# Effect of Changes in Knit Structure and Density on the Mechanical and Hand Properties of Weft-Knitted Fabrics for Outerwear

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## ABSTRACT

This study focuses on the mechanical properties of weft knits for outerwear as a function of knit structure and density and the relationships between hand, structure, and density. Eighteen weft knits are produced with six different structures (1 × 1 rib, half-cardigan rib, half-milano rib, interlock, single-pique, and crossmiss interlock) and three different densities (loose, medium, tight). The mechanical properties and hand values of the fabrics are measured using the KES-F method. Tensile properties increase for fabrics with a higher density, as do bending and shear properties. Compression values decrease somewhat as knit density increases but differences in compression values are not very large. Surface properties such as softness and smoothness increase with density. Specific findings for tensile properties reveal that the single-pique and the crossmiss interlock can not absorb external stress as much as the 1 × 1 rib and the interlock when stresses are applied in the course direction. Knits with tuck and miss stitches (half-cardigan rib, half-milano rib, single-pique, and crossmiss interlock) have better dimensional stability than fabrics with only knit stitches. Testing of primary hand values shows increased stiffness and fullness and softness and decreased smoothness as knit density increases. Total hand value increases with knit density. Double knits show higher total hand values than single knits. Half-milano rib and crossmiss interlock structures have the highest total hand values. Based on the tests results and an understanding of current market needs for dimensionally stable fabrics with a soft hand, we conclude that knit structures with combined miss and tuck stitches exhibit properties appropriate for outerwear fabrics for the winter season.

The hand of textile products is an evaluation of their multifaceted characteristics as perceived by the human senses [16]. Sensory perception of fabric hand is an important factor in judging the quality of fabrics used in apparel products, both at the point-of-sale and as the garment is worn. Fabric hand is related to important textile properties such as elasticity, flexibility, and surface properties. Hand properties have an impact on how fabric is perceived as regards comfort and aesthetic appeal. Therefore, an understanding of both hand and mechanical properties relative to knit structure and density can be an important tool in producing fabrics that are perceived as comfortable and aesthetically appealing.

The Kawabata system is the primary method of objectively characterizing fabric hand. Kawabata began his research into the evaluation of fabric hand in 1975. He organized the Hand Evaluation and Standardization Committee of the Textile Machinery Society of Japan. He developed an analysis that defines aspects of the expert perception of "hand" and established the translation formulas that can reliably translate the mechanical properties of fabric into expert's hand perception. He designed a system of instrumentation, the KES-F system, for measuring the fundamental mechanical properties of fabric as related to hand. The results of his research [8] and his collaborators' work probably represent the most

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thorough investigation of hand values in relation to mechanical properties.

Many studies have reported the results of judging the objective hand of fabrics based on their mechanical properties [1-3, 17-20, 23]. Others have reported that the mechanical properties of knitted fabrics vary according to knit structures, fibers, yarns, and densities, which in turn affect the knit's hand significantly [4-5, 12-14]. Hallos *et al.* [5], Knapton *et al.* [12-14], and Gibson and Postle [4] objectively examined the hand of fabrics from their mechanical properties.

Hallos *et al.* [5] measured the principal physical properties involved in subjectively evaluating the hand of a group of jersey double knits, and demonstrated that hand is affected by parameters such as fiber type and yarn and fabric structure, using polar diagrams to demonstrate these relationships. Knapton *et al.* [12-14] reported that the dimensional stability and knit performance of such fabrics are influenced by components such as knit structure, stitch length, and cover factor. Gibson and Postle [4] attempted to define the relationship between hand and bending and shear properties of both woven and knitted fabrics. Notably, Chen *et al.* [2] asserted that in order to evaluate the hand of knitted fabrics, it is necessary to define the relationship between the kinds of knit structures and the characteristic hand value.

Most of the studies relating hand and mechanical properties have involved woven fabrics, but more research is needed on the effect of knitting conditions and diverse structures on the mechanical properties and hand of knits. Detailed systematic studies of the knitting conditions necessary for obtaining desired wear performance and hand are necessary in order to develop appropriate weft knits for current market conditions. In this study, we have reduced the variables by engineering samples in which only the knit structure and density of the samples vary in order to isolate the effects of these variables. The goals of our research are to study changes in mechanical properties of weft knits as a function of structure and density and to investigate relationships between hand, knit structure, and density.

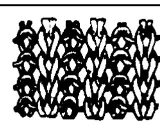
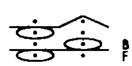
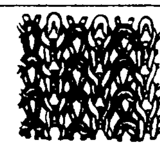
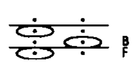
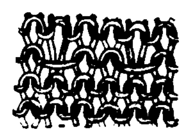
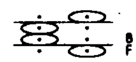
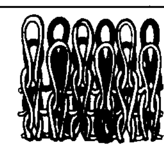
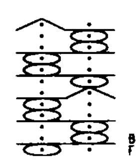
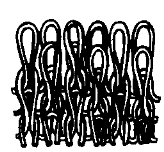
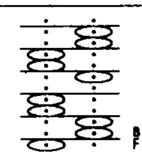
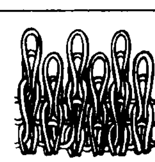
## Experimental

Eighteen weft knits were produced with different structures (1 × 1 rib, half-cardigan rib, half-milano rib, interlock, single-pique, and crossmiss interlock) and three densities (loose, medium, tight) for this study. The chosen structures and three densities were based on the kinds of stitch structures and methods currently used in the industry.

### ENGINEERED FABRICS

One hundred percent cotton yarn (2/20's) was used in knitting all the samples; 100 × 200 cm pieces of fabric were knitted at a rate of 24 traverse/m using a 7 gauge electric weft knitting machine (Shima Seki-214KI, latch needle flat bed machine). Three single knit structures were created: a 1 × 1 rib, a half-cardigan rib combining the 1 × 1 rib with a tuck stitch, and a half-milano rib combining the 1 × 1 rib with a miss stitch. Three double knit structures were created: an interlock (a double plain stitch), a single-pique combining the interlock with a long and short needle tuck, and a crossmiss interlock combining the interlock with a long and short needle miss. The structures of the knitted fabrics created for the study are shown in Table I. Weft knits show regular vertical ribs, double knits are rather thicker and close-woven, and single knits are loose with good drape when touched.

TABLE I. Structure of knit fabrics created for this study.

| Structure | | Notation[a] | | |
|---|---|---|---|---|
| Single knit | 1×1 rib |  | B F 1 |  |
| | Half-cardigan rib |  | B F 2 1 |  |
| | Half-milano rib |  | B F 2 1 |  |
| Double knit | Interlock |  | B F 2 1 |  |
| | Single-pique |  | B F 6 5 4 3 2 1 |  |
| | Crossmiss interlock |  | B F 6 5 4 3 2 1 |  |

[a]F= Front needle bed. B=Back needle bed.
= knit loop. = tuck loop. = miss loop

Three 100 cm × 200 cm fabric pieces were knitted for each of the six different structures using three different machine tensions (loose, medium, and tight) of 55, 60, and 65, resulting in small but measurable differences in the fabrics. We chose these settings based on common industry practices.

### RELAXATION TREATMENT

The fabrics from the knitting machine were air dried for 48 hours in standard conditions (20°C, 60% RH), then treated to eleven cycles of mechanical relaxation using repeated washings and tumble dryings as suggested by Heap *et al.* [6, 7].

The fabrics were washed for 60 minutes at 60°C in a revolving drum washing machine (Bloomberg Co.) with 0.5% detergent (Persil, 5 mg/1L). After the final spin cycle, the samples were tumble dried for 90 minutes at 70°C, then put through the wash cycle using cold water followed by a tumble dry cycle at 70°C. This process continued until the fabrics did not change in size. Samples were then stored for 48 hours under standard conditions, after which their mechanical properties were measured and hand values calculated.

### DIMENSIONAL MEASUREMENTS

Based on the standard method KS K 0512, the knitted fabrics were placed on a flat surface until they were free of wrinkles and tension [15]. Wale or course count per 100 cm of fabric was measured and then converted to wale or course count per cm. Differences between the loosest and tightest samples varied according to the knit structure, from 0.18 to 0.71 wales/cm in the wale direction and from 0.11 to 2.24 courses/cm in the course direction. The density of the medium sample as indicated by wale and course count was always a value between the loosest and tightest samples, but it was not always at a midpoint between them.

Weights were obtained from an average of three measurements of two 20 × 20 cm samples of each fabric using the balance, and they are reported in g/m$^2$. For all samples, the weight increased as the knit density increased, and double knit weights were greater than single knit weights.

The stitch length of the knitted fabrics was measured to determine the unit stitch length. These measurements are averaged values from two 20-cm square samples cut from the center of the knits. First, each sample was marked and cut at 100 wale intervals, then the sample was unraveled and pre-tension was applied at the ends of the yarn. The yarn was then measured and the resulting figure was divided by 100. The stitch length from an average of ten measurements from each sample was used in the following equation to obtain the structural cell stitch lengths ($SCSL$) [13, 21]:

$$SCSL\ (\text{cm}) = (\text{total length of thread used in one cycle of knitting}/N) \times Nt\ ,$$

where $N$ = tex of yarn, and $Nt$ = number of needles needed for a minimum repeat unit of knitting.

Fabric weights, knit densities, and the SCSL of each sample are shown in Table II. The $SCSL$ of each sample decreases as the knit density increases and is greatest for the single-pique and crossmiss interlock samples. Fabric weights also increase with knit densities.

TABLE II. Weight, knit density, and SCSL (structural cell stitch length) of the knit samples.

| Structure of knitted fabrics | | Weight, g/m$^2$ | Knit density, wale/cm × course/cm | SCSL, cm |
|---|---|---|---|---|
| Single knits | | | | |
| 1 × 1 rib | loose | 590 | 6.31 × 3.70 | 2.58 |
| | medium | 620 | 6.74 × 4.11 | 2.43 |
| | tight | 660 | 7.50 × 4.71 | 2.22 |
| Half-cardigan rib | loose | 550 | 3.04 × 2.74 | 3.71 |
| | medium | 580 | 3.49 × 3.35 | 3.46 |
| | tight | 620 | 3.75 × 3.85 | 3.19 |
| Half-milano rib | loose | 630 | 4.40 × 4.20 | 4.17 |
| | medium | 650 | 4.45 × 5.58 | 3.94 |
| | tight | 670 | 4.58 × 6.44 | 3.65 |
| Double knits | | | | |
| Interlock | loose | 680 | 3.43 × 3.31 | 2.85 |
| | medium | 730 | 3.66 × 3.60 | 2.75 |
| | tight | 820 | 3.70 × 4.23 | 2.54 |
| Single-pique | loose | 750 | 2.65 × 3.01 | 6.80 |
| | medium | 810 | 2.85 × 3.31 | 6.72 |
| | tight | 860 | 3.02 × 3.53 | 6.24 |
| Crossmiss interlock | loose | 850 | 3.48 × 2.84 | 7.20 |
| | medium | 880 | 3.66 × 3.23 | 6.74 |
| | tight | 900 | 3.85 × 3.73 | 6.51 |

### MEASUREMENT OF MECHANICAL PROPERTIES

The mechanical properties of the eighteen knits with varying knit structures and densities were measured using the standard KES-F measurement method. For each knit structure and density, each measurement was made twice on two separate samples cut from the center of the knitted fabrics, and the four resulting values were averaged. Sixteen properties were measured under standard conditions, including tensile, bending, shear, compression, and surface properties, as well as thickness and weight of the knitted fabrics. Each property tested, unit of measurement, and apparatus used is listed in Table III. The final values consist of the results from sixteen tests.

Because anisotropy is a consideration in knit fabrics, eleven of the tests (tensile, bending, shear, and surface

TABLE III. Basic mechanical properties.

| Properties | Symbol | Characteristic value | Unit | Apparatus |
|---|---|---|---|---|
| Tensile[a] | *LT* | linearity of load-extention (tensile linearity) | none | |
| | *WT* | tensile energy | g.cm/cm$^2$ | KES-FB1 |
| | *RT* | tensile resilience | % | |
| Bending[a] | *B* | bending rigidity | g.cm$^2$/cm | KES-FB2 |
| | *2HB* | bending hysteresis | g.cm/cm | |
| Shear[a] | *G* | shear stiffness | g/cm.degree | |
| | *2HG* | hysteresis of shear force at 0.5 of shear angle | g/cm | KES-FB1 |
| | *2HG5* | hysteresis of shear force at 5 of shear angle | g/cm | |
| Compression | *LC* | linearity of compression-thickness curve (compression linearity) | none | |
| | *WC* | compression energy | g.cm/cm$^2$ | KES-FB3 |
| | *RC* | compression resilience | % | |
| Surface[a] | *MIU* | coefficient of friction | none | |
| | *MMD* | mean deviation of MIU | none | KES-FB4 |
| | *SMD* | mean deviation of surface contour (geometric surface roughness) | μm | |
| Thickness | *T* | fabric thickness at pressure 0.5 gf/cm$^2$ | mm | KES-FB3 |
| Weight | *W* | fabric weight per unit area | g/m$^2$ | balance |

[a] These properties were tested in both wale and course directions.

properties) were measured in both wale and course directions. The twenty-two values from these tests plus the values from the compression tests, weight, and thickness resulted in twenty-seven values for each of the eighteen samples. Averages of the wale and course measurements were calculated for ease of comparison.

Sample sizes of 20 × 20 cm were used to measure all properties except bending, where the sample size was 5 × 5 cm due to the strong bending tendency of the fabrics. Two swatches were used for each test, with one tested in the wale direction and the other in the course direction. After the measurements were completed, all values were converted to standard units. Because a limited number of swatches were tested for each value, it was critical to produce uniformly manufactured fabrics. Uniformity was maintained by careful control of all knitting variables. Not enough data were generated for statistical comparisons, so values were compared to determine trends in the data.

### HAND VALUE CALCULATIONS

Fabric hand consists of sensory perceptions that are related to the fabric's mechanical properties. Standards for evaluating the hand of a fabric are based on whether it will perform well and be acceptable for use as a clothing material. The primary hand values are stiffness (Koshi), smoothness (Numeri), and fullness and softness (Fukurami). The hand measurement of stiffness (Koshi) is an expression of combined sensations of resistance, elasticity, and plasticity when fabrics are manipulated by hand. It is related to the mechanical properties of bending and shear and to surface properties. The hand measurement of smoothness (Numeri) refers to the surface softness or harshness of the tactile response when fabrics are handled and is generally related to the tensile, bending, and surface properties of the fabric. The hand measurement of fullness and softness (Fukurami) represents the combined sensations of heaviness and thickness. We calculated Koshi, Numeri, and Fukurami hand values of the samples from this study with the results from sixteen tests of mechanical properties, using averages of wale and course values in these calculations. We used the KN-402-KT equation [9, 10] to calculate the primary hand values of stiffness (Koshi), smoothness (Numeri), and fullness and softness (Fukurami) for knit outerwear fabrics with the following formula:

$$Y(HV) = C_o + \sum_{i=1}^{16} C_i \frac{X_i - \bar{X}_i}{\sigma_i} \quad ,$$

where $Y(HV)$ = primary hand value, $C_o$, $C_i$ = constant parameters, and $X_i$, $\sigma_i$ = mean and standard deviation of mechanical property measurements $X(i)$.

We calculated the total hand value (*THV*), the sum of hand values (*HV*), from the KN-301-Winter equation [11]:

$$THV = C_o + \sum_{i=1}^{k} Z_i \quad ,$$

where $Z_i = C_{i1}[(Y_i - M_{i1})/\sigma_{i1}] + C_{i2}[(Y_i^2 - M_{i2})/\sigma_{i2}]$, $Y_i$ = primary hand value $i$, $M_{i1}$, $M_{i2}$, $\sigma_{i1}$, $\sigma_{i2}$ = mean and standard deviation of $Y$ and $Y^2$, and $C_{i1}$, $C_{i2}$ = constant parameters.

## Results and Discussion

### MECHANICAL PROPERTIES OF WEFT KNITS

Eighteen kinds of weft knits with varying knit structures and densities were constructed, and their tensile,

TABLE IV. Tensile properties of the knit samples.[a]

| Knit structure | Density | *LT*-W | *LT*-C | *LT*-A | *WT*-W | *WT*-C | *WT*-A | *RT*-W | *RT*-C | *RT*-A |
|---|---|---|---|---|---|---|---|---|---|---|
| Single knit | | | | | | | | | | |
| 1 × 1 rib | L | 0.314 | 0.356 | 0.335 | 20.139 | 22.246 | 21.193 | 24.331 | 23.100 | 23.716 |
| | M | 0.361 | 0.381 | 0.371 | 43.904 | 63.520 | 53.712 | 39.063 | 16.606 | 27.834 |
| | T | 0.376 | 0.380 | 0.378 | 48.510 | 94.276 | 71.393 | 36.364 | 24.948 | 30.656 |
| Half-cardigan rib | L | 0.295 | 0.319 | 0.307 | 61.054 | 56.840 | 58.947 | 28.571 | 25.001 | 26.786 |
| | M | 0.321 | 0.361 | 0.341 | 68.600 | 52.038 | 60.319 | 31.500 | 25.047 | 28.274 |
| | T | 0.338 | 0.370 | 0.354 | 71.840 | 65.050 | 68.445 | 50.500 | 22.736 | 36.618 |
| Half-milano rib | L | 0.354 | 0.383 | 0.368 | 45.472 | 66.542 | 56.007 | 27.155 | 22.239 | 24.697 |
| | M | 0.403 | 0.407 | 0.405 | 39.690 | 86.142 | 62.916 | 32.593 | 19.795 | 26.194 |
| | T | 0.412 | 0.421 | 0.416 | 58.310 | 133.770 | 96.040 | 26.800 | 27.500 | 27.150 |
| Double knit | | | | | | | | | | |
| Interlock | L | 0.383 | 0.394 | 0.389 | 66.444 | 96.236 | 81.340 | 9.882 | 15.479 | 12.680 |
| | M | 0.379 | 0.388 | 0.389 | 68.796 | 98.690 | 83.743 | 12.108 | 16.900 | 14.504 |
| | T | 0.410 | 0.375 | 0.392 | 69.290 | 99.870 | 84.580 | 12.100 | 16.900 | 14.500 |
| Single-pique | L | 0.342 | 0.368 | 0.354 | 63.798 | 54.096 | 58.947 | 14.747 | 14.855 | 14.801 |
| | M | 0.355 | 0.360 | 0.357 | 56.056 | 58.088 | 57.068 | 19.056 | 20.600 | 19.828 |
| | T | 0.372 | 0.348 | 0.360 | 53.112 | 66.150 | 59.633 | 21.956 | 21.037 | 21.496 |
| Crossmiss interlock | L | 0.336 | 0.368 | 0.352 | 49.784 | 57.180 | 53.482 | 14.567 | 14.100 | 14.334 |
| | M | 0.367 | 0.399 | 0.383 | 49.294 | 57.918 | 53.606 | 14.513 | 14.721 | 14.617 |
| | T | 0.373 | 0.409 | 0.391 | 47.824 | 65.268 | 56.546 | 22.746 | 22.823 | 22.784 |

[a] *LT* = tensile linearity, *WT* = tensile energy (g.cm/cm$^2$), *RT* = tensile resilience (%), W = wale, C = course, A = average, L = loose, M = medium, T = tight.

bending, shear, compression, and surface properties, along with thickness and weight, were measured using the KES-F method under standard measurement conditions. The results are shown in Tables IV to X.

### *Tensile Properties*

The tensile properties of knitted fabrics are related to their relaxation and resilience characteristics. High modulus and *RT* (tensile resilience) values indicate that the fabric is less likely to stretch easily when external forces are applied. Knitted fabrics with high *RT* have greater dimensional stability with low relaxation and high resilience characteristics. Tensile values are shown in Table IV.

Tensile properties and density: The mean values of *LT* (linearity of load-extension), *WT* (tensile energy), and *RT* (tensile resilience) tended to increase as the density increased for each of the six constructions. The exceptions were in the double knit interlock samples, in which the average *LT* decreased slightly from the loose to medium samples and the average *RT* decreased from the medium to tight samples.

Tensile properties and construction: Values for the low, medium, and high density samples were averaged to compare differences due to the knit structure. The order of the *LT* values (low to high) of the single knits was half-cardigan, 1 × 1 rib, and half-milano, and the order of the double knits was single-pique, crossmiss, and interlock. The order of the *WT* values (low to high) was 1 × 1 rib, half-cardigan, and half-milano for single knits, and crossmiss, single-pique, and interlock for double knits. The order of the *RT* values (low to high) was half-milano, 1 × 1 rib, and

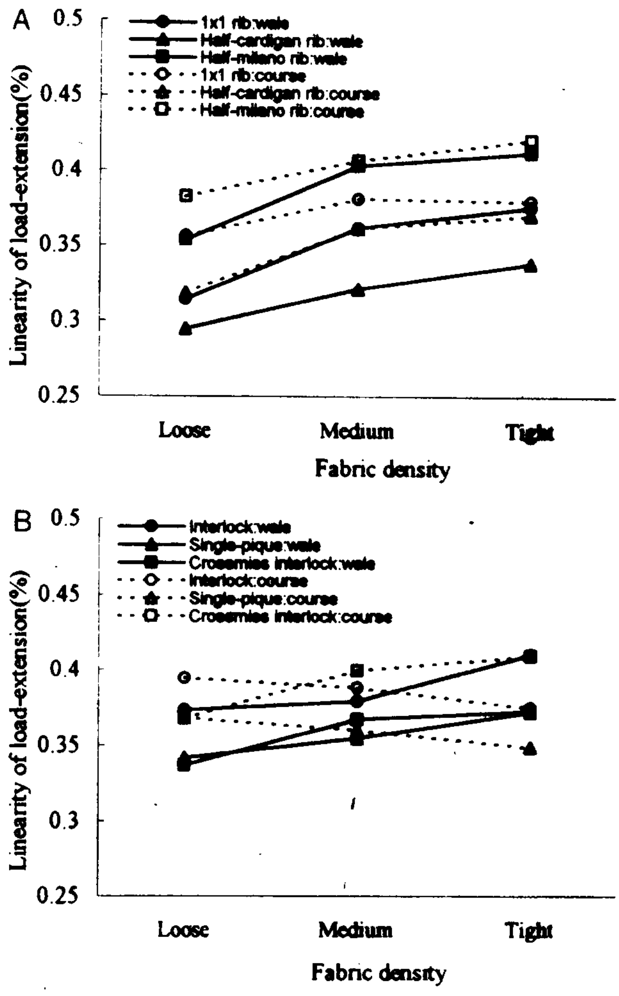



FIGURE 1. Linearity of load extension (*LT*) of sample fabrics: (A) single knits, (B) double knits.

half-cardigan for single knits, and interlock, single-pique, and crossmiss for double knits.

The *RT* value was much greater in the wale direction than the course direction for 1 × 1 rib, half-cardigan, and interlock. Differences in *RT* values for the wale and course directions were negligible in half-milano, single-pique, and crossmiss interlock. The *RT* of single and double knits increased with knit density and was affected by the direction and knit structure.

Such directional differences are the result of stitch formations in the knit structure. Elongation is generally greater in the course direction than in the wale direction, since stitches of weft-knitted fabrics are connected in the wale direction. The 1 × 1 rib and interlock samples are constructed using knit stitches that have excellent stretch properties, and therefore samples have the ability to absorb external stress applied in the course direction.

Figures 1, 2, and 3 show the *LT*, *WT*, and *RT* values of the sample knits as a function of structure and density.

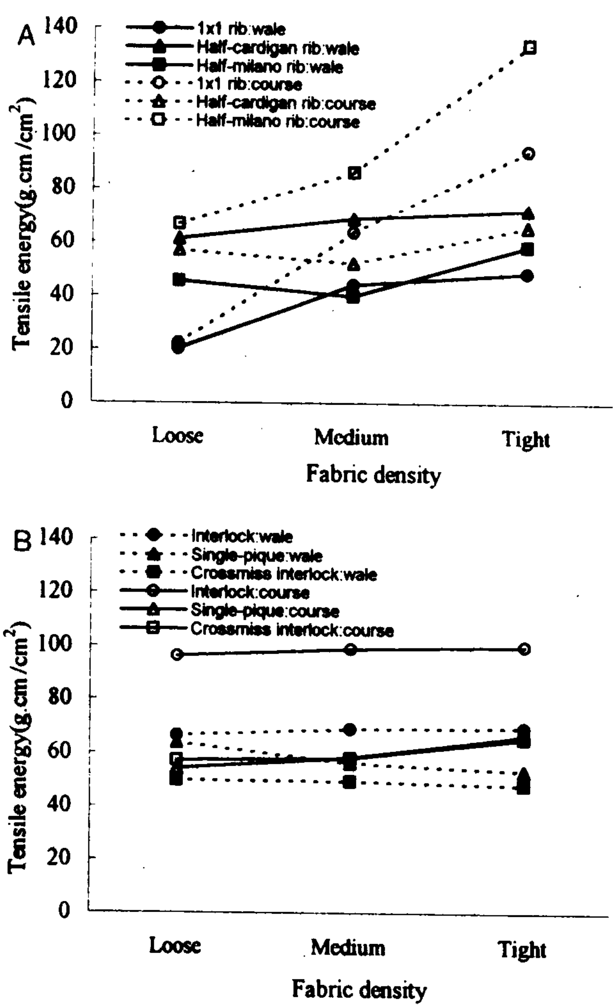



FIGURE 2. Tensile energy (*WT*) of sample fabrics: (A) single knits, (B) double knits.

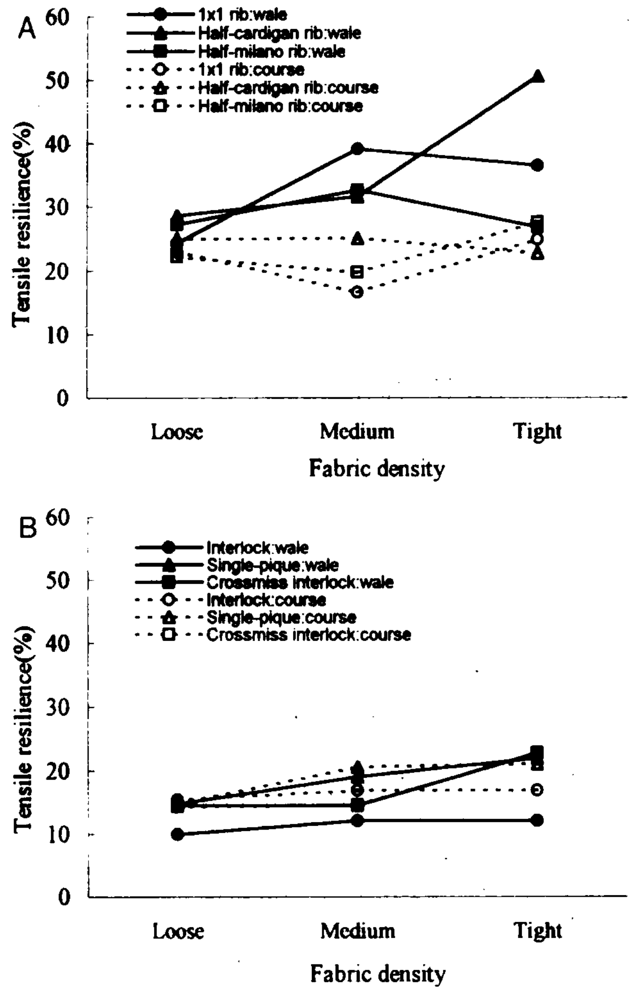



FIGURE 3. Tensile resilience (*RT*) of sample fabrics: (A) single knits, (B) double knits.

### *Bending Properties*

A fabric's bending characteristics contribute to differences in the way it conforms to the body. Fabrics with higher values of bending rigidity and bending hysteresis will bend less easily.

Bending properties and density: As shown in Table V, mean values of *B* (bending rigidity) and *2HB* (bending hysteresis) increased with knit density. The larger values for bending properties for greater density knit samples are understandable, since increasing knit density means decreasing space for stitch movements as well as increased friction between the yarns.

Bending properties and construction: A comparison of the results by knit structure reveals a much lower bending rigidity and hysteresis of bending moment in single knits than in double knits. The order of the *B* and *2HB* values by construction was half-cardigan, 1 × 1 rib, half-milano, interlock, single-pique, and crossmiss interlock.

TABLE V. Bending properties of knit samples.[a]

| Knit structure | Density | *B*-W | *B*-C | *B*-A | *2HB*-W | *2HB*-C | *2HB*-A |
|---|---|---|---|---|---|---|---|
| Single knit | | | | | | | |
| 1 × 1 rib | L | 0.814 | 0.117 | 0.465 | 0.866 | 0.139 | 0.502 |
| | M | 1.034 | 0.182 | 0.608 | 1.176 | 0.172 | 0.674 |
| | T | 1.173 | 0.219 | 0.697 | 1.278 | 0.224 | 0.751 |
| Half-cardigan rib | L | 0.507 | 0.162 | 0.335 | 0.690 | 0.180 | 0.435 |
| | M | 0.590 | 0.280 | 0.435 | 0.790 | 0.408 | 0.599 |
| | T | 0.667 | 0.219 | 0.443 | 0.813 | 0.516 | 0.664 |
| Half-milano rib | L | 0.784 | 0.231 | 0.507 | 0.913 | 0.272 | 0.592 |
| | M | 1.216 | 0.303 | 0.760 | 1.372 | 0.448 | 0.910 |
| | T | 1.523 | 0.337 | 0.930 | 1.490 | 0.494 | 0.991 |
| Double knit | | | | | | | |
| Interlock | L | 1.788 | 0.336 | 1.062 | 1.776 | 0.537 | 1.156 |
| | M | 1.961 | 0.198 | 1.080 | 2.420 | 0.727 | 1.574 |
| | T | 2.960 | 0.588 | 1.774 | 3.574 | 0.659 | 2.117 |
| Single-pique | L | 1.850 | 0.426 | 1.138 | 2.317 | 0.934 | 1.625 |
| | M | 1.706 | 0.791 | 1.249 | 2.857 | 0.953 | 1.905 |
| | T | 3.167 | 0.889 | 2.025 | 3.631 | 1.156 | 2.394 |
| Crossmiss interlock | L | 2.738 | 0.295 | 1.516 | 3.364 | 1.245 | 2.305 |
| | M | 4.037 | 1.016 | 2.526 | 4.312 | 1.392 | 2.852 |
| | T | 4.144 | 0.970 | 2.557 | 4.608 | 1.613 | 3.113 |

[a] *B* = bending rigidity (g.cm$^2$/cm), *2HB* = bending hysteresis (g.cm/cm), W = wale, C = course, A = average, L = loose, M = medium, T = tight.

Figures 4 and 5 represent the *B* and *2HB* of single and double weft-knitted structures in the course and wale directions. The *B* and *2HB* values were remarkably greater in the wale direction. The *B* values in the wale direction were 5–7 times, 2–3 times, 3–4 times, 6–9 times, 2–4 times, and 4–9 times greater for 1 × 1 rib, half-cardigan, half-milano, interlock, single-pique, and crossmiss interlock, respectively. In all samples, the course direction exhibited a lower bending rigidity than the wale direction. We attribute this to the action of the stitches in the course direction.

According to Skelton and Schoppee [22] "weft-knit structures in general are characterized by higher flexibility (lower values of both elastic rigidity *B* and frictional bending moment $M_o$) for bending about an axis parallel to the wales". The gaps within the knitted fabric decrease as the density increases due to low *SCSL* per *SKC* (structural unit cell). As a consequence of decreased movement of the yarn, the movement of each stitch is suppressed, and *B* and *2HB* therefore decrease.

The crossmiss interlock, which was constructed by combining a knit and miss stitch, showed higher bending rigidity than the 1 × 1 rib in both course and wale directions. Such behavior is thought to result from fabrics receiving less stress from the curved areas in the course direction, since threads tend to have more freedom of movement and fabrics have higher stretch properties in the course direction.

*Shear Properties*

Shear properties are important factors affecting surface fitting characteristics of knits, since they generally have a particularly low resistance to shear deformation. These properties are represented by *G* (shear stiffness) and *2HG*, *2HG5* (shear hysteresis measured at two different angles), which are related to elasticity and plasticity, respectively.

Shear properties and density: As shown in Table VI, mean values of the shear properties of the knit increase with knit density. Shear stiffness is affected by the slipperiness at warp-weft yarn intersections and elastic deformation and bending deformation of the yarns, while shear hysteresis is influenced by the coefficient of friction, contact length, and warp-weft yarn density [4, 21]. Higher stitch density increases resistance to slippage between yarns or fibers, warp-weft contact, and fiber contact in the intersections.

Shear properties and construction: Figure 6 shows the differences in shear stiffness between the wale and course directions. For all fabrics, shear stiffness values were higher in the wale direction. The shear stiffness of samples with varying knit structures decreased in the following order: half-cardigan, half-milano, and 1 × 1 rib for single knits, and crossmiss interlock, single-pique, and interlock for double knits. These results are similar to those for high bending rigidity in the wale and course directions for the samples with tuck and miss stitches.

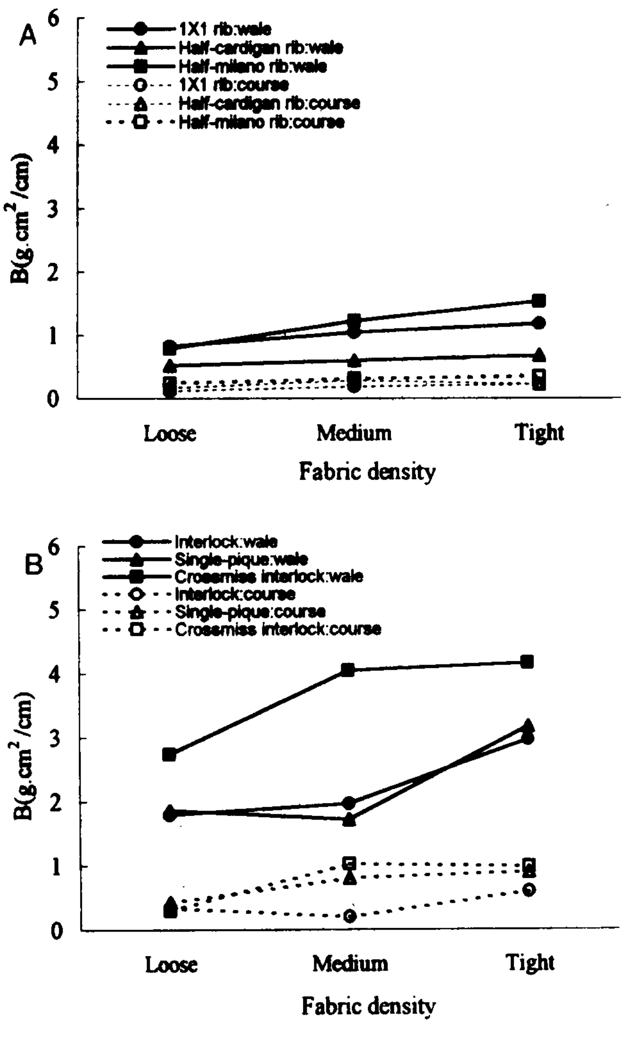



FIGURE 4. Bending rigidity ($B$) of sample fabrics: (A) single knits, (B) double knits.

## *Compression*

Compression measurements give an indication of the knitted fabric's resilience and fullness, important factors in determining comfort and hand.

Compression values and density: Values of *WC* (compression energy) and *RC* (compression resilience) decrease in fabrics that feel thicker and denser to the touch. Table VII shows that the mean values of *WC* (compression energy) and *RC* (resilience) generally decreased as knit density increased. Exceptions were *WC* for double knit and *RC* for half-milano and interlock. The general decrease in *WC* and *RC* values may be due to the knitted fabric's curved stitch structure, since higher densities result in a smaller stitch space, lower resilience, and lower compression energy. On the other hand, *LC* (compression linearity) varies greatly among the samples. No clear pattern emerges in this case.

Compression values and construction: The compression values did not show consistant differences among the different knit structures.

## *Surface Properties*

Surface properties are related to the fabric's smoothness and are represented by the *MIU* (surface coefficient of friction), the *MMD* (mean deviation of *MIU*), and *SMD* (mean deviation of surface contour). *MIU*, *MMD*, and *SMD* increase as surface properties in the fabric increase.

Surface properties and density: Table VIII shows that the *MIU*, *MMD*, and *SMD* values generally increased as knit density increased. We observed these trends for all knit samples except the half-milano rib; here the *MIU* values decreased slightly as density increased. The *MIU* of the crossmiss interlock, the *MMD* of the single-pique, and the *SMD* of the 1 × 1 rib also showed no increase or a very small decrease as density changed.

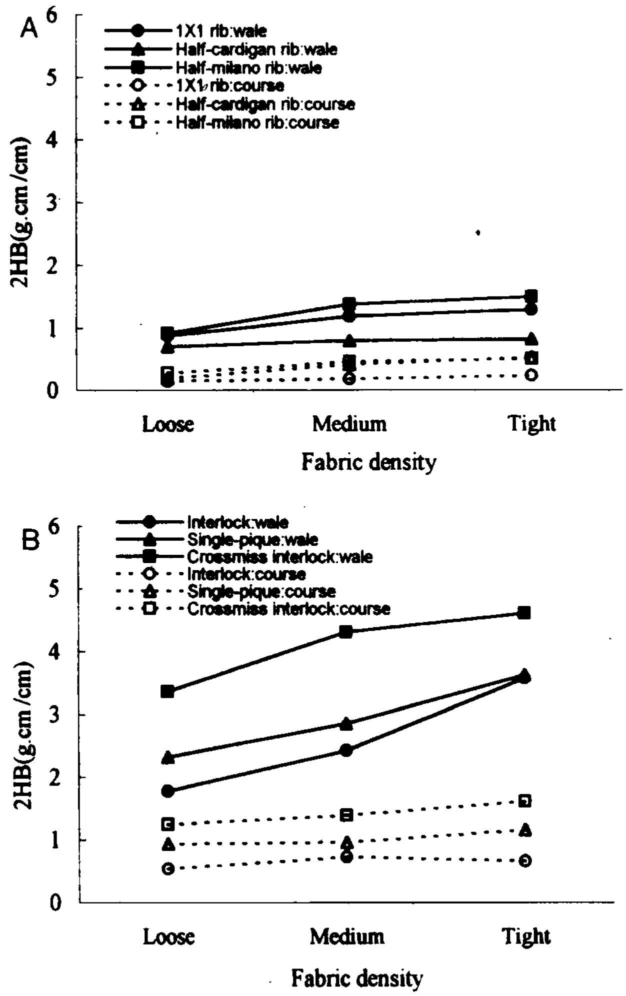



FIGURE 5. Hysteresis of bending moment ($2HB$) of sample fabrics: (A) single knits, (B) double knits.

TABLE VI. Shear properties of knit samples.[a]

| Knit structure | Density | *G*-W | *G*-C | *G*-A | *2HG*-W | *2HG*-C | *2HG*-A | *2HG5*-W | *2HG5*-C | *2HG3*-A |
|---|---|---|---|---|---|---|---|---|---|---|
| Single knit | | | | | | | | | | |
| 1 × 1 rib | L | 0.274 | 0.196 | 0.235 | 0.862 | 0.862 | 0.862 | 0.951 | 0.926 | 0.935 |
| | M | 0.321 | 0.221 | 0.271 | 1.014 | 0.858 | 0.936 | 1.122 | 0.946 | 1.034 |
| | T | 0.395 | 0.309 | 0.352 | 1.299 | 1.524 | 1.411 | 1.450 | 1.627 | 1.539 |
| Half-cardigan rib | L | 0.372 | 0.331 | 0.352 | 1.362 | 1.191 | 1.277 | 1.465 | 1.328 | 1.397 |
| | M | 0.436 | 0.385 | 0.411 | 1.539 | 1.460 | 1.499 | 1.676 | 1.602 | 1.639 |
| | T | 0.505 | 0.446 | 0.475 | 1.877 | 1.720 | 1.798 | 2.009 | 1.877 | 1.943 |
| Half-milano rib | L | 0.336 | 0.348 | 0.342 | 1.034 | 1.259 | 1.147 | 1.122 | 1.357 | 1.240 |
| | M | 0.414 | 0.338 | 0.376 | 1.259 | 1.328 | 1.294 | 1.309 | 1.426 | 1.367 |
| | T | 0.419 | 0.429 | 0.474 | 1.490 | 1.602 | 1.546 | 1.691 | 1.759 | 1.725 |
| Double knit | | | | | | | | | | |
| Interlock | L | 0.434 | 0.419 | 0.462 | 1.426 | 1.691 | 1.558 | 1.553 | 1.798 | 1.676 |
| | M | 0.519 | 0.492 | 0.506 | 1.676 | 2.127 | 1.901 | 1.852 | 2.269 | 2.063 |
| | T | 0.635 | 0.549 | 0.592 | 2.132 | 2.264 | 2.198 | 2.381 | 2.450 | 2.416 |
| Single-pique | L | 0.512 | 0.522 | 0.517 | 1.700 | 2.024 | 1.862 | 1.864 | 2.181 | 2.022 |
| | M | 0.590 | 0.568 | 0.579 | 1.882 | 2.210 | 2.046 | 2.112 | 2.421 | 2.266 |
| | T | 0.728 | 0.700 | 0.714 | 2.323 | 2.550 | 2.436 | 2.626 | 2.990 | 2.808 |
| Crossmiss interlock | L | 0.483 | 0.441 | 0.462 | 1.450 | 1.710 | 1.580 | 1.671 | 1.877 | 1.774 |
| | M | 0.744 | 0.586 | 0.664 | 2.318 | 2.200 | 2.259 | 2.646 | 2.416 | 2.531 |
| | T | 0.791 | 0.671 | 0.731 | 2.279 | 2.426 | 2.352 | 2.656 | 2.671 | 2.663 |

[a] *G* = Shear stiffness (g/cm.degree), *2HG* = hysteresis of shear force at 0.5 of shear angle (g/cm), *2HG5* = hysteresis of shear force at 5 of shear angle (g/cm), W = wale, C = course, A = average, L = loose, M = medium, T = tight.

Surface properties and construction: We did not detect large surface structural differences between the knit stitch, tuck stitch, and miss stitch. This can be attributed to the obvious surface roughness of weft-knitted fabrics in the wale direction, which makes it difficult to detect changes in the surface properties arising from fine stitch structural differences. The differences between *SMD* values increased in the following order based on the knit structure: 1 × 1 rib, half-cardigan, and half-milano for single knits, and crossmiss interlock, single-pique, and interlock for double knits. When we compared values for the wale and course directions, the *SMD* values in the wale direction were generally much lower.

### *Thickness and Weight*

The thickness and weight of knitted fabrics are characteristic values related to the drape and fullness of clothing. Thickness increases in higher density samples. The weight, thickness, and weight/thickness ratio (*W/T*) for each of the samples is shown in Table IX. For loose density fabrics, *W/T* values were low, resulting in high air content and superior volume. Thickness and weight did not show large differences for the different knit structures.

## HAND OF WEFT KNITS

An objective evaluation of sensory responses to fabrics plays an important role in providing data to assess the appropriateness of fabrics for various end

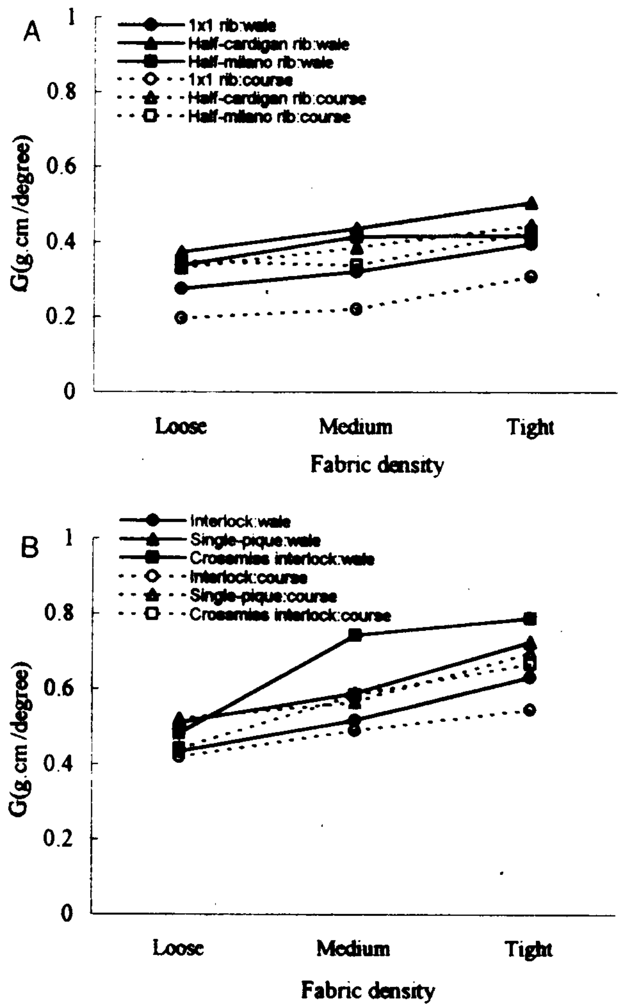



FIGURE 6. Shear stiffness (*G*) of sample fabrics: (A) single knits, (B) double knits.

TABLE VII. Compression properties of knit samples.[a]

| Knit structure | Density | *LC* | *WC* | *RC* |
|---|---|---|---|---|
| Single knit | | | | |
| 1 × 1 rib | L | 0.610 | 1.990 | 39.931 |
| | M | 0.595 | 1.963 | 39.362 |
| | T | 0.602 | 1.496 | 31.213 |
| Half-cardigan rib | L | 0.426 | 2.007 | 36.431 |
| | M | 0.491 | 2.007 | 34.542 |
| | T | 0.609 | 1.917 | 27.820 |
| Half-milano rib | L | 0.588 | 2.007 | 29.212 |
| | M | 0.614 | 1.719 | 31.369 |
| | T | 0.590 | 1.621 | 27.133 |
| Double knit | | | | |
| Interlock | L | 0.664 | 2.007 | 28.710 |
| | M | 0.696 | 1.960 | 27.841 |
| | T | 0.665 | 1.507 | 29.962 |
| Single-pique | L | 0.666 | 2.007 | 34.770 |
| | M | 0.797 | 2.007 | 32.838 |
| | T | 0.712 | 1.617 | 30.764 |
| Crossmiss interlock | L | 0.752 | 1.785 | 34.179 |
| | M | 0.721 | 1.602 | 30.422 |
| | T | 0.759 | 1.617 | 29.489 |

[a] *LC* = compression linearity, *WC* = compression energy (g.cm/cm$^2$), *RC* = compression resilience (%), L = loose, M = medium, T = tight.

uses. Thus, we evaluated the samples in comparison with the appropriate terminology to assess sensory responses to knitted fabrics for outerwear for the winter season (KN-402-KT). Table X and Figure 7 show the values of stiffness (Koshi), smoothness (Numeri), fullness and softness (Fukurami), and total hand values *THV* of the sample knits for outerwear as a function of knit structure and knit density.

Fabrics tended to become stiffer, rougher surfaced, and less full and soft as the density increased. Stiffness values for double knits were much higher than those for single knits. The 1 × 1 rib fabric at all density levels was the least stiff and the smoothest surfaced sample of all the fabrics; it was intermediate in fullness and softness. The half-cardigan rib was the smoothest surfaced and the fullest and softest in the sample with the loose density. The half-milano fabric at all three densities exhibited the least fullness and softness of all six fabrics; it was intermediate in smoothness and stiffness.

The interlock fabric was intermediate in stiffness, smoothness, and fullness and softness. The crossmiss interlock was the stiffest fabric of all and tended to be smoother surfaced and fuller and softer. Last, the single-pique tended to be fuller and softer; it was intermediate in stiffness and smoothness.

Consequently, the 1 × 1 rib was the least stiff and the crossmiss interlock was the most stiff of all fabrics. The half-cardigan and single-pique fabrics, which had a combined tuck stitch compared to 1 × 1 rib and interlock with only a knit stitch, were smoother fabrics and showed the most fullness and softness of all. This is related to the low bending and compression properties of the knit structure. The fullness and softness trend is similar to the changes in smoothness. Fabrics with a knit structure of tuck and miss had distinctly higher softness values.

TABLE VIII. Surface properties of knit samples.[a]

| Knit structure | Density | *MIU*-W | *MIU*-C | *MIU*-A | *MMD*-W | *MMD*-C | *MMD*-A | *SMD*-W | *SMD*-C | *SMD*-A |
|---|---|---|---|---|---|---|---|---|---|---|
| Single knit | | | | | | | | | | |
| 1 × 1 rib | L | 0.457 | 0.422 | 0.440 | 0.017 | 0.019 | 0.018 | 4.562 | 10.220 | 7.391 |
| | M | 0.493 | 0.452 | 0.473 | 0.017 | 0.021 | 0.020 | 4.562 | 10.220 | 7.391 |
| | T | 0.507 | 0.556 | 0.532 | 0.018 | 0.026 | 0.022 | 5.517 | 12.163 | 8.840 |
| Half-cardigan rib | L | 0.490 | 0.426 | 0.458 | 0.015 | 0.017 | 0.016 | 7.996 | 10.496 | 9.246 |
| | M | 0.490 | 0.476 | 0.483 | 0.017 | 0.022 | 0.020 | 8.928 | 11.044 | 9.986 |
| | T | 0.489 | 0.501 | 0.495 | 0.019 | 0.026 | 0.023 | 10.770 | 13.376 | 12.073 |
| Half-milano rib | L | 0.546 | 0.569 | 0.557 | 0.017 | 0.024 | 0.021 | 6.458 | 13.466 | 9.962 |
| | M | 0.547 | 0.551 | 0.549 | 0.019 | 0.032 | 0.025 | 6.827 | 15.817 | 11.322 |
| | T | 0.550 | 0.542 | 0.546 | 0.019 | 0.034 | 0.026 | 8.340 | 19.296 | 13.818 |
| Double knit | | | | | | | | | | |
| Interlock | L | 0.401 | 0.425 | 0.413 | 0.013 | 0.022 | 0.018 | 3.758 | 9.246 | 6.502 |
| | M | 0.409 | 0.438 | 0.424 | 0.013 | 0.023 | 0.018 | 3.925 | 10.035 | 6.980 |
| | T | 0.451 | 0.470 | 0.461 | 0.016 | 0.025 | 0.020 | 4.302 | 10.499 | 7.401 |
| Single-pique | L | 0.443 | 0.446 | 0.444 | 0.017 | 0.022 | 0.019 | 1.504 | 1.779 | 1.642 |
| | M | 0.455 | 0.454 | 0.455 | 0.017 | 0.020 | 0.019 | 1.426 | 1.877 | 1.651 |
| | T | 0.475 | 0.459 | 0.467 | 0.019 | 0.025 | 0.022 | 1.460 | 1.921 | 1.691 |
| Crossmiss interlock | L | 0.366 | 0.460 | 0.413 | 0.013 | 0.023 | 0.018 | 0.975 | 1.475 | 1.225 |
| | M | 0.370 | 0.460 | 0.410 | 0.014 | 0.024 | 0.019 | 1.299 | 1.627 | 1.463 |
| | T | 0.378 | 0.453 | 0.416 | 0.015 | 0.026 | 0.020 | 1.686 | 1.700 | 1.693 |

[a] *MIU* = coefficient of friction, *MMD* = mean deviation of *MIU*, *SMD* = mean deviation of surface contour (μm), W = wale, C = course, A = average, L = loose, M = medium, T = tight.

TABLE IX. Thickness, weight, and weight/thickness ratio of knit samples.[a]

| Knit structure | Density | Thickness | Weight | Weight/thickness |
|---|---|---|---|---|
| Single knit | | | | |
| 1 × 1 rib | L | 4.150 | 590 | 14.220 |
| | M | 4.228 | 622 | 14.720 |
| | T | 4.299 | 661 | 15.375 |
| Half-cardigan rib | L | 4.002 | 551 | 13.774 |
| | M | 4.113 | 585 | 14.224 |
| | T | 4.212 | 621 | 14.750 |
| Half-milano rib | L | 3.982 | 639 | 16.055 |
| | M | 4.021 | 654 | 16.272 |
| | T | 4.112 | 671 | 16.324 |
| Double knit | | | | |
| Interlock | L | 4.632 | 682 | 14.705 |
| | M | 4.721 | 732 | 15.507 |
| | T | 4.812 | 829 | 17.223 |
| Single-pique | L | 4.512 | 752 | 16.673 |
| | M | 4.622 | 812 | 17.577 |
| | T | 4.763 | 862 | 18.097 |
| Crossmiss interlock | L | 4.502 | 855 | 18.982 |
| | M | 4.583 | 882 | 19.251 |
| | T | 4.623 | 901 | 19.493 |

[a] $T$ = thickness at pressure 0.5 gf/cm$^2$ (mm), $W$ = weight per unit area (g/m$^2$), L = loose, M = medium, T = tight.

### *Total Hand Value*

The total hand values obtained from primary hand values are shown in Figure 8. We calculated these values using the KN-301 winter equation.

*THV* increased as the knit density rose. Double knits exhibited much higher *THV* than single knits. The *THV* of the crossmiss interlock was the highest of all six fabrics.

## Conclusions

To study the effect of knitting conditions on the mechanical and hand properties of weft knits, we produced eighteen different kinds of weft knits with varying structures and densities. We measured the mechanical properties and hand values of these samples with the KES-F method. We can draw the following conclusions from this study.

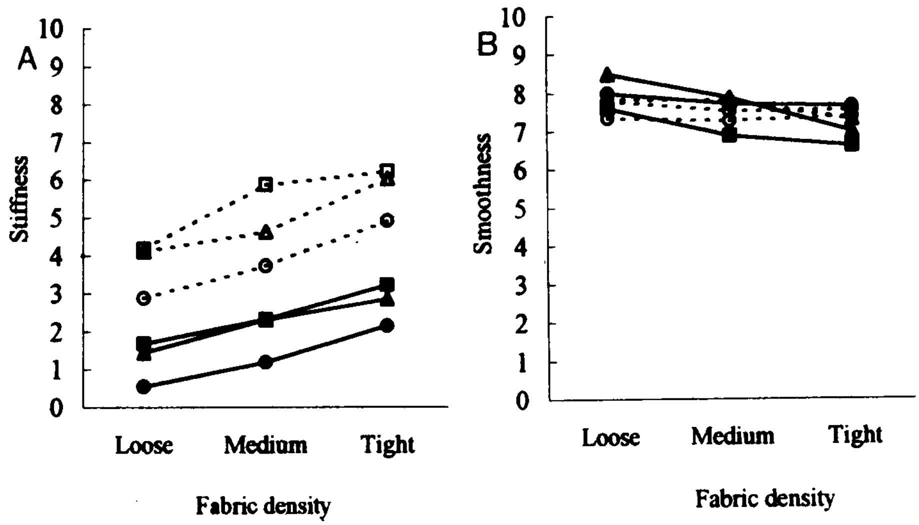
Tensile properties such as average strength, strain, and elongation of weft knitted fabrics generally increased with knit density. The knit stitches of the single-pique and crossmiss interlocks were replaced by tuck and miss stitches at regular intervals in the course direction. Therefore, these fabrics could not absorb as much external stress in the course direction compared to the interlock. The interlock sample had greater stretch properties in the course direction.

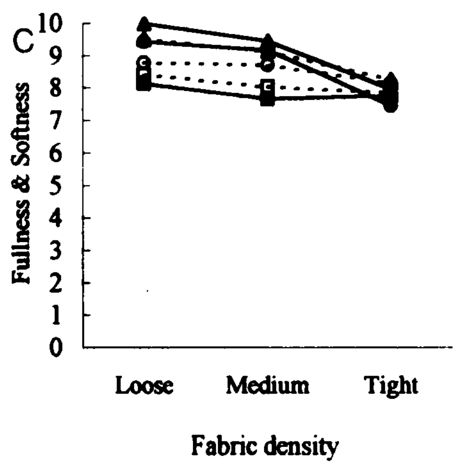
Bending properties such as average bending rigidity and hysteresis of weft knits increased with knit density. The *B* and *2HB* values were remarkably greater in the wale direction. Values associated with bending properties were lower in single knits than double knits. Based on these characteristics, it is likely that the single-pique and crossmiss interlock double knits will perform poorly in conforming to a curved surface compared to an interlock. Current market-driven goals of providing fabrics that conform to the body silhouette are met by the interlock.

TABLE X. Hand values of the knit samples.

| Knit structure | Density[a] | Stiffness (Koshi)[b] | Smoothness (Numeri)[c] | Fullness & softness (Fukurami)[d] | *THV* |
|---|---|---|---|---|---|
| Single knit | | | | | |
| 1 × 1 rib | L | 0.56 | 7.98 | 9.42 | 2.87 |
| | M | 1.08 | 7.68 | 9.15 | 3.02 |
| | T | 2.14 | 7.63 | 7.45 | 3.82 |
| Half-cardigan rib | L | 1.52 | 8.51 | 9.96 | 3.55 |
| | M | 2.36 | 7.86 | 9.46 | 3.61 |
| | T | 2.89 | 6.97 | 7.96 | 3.60 |
| Half-milano rib | L | 1.60 | 7.59 | 8.06 | 3.47 |
| | M | 2.35 | 6.87 | 7.66 | 3.39 |
| | T | 3.28 | 6.60 | 7.76 | 3.54 |
| Double knit | | | | | |
| Interlock | L | 2.88 | 7.33 | 8.73 | 3.65 |
| | M | 3.74 | 7.25 | 8.68 | 3.88 |
| | T | 4.90 | 7.35 | 8.14 | 4.30 |
| Single-pique | L | 4.16 | 7.86 | 9.59 | 4.11 |
| | M | 4.65 | 7.71 | 9.13 | 4.25 |
| | T | 6.03 | 7.29 | 8.05 | 4.40 |
| Crossmiss interlock | L | 4.22 | 7.99 | 9.18 | 4.34 |
| | M | 5.89 | 7.51 | 8.03 | 4.53 |
| | T | 6.22 | 7.34 | 7.08 | 4.57 |

[a] L = loose, M = medium, T =tight. [b] A higher value indicates a stiffer fabric. [c] A higher value indicates a smoother fabric. [d] A higher value indicates a fuller and softer fabric.



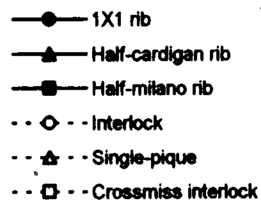




FIGURE 7. Primary hand values of sample fabrics: (A) stiffness (a higher value indicates a stiffer fabric), (B) smoothness (a higher value indicates a smoother fabric), (C) fullness and softness (a higher value indicates a fuller and softer fabric).

Properties such as average shear strain, rigidity, and stress of weft-knitted fabrics increased with knit density. Shear stiffness was greater in the wale direction compared to the course direction. For all fabrics, shear stiffness values were higher in the wale direction. Interlock fabrics will better satisfy current market needs for fluid, soft fabrics that conform to the body.

Compression values of the knit samples generally decreased with knit density because a structure with curved stitches leads to decreasing compression resilience and compression energy as the stitch space becomes smaller.

Surface properties such as softness and smoothness generally increased with knit density for all fabrics. We observed no large differences in the surface properties of the different knit structures.

Regarding the primary hand values of weft knits, the fabrics tended to become stiffer, rougher surfaced, and less full and soft as the density increased. Stiffness values for double knits were much higher than those for single knits.

At all density levels, the 1 × 1 rib fabric tended to be the least stiff and the smoothest surfaced of all six fabrics. The half-cardigan rib was the smoothest surfaced and fullest and softest at a loose density. The half-milano fabric at all densities was the least full and soft of all six fabrics.

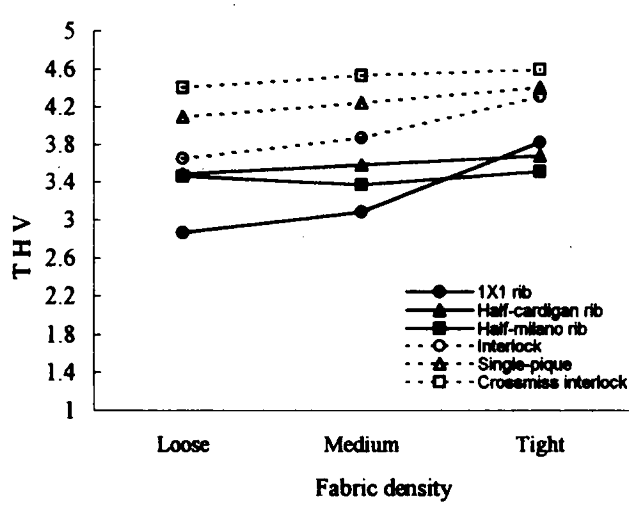



FIGURE 8. Total hand value (*THV*) of sample fabrics.

The crossmiss interlock was the stiffest of all fabrics and tended to be smoother surfaced and fuller and softer. Last, the single-pique tended to be fuller and softer.

Total hand values increased as knit density rose. Double knits exhibited much higher *THV* than single knits. The *THV* of the crossmiss interlocks were highest of all six fabrics.

Choices of preferred fabrics made in this study correspond to recent fashion trends that emphasize surface softness and fluidity for knit clothing. This analysis of the desired properties of knit fabrics can be used to choose knitting structures and densities of double weft knit fabrics for outerwear based on the current preferred properties of the market. Different properties may become desirable in knit fabrics as fashions and trends change. Whatever the desired properties, studies of mechanical properties and hand of different fabrics will assist apparel designers and textile manufacturers in choosing appropriate textile structures and densities. Detailed systematic studies made by controlling variables of knitting conditions must be conducted in order to develop knitted fabrics with the desired performance and hand.

ACKNOWLEDGMENTS

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