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Ultrafine Wools: Comfort and Handle Properties for Next to Skin
Knitwear and Manufacturing Performance

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ABSTRACT

This study aimed to quantify the skin comfort and handle properties of a range of wool fabrics
produced from ultrafine wool (13.7-15.1 \( \mu \)m) and in doing so determine if differences in fibre
diameter and staple crimp frequency (5.3-7.1 crimps/cm) were important in these properties.
The fabrics were evaluated using a range of subjective and objective measurement techniques
including: the Wool ComfortMeter; the Wool HandleMeter; and in wearer trials. This work
indicated that the single jersey fabrics made from ultrafine wool are approaching the limit of
objective and subjective evaluation of next to skin comfort. The results from the Wool
ComfortMeter, Wool HandleMeter and the wearer trial show that there were no
significant effects that can be attributed to wool staple crimp (fibre curvature) in these
ultrafine wool fabrics. The work also demonstrated a difference in the manufacturing
response when knitted fabric made from wool of different fibre diameter (13.7-23.7 \( \mu \)m), and
using yarns of the same count, resulted in a progressively higher fabric mass per unit area as
mean fibre diameter was progressively reduced.

Key Words: wearer trial; sensory evaluations, fibre properties; fabric mass per unit area;
Wool ComfortMeter; Wool HandleMeter
Introduction
Commercially important keratin fibres are harvested from a number of animals including sheep, goats, camels, alpaca, vicuña, rabbits and yak. The fibres grown by these animals have a number of subjectively and objectively determined traits that are associated with the perceived quality and price [1-5]. Of these traits three appear to be responsible for a significant component of the perceived quality and price being low mean fibre diameter, scarcity of fibre supply and the perceived comfort (softness) of garments made from these fibres. Other attributes which may also affect the perception of these fibres include the exotic locations associated with the origin of these fibres, as perceived by western consumers, and the luxury and expensive nature of the textiles which are produced with these fibres. In all cases the finer, rarer and softer the fibre the higher the price paid for the fibre. Of these three attributes mean fibre diameter and supply can be objectively measured. While the softness of these semi-processed fibres can only be measured as the resistance to compression [6], the comfort associated with wearing textiles made from these fibres cannot be directly measured until garments are manufactured and evaluated in expensive wearer trials.

Researchers have recently attempted to predict wearer comfort by correlating it to objectively measured attributes such as softness of handle of raw fibre or with compression properties of semi-processed or processed fibre [7-8]. Two fibres, that have had the majority of work done on them, in an attempt to understand the basis for the price and comfort differences, are wool and cashmere. Over the years a number of differences have been identified between wool and cashmere. The most obvious differences are cuticle cell structure, whereby cashmere fibres have in general less scales per unit length of fibre, less layers (fewer) of the cuticle scales surrounding fibres, and a lower cuticle scale height compared with wool fibres [9-10]; and fibre curvature in which cashmere fibres have a lower fibre curvature in general than apparel wool fibres [6,11,12]. Other less obvious differences include the identification of differences in intra and inter cellular lipids [13-14], fibre surface tension [14] and fibre ellipticity [15].
All of these different attributes are likely to impact on fibre mechanical properties, and thereby affect fabric bending, shear and tensile properties [7,16] and ultimately wearer comfort.

For any fibre property to have a major influence on fabric comfort and handle means the properties have to compliment the high level interactions occurring at the yarn and fabric level after the processes of scouring, combing, spinning, weaving or knitting, dyeing and finishing. As a general rule, and as most wool producers appreciate, the finer the wool the better the next-to-skin comfort [17]. However, this general rule only applies when other fabric construction and fibre properties are reasonably similar. Extremes in some other wool fibre characteristics such as fibre diameter distribution [18-19], as well as fabric construction (e.g. tightness) and yarn, knitting, dyeing and finishing parameters and treatments (e.g. softeners) can all have a significant influence on the assessment of next-to-skin comfort and fabric handle [20-21]. Analysis suggests only 60% to 70% of next-to-skin prickle comfort is due to the mean fibre diameter of the wool used [17,22].

The higher value textiles are predominantly composed of very fine fibres (mean fibre diameter < 17.5 µm). Unfortunately, published research in this area is scarce and knowledge has been tightly held as proprietary information. It is difficult to locate objective evaluation of fabrics made of superfine (< 18.5 µm) or ultrafine (< 16 µm) animal fibre, and what little information that is available is frequently without statistical comparisons and from unreplicated experiments so that it is not possible to make objective comparisons. Of the 100’s of fabrics tested as part of long-term investigations conducted by the Australian Co-operative Research Centre for Sheep Industry Innovation, it was found that only two pure wool fabrics with mean fibre diameters less than 18 µm had been tested - single jersey fabrics made from 16.2 and 16.3 µm wool. Relative to other wool and non-wool fabrics these were among the best performers for next-to-skin comfort and handle. This lead to the attribution of
various subjective and objectively determined fibre traits to aspects of comfort and handle properties of wool without adequate scientific support of data from ultrafine wool fibres.

Mean fibre diameter is one trait that has been examined in detail, especially with respect to fabric evoked discomfort in next-to-skin knitwear. Garnsworthy and co-workers [23-24] proposed that prickle discomfort was caused by fibre ends that were able to exert a force of greater than 75 mgf on the skin eliciting a response from a sub cutaneous pain receptor. Drawing similarities to a Euler column they then determined this was equivalent to a mean fibre >30 μm in diameter if the free fibre end was 2 mm long. The validity of that approximation has been questioned given the “curvy” nature of the fibres protruding from the surface of the fabric [25]. The “curvy” fibres would buckle well below the calculated force of a Euler column thus potentially making the presence of these fibres a poor predictor of fabric evoked prickle. In a series of studies to evaluate the potential fabric prickle discomfort sensations of knitwear, the proportion of fibres with fibre diameters > 24 μm to > 40 μm were not significant predictors of wearer assessed fabric evoked prickle once the mean fibre diameter was included in prediction models [17,21]. Indeed recent evaluation of Eulers law had led investigators to conclude that fibres as fine as 10 μm could provoke prickle discomfort provided their protruding length was short enough [26].

Raw fibre crimp or curvature also has been shown to influence the mechanical, wear and handle attributes of fabrics when certain variables are controlled [7,16,27] but the same effect is not always seen in other reports where curvature has not been measured, or where tight control of fibre properties has not been implemented and where experimental replication is absent. Variation in fibre curvature of superfine wool has been shown to affect the instrumental assessment of fabric comfort properties along with significant interactions between fibre properties and various yarn and fabric characteristics [28].
More recently developments have occurred in the direct measurement of fabric attributes that have allowed the accurate prediction of aspects of next-to-skin comfort [22] and fabric handle [29]. These measurements allow a holistic approach to the prediction of next-to-skin comfort and handle by making the critical measurement on the finished fabric, thus taking into consideration all the prior processing and other chemical treatments that have such a significant influence. Importantly, the instrument predictions from this work showed there was scope to have even better next-to-skin comfort and handle. It was decided that there was merit in having a clearer understanding of the relationship between comfort and handle on one side, and wool fibre diameter and consumer perception of quality on the other side. It was believed the outcome could also help to guide research and marketing plans for these ultrafine wools. Ideally, researchers could aim to understand the differential value per 1-μm change in wool mean fibre diameter in terms of consumers’ assessment, and measured values, of comfort and handle of knitwear.

In the absence of data on the evaluation of ultrafine wool knitwear for next-to-skin wear (mass per unit area of < 220 g/m²) this work aimed to examine the role of mean fibre diameter and fibre staple crimp frequency (fibre curvature) on the comfort and handle of a set of 4 wool single jersey knitted fabrics made from ultrafine wool (< 16 μm). It also aimed to determine if mean fibre diameter influenced fabric mass/unit area of the ultrafine wool fabrics by evaluating single jersey knitted fabrics before and after relaxation in water.
Materials and methods

Fabric manufacture and testing

As it was not possible to obtain sufficient quantities of single jersey fabric made from < 16 μm wool it was necessary to buy greasy wool and produce the fabric and garments. This approach provided control over the fibre, yarn, fabric and garment characteristics and was therefore able to ensure the fabrics and garments were similar to those used previously in garment wearer trials and so have greater relevance for comparisons with our previous research results.

Four lots of wools originating from the New England area of New South Wales, Australia, each 100 kg, were purchased in 2010. Two of the lots had a mean fibre diameter of 13.8 μm and the other two lots 15.0 μm. At each diameter one lot was traditional high staple crimp wool while the other lot was considered by the wool selling brokers and growers to represent Merino wools of lower staple crimp structure and style.

A suite of measurements were carried out at the Australian Wool Testing Authority Ltd, North Melbourne, Victoria, Australia to characterise the greasy wools. Measurements include: mean fibre diameter; fibre diameter distribution including coefficient of variation (CVD, %) and fibre curvature (°/mm) were measured using 10 separate 1,000 snippet measurements by the Laserscan [30]. To ensure we could compare later results when wool top was tested, all Laserscan measurements were done in an isopropyl alcohol solution. Staple length and strength were measured on the Atlas machine [31]. Resistance to compression was measured on scoured wool [32]. Staple crimp frequency measurements (crimps/cm) were made on 20 staples randomly sampled from the wool display random grab samples taken from each of the lots. The staple crimp frequency was determined using a hand held, graduated crimp gauge with a scale representing 2-8 crimps/cm with 1-increment steps.
The wool was scoured, combed and spun in the Biella region of Italy; knitted on a 24 gauge machine; dyed and finished; and converted into long sleeve T shirts. The companies were experienced in processing such ultrafine wool and were able to ensure there was no cross-contamination from these individual small lots or with other wools they were processing. After the wools were scoured and combed they were again tested to determine the measured properties. The tests were conducted to ensure the top was of appropriate quality for spinning and to see if the fibre differences resulted in a difference in measured top characteristics. The yarn was then spun into a 1/40 Nm yarn with 500 tpm. The yarn count was selected to match the vast majority of the fabrics already used in the wearer trials and development of the Wool ComfortMeter [17,22]. The low to mid-range twist level of 500 tpm (α=79) was selected to allow the possibility of single fibre properties to express themselves within the yarn and therefore fabric characteristics without unduly effecting the knitting performance and fabric durability properties, especially pilling. The yarn was tested for yarn evenness (U%), yarn thick places (+50%), yarn thin places (-50%), neps (+200%) and hairiness (Uster units) were measured (Uster Tester 3 v2.50 (Zellweger Uster AG, Uster, Switzerland). Yarn breaking force, elongation and tenacity were determined using a Uster Tensorapid 3 v.6.1 with an IWTO flat clamp.

The yarn was knitted into a single jersey structure on a 24 gauge circular knitting machine using positive feed to a worsted cover factor of 1.28 (3.34 mm loop length) using the definition of cover factor as: CF = 1/(L × √Nw), where loop length L is inches and Nw is worsted count. These yarn and fabric construction specifications were used to match previous fabrics manufactured using wools of diameters ranging from 17.5 μm to 21.2 μm for wearer trials [33]. These specifications usually resulted in a fabric mass per unit area of between 160 and 180 g/m².
The fabrics were then dyed together in a single jet dyeing machine and given a decatised finish to reduce the relaxation shrinkage to an acceptable level. Long sleeved T shirts were then manufactured using the same pattern as used for all garments in the wearer trials and the garments were evaluated in the DAFWA wearer trials for prickle [17,33].

The wearer trial protocol has been described [33] but briefly garments of standard sizes and known construction were evaluated under a set protocol in a range of controlled environments by about 25 participants per garment. The test protocol consisted of 5 sequential stages: 1, pre-trial acclimatisation in an office environment (23°C and 45% RH) when no measurements were made; 2, 15 minutes with the test garment being worn in an office environment (23°C and 45% RH); 3, 15 minutes in hot environment (40°C, 24% RH); 4, hot active session in hot environment (40°C, 24% RH), where the participant spent 15 minutes on a treadmill; and 5, return to office environment, where the final 15 minutes was spent. Wearers scored prickle sensations of garments on a scale of 1 to 9. The assessment responses were: 1, not detected; 2, just detected/threshold; 3, slightly detected; 5, moderately detected; 7, very detected; 9, extremely detected. By the use of linked garments between each trial, a weighted wearer prickle assessment could be determined [33].

The fabrics were tested using the draft test methods for the Wool ComfortMeter [34], Wool HandleMeter [35] and fabric mass per unit area was determined. The Wool HandleMeter is based on the ring test whereby a circular fabric sample is pushed or pulled through a circular orifice. It has been found that the withdrawal force is related to KESF handle values [36] and the peak force is positively correlated with fabric mass per unit area, bending rigidity and bending hysteresis and in good agreement with subjective ranking of fabrics [37]. Pan and Yen [38] related the force by displacement curves to 16 fabric mechanical properties measured by the KESF system. The development of the PhabrOmeter Fabric Evaluation System (NU Cybertek Inc., Davis, CA, USA) [39], allowed the automatic performance of the
ring test on a variety of fibrous sheets [40] and the determination of the “relative hand value”, “drape index” and “wrinkle recovery rate”. The Wool HandleMeter uses the same principle of pushing a circular fabric sample through a nozzle as the Phabrometer, however, the associated force by displacement curve is quantified by a set of 8 objective parameters and these are used to predict a set of 7 bipolar handle attributes suitable to describe light weight single jersey knitted fabrics (Table 1). The limited application of the Wool HandleMeter to light weight single jersey fabrics means that the handle attributes predicted (Table 1) can be in the form of specific, easy to understand and very descriptive terms. These parameters were calibrated using a panel of fabric evaluation experts [29]. For each Wool HandleMeter parameter the predicted value varies between 1 and 10, with 1 associated with the first term for the parameter and 10 being associated with the last term for the parameter. The mean fibre diameter was again determined using one of the garments as the source of fibres for the measurement using the same method as for raw wool [30]. Treatment effects for fibre diameter (diameter: 13 µm; 15 µm) and for fibre staple crimp frequency (crimp: low; high) were determined using ANOVA [41] and the $p$-values for significant effects are provided.

**Table 1 Description of each Wool HandleMeter parameter [derived from 42]**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Descriptor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean/Hairy</td>
<td>Surface property: 1, extremely clean; 10, brushed/raised (very hairy).</td>
</tr>
<tr>
<td>Rough/Smooth</td>
<td>Surface property: 1, very very rough; 10, extremely smooth.</td>
</tr>
<tr>
<td>Hard/Soft</td>
<td>Flexural property: 1, extremely hard; 10, extremely soft.</td>
</tr>
<tr>
<td>Light/Heavy</td>
<td>Bulk property: 1, extremely light; 10 extremely heavy.</td>
</tr>
<tr>
<td>Overall Handle</td>
<td>Overall fabric handle: 1, poor; 10, excellent.</td>
</tr>
</tbody>
</table>

**Effect of mean fibre diameter on fabric mass per unit area**

A subsequent experiment was performed to determine if mean fibre diameter influenced fabric mass/unit area of the ultrafine wool fabrics. Nine 1/40Nm yarns were spun using wool with mean fibre diameters ranging from 13.7 to 23.7 µm. Yarns were knitted on the same 24 gauge circular knitting machine with all machine adjustments left the same and with the same
stitch length of 3.34 mm as used for the ultrafine fabrics. The fabrics had their mass/unit area determined after 24 hours conditioning and then again after relaxation for one hour in a static 40°C soak in water, followed by drying and reconditioning [43]. Multiple linear regression analysis was used to relate the effects of relaxation, when used as a factor (Control, before relaxation or, After relaxation) and mean fibre diameter to fabric mass per unit area [41].

**Results and discussion**

The mean measured attributes of the different raw wools are provided in Table 2. The differences based on the mean fibre diameter were confirmed. The differences based on the staple crimp frequency were confirmed with wools W 1 and W 3, both considered to be high crimp wools, averaging more staple crimps/cm ($p$-value = 0.036). However, while these wools had higher fibre curvature than W 2 and W 4, the high variance in fibre curvature and low replication resulted in no significant differences in fibre curvature ($p$-value = 0.11). There were no differences in other raw wool characteristics between the wools of different diameter or staple crimp (Table 2).

The mean measured attributes of the tops made from the different wools are provided in Table 3. The differences in mean fibre diameter were still present for the 13 and 15 μm wools. The wool tops were still well matched for the other measured parameters in the diameter and staple crimp treatments. There were small differences in the variability of fibre length in the W 2 top compared with its partner W 1. This can be seen in the CV% Hauteur, percentage of fibres less than 40 mm and the longest 5% of fibres. The differences between the fibre curvature of the tops for the different staple crimp frequency wools now averaged 8 °/mm, less than the differences between the fibre curvature of the raw wools of 11 °/mm (Table 2) and these differences were still not significantly different. The reduction in the difference of the fibre curvature between wools of different raw fibre curvature during top making as has been observed elsewhere [12]. Top making resulted in a 13 °/mm increase in
fibre curvature of the 13 \( \mu \)m wools compared with the 15 \( \mu \)m wools (\( p \)-value = 0.058) suggesting the fibre removed in the noil was less crimped than fibre which remained in the top.

Table 2 Measurements taken on the raw wool and the \( p \)-value for treatment effects (abbreviation: ns, \( p \)-value > 0.05)

<table>
<thead>
<tr>
<th>Wool</th>
<th>Mean fibre diameter ( \mu )m</th>
<th>Staple crimp frequency /cm (sd)</th>
<th>CVD %</th>
<th>Fibre curvature (^{\circ}/\text{mm} )</th>
<th>Staple length mm</th>
<th>Staple strength N/ktx</th>
<th>Resistance to compression kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>W 1</td>
<td>13.7</td>
<td>7.05 (0.60)</td>
<td>18</td>
<td>124</td>
<td>74</td>
<td>38</td>
<td>7.0</td>
</tr>
<tr>
<td>W 2</td>
<td>13.8</td>
<td>5.50 (0.61)</td>
<td>18</td>
<td>117</td>
<td>80</td>
<td>37</td>
<td>6.8</td>
</tr>
<tr>
<td>W 3</td>
<td>14.8</td>
<td>6.55 (0.69)</td>
<td>17</td>
<td>132</td>
<td>69</td>
<td>42</td>
<td>8.7</td>
</tr>
<tr>
<td>W 4</td>
<td>15.1</td>
<td>5.25 (0.64)</td>
<td>16</td>
<td>117</td>
<td>69</td>
<td>38</td>
<td>7.1</td>
</tr>
</tbody>
</table>

Treatment effects \( p \)-value

| Diameter | 0.017 | ns | ns | ns | ns | ns | ns | ns |
| Crimp    | ns    | 0.036 | ns | ns | ns | ns | ns | ns |

Table 3 Measurements taken on the wool tops and the \( p \)-value for treatment effects (abbreviation: ns, \( p \)-value > 0.05)

<table>
<thead>
<tr>
<th>Wool</th>
<th>Mean fibre diameter, ( \mu )m</th>
<th>Fibre curvature, (^{\circ}/\text{mm} )</th>
<th>CVD, %</th>
<th>Hauteur, mm</th>
<th>CV Hauteur, %</th>
<th>% fibres &lt; 40 mm</th>
<th>Longest 5% of fibres, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>W 1</td>
<td>13.7</td>
<td>138</td>
<td>19.0</td>
<td>69.4</td>
<td>37</td>
<td>18</td>
<td>109</td>
</tr>
<tr>
<td>W 2</td>
<td>13.8</td>
<td>130</td>
<td>20.2</td>
<td>69.1</td>
<td>44</td>
<td>22</td>
<td>117</td>
</tr>
<tr>
<td>W 3</td>
<td>14.9</td>
<td>128</td>
<td>20.3</td>
<td>70.7</td>
<td>34</td>
<td>15</td>
<td>108</td>
</tr>
<tr>
<td>W 4</td>
<td>15.1</td>
<td>120</td>
<td>20.8</td>
<td>69.1</td>
<td>36</td>
<td>16</td>
<td>108</td>
</tr>
</tbody>
</table>

Treatment effects \( p \)-value

| Diameter | 0.008 | ns | ns | ns | ns | ns | ns |
| Crimp    | ns    | ns | ns | ns | ns | ns | ns |

The yarn properties are summarised in Table 4. Yarn strength and elongation, in conjunction with evenness, thin places and thick places, are important indicators of knitting performance and efficiency. The results show the yarn’s attributes were generally not affected by diameter or staple crimp. The yarns had excellent strength and evenness compared with yarns made from coarser wools. The results suggest there were differences in the yarn evenness where the yarns made from the finer wools are more even (8.6 versus 9.7 U%). This is not surprising as
more fibres in the yarn cross section will improve yarn evenness [44]. The yarns made from the lower curvature wools exhibited greater hairiness (6.1 versus 5.8 Uster units), a finding reported previously for lower curvature wool yarns [45]. The fabrics were knitted with no noticeable difference in the knitting performance as commented upon by the knitter. This comment is reasonable given the similar characteristics measured on the yarns.

Table 4 Mean strength, elongation, evenness and hairiness of 1/40 Nm yarns with 500 tpm produced from wools of different raw wool properties by commercial processors and the p-value for treatment effects (abbreviation: ns, p-value > 0.05)

<table>
<thead>
<tr>
<th>Wool</th>
<th>Yarn strength, cN</th>
<th>Yarn elongation, %</th>
<th>Yarn evenness, U %</th>
<th>Yarn thin places, -50%km</th>
<th>Yarn thick places, +50%km</th>
<th>Neps, +200%/km</th>
<th>Yarn hairiness (Uster units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W 1</td>
<td>188</td>
<td>27</td>
<td>8.8</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>5.7</td>
</tr>
<tr>
<td>W 2</td>
<td>195</td>
<td>30</td>
<td>8.4</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>6.0</td>
</tr>
<tr>
<td>W 3</td>
<td>193</td>
<td>26</td>
<td>9.7</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>5.9</td>
</tr>
<tr>
<td>W 4</td>
<td>179</td>
<td>28</td>
<td>9.8</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>6.2</td>
</tr>
</tbody>
</table>

Treatment effects p-value

<table>
<thead>
<tr>
<th>Diameter</th>
<th>ns</th>
<th>ns</th>
<th>0.031</th>
<th>ns</th>
<th>ns</th>
<th>ns</th>
<th>ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crimp</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
</tbody>
</table>

These results show that the differences in the greasy wool characteristics have translated into small, and mostly not significant differences in some yarn characteristics important in subsequent processing. The results from the Wool ComfortMeter, Wool HandleMeter and the wearer trial show that there were no significant effects that can be attributed to wool staple crimp in the ultrafine wools (Table 5). The results also show that the Wool ComfortMeter values were affected by mean fibre diameter but that the effect of diameter on the Wearer Trial prickle assessment was not significant (p-value = 0.095). The Wool ComfortMeter values demonstrate a continuing decrease in the presence of fibres capable of eliciting a prickle response as mean fibre diameter is reduced even in these ultrafine wool fabrics, but the wearer trial ratings have reached their lower limit of sensitivity. Wool ComfortMeter values of less than 100 means that the average wearer is not able to feel any prickle sensation and the wearer trial prickle assessment value of less than 2 confirms that [17,22].
The difference in Wool HandleMeter values are much closer to the critical difference for the test but show no consistent trend. The small changes in Wool HandleMeter values are consistent with recent work [47] that showed the handle parameters of wool single jersey knitted fabrics were influenced by the fabric properties of thickness, density and mass per unit area and fibre properties had a negligible effect.

These results could mean that we have reached the highest levels of next-to-skin comfort that can be measured both subjectively and objectively.

Table 5 Wearer trail prickle assessment, Wool ComfortMeter and selected Wool HandleMeter measurements of the fabrics (lower numbers associated with first term, higher numbers associated with last term). The p-values for treatment effects are shown (abbreviation: ns, p-value > 0.05)

<table>
<thead>
<tr>
<th>Wool</th>
<th>Prickle score</th>
<th>Wool ComfortMeter</th>
<th>Wool Handle Meter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Hard/Soft Rough/Smooth Clean/Hairy Light/Heavy Overall</td>
</tr>
<tr>
<td>W 1</td>
<td>1.5</td>
<td>35</td>
<td>5.3 4.0           5.8 5.9 4.6</td>
</tr>
<tr>
<td>W 2</td>
<td>1.5</td>
<td>49</td>
<td>5.6 4.3           5.9 5.6 4.9</td>
</tr>
<tr>
<td>W 3</td>
<td>1.6</td>
<td>82</td>
<td>5.6 4.6           5.5 5.7 5.2</td>
</tr>
<tr>
<td>W 4</td>
<td>1.7</td>
<td>87</td>
<td>5.5 4.2           5.9 5.5 4.8</td>
</tr>
</tbody>
</table>

Treatment effects p-value

<table>
<thead>
<tr>
<th>Diameter</th>
<th>Crimp</th>
<th>ns</th>
<th>ns</th>
<th>ns</th>
<th>ns</th>
<th>ns</th>
</tr>
</thead>
</table>

An interesting observation was made when the fabric mass/unit area was related to the mean fibre diameter of the wool fibres. It was noticed that the fabrics made from ultrafine wools had greater mass/unit area than expected on the basis of many other fabrics produced for the wearer trials using the same yarn count. There are four main variables in single jersey knitting which will determine the fabric mass/unit area. They are yarn count, machine gauge, stitch length and yarn twist [46]. As all these variables were kept constant during manufacture we expected to see a fabric of consistent mass/unit area produced regardless of the mean fibre diameter. We therefore determined if wool mean fibre diameter also influenced final fabric mass/unit area by conducting the further study using 9 yarns. An effect of mean fibre diameter could be expressed through variations in yarn mechanical properties.
due to higher inter-fibre friction, and this in turn could be due to the greater number of fibres in the cross section of yarns made from finer fibres. The best linear model for predicting fabric mass per unit area before relaxation is shown in Equation 1, and after relaxation in water in Equation 2. Standard errors are shown in brackets.

Fabric mass per unit area before relaxation (g/m$^2$) = 175.9 (5.31) – 2.2 (0.28) × mean fibre diameter (1)

Fabric mass per unit area after relaxation (g/m$^2$) = 175.9 (5.31) + 25.7 (1.87) – 2.2 (0.28) × mean fibre diameter (2)

When these two equations are expressed as a single model the multiple correlation coefficient was 0.97, the percentage of variance accounted for was 93.4% and the residual SD was 3.97. The major share of variation, 68.9% of total variation could be attributed to differences due to relaxation ($p <0.001$). The addition of the term for mean fibre diameter ($p<0.001$) accounted for a further 24.5% of variance. Mean fibre diameter alone accounted for 16.4% of the variance. There was no evidence of a curvilinear response to mean fibre diameter as the inclusion of the quadratic term (mean fibre diameter$^2$) was not significant ($p = 0.18$). The raw and predicted results for fabric mass per unit area are shown in Figure 1. The fabric mass/unit area increased after relaxation and declined as the mean fibre diameter of the yarn increased.
Figure 1 The relationships between mean fibre diameter of wool fabrics and the resultant mass per unit area (g/m²) for fabrics before relaxation (■) and after relaxation (□) with the predicted responses shown as parallel straight lines.

This result was unexpected and could not be linked to other yarn measurements of count, twist, strength and elongation in which all yarn results fell within tight limits and showed no relationship with fabric mass per unit area. Munden described the impact of variations in stitch length, and noted that variations in yarn tension, yarn friction and moisture content may alter stitch length by up to 40% [46]. However in our case stitch length was controlled. It is possible that the fabrics composed of the finer fibres, which are more flexible (less rigid) than coarser fibres, can move more easily into a fully relaxed state and the resulting fabric having a higher mass per unit area. An alternative explanation is that fabrics composed of finer wool have greater felting shrinkage compared with fabrics composed of coarser wool, but this does not explain why this effect has occurred before relaxation given that the predicted responses for the relaxed and unrelaxed fabrics were parallel (Figure 1, Equations 1, 2).
CONCLUSION

The results from the Wool ComfortMeter, the Wool HandleMeter and the wearer trials show that the single jersey fabrics manufactured from ultrafine wools have resulted in a benchmark fabric for handle and comfort.

The results also show that:

- we have potentially reached the lowest levels of skin irritation that can be measured both subjectively and objectively;
- wool staple crimp frequency (crimp) provided no discernible effects upon wearer and laboratory assessments of prickle nor handle assessment within the narrow range investigated;
- fabrics made from 1/40Nm yarns made from wools that differ in their mean fibre diameter will produce fabrics of different relaxed mass/unit area when other specifications are held constant; and
- a number of yarn characteristics such as strength, elongation, thin places, thick places, and hairiness were not affected by the differences in fibre diameter or staple crimp frequency evaluated in the present work but finer wool produced more even yarns.

ACKNOWLEDGEMENTS

The authors thank Sig. Piergiorgio Minazio, Woolmark Company, Biella Italy, for locating the processing companies and ensuring all processing went according to plan.

The authors also thank the staff at the Design for Comfort Laboratory, Perth.

References


