “ crispness”.
4. For similar reasons, *Y[4]* and *Y[5]* are termed “roughness” and “stiffness”, respectively.

Table 4. *Correlation between five primary hand features and sixteen KES parameters; * Significant at the 0.05 level ** Significant at the 0.01 level.*

Properties	Y[1]	Y[2]	Y[3]	Y[4]	Y[5]
LT	0.684**	0.312	0.399**	0.409**	0.556**
Log *WT*	-0.290	-0.512**	0.666**	-0.236	-0.223
RT	-0.786**	-0.293	0.281	0.152	-0.588**
Log *B*	0.836**	-0.120	0.220	-0.334*	0.738**
Log *2HB*	0.922**	- 0.062	0.102	-0.290	0.818**
Log *G*	0.833**	0.281	0.361*	0.141	0.702**
Log *2HG*	0.962**	0.178	0.027	0.00	0.749**
Log *2HG5*	0.956**	0.195	0.062	0.031	0.748**
LC	-0.549**	- 0.466**	0.111	-0.545**	-0.448**
Log *WC*	-0.169	- 0.843**	-0.078	0.049	-0.167
RC	-0.717**	- 0.573**	-0.152	-0.136	-0.497**
MIU	0.263	- 0.080	-0.524**	-0.553**	-0.397*
Log *MMD*	0.397	- 0.397**	-0.503**	0.343*	-0.519**
Log *SMD*	-0.613**	- 0.013	-0.482**	-0.363*	-0.763**
Log *T*	-0.21	- 0.821**	-0.264	0.264	-0.310
Log *W*	-0.154	- 0.055	0.682**	-0.265	0.383*

Table 5. *Correlation between pulling-through features, primary hand values and WD-values; * Significant at the 0.05 level ** Significant at the 0.01 level.*

Properties	F_m	H_m	A	S_f	S_s	S_p
Y[1]	0.740**	0.389*	0.732**	0.780**	0.615**	0.536**
Y[2]	0.055	-0.290	0.053	0.02	-0.02	0.07
Y[3]	0.11	0.110	0.049	0.391*	-0.16	0.342*
Y[4]	-0.370*	-0.610**	-0.360*	0.259	-0.450**	-0.450**
Y[5]	0.784**	0.481**	0.802**	0.593**	0.797**	0.580**
WD	0.786**	0.496**	0.778**	0.747**	0.679**	0.606**

Therefore, five primary hand features (descriptors): “firmness”, “stiffness”, “fullness”, “roughness” and “crispness” are used to evaluate the handle of summer T-shirt knits. In order to understand how primary handle features are associated with features extracted from the pull-through curves of summer suiting, a statistical correlation analysis was made using the mechanical and surface properties of the fabrics, and *WD* values as dependent variables. ***Table 5*** shows the correlation coefficients of this analysis. Although there is no relationship between the primary hand feature Y_2 and those of the pull-through curve, the results of the correlation analysis show a high correlation between the features of the pulling-through curve selected and the *WD* value. This may be attributed to the fact that the primary hand feature Y_2 has less of an effect on the *WD* value compared with other primary hand features. The maximum pulling force (F_m) has the greatest correlation (0.786) with the *WD* value. ***Figure 5*** (see page 68) shows the relationship between the maximum pulling-through force and *WD* values. This high correlation shows the effectiveness of the PDP-method in detecting changes in fabric handle affected by different parameters.

Conclusion

In this paper, an objective measuring method was used to evaluate the handle of summer T-shirt knits. In this technique, the test was performed by a special pulling device, mounted on a tensile testing machine consisting of two transparent horizontal plates: a replaceable base plate with a hole in the centre and a distance plate placed at a specified distance from the base plate. Since there is no standard method of assessing the handle of summer knitted suiting, a mathematical method (Weighted Euclidean Distance method) was applied which highly correlates with the results of the KES-F system. By using the Weighted Euclidean Distance procedure, it could be concluded that five primary hand features: “firmness”, “stiffness”, “fullness”, “roughness” and “crispness” are used together to evaluate the handle of the summer T-shirts knits. Afterwards the total handle values (*WD* values) were calculated for the knitted fabrics without any recourse to subjective evaluation. Using correlation analysis, the results of this mathematical method and pull-through curve features were compared . The correlation analysis revealed that the features of the pull-through curve corresponded to the result of the Weighted Euclidean Distance method (WD-values). The PDP method demonstrated effective-

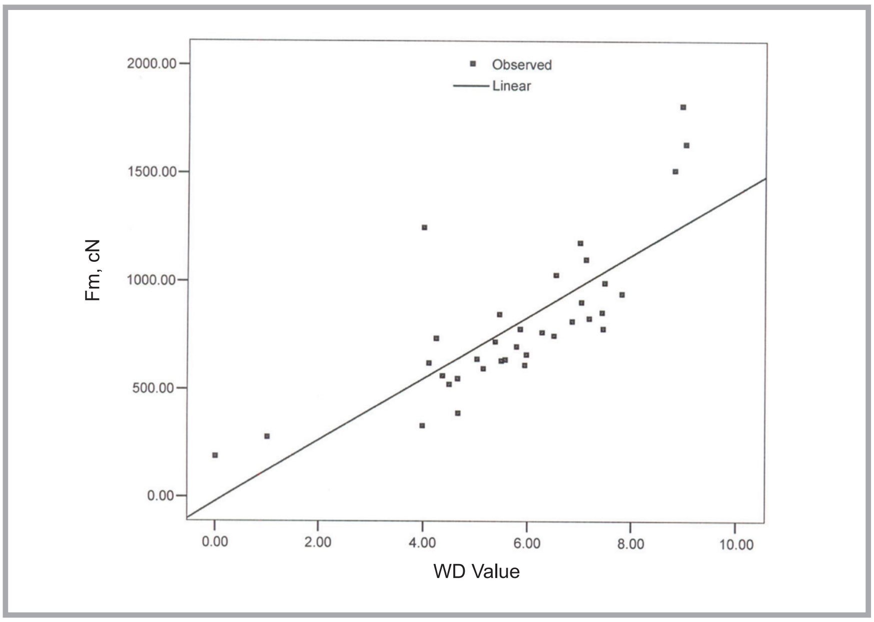

Figure 5. *Relationship between the maximum pulling-through force and WD values.*

ness in detecting changes in fabric handle affected by different parameters. This test method could be a useful quantitative method of determining fabric handle during product development, quality control and consumer preference studies.

Editorial notes

1) *Pulling-through method with distance plate.*
2) *Consider the square matrix A. We say that λ is an eigenvalue of A if there exists a non-zero vector x such that Ax = λx. In this case, x is called an eigenvector (corresponding to λ).*

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