This is an Accepted Manuscript of an article published by Taylor & Francis in "Journal of the Textile Institute" on 27th September 2019, available online: https://www.tandfonline.com/doi/abs/10.1080/00405000.2019.1670924

Canonical analysis of the Kawabata and sliding fabric friction measurement methods

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Abstract

The aim of this study was to identify the latent structure and potential relationships between two sets of frictions measurements of warp-and-weft fabrics made with the sliding method and the Kawabata system (KES FB-4 method). First, linear relationships between all pairs of friction-related variables for the two methods were assessed and found to be weak and statistically not significant in most cases. Second, linear regression was applied to the variables previously exhibiting significant correlation only but the variables were found not to be useful for developing accurate predictive models. Third, multiple linear regression between a Kawabata variable and various parameters of the sliding method was used to construct a model that proved inaccurate owing to multicollinearity in the regressors; also, the method only allowed a single dependent variable to be related. This was not the case with canonical correlation, which allowed two sets of variables to be correlated through multivariate analysis. This technique revealed a significant relationship between the two sets of friction-related variables.

Key words: Fabric friction, Kawabata system, sliding method, canonical correlations.

1. Introduction

The frictional properties of fabric surfaces are important because they influence the abrasion resistance, shrinkage and aesthetic qualities of fabrics (Howell, Mieszkis & Tabor, 1959), (Ajayi, 2008). Friction also influences fabric touch. This property not only provides an objective measure of fabric quality but also is a key factor for evaluating hand (Kawabata, 1980; Ajayi,1992b; Ajayi, 2008; Carrera-Gallissà et al., 2017). Because it restricts the number of layers that can be stacked in cutting fabric, friction also affects drapeability (Apurba et al., 2005). In recent years, fabric friction has also become a useful attribute with a view to assessing tactile properties in next-to-skin medical and sports apparel (Ramalho et al., 2013).

A number of studies have related fabric friction to structural properties such as fabric type and composition, yarn type, weave and density and finishing treatment (Carr, Posey, & Tincher, 1988; Zurek, Jankowiak, & Frydrych, 1985; Ajayi, 1992a; Ajayi, Elder, Kolawole, Bello, & Darma,1995; Ajavi & Elder, 1997; Ajayi, 2008).

Fabric friction is usually measured with one of the following three methods:

(a) The *Kawabata Evaluation System for Fabrics* (KES-F), which measures compression, bending, shearing and surface friction forces to assess surface micro-roughness and determine the friction coefficient (Kawabata, 1980).

(b) The *sliding method*, which measures the friction force against a parallelepipedal weight of known mass sliding over a fabric specimen with a modified Instron dynamometer (Ajayi, 1992; Carrera-Gallissà et al., 2017). This method has several variants (Das et al., 2005; Ramalho et al., 2013).

(c) *The FRICTORQ method*, which estimates the coefficient of friction between two parallel fabric surfaces by measuring torque. The method pulls a fabric specimen through a ring. The upper element has a ring-shaped contact surface that is placed on a horizontally lying flat specimen whereas the lower element rotates at a constant angular velocity around a vertical axis. The coefficient of friction is proportional to the torque measurement provided by a high-precision sensor (Lima & Hes, 2002; Lima et al., 2005a; Lima et al., 2005b).

Although the Kawabata system (KES-F) affords accurate measurements of physico–mechanical properties, the sophisticated equipment needed makes it expensive to use; also, KES-F only provides a fraction of industrially useful information. These shortcomings have boosted the development of faster, more economical alternatives such as the sliding method.

The primary aim was not to compare two different measurement methods, but rather to identify the latent structure of two sets of results obtained under preset conditions with them.

One other aim of this work was to explore the potential relationship between friction-related parameters as determined with the Kawabata system and the sliding method in order to identify potential correlations with a view to enabling easier quantification of fabric friction.

2. Friction measurement methods

In 1699, Amontons proposed the following linear relationship (the friction law):

$$F = \mu N \tag{1}$$

where F is the friction force, in newtons, N the normal force or load acting on the contact surface and μ a proportionality constant known as the "coefficient of friction". However, viscoelastic materials such as fabrics fit the following non-linear equation, proposed by Bowden and Tabor (1954), more closely:

$$F = C\,N^n \quad (2)$$

where C is the coefficient of contact and n the friction index. With n = 1, C = μ. Equation 1 can be rewritten as follows:

$$F/A = C\,(N/A)^n \quad (3)$$

where A is the apparent contact area, in m^2. This equation can be expressed in linear (logarithmic) form as

$$\lg(F/A) = \lg C + n\lg(N/A) \quad (4)$$

which can be written in simpler terms as

$$\lg F_P = \lg C + n\lg P \quad (5)$$

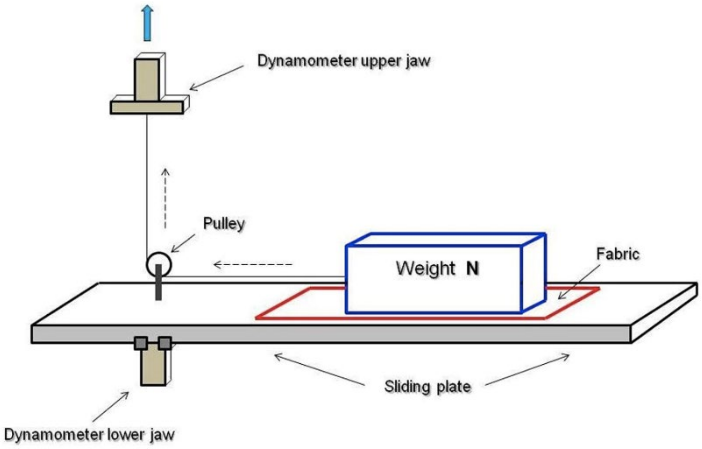
The coefficient of contact and the friction index are typically used to calculate the friction factor *R*, which facilitates quantification of some frictional properties of fabrics (Hermann et al., 2004).

$$R = \frac{C}{n}\,(\mathrm{Pa})^{1-n} \quad (6)$$

In the sliding method, the dynamometer upper jaw, which is connected to the loading cell, retains a parallelepipedic weight of mass *N* travelling across a sliding plate held by the dynamometer lower jaw. The fabric to be measured is placed on the plate and, as the lower jaw descends, the wire clamped by the upper jaw drags the weight to the left, thereby creating friction with the fabric (Figure 1). The dynamometer lower jaw measures the resistance *F* (friction force) of the weight to sliding on the fabric-covered plate. The weight can also be wrapped in fabric in order to assess friction between two fabric surfaces (Ajayi, 1992a, 1992b; Carrera-Gallissà et al., 2017) (Figure 1). The operating conditions of the sliding test were as follows:

- Slide material: polished brass.
- Slide weight: 100, 200, 300, 400 and 500 g.
- Contact surface area: 20 cm^2.
- Plate travel speed: 300 mm/min.
- Atmospheric conditions: 20 °C and 65% RH.

Figure 1. Friction measurement equipment for the sliding method.



The KES-FB4 module (Kawabata, 1980) determines the following fabric surface properties: mean coefficient of friction (MIU), mean deviation of the coefficient (MMD) and surface roughness deviation (SMD), which are defined as follows (figure 1):

$$\mathrm{MIU}=\frac{1}{L}\int_0^X \mu \, dL \qquad (6)$$

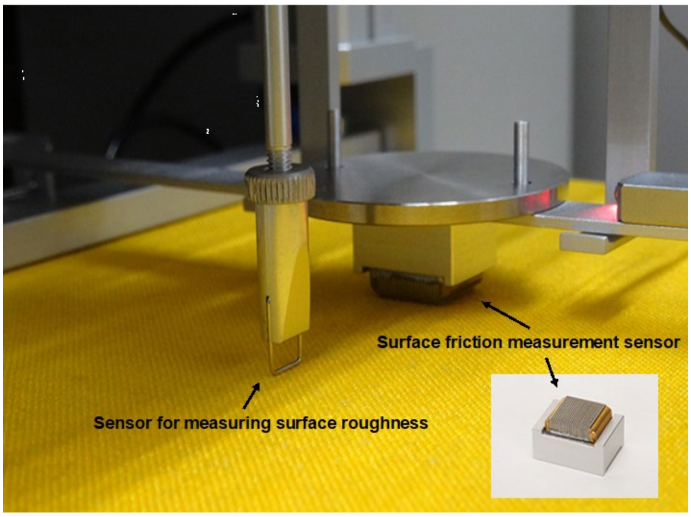
$$\mathrm{MMD}=\frac{1}{L}\int_0^X \left|\mu-\bar{\mu}\right| dL \qquad (7)$$

$$\mathrm{SMD}=\frac{1}{L}\int_0^X \left|T-\bar{T}\right| dL \qquad (8)$$

where *L* denotes maximum measured length and *T* thickness.

The head used to measure surface roughness consists of 0.5 mm thick piano string (Figure 2) and works at a contact force of (10 ± 0.5) g that is triggered by a spring with a constant of (25 ± 1) g/mm. When the head falls outside the test limits, the natural frequency of the system exceeds 30 Hz. Surface friction is measured with a head consisting of 10 piano strings (Figure 2, right) identical with that used to measure roughness and arranged in such a way that they apply a compression force of 50 g (heavy weight) to the fabric surface. With both types of measurements, the specimen is moved by 2 cm at a constant speed of 0.1 cm/s over a horizontal flat steel plate so that it is subjected to a stress force of 20 g/cm.

Figure 2. KES-F measuring equipment. Surface roughness sensor (left) and surface friction measurement sensor (right).



3. Materials and results

The materials studied were drapery warp-and-weft fabrics (Table 1). Table 2 shows their friction factors as calculated from eqs 1 to 5, and Table 3 their friction and roughness parameters as obtained from eqs 7 to 9.

Table 1. Fabric specimens studied.

Fabric no.	Fabric type	Composition (%)	Weave	GSM (g/m^2)
1	Women drapery	CO/WO/PA 76/19/5	Two-sided cloth	309.14
2	Women drapery	PES/VISC/ELAST 64/31/5	Double cloth	371.45
3	Winter men suit drapery	WO 100%	Serge	191.08
4	Summer men suit drapery	VISC/WO/PES 43/34/24	Taffeta	171.25
5	Winter men suit drapery	WO 100%	Serge	209.00
6	Winter men suit drapery	PES/RAI/ELAST 78/18/4	Taffeta	341.33
7	Women drapery	WO 100%	Satin	299.41
8	Drapery	WO/EA 99/1	Crêpe	232.16
9	Women drapery	WO/PC 60/40	Double cloth	447.41
10	Drapery	WO/PA 90/10	Double cloth	333.26
11	Winter men suit drapery	PES/RAI/ELAST 65/31/4	Taffeta	221.17

Table 2. Friction factors of the fabrics.

Fabric no.	**R(Pa)$^{1-n}$ static**		**R(Pa)$^{1-n}$ dynamic**	
	Weft	**Warp**	**Weft**	**Warp**
1	101.199	81.151	91.562	73.791
2	101.645	82.982	85.492	67.953
3	25.066	69.574	20.083	69.480
4	49.508	86.831	38.500	74.785
5	64.656	69.218	59.132	63.309
6	111.064	64.813	97.275	60.935
7	85.854	61.839	76.078	57.322
8	39.689	63.020	30.315	53.948
9	92.972	54.020	83.005	53.590
10	91.638	87.681	77.793	78.542
11	59.556	66.254	48.655	57.059

Table 3. KES friction and roughness parameters for the fabrics.

Fabric no.	**MIU**		**MMD**		**SMD**	
	Weft	**Warp**	**Weft**	**Warp**	**Weft**	**Warp**
1	0.164	0.145	0.021	0.020	5.227	7.468
2	0.274	0.262	0.022	0.024	6.857	7.994
3	0.148	0.168	0.014	0.012	8.851	4.03
4	0.183	0.173	0.020	0.020	9.361	7.187
5	0.140	0.133	0.014	0.012	4.768	6.092
6	0.213	0.175	0.014	0.014	5.234	6.381
7	0.274	0.262	0.022	0.024	6.857	7.994
8	0.230	0.194	0.018	0.020	8.291	10.674
9	0.226	0.222	0.019	0.015	5.843	6.327
10	0.255	0.255	0.019	0.022	9.108	10.08
11	0.231	0.216	0.017	0.016	6.038	6.712

3.1 Canonical correlation analysis

Canonical correlation analysis is used to relate two sets of variables X and Y by identifying those pairs of independent linear combinations exhibiting the highest correlation. Thus, a linear combination of the each of the two sets of variables $U = \mathrm{a}X$ and $V = \mathrm{b}Y$ (where a and b are two weighting factors) is used to identify the a and b values maximizing correlation between U and V under the constraint that the variances of both should be unity.

The problem involves solving the following eigensystem:

$$\left(S_{yy}^{-1}S_{yx}S_{xx}^{-1}S_{xy}-\lambda^{2}I\right)a=0$$

$$\left(S_{xx}^{-1}S_{xy}S_{yy}^{-1}S_{yx}-\lambda^{2}I\right)b=0$$

where the subscripts correspond to the covariance matrices for the two sets of variables (X and Y) and λ is canonical correlation between U and V. Calculations can also be made with correlation matrices (R).

4. Discussion

As noted in the Introduction, the aim of this work was to identify potential correlations between the variables of two friction measurement methods. The variables of the sliding method were as follows:

X_1 = coefficient R of static friction in the weft direction ($R_{\text{stat weft}}$).
X_2 = coefficient R of static friction in the warp direction ($R_{\text{stat warp}}$).
X_3 = coefficient R of dynamic friction in the weft direction ($R_{\text{dyn weft}}$).
X_4 = coefficient R of dynamic friction in the warp direction ($R_{\text{dyn warp}}$).

On the other hand, the Kawabata system (KES-4) comprised the following set of variables:

Y_1 = coefficient MIU of friction in the weft direction (MIU_{weft}).
Y_2 = coefficient MIU of friction in the warp direction (MIU_{warp}).
Y_3 = mean deviation MMD in the weft direction (MMD_{weft}).
Y_4 = mean deviation MMD in the warp direction (MMD_{warp}).
Y_5 = mean roughness deviation SMD in the weft direction (SMD_{weft}).
Y_6 = mean roughness deviation SMD in the warp direction (SMD_{warp}).

The sign and magnitude of the linear relationships between pairs of variables of the two methods were determined from their Pearson's correlation coefficients, which are shown, together with the significance of each correlation, in brackets, in Table 4. As can be seen, most correlations were not significant, that is, α exceeded 0.05 or 0.1 —the latter is the usual choice for non-critical industrial processes. By exception, α was lower than 0.01 between the variables X_1 ($R_{\text{stat weft}}$) and Y_5 (SMD_{weft}), and nearly 0.05 for X_3 ($R_{\text{dyn weft}}$) and Y_5 (SMD_{weft}).

Table 4. Correlation matrix between X and Y variables.

Variable	**Y_1**	**Y_2**	**Y_3**	**Y_4**	**Y_5**	**Y_6**
X_1	0.42 (0.19)	0.32 (0.33)	0.39 (0.22)	0.31 (0.34)	–0.54 (0.08)	0.17 (0.59)
X_2	–0.05 (0.86)	0.00 (0.99)	0.32 (0.32)	0.41 (0.20)	0.42 (0.19)	0.25 (0.45)
X_3	0.36 (0.26)	0.26 (0.42)	0.36 (0.27)	0.26 (0.43)	–0.59 (0.05)	0.13 (0.69)
X_4	–0.25 (0.44)	–0.13 (0.70)	0.17 (0.60)	0.19 (0.56)	0.41 (0.20)	0.02 (0.93)

Figures 3 and 4 show the average lines illustrating correlation between Y_5 in the Kawabata system and the variables X_1 and X_3, respectively. The corresponding least-squares regression equations, with a p value of 0.069 and 0.047, respectively, provided a coefficient of determination as corrected for the number of degrees of freedom R^2 = 24.41% and R^2 = 29.79% , respectively. Therefore, $R_{\text{stat weft}}$ and $R_{\text{dyn weft}}$ accounted for only a very small proportion of the variability in SMD. As can be seen from Figures 3 and 4, SMD was similarly correlated to both variables because the regressors were highly correlated (r = 0.99). This near-linear relationship between the regressors can adversely affect the usefulness of a multiple regression model for elucidating the behaviour of the variable SMD_{weft} from eq. 9 (p = 0.028 and $R^2_{\text{corrected}}$ = 48.79). Multicollinearity was quantified through variance inflation factors (VIFs), which were very large (110.4) and hence suggestive of high variance in the regression coefficients.

$$\text{SMD}_{\text{weft}} = 7.6464 + 0.3060\, R_{\text{stat weft}} - 0.3665\, R_{\text{dyn weft}} \tag{10}$$

Figure 3. Fitting of the model to SMD_{weft}–$R_{\text{stat weft}}$ data

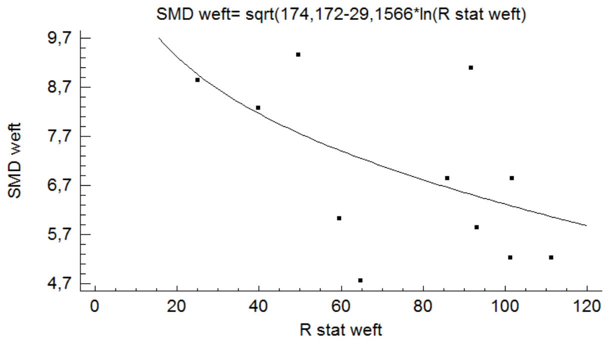
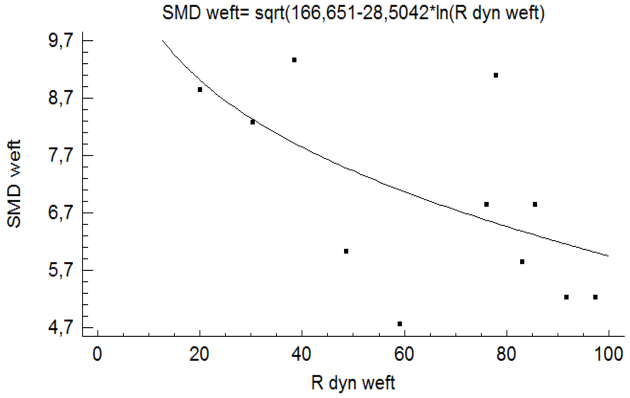


Figure 4. Fitting of the model to SMD_{weft}–$R_{\text{dyn weft}}$ data.



In addition, the linear regression method only allows a single dependent variable to be related at a time. This is not the case with canonical correlation analysis, which allows two sets of variables to be simultaneously compared.

The maximum number of canonical variables (i.e., functions or linear combinations of the original variables) that can be obtained from two sets of variables coincides with that of the smaller set. In our case, the smaller set was that for the sliding method, which comprised 4 variables. Tables 5 and 6 show the coefficients of correlation of these canonical variables (viz., a_{ij}, with i =1–4 and j =1–4, and b_{ij}, with i = 1–4 and j =1–6) with the original variables in standardized form, and Table 7 shows the four canonical correlations and their significance.

Table 5. Coefficients of the canonical variables for the X set.

	Variable	U_1	U_2	U_3	U_4
$\boldsymbol{R}_{\mathbf{stat\ weft}}$	X_1	10.837	8.738	2.091	5.730
$\boldsymbol{R}_{\mathbf{stat\ warp}}$	X_2	–1.392	–2.139	1.980	–1.858
$\boldsymbol{R}_{\mathbf{dyn\ weft}}$	X_3	–10.478	–9.431	–2.128	–5.097
$\boldsymbol{R}_{\mathbf{dyn\ warp}}$	X_4	0.483	2.100	–1.441	2.223

Table 6. Coefficients of the canonical variables for the Y set.

	Variable	V_1	V_2	V_3	V_4
$\mathbf{MIU}_{\mathbf{weft}}$	Y_1	3.104	0.672	0.447	–1.326
$\mathbf{MIU}_{\mathbf{warp}}$	Y_2	–1.690	–0.438	–0.829	1.671
$\mathbf{MMD}_{\mathbf{weft}}$	Y_3	0.512	–0.029	–0.757	0.919
$\mathbf{MMD}_{\mathbf{warp}}$	Y_4	–1.343	–0.533	1.852	–0.340
$\mathbf{SMD}_{\mathbf{weft}}$	Y_5	0.374	1.122	0.240	–0.048
$\mathbf{SMD}_{\mathbf{warp}}$	Y_6	–0.251	–0.296	–0.205	–0.332

The eigenvalues λ in Table 7 are coefficients of determination R^2 and thus measures of the proportion of variance shared among the canonical variables. Also, canonical correlations are correlations between canonical variables. Wilks' lambda test confirmed the null hypothesis (i.e., that the canonical correlation was zero) and provided a value exhibiting a chi-squared random distribution with a given number of degrees of freedom leaving an area quantified by the p value on the right.

Table 7. Canonical correlations between the sliding method and the Kawabata system. DF degrees of freedom.

No.	**Eigenvalue**	**Canonical correlation**	**Wilks' lambda**	**Chi-squared**	**DF**	***P***
1	0.992	0.995	0.000	41.230	24	0.015
2	0.967	0.983	0.013	19.501	15	0.191
3	0.550	0.742	0.407	4.040	8	0.853
4	0.093	0.305	0.906	0.441	3	0.931

Only the first canonical correlation was significant, with a p value less than 0.05 or 0.10.

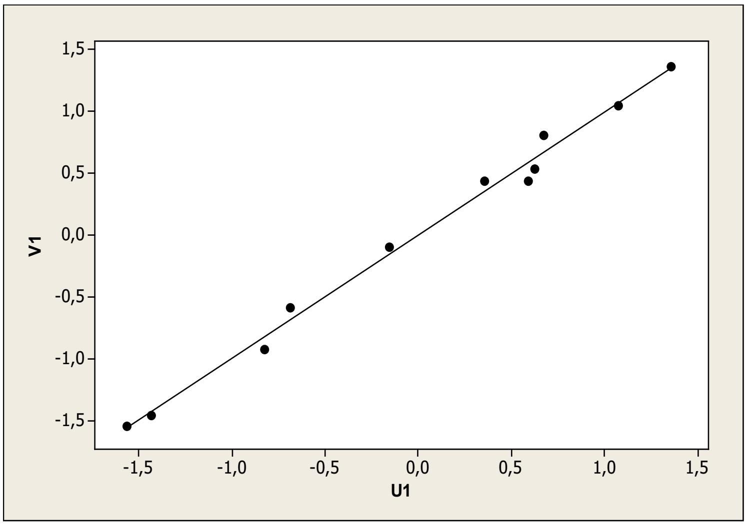
Figure 5 shows a plot of scores between the sets of variables X and Y as obtained from the first canonical variable for each set (U_1 and V_1) to illustrate the relationship between the canonical variables. These two non-standardized variables are defined in eqs 11 and 12:

$$U_1 = 2.3873 + 0.3796\ R_{\text{stat weft}} - 0.1233\ R_{\text{stat warp}} - 0.3961\ R_{\text{dyn weft}} + 0.0054\ R_{\text{dyn warp}} \quad (11)$$

$$V_1 = -4.4011 + 64.9491\ \text{MIU}_{\text{weft}} - 36.5572\ \text{MIU}_{\text{warp}} + 164.4923\ \text{MMD}_{\text{weft}} - 366.7082\ \text{MMD}_{\text{warp}} + 0.2214\ \text{SMD}_{\text{weft}} - 0.3155\ \text{SMD}_{\text{warp}} \quad (12)$$

Coefficients a_{ij} (Table 5) and b_{ij} (Table 6) are the canonical weights and represent the relative contributions to the canonical variables. As can be seen, the X variables most markedly contributing to the canonical variable U_1 were X_1 ($R_{\text{stat weft}}$) and X_2 ($R_{\text{dyn weft}}$). Similarly, the Y variables exhibiting the greatest contributions to the canonical variable V_1 were Y_1 (MIU_{weft}), Y_2 (MIU_{warp}) and Y_4 (MMD_{weft}). However, canonical weights are usually rather unstable (variable), so it is preferable to describe canonical variables in terms of their correlation with the original variables by using so-called "canonical loadings". Table 8 shows the corresponding direct loadings (r_{xu} and r_{yv}) and cross-loadings (r_{xv} and r_{yu}).

Figure 5. Relationship between the scores for the two sets of variables.



Direct loadings, which represent the variance a given variable shares with its canonical counterpart, can vary markedly among samples. For this reason, cross-loadings usually provide a more accurate picture of correlations between variables. Based on our cross-loadings, U_1 was correlated to the same extent with all X variables, whereas V_1 was highly correlated with MIU_{weft} and MIU_{warp} only.

Table 8. Canonical loadings for the variables U_1 and V_1.

	Variable	**U_1**	**V_1**
$R_{\text{stat weft}}$	X_1	0.315	0.314
$R_{\text{stat warp}}$	X_1	–0.487	–0.485
$R_{\text{dyn weft}}$	X_1	0.267	0.266
$R_{\text{dyn warp}}$	X_1	–0.606	–0.604
MIU_{weft}	Y_1	0.725	0.728
MIU_{warp}	Y_2	0.595	0.598
MMD_{weft}	Y_3	0.101	0.101
MMD_{warp}	Y_4	0.165	0.166
SMD_{weft}	Y_5	–0.062	–0.062
SMD_{warp}	Y_6	0.220	0.221

Although canonical correlation squared is a straightforward proxy for shared variance, such a variance is shared by linear combinations of the sets of variables, so it fails to reflect the variance for a specific set. This bias was avoided here by using a redundancy index that was calculated as the squared multiple correlation coefficient between set X (sliding method), defined by U_1, and each variable in set Y (MIU_{weft}, MIU_{warp}, MMD_{weft}, MMD_{warp}, SMD_{weft} and $\text{SMD}_{\text{warp},}$), and then obtaining an average multiple correlation coefficient.

The redundancy index is a measure of the ability of a set of variables X as a whole to explain the variance in each variable of another set Y. The redundancy index for our sets was low:

$$\overline{R}^2 = \frac{\sum_1^6 r_{u,y}^2}{6} = \frac{0.526 + 0.354 + 0.0039 + 0.0048 + 0.027 + 0.010}{6} = 16.2$$

The redundancy index was also calculated as the multiple correlation coefficient of set Y (Kawabata system), defined in terms of V_1 and each of the variables in X ($R_{\text{stat weft}}$, $R_{\text{stat warp}}$, $R_{\text{dyn weft}}$ and $R_{\text{dyn warp}}$):

$$\overline{R}^2 = \frac{\sum_1^6 r_{vx}^2}{4} = \frac{0.0989 + 0.235 + 0.0712 + 0.369}{4} = 19.3$$

This index is a measure of the ability of set Y as a whole to explain the variance in each variable of X, and was also low here.

5. Conclusions

Friction is an important property of fabrics as it influences their touch, hand and tailorability. Friction can be measured with various testing methods based on different physico–mechanical processes.

Although the KES-4 and sliding methods rely on different measurement principles, subjecting two sets of measurements of warp-and-weft fabrics made under preset experimental conditions with the two methods to canonical correlation multivariate analysis revealed an latent structure in both. Such a structure can be defined in terms of canonical variables that relate the two sets in a significant manner. The equations, however, have a low predictive capacity.

Because the two measurement methods examine the same phenomenon, their overall results are inevitably related. However, the KES-4 method assesses friction with a head similar to that typically used for micro-roughness in human fingerprints, whereas the sliding method measures friction of a flat surface moved over a micro-rough material (fabric).

Disclosure statement

No potential conflict of interest was reported by the authors.

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