Developing Physical Softness Models for Facial Tissue Products

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A series of physical softness models were developed for facial tissue products. To this end, subjective softness data were obtained by panelists by means of round-robin pair-comparison methods. Overall softness was found to mainly consist of bulk and surface softness. Bulk softness was determined by measuring the tensile modulus (*TM*) from tensile testing. In contrast, the surface softness considered the mean absolute de*via*tion (*RMAD*) from the roughness average (R_a) and the mean absolute de*via*tion (*FMAD*) from the average coefficient of friction ($\bar{\mu}$), respectively, which were determined by profilometry. The developed models exhibited strong correlations with subjective softness. In particular, surface softness was found to contribute more to the overall softness than bulk softness. Overall, the developed models can serve as guidance for developing tissue products.

DOI: 10.15376/biores.19.1.116-133

Keywords: Facial tissue; Physical softness model; Pair-comparison test; Interval scale value (ISV); Bulk softness; Surface softness; Tensile modulus (TM); Surface roughness (R_a and RMAD); Surface friction ($\bar{\mu}$ and FMAD)

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INTRODUCTION

Strength, softness, and absorbency are key attributes that consumers consider in hygiene paper products, such as bathroom tissues, facial tissues, and paper towels. However, it is critically important to realize that these attributes are subjective, which can be quite different from objective or physical properties. These may even be contradictory, resulting in mistakes when evaluating the in-use properties of the products.

To avoid making such mistakes while measuring the physical properties, various hygiene paper producers still heavily rely on subjective evaluation, especially sensory panel tests (SPTs) with well-trained panelists under controlled environments (Hollmark and Ampulski 2004; Rosen *et al*. 2014; Ko *et al.* 2015; 2016; 2017a; Lee *et al.* 2017a; Park 2017). Nevertheless, there have been continuous efforts to develop the physical test methods which can be used for predicting the subjective attributes because their benefits are too great to be ignored (Ko *et al.* 2015; 2016; Pawlak *et al*. 2022). Table 1 lists some of the potential benefits of physical test methods.

Softness is considered the most subjective property for hygiene papers, among the attributes of strength, softness, and absorbency. In particular, softness is extremely difficult to define because several factors may contribute to the softness attributes. It may even be impossible to unequivocally define softness. Since the pioneering work by Hollmark, steady progress on developing physical softness models of hygiene paper products has been made (Hollmark 1976; 1983a; 1983b). An excellent and thorough review on this subject has been done by Ramasubramanian (2002). Currently, it is generally accepted that subjective softness mainly consists of two components, namely bulk- and surface-softness (Ampulski *et al.* 1991; Beuther *et al.* 2012; Ko *et al.* 2017a; Pawlak *et al*. 2022).

Table 1. Benefits of Physical Test Methods

Benefits
Cost effectiveness - Economical
Time effectiveness - Faster for testing
Process control as well as product quality control
Guidance to product development
Obtaining intellectual properties (for Patent Claims)
Marketing and Advertising

Ko *et al.* (2015; 2017a; 2018) developed several softness models for bathroom tissue products. To this end, the tensile modulus (*TM*), which is defined as the slope between two selected points in a load–elongation curve, has been determined for bulk softness. Meanwhile, surface roughness and friction have been determined using a surface profilometer for surface softness (Ko *et al.* 2015; 2017a; 2018). Friction alone was established to be sufficient for bathroom tissue products.

To date, existing works on the softness of hygiene paper have mainly been limited to bathroom tissue products. Limited works have been available on other hygiene paper products, such as facial tissues, paper towels, and napkins. Among these products, softness is believed to be especially important to facial tissue products.

As such, the main objective of this study is to develop physical softness models of facial tissue products following the same principles which have been used for developing the models for bathroom tissue products. Another objective is to demonstrate the use of physical softness models as a guidance for product development.

Test Methods of Subjective Attributes

Reliable and reproducible data of the in-use properties from users is a prerequisite in developing physical models to predict subjective attributes. In particular, the physical properties should be relevant to the in-use properties.

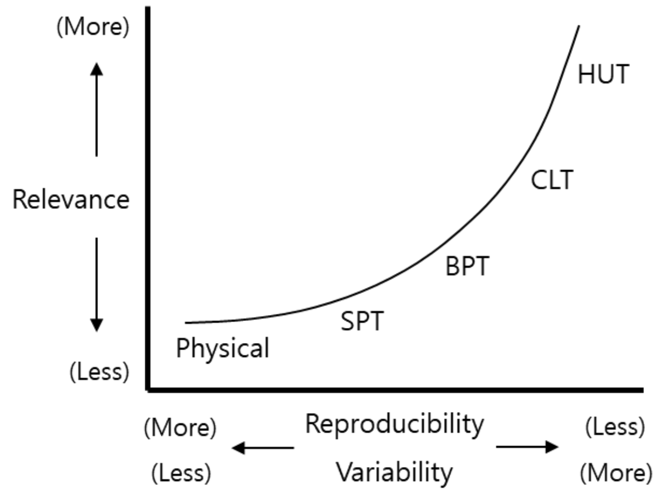

Fig. 1. Relevance *vs*. reproducibility and variability of different test methods

As subjective test methods to obtain the in-use properties, the home-use tests (HUTs), the Central Location Tests (CLTs), the Building Panel Tests (BPTs), and the sensory panel tests (SPTs) have been used (Lee *et al.* 2017a; Ko *et al.* 2018).

Figure 1 shows the relevance of each test method against its reproducibility and variability. HUTs have the highest relevance for obtaining in-use properties; however, this approach provides the largest variability and lowest reproducibility. The results of physical methods are in contrast to those of HUT, *i.e.*, physical methods have the lowest relevance but the lowest variability and highest reproducibility.

In practice, among subjective tests, SPTs have been the most widely used because it is the cheapest and the easiest practice to collect data from well-trained panelists. In this method, a panelist acts like a human-machine under a highly controlled environment to obtain good correlation with physical tests.

Data Acquisition Methods for the Subjective Tests

Once the subjective evaluation method was chosen, the data acquisition method from the rating, ranking order, and pair-comparison was selected. The advantages and disadvantages of each method have been discussed in a previous study (Lee *et al.* 2017a; Ko *et al.* 2018).

The Thurstone Interval Scale

In developing physical models for predicting subjective evaluation, it is critically important that the subjective evaluation value should be linear and continuous on equal intervals, as is the case with physical measurements, such as length, weight, and temperature. However, the numbers from the ranking order and rating are not linear and continuous on an equal scale (Ko *et al.* 2017a; Lee *et al.* 2017a).

Thurstone (1927) introduced the interval scale value (ISV), which is determined using pair-comparison testing. Percentage data is converted to ISV, which is linear and continuous on equal intervals. Statistically speaking, it is the Z-value from normal deviates (Lee *et al.* 2017a, Ko *et al.* 2018). ISV performs like a physical measurement. Table 2 shows the P, %- preference *vs.* ISV (Z-Value). It shows that ISV is linear and continuous, unlike P, %-preference.

Table 2. P, %-preference vs. ISV (Z-value) in a Pair-comparison Test

P	ISV (Z-value)
50.0/50.0	0.0
69.1/30.9	0.5
84.1/15.9	1.0
93.3/6.7	1.5
97.7/2.3	2.0
99.4/0.6	2.5
99.9/0.1	3.0

The Round-Robin Pair-Comparison Tests

Although the Thurstone interval scale theory constitutes a method for obtaining ISV using pair-comparison tests, it does not show for the case where more than two products are to be pair-compared.

When more than two-products are to be pair-compared, a full round-robin pair-comparison test is necessary (Ko *et al*. 2017a). As a numerical illustration, when five samples are compared (n = 5), 10 pair-comparison tests would be required, according to Eq. 1,

$$N = n(n-1)/2 \qquad (1)$$

where N is the number of pair-comparison tests required; and n is the number of test products.

However, there are two major problems in full round-robin pair-comparison tests. First, N increases rapidly as n increases, according to Eq. 1. For example, when n = 10, N is 45. Such a large number of tests may be time consuming and impractical.

Second, ISV is extremely sensitive to small changes in the %-preference for P values that are lower than 10 or higher than 90, as shown in Fig. 2. This indicates that it is difficult to obtain reliable ISVs from a pair of products whose softness attributes are widely different. Nonetheless, pair-comparison testing is extremely effective in obtaining reliable ISVs from a pair of products whose attributes are very close.

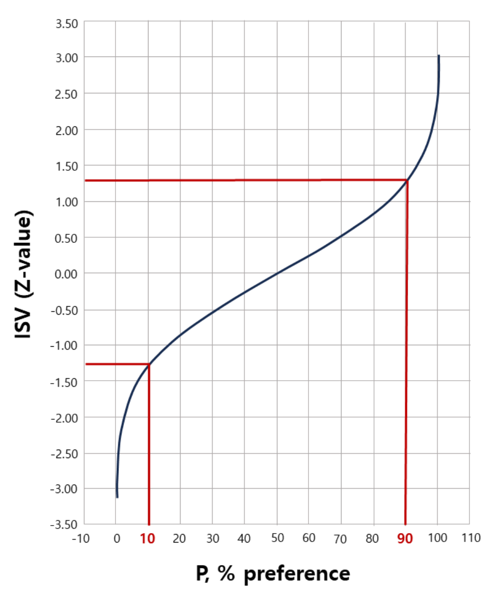

Fig. 2. ISV (Z-value) vs. P, %-preference

The Subgrouping Round-Robin Pair-Comparison Method (The Ko-Method)

To solve the above problems with the full round-robin pair-comparison, Ko *et al.* (2017a) have suggested that products should be divided into subgroups containing fewer test samples. This method is referred to as the Ko-method for convenience.

For n = 10, each panel should be tested with N = 45 for a full round-robin pair-comparison ($N = 10 \times 9/2 = 45$).

Full Round-Robin Pair-Comparison: Sample 1~10

However, if the full group is divided to two subgroups;

Subgroup One: Sample 1, 2, 3, 4, 5
Subgroup Two: Sample 5, 6, 7, 8, 9, 10

It is noted that Sample 5 appears in both subgroups as a linker. Such a sample linking two subgroups is referred to as an anchor sample. In this case, the number of pair-comparison tests by two subgroups required;

Subgroup One: $N_1 = 5 \times 4/2 = 10$
Subgroup Two: $N_2 = 6 \times 5/2 = 15$
Total: $N = N_1 + N_2 = 25$

To compare with the full round-robin pair-comparison tests which require N = 45, the subgrouping method requires N = 25, which is a reduction of approximately 45% from the full-robin pair-comparison tests (N = 45), thereby addressing its first problem.

The second problem of the full round-robin method is the high sensitivity of ISV to small changes in P, % preference. This can be addressed by avoiding the pairing of two products where P is lower than 20 or higher than 80, as shown in Fig. 2.

Thus, the Ko-method can solve the problems of full round-robin pair-comparison method and provide reliable ISV from a pair of two products whose attributes are very close.

The Softness Models of Hygiene Paper Products

Hollmark's pioneering work on tissue softness in the early 1980s established two components for the subjective softness of tissue, namely bulk- and surface-softness (Hollmark 1983a,b; Ko *et al*. 2017a).

For surface softness, surface roughness and friction have been determined (Kawabata and Niwa 1989; Yokura *et al.* 2002; Hollmark and Ampulski 2004; Ko *et al.* 2015; 2017a; 2018).

Tensile Properties for Bulk Softness Determination

Since Ko *et al.* (2017a), it has also been accepted that bulk softness should be determined using *TM* from tensile testing (Hollmark 1983a; 1983b; Habeger *et al.* 1989; Ampulski *et al.* 1991; Spendel 1990; Harper *et al.* 2002; Dwiggins *et al.* 2003; Beuther *et al.* 2012; Ko *et al.* 2015; 2017a; 2018).

TM is the slope between two points in a load-elongation curve (Ko *et al.* 2015). ISO 12625-4 (2022) defines the slope between two force points at 2 and 22 N/m from a tensile force–elongation curve, as calculated according to Eq. 2 (unit: N/m),

$$TM = \{1{,}000 \times l \times (f_2 - f_1)\} / \{w \times (e_2 - e_1)\} \quad (2)$$

where *TM* is the tensile modulus (N/m); *l* and *w* are the gauge length (100 mm) and initial width of the test piece (50 mm), respectively; f_1 and f_2 are the forces closest to 2.0 and

22.0 N/m, respectively; and e_1 and e_2 are the elongation distances (mm) closest to 2.0 and 22.0 N/m, respectively (ISO 12625-4 2022).

The difference between tensile stiffness and *TM* is shown in Fig. 3. Tensile stiffness is the initial slope from the origin, whereas *TM* is the slope between two specified points (e_1 and e_2). The Young's modulus can be calculated according to Eq. 3.

$$\text{Young's modulus} = \text{Tensile stiffness} / \text{Thickness} \tag{3}$$

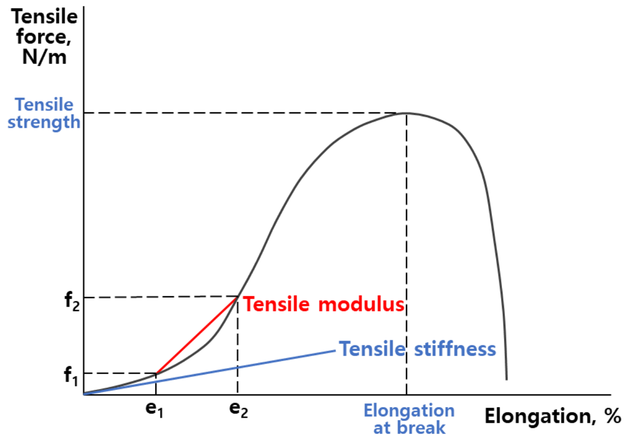

Fig. 3. Tensile stiffness and tensile modulus in a tensile force–elongation curve

As the tensile force–elongation curve of tissue products is not linear, it is extremely difficult, if not impossible, to determine tensile stiffness. Tensile strength (*TS*) is defined as the maximum tensile force per unit width that a test piece can withstand before breaking (ISO 12625-4 2022). The tensile force at the elongation at break is calculated according to Eq. 4, as follows,

$$TS = 10^3 \times \bar{F} / w \tag{4}$$

where *TS* is the tensile strength (N/m); $\bar{F}$ is the maximum tensile force (N); and *w* is the initial width (mm) of the test piece (ISO 12625-4 2022).

Surface Roughness and Friction for the Surface Softness Determination

A stylus-contact type surface tester has been used to determine both surface roughness and friction of bathroom tissue products (Spendel 1990; Ampulski *et al*. 1991; Dwiggins *et al*. 2003; Harper *et al*. 2002; Yokura *et al.* 2004; Beuther *et al.* 2012; Park 2017; Ko *et al.* 2018; Moon 2021; Lee *et al.* 2023). ISO 12625-18 (2022) presents the determination of the friction of bathroom tissue products. However, to date, few works on the softness of facial tissue products have been available.

Among commercially available surface testers, only the Kawabata surface tester (Model: KES-SESRU, Kato Tech, Kyoto, Japan) can simultaneously measure both the surface roughness and friction from the same scan lines (Kato Tech 2018a,b). Recently, this tester has been successfully used for bathroom tissue products (Ko *et al.* 2017a,b; 2018; Lee *et al.* 2017b; Park 2017; Moon 2021; Lee *et al.* 2023). As such, the Kawabata surface tester was used to determine both the surface roughness and friction of facial tissue samples in this study.

Surface Roughness Determination

Figure 4 shows the surface roughness profiles of a facial tissue sample (FT2) in the machine direction (MD) and cross-to-the machine direction (CD), as obtained using the Kawabata KES surface tester (Model: KES-SESRU, Kato Tech Co., Ltd., Kyoto, Japan), as an illustration.

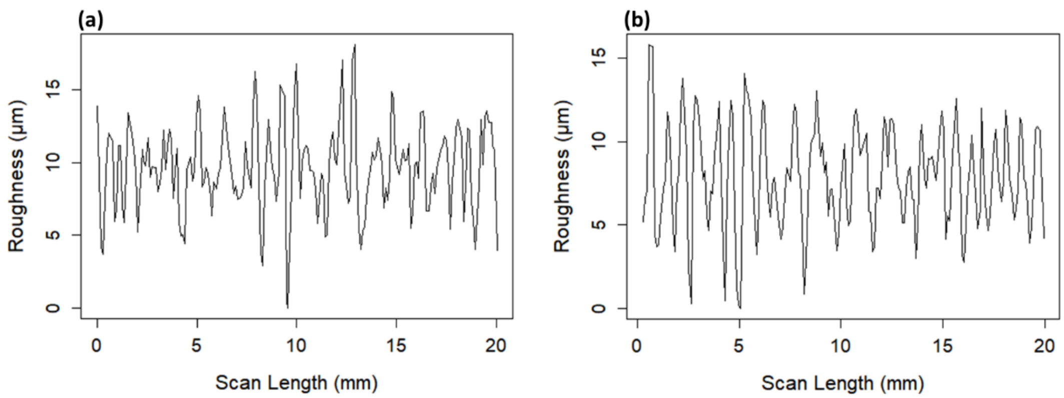

Fig. 4. Surface roughness profiles of a facial tissue sample (FT2) in the (a) MD and (b) CD

From such a surface roughness profile in Fig. 4, the average of surface roughness (R_a) and the mean absolute deviation (*RMAD*) from R_a are calculated according to Eqs. 5 and 6, respectively:

$$R_a = \frac{1}{N}\sum_1^N |R_i| \quad (5)$$

$$RMAD = \frac{1}{N}\sum_1^N \left||R_i| - R_a\right| \quad (6)$$

where R_a is the roughness average (µm); R_i is the roughness (µm) at scanning point *i*; and *N* is the number of data points in the scan length.

Surface Friction Determination

Figure 5 shows the surface friction profiles of a facial tissue sample (FT2) in the MD and CD, which were obtained simultaneously with the roughness profile in Fig. 4.

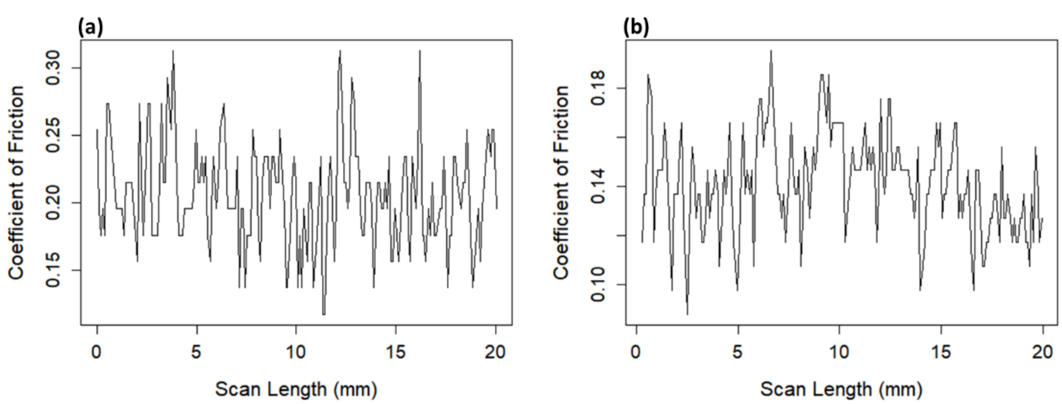

Fig. 5. Surface friction profiles of a facial tissue sample (FT2) in the (a) MD and (b) CD

A recently published ISO standard (ISO 12625-18 2022) outlines the determination of the friction of tissue products. The average coefficient of friction (COF, $\bar{\mu}$) and the mean absolute deviation (*FMAD*) from $\bar{\mu}$ are calculated according to Eqs. 7 and 8, respectively (ISO 12625-18 2022):

$$\bar{\mu} = \frac{1}{N}\sum_{1}^{N}\mu_i \quad (7)$$

$$FMAD = \frac{1}{N}\sum_{1}^{N}|\mu_i - \bar{\mu}| \quad (8)$$

where $\bar{\mu}$ is the average COF; *N* is the number of data points from the scan length; μ_i is the COF at point *i;* and *FMAD* is the mean absolute deviation from $\bar{\mu}$.

EXPERIMENTAL

Subjective Softness Evaluation

To obtain the subjective softness of seven facial tissue samples in an interval scale, the previously mentioned subgrouping pair-comparison method was used (Ko *et al.* 2015; 2017a; 2018). In the present study, it is referred to as the Ko-method for convenience.

Prior to grouping the seven samples into two subgroups, a ranking method was used to select the anchor sample. As a result, FT4 was ranked in the middle and selected as the anchor sample. Table 3 shows the subgrouping pairs of SG1 and SG2. After subgrouping, each pair-comparison test was performed by 100 untrained panelists (Ko *et al.* 2017a; 2018; Park 2017).

Table 3. The Subgrouping Pairs

SG1	SG2
FT1	
FT2	
FT3	
FT4	FT4
	FT5
	FT6
	FT7
SG, subgroup	
FT4, anchor sample	

Facial Tissue Samples

Table 4 lists seven commercial two-ply facial tissue samples, and all physical properties were measured for not one-ply, but two-ply samples. The samples were conditioned at a temperature of 23 ± 1 °C and relative humidity of 50 ± 2% for more than 48 h, according to ISO standard 187 (1990).

The optical photographs of the samples were taken using Optitopo surface deviation (OSD, L&W, Sweden). As all products were two plies, there was no pattern difference in the optical photographs between the top and bottom layers of each sample. Accordingly, only the top layer of the sample was used to determine the surface roughness and friction. Figure 6 shows the top layers of the seven facial tissue samples with the arrows indicating the MD.

Table 4. Properties of the Facial Tissue Samples

Sample	Basis Weight (g/m^2)	Thickness (mm)	Density (g/cm^3)
FT1	22.9	0.077	0.30
FT2	20.5	0.076	0.27
FT3	14.7	0.046	0.32
FT4	15.6	0.063	0.25
FT5	13.7	0.051	0.27
FT6	12.9	0.055	0.23
FT7	13.6	0.053	0.26

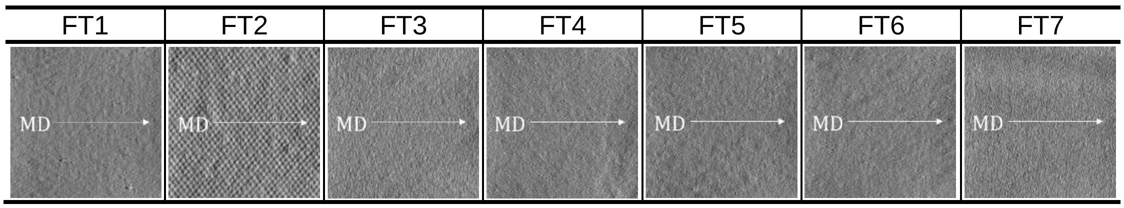

Fig. 6. Optical photographs of the facial tissue samples

Tensile Modulus Determination

A tensile tester from MTS, Eden Prairie, Minneapolis, USA (Criterion® Model 41) was used under the following conditions according to ISO 12625-4 (2022): sample length was 150 mm; sample width was 50 mm; load cell was 50 N; span length was 100 mm; and strain rate was 50%/min. *TM* was calculated according to Eq. 2. The samples were measured 10 times along the MD and CD.

Surface Roughness and Friction Testing

The surface roughness and friction of the samples were simultaneously measured using a Kawabata surface tester (Model: KES-SESRU, Kato Tech, Kyoto, Japan). Figure 7 shows the configuration of the Kawabata surface tester with a U-tube stylus.

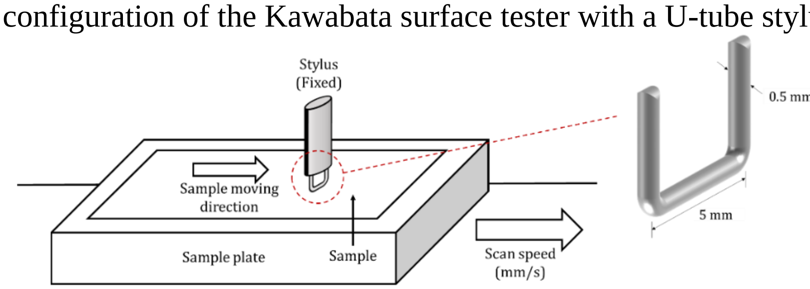

Fig. 7. Configuration of the Kawabata surface tester with a U-shaped stylus

The sample plate, instead of the stylus, moves during measurement. The testing conditions were as follows: contact force was 5 g (force); scan length was 20 mm; scan speed was 1 mm/s; and data acquisition rate was 10 Hz (or 10 point/s). The gravitational force (g_f) is the mass in grams multiplied by the gravitational constant, g. For each sample, 10 measurements were taken in the MD and CD.

RESULTS AND DISCUSSION

The Subjective Softness Values (ISV)

Table 5 shows the ISV Softness of SG1 and SG2 and final ISV Softness obtained by linking two subgroups with FT4 as the anchor. The anchor sample, FT4, has the softness ISV of 0.00 in SG1, but 0.53 in SG2 and final. The final ISV Softness was used for developing the facial tissue softness models. Among the seven facial tissue samples, FT1 has the highest final ISV of 1.69, indicating it is rated softer than FT7 by 95% and FT4 by 88%, as shown in Fig. 2.

Table 5. ISV Softness of Seven Facial Tissue Samples

Sample	ISV Softness		
	SG1	SG2	Final
FT1	1.16		1.69
FT2	0.00		0.53
FT3	0.11		0.64
FT4	0.00	0.53	0.53
FT5		0.15	0.15
FT6		0.23	0.23
FT7		0.00	0.00

Tensile Properties

Table 6 summarizes the tensile properties of the seven facial tissue samples. *TM* was calculated according to Eq. 2, and *TS* and elongation at break % were determined according to ISO 12625-4 (2022). The geometric mean (GM) was calculated as the square root of the product of the MD and CD values.

The Facial Tissue Softness Models

Table 7 summarizes the ISV softness and physical properties used for developing the softness models. R_a, *RMAD*, $\overline{\boldsymbol{\mu}}$, and *FMAD* were calculated according to Eqs. 5 through 8, respectively.

After intensive review, Ramasubramanian (2002) concluded that a power-law model may be applicable to the softness models for tissue products, that is,

$$Softness = cX^{m}Y^{n} \tag{9}$$

where *X* is the bulk softness; *Y* is the surface softness; and *c*, *m*, and *n* are the curve fitting coefficients. The power-law model can be linearized by taking the logarithm of each value (Ko *et al.* 2018). Consequently, a series of facial tissue softness models have been developed. For three-parameter (3-P) Models, Eq. 10 was used,

$$ISV\ Softness = C + m\log TM + n\log RMAD + l\log FMAD \tag{10}$$

where *C*, *m*, *n*, and *l* are the curve fitting coefficients (Ko *et al.* 2018). For two-parameter (2-P) Models, either Eq. 11 or Eq. 12 was used.

$$ISV\ Softness = C + m\log TM + n\log RMAD \tag{11}$$

$$ISV\ Softness = C + m\log TM + l\log FMAD \tag{12}$$

Table 6. Tensile Properties of the Seven Facial Tissue Samples

Sample	Tensile Modulus (N/m%)			Tensile Strength (N/m)			Elongation at Break (%)		
	MD	CD	GM	MD	CD	GM	MD	CD	GM
FT1	7.20	15.52	10.57	156.2	69.2	103.97	33.15	6.90	15.12
FT2	9.77	9.94	9.86	137.1	76.0	102.08	17.91	9.86	13.29
FT3	9.60	10.59	10.08	114.2	48.6	74.50	18.81	6.49	11.05
FT4	7.26	12.96	9.70	135.7	59.8	90.08	30.75	5.14	12.57
FT5	14.12	16.46	15.25	180.2	60.58	104.48	21.86	5.19	10.65
FT6	10.67	21.74	15.23	187.7	87.92	128.46	30.18	5.74	13.16
FT7	7.75	11.10	9.27	115.4	49.57	75.63	21.12	6.73	11.92

Table 7. Softness ISV and Physical Properties of the Seven Facial Tissue Samples

Sample	ISV Softness	*TM* (N/m%)			R_a (μm)			*RMAD* (μm)			$\bar{\mu}$			*FMAD*		
		MD	CD	GM	MD	CD	GM	MD	CD	GM	MD	CD	GM	MD	CD	GM
FT1	1.69	7.20	15.52	10.57	2.18	2.27	2.22	1.33	1.41	1.37	0.21	0.11	0.15	0.031	0.015	0.021
FT2	0.53	9.77	9.94	9.86	2.25	3.97	2.99	1.38	2.18	1.73	0.20	0.13	0.16	0.030	0.023	0.026
FT3	0.64	9.60	10.59	10.08	4.14	2.33	3.10	2.59	1.46	1.94	0.12	0.12	0.12	0.023	0.016	0.019
FT4	0.53	7.26	12.96	9.70	3.03	2.38	2.69	1.84	1.43	1.62	0.15	0.10	0.12	0.034	0.015	0.023
FT5	0.15	14.12	16.46	15.25	2.78	2.49	2.63	1.73	1.55	1.64	0.18	0.11	0.14	0.035	0.015	0.023
FT6	0.23	10.67	21.74	15.23	3.13	2.38	2.73	1.85	1.47	1.65	0.13	0.11	0.12	0.020	0.015	0.017
FT7	0.00	7.75	11.10	9.27	3.77	2.51	3.08	2.24	1.51	1.84	0.17	0.12	0.14	0.039	0.016	0.025

The results obtained by the regression analysis were as follows:

1) 3-P Models (*TM*, *RMAD*, and *FMAD*)
   a) MD properties only ($R^2 = 0.58$)
   $$ISV = 1.41 - 2.83 \log TM - 2.97 \log RMAD - 1.72 \log FMAD \quad (13)$$
   b) CD properties only ($R^2 = 0.08$)
   $$ISV = 14.91 + 0.67 \log TM - 8.47 \log RMAD + 7.53 \log FMAD \quad (14)$$
   c) GM properties ($R^2 = 0.77$)
   $$ISV = 0.52 - 4.05 \log TM - 9.36 \log RMAD - 3.83 \log FMAD \quad (15)$$
2) 2-P Models
   A) *TM* and *RMAD*
      a) MD properties only ($R^2 = 0.48$)
      $$ISV = 3.57 - 2.43 \log TM - 2.68 \log RMAD \quad (16)$$
      b) CD properties only ($R^2 = 0.03$)
      $$ISV = 1.22 - 0.32 \log TM - 1.67 \log RMAD \quad (17)$$
      c) GM properties ($R^2 = 0.65$)
      $$ISV = 5.35 - 2.65 \log TM - 9.09 \log RMAD \quad (18)$$
   B) *TM* and *FMAD*
      a) MD properties only ($R^2 = 0.28$)
      $$ISV = 1.49 - 2.85 \log TM - 1.17 \log FMAD \quad (19)$$
      b) CD properties only ($R^2 = 0.01$)
      $$ISV = -0.91 - 0.24 \log TM - 0.96 \log FMAD \quad (20)$$
      c) GM properties ($R^2 = 0.16$)
      $$ISV = -2.06 - 2.75 \log TM - 3.30 \log FMAD \quad (21)$$

Discussions of Facial Tissue Softness Models

Once a physical softness model is developed, a Predicted ISV Softness can be calculated by substituting the physical parameters to the model. It is noted that all the above models (Eq. 13 and 15 to 21) have constants with negative signs for each parameter. This indicates that the subjective softness should be inversely related to the *TM*, surface roughness, and friction. As such, in addition to the low R^2 values, Eq. 14 should be excluded from the models.

Thus, in developing the softness models, it is most important that they should be technically sound. Simply making a judgment based on the R^2 value only can lead to a faulty conclusion. Equations 13, 15, 16, and 18 have shown relatively high correlation with the ISV Softness. Table 8 shows the results of the ISV Softness and Predicted ISV Softness calculated from these equations.

Table 8. ISV Softness and Predicted ISV Softness using the 3-P (*TM*, *RMAD*, and *FMAD*) and 2-P (*TM* and *RMAD*) Models

Sample	ISV Softness	Predicted ISV Softness from the 3-P Models (*TM*, *RMAD*, *FMAD*)		Predicted ISV Softness from the 2-P Models (*TM*, *RMAD*)	
		MD	GM	MD	GM
FT1	1.69	1.26	1.53	1.07	1.32
FT2	0.53	0.86	0.35	0.71	0.48
FT3	0.64	0.27	0.36	0.00	0.00
FT4	0.53	0.76	0.85	0.69	0.76
FT5	0.15	0.00	0.00	0.06	0.19
FT6	0.23	0.68	0.48	0.28	0.17
FT7	0.00	0.33	0.27	0.39	0.31

3-P Models (TM, RMAD, and FMAD)

Figure 8 shows the comparison between ISV Softness and Predicted ISV Softness calculated from the 3-P Models for the MD and GM (Eq. 13 and 15, respectively). It shows the general trend between the two models although the GM Model had a much higher R^2 value than the MD Model.

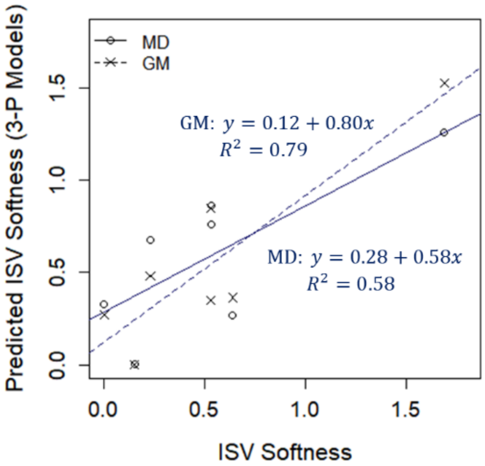

Fig. 8. Predicted ISV softness from the 3-P Models (*TM*, *RMAD*, and *FMAD*) vs. ISV softness

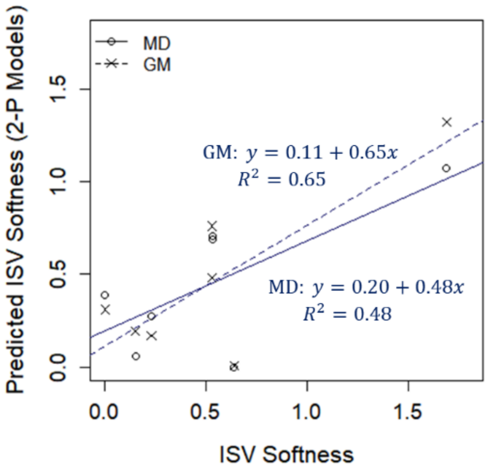

Fig. 9. Predicted ISV softness from the 2-P Models (*TM* and *RMAD*) vs. ISV softness

2-P Models (TM and RMAD)

Figure 9 shows a comparison between the ISV Softness and Predicted ISV Softness calculated from the 2-P Models (*TM* and *RMAD*) for the MD and GM (Eq. 16 and 18, respectively). Similar to the 3-P Models, the GM Model exhibited higher correlation than the MD Model.

Figure 10 shows a comparison between the Predicted ISV Softness from the 3-P (*TM*, *RMAD*, and *FMAD*) and 2-P (*TM*, and *RMAD*) Models. Both models exhibited high correlation values with a slope of 1.0. This suggests that the 2-P Models (*TM* and *RMAD*) can be used as facial tissue softness models. In contrast, for bathroom tissue products, *FMAD* was found to be much better correlated with the ISV Softness than *RMAD* (Park 2017; Ko *et al*. 2018).

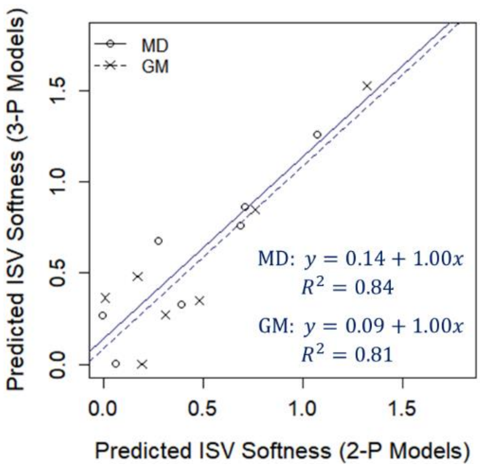

Fig. 10. Predicted ISV softness using the 3-P (*TM*, *RMAD*, and *FMAD*) vs. 2-P (*TM*, and *RMAD*) Models

Validation of the Physical Softness Models for Facial Tissue

A physical model should be able to provide the direction to improve and develop the products. To do so, the model should be able to predict the subjective softness values prior to the subjective tests. Preferably, a normalization of each physical parameter in the model is necessary.

Normalization of Facial Tissue Softness Model

Normalization is a process of converting the value of each variable to 0 and 1, according to Eq. 22,

$$X_n = (X - X_{min})/(X_{max} - X_{min}) \quad (22)$$

where X_n, X_{max}, and X_{min} are the normalized, maximum, and minimum values of X, respectively (Ko *et al.* 2018). In Eq. 22, $X_n = 1$ when $X = X_{max}$ and $X_n = 0$ when $X = X_{min}$.

Once, the physical softness is normalized according to Eq. 22, each component contribution to the softness can be calculated according to Eqs. 23–27,

1) 3-P Models (*TM, RMAD,* and *FMAD*)

$$TM, \% = 100 \times |m|/(|m| + |n| + |l|) \quad (23)$$

$$RMAD, \% = 100 \times |n|/(|m| + |n| + |l|) \quad (24)$$

$$FMAD, \% = 100 \times |l|/(|m| + |n| + |l|) \quad (25)$$

2) 2-P Models (*TM* and *RMAD)*

$$TM, \% = 100 \times |m|/(|m| + |n|) \quad (26)$$

$$RMAD, \% = 100 \times |n|/(|m| + |n|) \quad (27)$$

where *m*, *n*, and *l* are the curve-fitting coefficients of *TM*, *RMAD*, and *FMAD*, respectively (Ko *et al.* 2018).

Table 9 shows the contributions of the bulk softness determined by *TM* and the surface softness determined by *RMAD* and *FMAD* to the overall softness of seven facial tissue samples. The contribution of each component to the overall softness depends on the selected softness model. It is, however, remarkable that the 3-P GM and 2-P GM Models showed identical results of the contribution of the bulk- and surface- softness. In particular, both models suggest that the overall softness of facial tissue samples comprises approximately 30% bulk softness and 70% surface softness. Furthermore, the surface softness may consist of approximately 47% surface roughness and 23% friction, suggesting that the surface roughness is twice as important as friction.

Table 9. Contribution of Bulk and Surface Softness to the Overall Softness of Facial Tissue

	3-P Models (*TM*, *RMAD*, *FMAD*)		**2-P Models (*TM*, *RMAD*)**	
	MD	**GM**	**MD**	**GM**
R^2	0.58	0.77	0.48	0.65
C (constant)	1.53	2.06	1.16	1.55
m (*TM*)	−0.83	−0.88	−0.71	−0.57
n (*RMAD*)	−0.86	−1.41	−0.78	−1.37
l (*FMAD*)	−0.50	−0.69	-	-
Contribution, %				
TM	37.9	29.5	47.7	29.4
RMAD	39.3	47.3	52.3	70.6
FMAD	22.8	23.2	-	-

These observations are in contrast with the findings of existing bathroom tissue softness models (Ko *et al.* 2015; 2017a; 2018). Previously, it was reported that *RMAD* may not be particularly useful for predicting the softness of bathroom tissues (Spendel 1990; Dwiggins *et al.* 2003; Beuther *et al.* 2012; Ko *et al.* 2017a). Instead, *FMAD* has been suggested for 2-P softness models for bathroom tissues (Dwiggins *et al.* 2003; Yokura *et al.* 2002; Yokura *et al*. 2004; Ko *et al*. 2017a).

The results in this work emphasize that physical softness models should be developed from subjective softness tests, since they will depend on the subjective softness data.

Applications of the Facial Tissue Physical Softness Model

As a numerical illustration, if the physical properties increase the ISV by 0.5, a pair-comparison P, %-preference would predict a 70% *vs.* 30% win over the control sample, as shown in Table 2.

Table 10 shows the predicted pair-comparison P, %-preference of two samples when *TM*, *RMAD*, and *FMAD* of one sample are lowered by up to 30%, respectively. The results were obtained using the 3-P GM Model (*TM*, *RMAD*, and *FMAD*), according to Eq. 15. In that equation, it is noted that all coefficients of the physical parameters have negative (-) signs, indicating their inverse relationship to the subjective softness.

If the *TM* of the Sample is decreased by 10%, its preference would increase by 7% from 50% to 57%. Meanwhile, if the *RMAD* of the sample is decreased by 10%, its preference would increase by 17% from 50% to 67%. This means that *RMAD* is more influential than *TM* and *FMAD* in 3-P GM Models.

Table 10. Predicted Pair-Comparison P, %-preference of Facial Tissue Softness by Varying *TM*, *RMAD,* and *FMAD* Values in the 3-P GM Model (Eq. 15)

	TM		***RMAD***		***FMAD***	
	Control	**Sample**	**Control**	**Sample**	**Control**	**Sample**
0%	50	50	50	50	50	50
−10%	43	57	33	67	43	57
−20%	35	65	18	82	36	64
−30%	27	73	7	93	28	72
						(unit: %)

As another illustration, Table 11 presents the results obtained by the 2-P GM Model (*TM* and *RMAD*), according to Eq. 18. If the *TM* of the sample is decreased by 10%, its preference increased by 5% from 50% to 55%. Meanwhile, if the *RMAD* of the Sample is decreased by 10%, its preference increased by 16% from 50% to 66%. This is almost the same as the predicted preference of the 3-P GM Model (Table 11).

Table 11. Predicted Pair-Comparison P, %-preference of Facial Tissue Softness by Varying the *TM* and *RMAD* Values in the 2-P GM Model (Eq. 18)

	TM		***RMAD***	
	Control	**Sample**	**Control**	**Sample**
0%	50	50	50	50
−10%	45	55	34	66
−20%	40	60	19	81
−30%	34	66	8	92
				(unit: %)

The aforementioned illustrations suggest that the physical softness models are validated from subjective softness testing; consequently, a need for the subjective softness tests will be minimized. Thus, the physical models can be used as a guidance in developing or improving the products and desirability for tissue manufacturers.

CONCLUSIONS

1. A series of physical softness models for facial tissue products have been developed. For the model development, the round-robin pair-comparison methods have been used. It is the only method that can generate subjective evaluation data on interval-scale (or linear scale), referred to as the Thurstone Interval Scale (ISV), which is similar to physical measurements such as length, weight, and temperature.
2. To eliminate the problems with the conventional full round-robin pair-comparison tests, the subgrouping pair-comparison method, referred to as the Ko-method, has been applied. The distinctive advantages of the subgrouping method over the full round-robin method are that it requires much fewer panel tests while being more discernable when pair-products have similar softness.
3. It has been confirmed that for the bulk softness of facial tissue products, the tensile modulus (*TM*) can be used and for the surface softness, the mean absolute deviation from the roughness average (*RMAD*) and the mean absolute deviation from the friction average (*FMAD*) can be used. It is noted that all physical softness models (except Eq. 14) took negative constants for each parameter, indicating that subjective softness should be inversely related to the *TM*, surface roughness, and friction.
4. According to the physical softness models for facial tissue products, the 3-P GM (*TM*, *RMAD*, and *FMAD*) and 2-P geometric mean (GM) (*TM* and *RMAD*) models were found to be optimal. The physical softness models were normalized to determine the contributions of bulk- and surface- softness. The results showed that about 70% and 30% of the overall softness were attributable to the surface softness (*RMAD* and *FMAD*) and bulk softness (*TM*).
5. Pair-comparison preferences when adjusting the value of physical properties were predicted according to developed models. A physical softness model of facial tissue products should provide the direction to improve and develop products by predicting their subjective softness.

ACKNOWLEDGMENTS

This study was carried out with the support of the R&D Program for Forest Science Technology (Project No. FTIS 2019150B10-2323-0301), which was provided by the Korea Forest Service (Korea Forestry Promotion Institute).

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Article submitted: October 6, 2023; Peer review completed: October 28, 2022; Revised version received: November 3, 2023; Accepted: November 4, 2023; Published: November 8, 2023.
DOI: 10.15376/biores.19.1.116-133