Fibre-Based Components Determining Handle/Skin Comfort in Fabrics Made from Dehaired and Non Dehaired Llama Fibre

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Abstract

The term 'handle' has to do with how soft a fabric feels when placed against the skin. It is also a fundamental attribute of Comfort. This paper shows that fibre-based determinants from yarns and fabrics can be used as predictors of comfort differences between dehaired and non dehaired Llama fibres. The differences the panellists can detect when comparing dehaired and non dehaired variables are: overall fibre diameter (1.01 µm in yarn and 1.55 µm in fabric surface); fibre diameter coefficient of variation (5.31% in yarn); fibres >30 µm (7.66% in yarn and fabric surface); coarse fibres by weight (3.23% in yarn and 4.57% in fabric surface); coarse fibre mean diameter (3.5 µm in yarn and 3.2 µm in fabric surface). These differences are explained by the diameter of the lattice medulated fibres; non medulated fibre diameter (on fabric surface); and lattice medulated fibre frequency (on fabric surface). These differences can be taken as a cut-off for each fibre based variable when discriminating objectionable from desirable fibres during dehairing.

Keywords: Llama fibre, objectionable fibres, threshold, medulla, cuticular scales

Introduction

At present the term 'handle' refers to how soft a fabric feels against the skin. This term embodies several attributes: skin comfort (or itching), stiffness, smoothness, softness and bulkiness. Prickle (*pruritus*) is the key characteristic commercially demanded for next-to-skin wool garments, thus it applies mainly for garments used in contact with the skin (directly or indirectly). This characteristic has become increasingly significant (De Boos et al., 2002). Prickle, as part of overall handle, is one of the first considerations the potential wearer takes into account (Paek, 1979; Mack Swinbur et al., 1995). Each attribute of fabric handle has to do with the intrinsic properties of the raw fibre, the yarn spun from it and the resulting fabric or garment (Hunter et al., 1983; Frank et al., 2012a).

Most Llama fibre must be dehaired to reduce or eliminate the adverse prickle effect (Frank et al., 2011; Frank et al., 2012b). The dehairing process modifies the average diameter of the protruding fibres on the yarn/fabric surface, biased by its relation to the whole yarn or raw fibre (Frank et al., 2011; Frank et al., 2012a). This bias should be hypothetically greater than that effect detected by Naylor (1992a) for wool. The effect of dehairing on the frequency of certain fibres seems evident in the case of certain fibre type ends when seen as long loose fibre ends considerably more abundant than short ones (De Boos et al., 2002, Frank et al., 2007; Frank et al., 2011).

The dehairing process, as most textile processes, has a shortening effect on Llama fibre, concomitant with an increase in the industrialization cost. Dehairing experiences with Camel hair showed that the process can result in a shorter fibre due to fibre breakage. Fibre breakage increases with the number of dehairing runs given to the material. At the same time, the amount of runs has a profound effect on the coarse hair content of the down (Talebpour, 2008). Therefore, the fewer runs the material is given, the longer the average length of the dehaired fibre. The number of runs is finally decided on the basis of the percentage of objectionable fibres that can commercially be left in the down. This cut-off threshold is established by the trader or industrialist ordering the dehairing. In wool and nylon fabrics, the frequency of objectionable >30 μm fibres detected by some of the panellists on fabrics is around or less than 3% (Naylor & Phillips, 1997).

The fibre attributes affecting the comfort in a superfine wool/cashmere blend fabric are the average fibre diameter and the frequency of medulated fibre (Naebe & McGregor, 2013). Since the medulla determines the fibre type and is, as well, associated with fibre diameter, it can be hypothesized that it could be a good indicator, or determinant, of fabric comfort. This can also be demonstrated with some other external characteristics of the fibre such as cuticle scale morphology and/or attributes measured as a scale index (Singh Mahal et al., 1951). Hausman (1920) found that the cuticle scales varied according to the cross section of the fibre, and that the cross section is closely related to the medulla/fibre type (Villarroel, 1959; Frank et al., 2007). Also, when fabrics were treated with silicones, the fibre/fibre friction effect was diminished with an important concomitant prickle reduction (Naylor et al., 1992). It is evident that the effect of the silicone treatment changed the cuticle scales characteristics.

The objective of this paper was to identify fibre-based determinants of yarn/fabrics that can be readily used as reliable predictor variables of the differences in handle/skin comfort when comparing dehaired and non dehaired Llama fibres.

Materials and Methods

Data Collection

Fabric Samples:

The Llama fibre fabrics used here were the same used to describe the characteristics identifying fleece types (Frank et al., 2007). They, therefore, allowed to test the effect of the dehairing process on fabric quality (Frank et al., 2011) while, at the same time, allowing to discriminate the physical effects of dehairing on the attributes of the fibres used to produce the yarns (Frank et al., 2012b).

Laboratory Processing of Samples:

Each fabric sample had a dimension of approximately 10 x 10 cm. Each sample was intensely humidified in a humidifying cabinet (>85% RH through micro drops) and then deep-frozen on a freezing microtome equipped with a Peltier cell device (-45º C). From the deeply frozen fabric surfaces fibres were cut at a distance approximately 30 μm apart with a razor blade mounted on a pre-surgical razor device, until the shaving showed some cut fibre loops that indicated that a non protruding fibre had been sectioned. The fibre ends protruding from the surface of the fabric show a net cross section and the sections of the fibre loops exhibit a bezel cut. When were observed, under the magnifying glass, some fibres with both ends with a bevel cut or with parts sectioned along the fibre, the shaving was interrupted. Then each section set of the razor blade (seen as ice particles) was stored on a Petri box without top and dried in a forced air drying oven and then stabilized at 65% R.H. and 20ºC.

Determination of Fibre-Based Variables

Whole Yarn:

Following a zigzag path from each fabric sample the yarn was extracted and then untwisted to allow the fibres to be dissected on a velvet board. Snips were cut with a fibre microtome (WIRA fibrotome) from each group of fibres (objectionable and desirable fibres), previously weighed in a precision balance (near 0.1 mg). The snips were then mounted on slides in glycerol-water and then observed and measured under a micro-projector to 500 X.

Surface Fabric:

The fibre sections, were placed on a stuffed velvet board and grouped as objectionable and desirable fibres, and then weighed on precision balance (near 0.1 mg) and afterwards mounted on slides with glycerol-water to study and measure them under a 500x micro-projector. If some looped fibre was detected, it was discarded from the measurement.

The number of fibres measured per sample (in yarn and fabric surface) was determined by an *n* providing a 95% confidence limit (CL), thus allowing for a range not greater that 5% units of the mean fibre diameter of each sample (Snedecor and Cochran, 1967). This procedure was originally used by Martinez et al. (1997) and by Frank et al. (2011).

Variable Descriptions

1st Class Variables: Those fibre-based variables that are routinely measured or otherwise arise from the dissection on the velvet board (macroscopic variables):

OWFD (μm): overall weighted fibre diameter.
FDCV (%): fibre diameter coefficient of variation
EF (μm): effective fineness defined in accordance with the following equation:
$EF=OWFD*\sqrt{(1+5(FDCV/100)^2)}$ (Anderson, 1976)
>30μm (%): frequency of fibres coarser than 30 μm
FFMD (%): fine desirable fibre mean diameter.
CFMD (μm): coarse objectionable fibre mean diameter.
FFW (%): fine desirable fibre weight/total fibre weight*100
CrFW (%): coarse objectionable fibre weight/total fibre weight*100

2nd class variables: Those fibre variables determined under micro-projector to identify the fibre type on the basis of medulla type:

CoFD (μm): continuous medulated fibre diameter
CoFF (%): continuous medulated fibre frequency
FFD (μm): fragmented medulated fibre diameter
FFF (%): fragmented fibre frequency
IFD (μm): interrupted medulated fibre diameter
IFF (%): interrupted medulated fibre frequency
LFD (μm): lattice medulated fibre diameter
LFF (%): lattice medulated fibre frequency
NMFD (μm): non medulated fibre diameter
NMFF (%): non medulated fibre frequency

Individual Fibre Analysis

Yarn Dissection to Classify Fibre Types:

Four samples were selected and described for each properly defined style. Approximately 10-20 fibres were separated for each spontaneously identified fibre type. The identification of the fibres was based on length, thickness, type of waviness, and the presence or absence of observable brightness. The samples were washed in standard laboratory conditions and dissected on a blue velvet cloth in the case of white fibres and on cream velvet for pigmented, under a 'daylight' standard 60 watt bulb illumination.

Once the fibre types were separated from the studied staple according to their macroscopic aspect, incidental observations were added to improve the accuracy of the classification: types of medulla (Wildman, 1955, Appleyard, 1978, Frank, 2001). Shapes, sizes and scale types were determined using the technique of cuticle embedding in a semi-gelatinized slide ("cast") (Wildman, 1955; Appleyard, 1978). The "cast" was observed with a phase contrast microscope, the diameter of the fibre was measured and the number of scales per 100 linear (n) microns counted (Singh Mahal, et al., 1951) and n then divided by 100 (n/100) to obtain the anteroposterior scale length. The scale height at the distal scale edge cannot be measured by optical microscopy; therefore, the measurement was performed with a scanning electron microscope (SEM) according to the methodology used by Phan et al. (1988), and adjusted to the requirements of a Camelid fibre according to Tonin et al. (1996).
The following variables were recorded for the individual fibre analysis:

Categorical Variables:

Medulla Types and Fibre Types (Frank et al., 2007).
Continuous variables:
FW: fibre weight (mg)
FD: fibre diameter (μm)

FL: fibre length (cm)
MD/FD: medulla diameter/fibre diameter ratio.
SN: number of linear scales in a 100 µm fibre length.
HI: height of linear scale or scale length [(100/SN)/FD] (Hausman Index) (Hausman, 1930)
SkI: (height of linear scale)^3/FD (Skinkle Index)
ScHei: height of the individual edge profile of the scale under SEM.
Wave 2: type of wave or crimp (6 scores) (Frank et al., 2007).

Bl: buckling load as: $Bl=\frac{\pi^3 * YM*DF^4}{31.9 * LF^2}$

were: YM: Young's Modulus at 5.4 GPa for desirable fibre (<37 µm) and 3.2 GPa for objectionable fibres (>37.5 µm) (King, 1967).

The FW was established by weighing a group of precisely counted fibres (n: 10 -20) on a balance accurate to 0.1 mg with a minimum weighing capacity of 10 mg. The fibres were conditioned at 65% R.H. and the total weight of the fibre group divided by the number of weighed fibres counted (Frank, 2001).

Statistical Evaluation

Comfort Evaluations:

The wearer panellist (n=18) established a rank for each pair of samples (dehaired vs. non dehaired): 1 for the less prickly and 2 for the more prickly. The Rank Sum for each sample was calculated by adding the ranks of the overall combinations for all judges and replications. This rank was used as a prickle scale with increasing prickliness corresponding to an increase in the value of the Comfort Rank Sum. The Wilcoxon test for paired samples (non-parametric equivalent of the paired samples t-test) was used to compare each sample pair: sample 1 (dehaired) vs. sample 2 (non dehaired) (Altman, 1991). A list of significant (p<0.05) variables between pairs for each of the 18 panellist was obtained. A Spearman correlation was calculated between the Comfort score and the 1st and 2nd variables.

ANOVA and among mean comparisons:

One-way ANOVA was performed for the medulla variables and fibre type comparisons. When it was found to be significant (p<0.05), a multiple comparisons by Least Significant Difference (LSD) was performed with the SSPS 17 version software.

Dependent t-test for paired samples:

The pairs for the dehaired (sample 1) and non dehaired (sample 2) sample scores, or between pairs of samples scores, were matched into meaningful groups (for example, drawn from the same significance difference obtained from the panellist). The average (X_D) and standard deviation (s_D) of those differences were used in the equation. The constant μ_0 is non-zero if it's required to test whether the average of the difference is significantly different from μ_0. The degree of freedom used is n−1 (Zimmerman, 1997). The one-tailed t test was chosen for this comparison, because the paired sample t-test does not have the normality and homogeneity of variance assumptions as the two-sample t-test, however, it does assume that the differences are normally distributed (Blair & Higgins, 1980).

Derivation of critical threshold t score (p <0.05):

The need to obtain the minimum value (cut-off) of *t* score significant to at least 5% for the difference in value between pairs of dehaired sample *vs.* non dehaired samples, led to the use of:

$$t=\frac{\overline{x}_D - \mu_0}{\frac{s_D}{\sqrt{n}}} \rightarrow \overline{x}_D = t * \frac{s_D}{\sqrt{n}} \quad \text{Equation 1}$$

where it is assumed that $\mu_0=0$ and the *t* score lays at p<0.05 for the respective degree of freedom; X_D is the minimum average difference that is significant at 5% when compared in pairs for each dehaired sample against the corresponding non dehaired one of the pair.

Results and Discussion

Only fibre-based variables for Comfort were used, as the results reported in Frank et al. (2011) show that the correlations between preferred fabric samples and the handle components were established as high. Thus the degree of Preference is correlated with the degree of Comfort (r =0.91; R^2 =0.83, p<0.001) or 83% of the fabric variation. Preference is strongly explained by the variation in fabric Comfort. The data is consistent with that reported by De Boos et al. (2002) and slightly greater than that of Naylor & Phillips (1995). To simplify the task, Comfort was the only variable considered given the high correlation observed between the variables composing the overall handle.

Differences between Dehaired and Non Dehaired Fibres

The fibre-based variables compared by pairs shown in Table 1 try to explain the Comfort determinant differences detected by the panellists when comparing dehaired samples (D) with non-dehaired (ND) ones (Frank et al., 2011; Frank et al., 2012b). The fibre-based variables within the yarn that explain the differences between D and ND, coincide approximately with alpaca fibre dehairing results (Wang et al., 2008) and dromedary hair dehairing results (Msahli et al. , 2008). The first three variables: OWFD (µm), FDCV (%), EF (µm) and >30µm (%) express the same criteria, since CrFW reflects the coarse fibre content on the basis of weight/weight, and >30 µm together with FDCV and EF basically reflect as well the coarse fibre content when it exceeds 24% (Lunney, 1983). Apparently the differences detected by the panellists are basically explained by the 2nd class variables: LFD and IFF. With the lattice medulla the reason is evident, however, no explanation was found for the frequency of interrupted medullas case.

In contrast, in the case of the protruding fabric fibres, the significant variables do not coincide with those of the yarn. However, the differences between the yarn and the protruding fabric fibres were explained by the 1st class variables, mainly CrFW (50%) plus the more protruding fabric fibres than the ones found in the non dehaired yarn samples (ND). This is fundamentally reflected in the variables identified by the lattice medulla types, coinciding with the findings of Naylor (1992a) where coarse protruding fabric fibres are the ones responsible for the differences in prickle sensation. It also coincides with findings in superfine wool/cashmere blends (Naebe & McGregor, 2013). It must be emphasized that in both dehaired and non dehaired conditions the difference between yarn and fabric surface is always significantly high, and always higher than on fabric surface (Naylor, 1992a).

Table 1: Paired Difference and Percentage Difference between Dehaired and Non Dehaired Fibre, Compared within Whole Yarn and Fabric Surface, and Overall Difference between Yarn And Surface

Variables	Whole Yarn (Y)			Fabric Surface (S)			Overall Diff. between Y-S	
	Dehaired	Non dehaired	Diff[1]	Dehaired	Non dehaired	Diff	Dehaired	Non dehaired
1st class								
OWFD (µm)	24.16	25.11	-0.95*	27.44	28.45	-1.01*	-11.93***	-11.73***
FDCV (%)	26.36	33.42	-7.06 ***	29.69	30.75	-1.06 ^{ns}	-12.64**	8.01^{ns}
EF (µm)	28.11	31.61	*-3.5* **	32.96	35.08	-2.13 ^{ns}	-4.85***	-3.48*
>30µm (%)	22.59	32.56	*-9.97****	30.00	29.36	0.64 ^{ns}	-32.78*	9.82^{ns}
FFMD (%)	22.90	22.95	-0.05 ^{ns}	24.51	25.25	-0.74 *	-7.04***	-10.04***
CFMD (µm)	40.95	47.05	-6.1 ***	43.62	46.69	-3.07 **	-6.52***	0.77^{ns}
FFW (%)	92.36	89.36	3.0 ^{ns}	82.62	82.80	-0.18 ^{ns}	11.8***	7.92*
CrFW (%)	7.64	10.64	-3.0 ***	17.38	17.20	0.18 ^{ns}	-56.04***	-38.13**
2nd class								
CoFD (µm)	30.60	31.23	-0.63 ^{ns}	34. 03	34.88	-0.85 ^{ns}	-11.18***	-11.69***
FFD (µm)	21.86	22.11	-0.25 ^{ns}	24.87	25.23	-0.36 ^{ns}	-13.8***	-14.14***
LFD (µm)	45.29	54.32	-9.03***	50.96	53.60	*-2.64* ^{ns}	-11.14**	1.34^{ns}
IFD (µm)	24.95	24.89	0.06 ^{ns}	28.07	28.08	*-0.01* ^{ns}	-11.13***	-11.36***
NMFD (µm)	19.39	19.24	0.15 ^{ns}	21.03	21.87	*-0.84* **	-7.78***	-12.0***
CoFF (%)	23.68	23.25	0.43 ^{ns}	36.89	29.93	6.96 *	-35.8***	-22.3***
FFF (%)	26.10	24.47	1.63 ^{ns}	15.71	23.15	-7.44**	66.13***	5.7^{ns}
LFF (%)	3.99	3.78	0.21 ^{ns}	1.72	3.55	-1.83***	132.2***	6.35^{ns}
IFF (%)	14.75	16.39	-1.64**	10.10	10.94	-0.84^{ns}	45.97*	49.8^{ns}
NMFF (%)	32.90	31.12	1.78 ^{ns}	35.58	32.43	3.15 ^{ns}	-7.5^{ns}	-4.02^{ns}

References: FDCV: fibre diameter coefficient of variation; CoFD: continuous medulated fibre diameter; >30µm: frequency of fibres coarser than 30 µm; FFD: fragmented medulated fibre diameter; FFMD: fine fiber mean diameter; CFMD: coarse fiber mean diameter; LFD: lattice medulated fiber diameter; IFD: interrupted medulated fibre diameter; OWFD: overall weighted fiber diameter; NMFD: non medulated fibre diameter; FFW: fine fiber weight; CFW: coarse fiber weight; CoFF: continuous medulated fibre frequency; FFF: fragmented fibre frequency; LFF: lattice medulated fiber frequency; IFF: interrupted medulated fibre frequency; NMFF: non medulated fibre frequency.

1 : Diff : dehaired - non dehaired in actual units

Table 2 shows the Spearman correlation between fibre-based variables and the Comfort Sum of Rank, after segregating the significant from the non significant samples to the paired Wilcoxon test data, even when separated by variables measured within the whole yarn and the fabric surface.

Within the group of samples where Comfort was not significant for between panellist's comparisons, only the yarn variables correlated significantly with Comfort, while fabric surface doesn't show a significant relationship. In contrast, in those fabrics significantly separated by group by the wearer panellists, a significant Spearman correlation coefficient is obtained between almost all fibre-based variables and Comfort, confirming once again a finding already detected in Table 1. Some differences between paired means comparisons and the Spearman correlation have to do with the different nature of the data used.

The 2nd Class variables COFD, LFF and FFD show as well a highly significant correlation with the 1st Class variables, highlighting them as good indicators of the difference between dehaired and non dehaired yarns and fabric surfaces. The Fibre Ends variable is not used here as it is based on the existing strong correlation between wool fibre diameter and fibre length (Naylor, 1992a), but in the case of the fibre used for this work this correlation is $r=0.56$ ($p<0.05$), which does not seem high enough to be used as a predictor of end fibre diameter.

Table 2: Spearman Correlations Between Fibre-Based Variables and Fabric Comfort within Whole Yarn and Fabric Surface, Within Samples That Result Significant or Not Significant Under Panelist Test

	Non-signicant pair by Panel Comfort				Signicant pair by Panel Comfort			
Variables	Yarn	sig	Surface	sig	Yarn	sig	Surface	sig
1st class								
OWFD	-0.46	**	-0.23	ns	-0.28	ns	-0.51	*
FDCV	-0.02	ns	-0.24	ns	-0.21	ns	-0.03	ns
EF (µm)	-0.37	*	-0.22	ns	-0.17	ns	-0.27	ns
>30µm	-0.53	***	-0.11	ns	-0.45	*	-0.53	**
FFMD	-0.35	*	-0.12	ns	-0.22	ns	-0.38	*
CFMD	-0.07	ns	-0.19	ns	-0.26	ns	0.01	ns
FFW	0.47	***	0.20	ns	0.61	**	0.58	**
CrFW	-0.47	***	-0.21	ns	-0.63	**	-0.61	**
2nd class								
CoFD	-0.44	**	-0.24	ns	-0.66	**	-0.71	***
FFD	-0.22	ns	-0.19	ns	-0.50	*	-0.41	*
LFD	-0.24	ns	-0.11	ns	0.11	ns	-0.16	ns
IFD	-0.26	ns	-0.43	*	-0.16	ns	-0.43	*
NMFD	-0.29	ns	-0.16	ns	0.07	ns	-0.39	*
CoFF	-0.32	*	0.09	ns	0.13	ns	-0.10	ns
FFF	0.54	***	0.04	ns	0.31	ns	0.06	ns
LFF	0.03	ns	-0.08	ns	-0.81	***	-0.62	***
IFF	0.07	ns	0.02	ns	-0.17	ns	-0.47	*
NMFF	-0.04	ns	-0.15	ns	-0.10	ns	0.01	ns

References: FDCV: fibre diameter coefficient of variation; CoFD: continuous medulated fibre diameter; >30µm: frequency of fibres coarser than 30 µm; FFD: fragmented medulated fibre diameter; FFMD: fine fiber mean diameter; CFMD: coarse fiber mean diameter; LFD: lattice medulated fiber diameter; IFD: interrupted medulated fibre diameter; OWFD: overall weighted fiber diameter; NMFD: non medulated fibre diameter; FFW: fine fiber weight; CFW: coarse fiber weight; CoFF: continuous medulated fibre frequency; FFF: fragmented fibre frequency; LFF: lattice medulated fiber frequency; IFF: interrupted medulated fibre frequency; NMFF: non medulated fibre frequency.

Association between fibre-based determinants and the dehairing effect

Relationship with Medulla Types

The medulla is proposed as a fibre structure, real or virtual, associated with the fibre diameter, fibre density, fibre weight (Scobie et al., 1998) and the type of cuticle scales (Hausman, 1920; Singh Mahal et al., 1951); however, the range of diameters of medulated and non-medulated fibres overlap (Orwin, 1979). On Figure 1, mean comparisons between types of medulla in relation to fibre weight, fibre diameter, medulla diameter/fibre ratio, the number of scales along the fibre length ratio, Hausman and Skinkle scale indexes, the buckling loading and fibre length, are depicted.

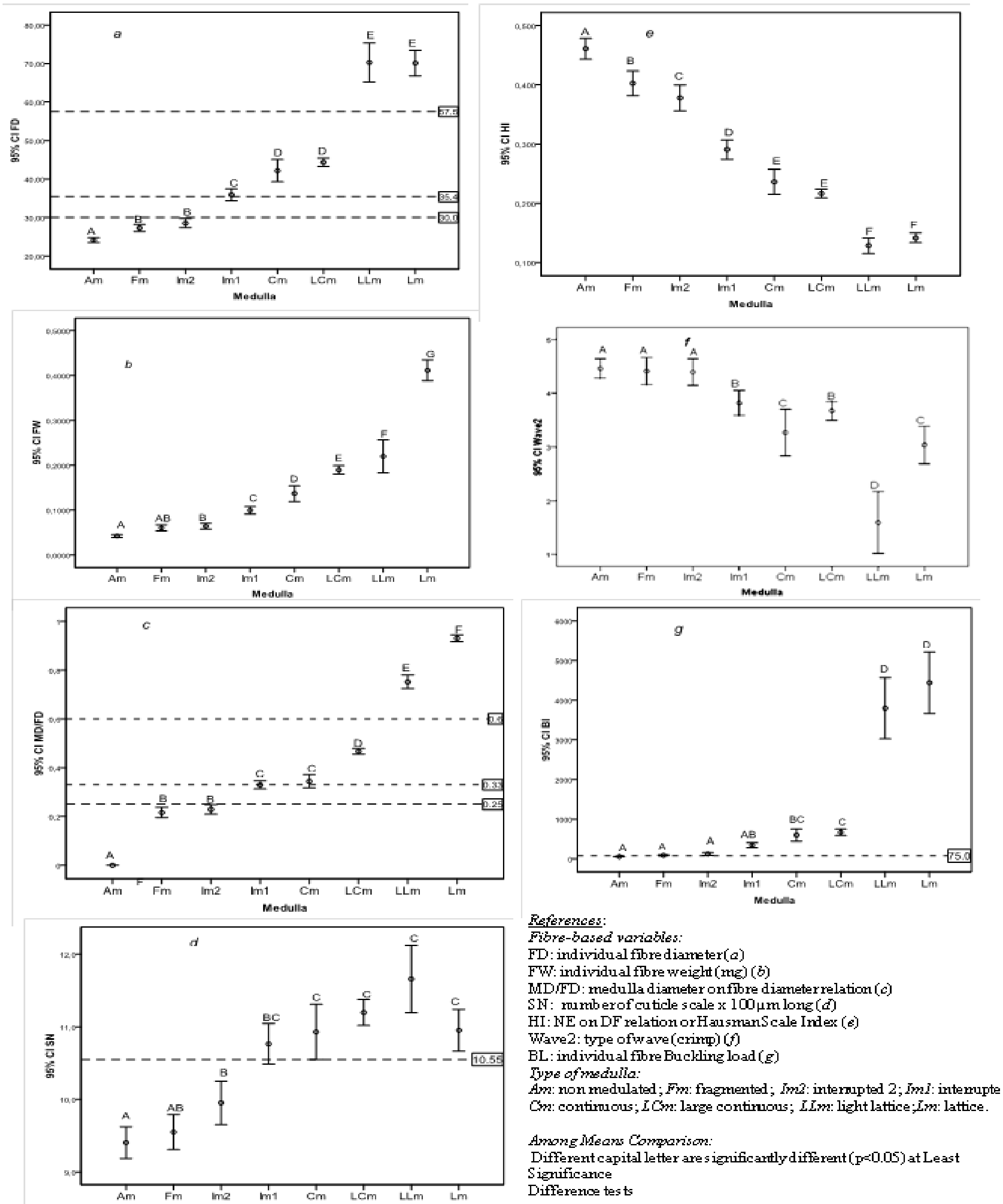


Figure 1: Confidence interval (95% CI) of fibre-based determinants on type of medulla.

In graph *a* of Figure 1, the horizontal dotted lines shows the fibre diameters greater than 30 µm above which the fibres result in skin itching (Naylor, 1992b). The dotted line to 35.4 µm shows the diameter at which the fibres change appearance (by changes in the cuticle scales), corresponding to the inflection point (´break point´) of the curve relating the potential law of the Hausman index (HI) against average diameter. In this case the IM1 has to do with this diameter while the fibres identified by a continuous non interrupted medulla lay above. The dotted line at 57.5 µm separate only two fibre types with strong lattice medulla and are statistically significant ($p < 0.05$) above that diameter.

Figure 3 (above) shows the frequency distribution of FD by medulla types, thus allowing to observe the clear location of >30 µm fibres.

The diameter variance explained by the medulla do not coincide with a work on Australian Alpacas were only an increase in FD for 10% of the variance accounted by medulation fibre frequency was detected in wool/cashmere blends (Naebe & McGregor, 2013), probably because the OFDA measuring the opacity grade and not the medulla type as in this work.

In Figure 1 b one can see that the Am, Fm and IM2 types are considerably lighter (FW) than the fibres having a significant medulla, within which the differences are statistically significant ($p <0.05$), even between the two types of lattice medulla (Llm and Lm). The appearance of the clear lattice type indicates that no liquid medium (glycerine) entered the medulla (Llm). Something similar could be happening with the intense humidification (conditioning) (> 80 % RH) they have undergone. Moreover the weight (FW) depends primarily on the diameter (FD), because the correlation between diameter and fibre weight is $r=0.75$ ($p<0.01$; $R2=56\%$), while the correlation between fibre length and fibre weight is only $r=0.17$ ($p<0.05$; $R2=3\%$). Therefore, much of the fibre weight depends on the fibre diameter, except as noted for Llm and Lm (not significant among themselves in diameter), but significantly ($p <0.05$) different in FW. Difference in FW between fibre types can clearly explain the different dehairing capacity (Algae & Megel, 1992).

In the Figure 1 c (MD/FD ratio) the dotted line at the 0.25 value corresponds to fibres having <30 um diameter. The value of 0.33 corresponds to the fibre diameter >35.4 um line, the fibres detected as changing the visual appearance (objectionable), in this case only the large continuous medulla fibres (LCM) appear above this value. The other horizontal line is the 0.6 MD/FD, theoretically identifying the difference between medulated fibres and medulated kemp fibres as compared to wool and mohair (Hunter, 1993). In this case, only the two different lattice types of medulla remain clearly above this value.

Thus in the graph *a* (FD) and the graph *c* (MD/FD), the CI (95%) shows a close dispersion of the values within each type of medulla, this is not consistent with studies done with mohair fibres, where the dispersion of FD and MD/FD ratios is much wider (Hunter et al., 2013).

Figure 1 *d* shows that SN differentiation is not as prominent as in the case of other fibre-based variables. At the same time, statistically significant differences ($p <0.05$) are found between Am, Fm against Im2 (higher SN). Im2 shows an intermediate situation against the other medulla types that do not differ significantly from each other ($p>0 .05$). The values of SN (Am, Fm and Im2) coincide with those reported for alpaca, camel, cashmere and mohair, while being considerably lower (about half) than those for most wools (Wortman et al., 1988). They are not coincident with those reported for South American Camelids by Valbonesi et al. (2010). The SN differences between fibres types were clearly demonstrated by Frank (2001). The SN differences between fibre types, however, coincide with Am, Fm, and maybe even with Im2 fibre types belonging to the undercoat of wild and/or mixed-wool species, as well as other types of medulla fibres attached to the outercoat, including the so called kemp fibres (similar to Llm and Lm) (Singh Mahal et al., 1951).

This situation changes significantly when using the Hausman index that relates the SN/FD as plotted in Figure 1 *e*. In this case the significant differences between fibre types are almost absolute, not only in the case of the two lattices differences, but also in all other present medulla. Fibres <30 μm have an above 0.34 HI (upper dashed line), while the Am, Fm and Im2 types lay above that level (in 92% of the cases). The other interrupted horizontal line (0.28) marks the level corresponding to 35.4 μm in FD as the breaking point identified by a curve fitted to a potential law model that relates HI to FD. Above the 0.34 HI there is no increase despite the increase in diameter, therefore, the HI (SN/FD) does not increase significantly. Something similar happens with the other scale index (Skinkle index) used in this work. This shows behaviour so similar to HI, therefore, has not been included in Figure 1.

In the Figure 1 *f* the distinction is not as clear as with the other fibre-based variables since it is an approximate measurement of a discrete variables (score 1-6). However this perfectly separates Am, Fm and Im2 (similar waves) of Im1 (slightly different waves). The same occurs with common continuous and continuous large medullas. The Clear lattice type is predominantly a type of wave 1-2, while the dark lattice type a rather kind of wave 3 (more wavy), both significant at mean comparison ($p<0.05$). Here it must be clarified that the two wave types clearly differ in fleece types (DC, IC, SC, Hl and L) (Frank et al., 2007) and, therefore, they may disrupt the fleece type effect on the graph *f*.

Figure 1 *g* shows a clearly marked difference in stiffness as determined by the diameter of slightly and non-medulated fibres present at the boundary (Bl=75 mgf), which is the limit at which a single fibre of 2 mm length can stimulate a skin receptor (Naylor, 1992b). All other fibre types stimulate the skin receptors. A clearly marked difference appears in the case of lattice medullas. This was even the case when different Young's modulus were used for both the finer and coarser fibres, according to findings with mohair (King, 1967).

In Figure 1, the graphs of fibre lengths (FL) relative to medulla types are not included as no statistically significant ($p > 0.05$) differences were obtained. The relationship between FL and medulla types is heavily modified by the fleece types (Frank et al., 2007).

Relationship with Defined Fibre Types

Figure 2 contains the plotted fibre-based determinants in relation to the fibre types spontaneously identified when dissecting a fleece staple on a velvet board. A study shows that the more efficient dehairing of cashmere is associated to the following attributes: white colour; longer raw cashmere; greater fibre curvature; lower vegetable matter; normal length guard hair and absence of visible matting (McGregor & Butler, 2008). Here the 6 fibre types are defined by length, fineness, crimp and brightness (Frank et al., 2007).

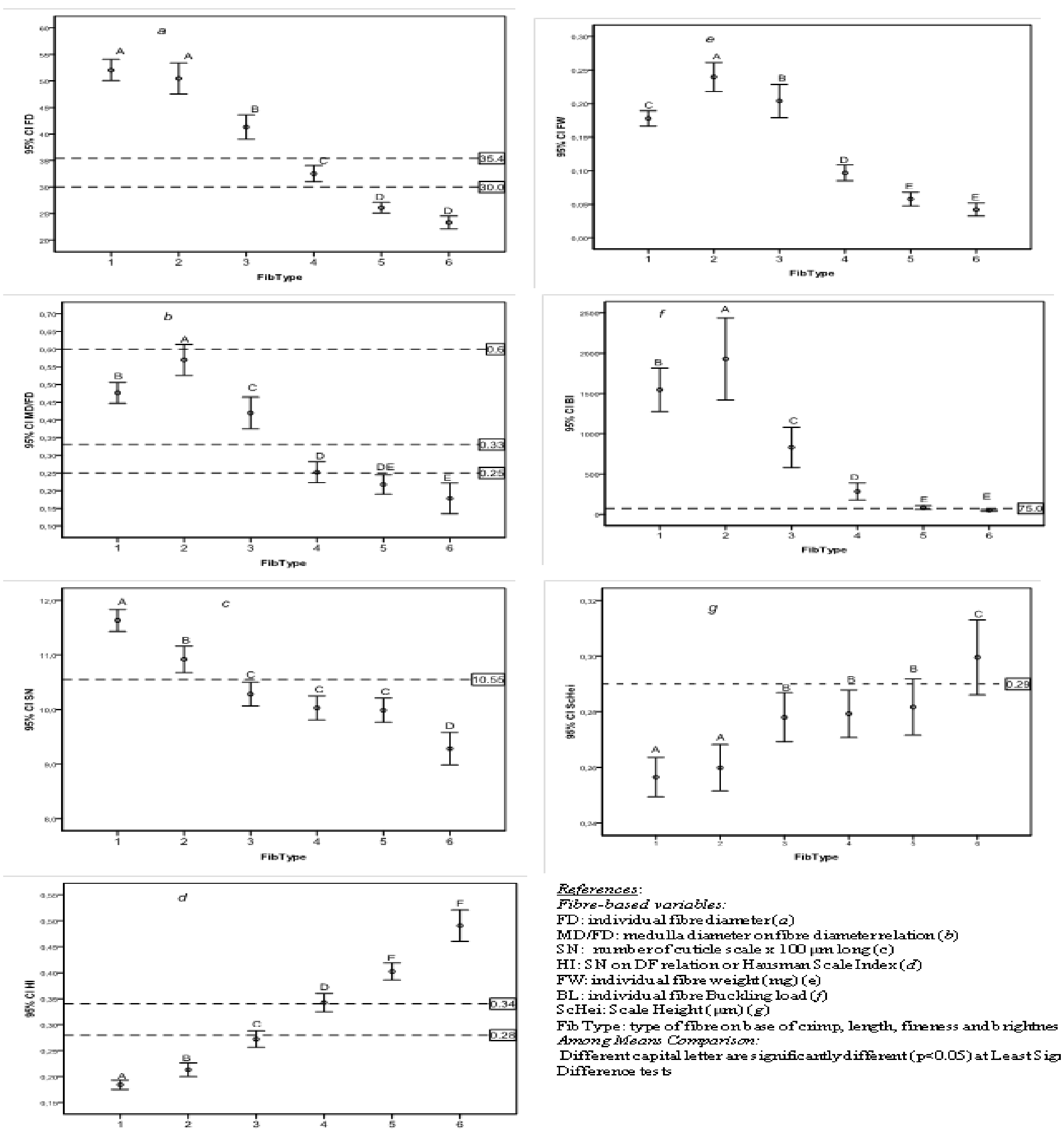


Figure 2: Confidence interval (95% CI) of fibre-based determinants on type of fibre.

Figure 2 *a* clearly shows that the fibre types that are longer and straighter are also stronger, but not always either brighter or opaque. Figure 3 (below) shows the frequency distributions of FD by fibre types and the clear location of >30 µm fibres.

Figure 2 *b* verifies that the below MD/FD: 0.25 clearly belongs to type 6, while in the case of between type 4 and 5 no significant difference are observed (p> 0.05), but this is not the case of the three fibre types below MD/FD: 0.33 corresponding to a FD: 35 µm. This threshold arises from a linear regression of MD/FD on FD as shown by 63% of the fibres dissected for this study. However, despite what is commonly hypothesized, few fibre types reach MD/FD: 0.6, which is the relationship corresponding to fibres commonly identified as kemp (Hunter, 1993). Fibre type 2 lays on the edge of the FD distribution of this relationship, probably showing that this fibre type is nor present in the South American Camelids fleeces. In general, fibre types 1, 2 and 3 spontaneously identified are clearly separated from the remaining objectionable and non objectionable fibres. This corresponds in part with other studies with Mohair verifying the differences between objectionable and non objectionable fibres. Very few of the objectionable medulated fibres had a MD/FD below 0.4; the majority lay between approximately 0.5 and 0.8, while no objectionable fibres were found between 0.2 and 0.7. A 53% of the non objectionable fibres had an MD/FD greater than 0.5 and only 18% greater than 0.6. For the objectionable fibres, approximately, 22% of them had a MD/FD below 0.5; 5% had a MD/FD below 0.4; and 3% below 0.35 (Hunter et al., 2013). This comparison with the Mohair data can be done using the graph in Figure 1 *c*.

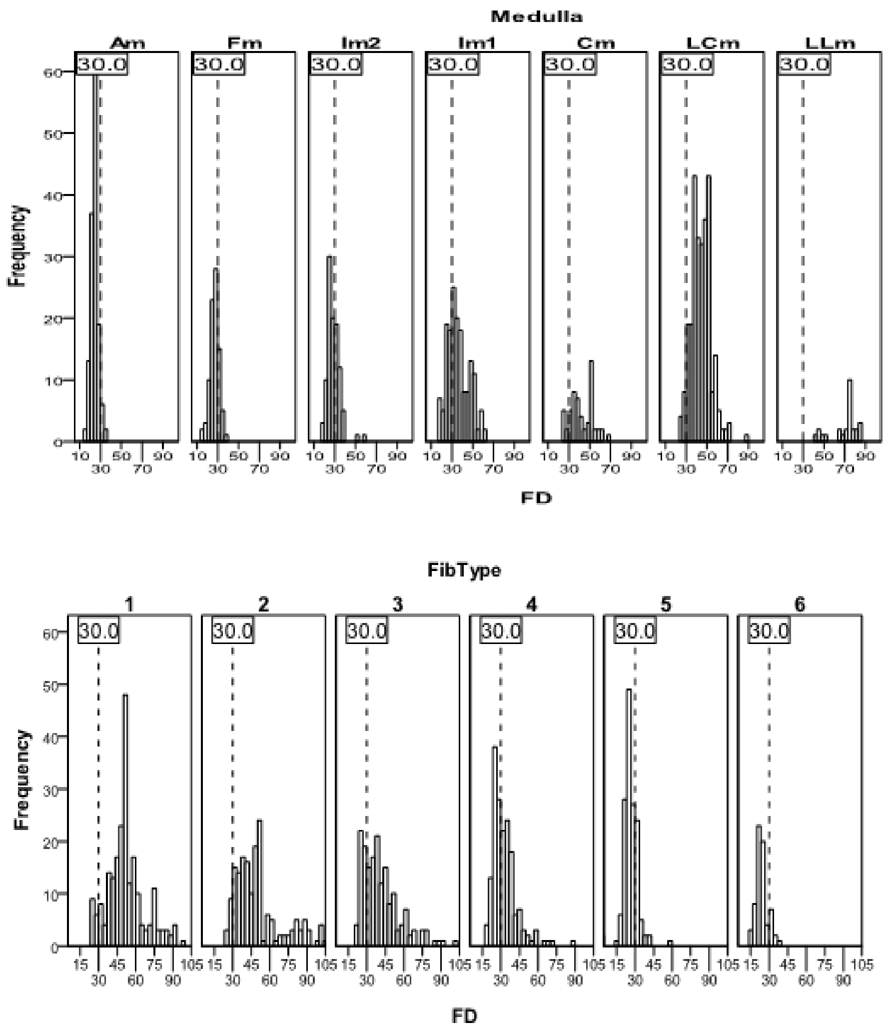
In Figure 2 *c* the ratio of total cuticle scales/100 µm ranges from 7 to 18 with a mean of 10.55 ± 3.2 cuticle scales. This average is similar to that of Merino wool (8.5 - 9), however in this case the range is (5.5 - 11) (Garner, 1967). In Australian Cashmere this range fluctuates between 7 -11 (Tucker et al., 1988). Types 5 and 6 have similar values than Cashmere and wool but it is evident that the thicker and straighter types exceed this value and are close to and above the maximum of the other fibres.

The Hausman index (HI) (graph *d* of Figure 2) shown a very clear statistical significant difference (p <0.05) among all fibre types. In Figure 1 *e*, above HI 0.34 shows the fibre types showing a larger quantity of cuticle scales related to FD, clearly demonstrating that the external appearance of these fibres can be deduced from the HI and can be clearly differentiate as fibre types. While progress has been made in the differentiation of fibres from various specialty fibre producing species (Wortman et al., 1988), no attempt has been carried out to identify fibre types within the same fleece and their relation to dehairing and its effect on the original fleece structure (Frank, 2001).

In Graph *e*, as in Figure 1 *b* the FW difference is mainly explained by the difference in FD and not by the length difference.

In Figure 2 *f* as in Figure 1 *g* the fibre-based determinant (Bl) is not measured but estimated from the respective equation (Naylor, 1992b). Only two fibre types are at the boundary of the 75 mgf required to stimulate a skin receptor and produce a prickle sensation.

Figure 2 *g*, includes a variable not used in Figure 1, the scale height (µm) at the edge of the scale. A SEM was used to measure it, but no high variability (low s.e.) was found. However, it presents statistically significant differences (p <0.05) which allow to separate fibre types in three groups. The maximum height reached by the scale height edge is below that of wool and is similar to that of other specialty fibres (Wortman et al., 1988). This fibre-based determinant does not reach significant differences (p>0.05) that would allow to differentiate fibres from Peruvian Alpaca Huacaya, Alpaca Suri and Llama Chaku (Valbonesi et al., 2010). This variable (Schei) shows a similar trend to HI while reversing the FD. When compared with SN, it can be seen that the greater number of scales correspond mostly to fibre types of smaller scale height. Like in the case of the HI, it appears to have a nonlinear behaviour with respect to FD. In Cashmere, Yang et al. (2005) found a Schei mean of 0.34 microns in FD below 18.0 µm and a Schei of 0.36 µm above this FD. This seems to contradict the trend observed in this work; however, it seems to be caused by technical problems of the Schei determinations of the Chinese institute.



Type of medulla:
Am: non medulated; *Fm*: fragmented; *Im2*: interrupted 2; *Im1*: interrupted 1; *Cm*: continuous; *LCm*: large continuous; *LLm*: light lattice; *Lm*: lattice.

Fib Type: type of fibre on base of crimp, length, fineness and brightness; score 1 - 6: from straighter and stronger to crimper and finer
Dotted line means: FD=30.0μm

Figure 3 : Distribution of FD within different type of fibre identify by type of medulla (above) or by visual morphological aspects (below).

Thresholds of Fibre-Based Determinants Obtained from between Dehaired and Non Dehaired Fibres

In Table 3, within the sample groups that were non significant to the panellist’s comparisons between dehaired and non dehaired samples, there are no significant differences ($p > 0.05$) at yarn-level and fabric surface. This occurs both within the first class and second class fibre-based variables. However, significant differences were found in both yarns and fabrics in those samples with significant results in the panellist’s Comfort score ($p < 0.05$).

Table 3: Differences between whole yarns and on fabric surface within-pair yarn and surface fibres differences for the variables that determine comfort in relation to the significant or no significant results of the evaluation by panelists. Determination of the critical score Student t (t crit) that reaches a least significant difference for p <0.05

Variables	Difference between Dehaired - Non Dehaired fibres (*t crit.*)[1]			
	Non-significant pair by Panel Comfort		Significant pair by Panel Comfort	
1st class	Yarn	Surface	Yarn	Surface
OWFD (µm)	-0.97 (*-1.34*)ns	0.71 (*-1.80*)ns	-1.36 (-1.01)**	-2.11 (*-1.55*)*
FDCV (%)	-0.66 (*-1.65*)ns	3.34 (*-1.02*)ns	-11.14 (*-5.31*)***	-3.86 (*-6.44*)ns
EF (µm)	-0.15 (*-2.05*)ns	1.06 (*-2.00*)ns	-5.62 (*-2.24*)***	-4.15 (*-4.65*)ns
>30µm (%)	-5.91 (*-7.74*)ns	8.55 (*-10.60*)ns	-12.54 (*-7.66*)**	-7.86 (*-7.67*)*
FFMD (µm)	2.77 (*-1.46*)ns	-0.43 (*-0.81*)ns	-1.85 (-1.18)**	-0.94 (*-0.70*)ns
CFMD (µm)	-9.34 (*-5.84*)*	-0.23 (*-0.47*)ns	-5.60 (-3.50)***	-5.00 (*-3.2*)**
FFW (%)	-6.15 (*3.71*)ns	-6.66 (*8.60*)ns	7.80 (3.23)***	4.68 (*4.57*)*
CFW (%)	6.15 (*-3.72*)ns	6.66 (*-8.60*)ns	-7.82 (-3.23)***	-4.68 (*-4.57*)*
2nd class				
CoFD (µm)	-0.91 (*-1.57*)ns	0.68 (*-2.24*)ns	-0.45 (*-1.23*)ns	-1.84 (*-0.98*)**
FFD (µm)	-0.76 (*-0.88*)ns	-0.27 (*-0.49*)ns	0.07 (*0.70*)ns	-0.41 (*-0.70*)ns
LFD (µm)	-0.35 (*-2.20*)ns	5.17 (*-3.38*)ns	-14.6 (*-8.20*)**	-7.60 (*-6.50*)*
IFD (µm)	-0.25 (*-0.87*)ns	0.11 (*1.36*)ns	0.26 (*0.68*)ns	-0.08 (*-1.15*)ns
NMFD (µm)	-0.78 (*-0.67*)ns	-0.92 (*-1.15*)ns	0.62 (*-0.67*)ns	-0.8 (*-0.67*)*
CoFF (%)	1.61 (*7.08*)ns	14.89 (*-12.13*)*	-0.32 (*-3.78*)ns	1.55 (*-6.81*)ns
FFF (%)	2.35 (*-3.90*)ns	-12.85 (*-7.80*)**	1.18 (*-4.02*)ns	-4.38 (*-8.01*)ns
LFF (%)	-2.58 (*-1.80*)*	-1.03 (*-0.79*)ns	1.99 (*-3.24*)ns	-2.40 (*-1.60*)*
IFF (%)	-2.5 (*-3.10*)ns	-6.33 (*-4.99*)*	-1.10 (*-2.37*)ns	2.23 (*7.60*)ns
NMFF (%)	1.13 (*7.27*)ns	5.31 (*11.42*)ns	2.20 (*3.99*)ns	3.00 (*10.36*)ns

References: FDCV: fibre diameter coefficient of variation; CoFD: continuous medulated fibre diameter; >30µm: frequency of fibres coarser than 30 µm; FFD: fragmented medulated fibre diameter; FFMD: fine fiber mean diameter; CFMD: coarse fiber mean diameter; LFD: lattice medulated fiber diameter; IFD: interrupted medulated fibre diameter; OWFD: overall weighted fiber diameter; NMFD: non medulated fibre diameter; FFW: fine fiber weight; CFW: coarse fiber weight; CoFF: continuous medulated fibre frequency; FFF : fragmented fibre frequency ; LFF : lattice medulated fiber frequency.; IFF: interrupted medulated fibre frequency; NMFF: non medulated fibre frequency.

1 : Equation 1

It is important here to emphasize that the FDCV results have a highly significant difference ($p<0.001$) for the yarn but are non significant for the fabric surface ($p>0.05$). The behaviour of the variables within the yarn and fabric surface shows a marked difference in both magnitude and significance between the dehaired and non dehaired samples. This is possibly caused by the greater variability of the measured variables of the shaved fibres from the surface or, as shown in Table 1, the samples shows a greater difference between the dehaired yarn and the non dehaired fabric surface. However, even if all variables coincide with respect to differences, the significance level is lower for the fabric surfaces.

Table 3 shows in brackets the critical level that must be reached in pair comparisons to achieve a statistical significance of at least 5% with a t Student test. It is notable that in this case the FDCV is around 5% (5.31%), EF around -2% (-2.24%) and OWFD about 1 µm (1.01 µm), indicating that the classic relationship regarding yarn uniformity with a 1 micron change in OWFD is equal to a 3-5% change in FDCV (Luney, 1983; Phillips, 1992).

There is as well a notable difference between the two measures of objectionable fibres: <30 um (frequencies) and CFW (w/w). This last measure (CFW) is considerably more precise and of a much lower magnitude (3.23 vs. 7.66%) needed to reach significance levels. This may be caused by the dehairing process breaking stronger than fine fibres (Msahli et al., 2008). When estimating the frequency under micro-projector, more strong fibres (snips) are counted.

When comparing dehaired and non dehaired pairs of the 1st Class variables, the differences can be mainly explained by the LFD variable (in yarns), where 14.6 µm shows a difference (p <0.01) and a critical score Student t (p <0.05) of 8.20 µm. This agrees in general with the work of Naylor & Phillips (1997), who found a difference of about 1.09% for <30 microns with children and adults. This difference when averaged gives approximately a Rank Sum of 77 which is the approximate level (75) Sum of ranking of the Friedman test, which was significant (p <0.05) in this work. For example, having more than 3% of fibres of <30 microns explains more than 90% of the uncomfortable fabric samples (Naylor & Phillips, 1997). Unexpectedly, this authors used two different measures for the fabric surface and the projecting fibre ends (% <30 microns and % <32 um respectively).

When comparing the findings in Table 3 with the results in Table 1, it is noteworthy that the contrast between yarn and surface (dehaired) are not totally reflected by the panellist's detections. This is probably due to the large variation of this measure.

However, the large difference between dehairing and non dehairing on yarns, agrees more with the differences the panellists can detect. This is reinforced by the Spearman correlation (Table 2) where, for example, CrFW, LFF (r = 0.63, p <0.01) and CrFW and its relationship to Comfort is r=-0.81 (p <0.001). This explains the differences the panellists detect in the fabric structure made from dehaired yarn in relation to the ones made from non dehaired yarn.

The relationship between bulk and comfort within the dehaired samples is r = 0.36 (p <0.05) (13% variance), and in the non dehaired samples r = 0.31 (p <0.05) (10%). The relationship between bulk and comfort is r = 0.28 (p <0.05) (8%) when the difference detected by the panellists is no significant, and r = 0.69 (p<0.001) (48% of variance) when it is significant, thus considerably higher, showing a strong relationship between bulk and comfort. When comparing the fibre-based variables of those samples detected as significant by the panellists within the yarn variables that are significantly correlated with bulk: FDCV (r = -0.31, p <0.05) (10%), % <30 um (r = -0.25, p <0.05) (6%) and CrFW (r = -0.30, p <0.05) (9%). When considering fabric surface, only CrFW (r = -0.26, p <0.05) (7%) has a low correlation. A relationship between softness and feltability was demonstrated for wool from diverse breeds. Feltability, measured as the diameter of a felt ball, is a bulk measure best predicted by mean fibre diameter, mean fibre curvature, scale height and scale length (Sumner, 2009). These results suggest that bulk, or resistance to compression, is one of the fibre-based variables that allows predicting Comfort positively (Madeley et al., 1998). This relationship is even more evident in the case of dehairing where the dehaired fibre show a higher curvature grade (Wang et al., 2008).

Conclusions

This paper was designed to identify fibre-based reliable determinants for yarn/fabrics that can serve as predictor variables of differences in handle/skin comfort between dehaired and non dehaired Llama fibres.

Changes in the macroscopically observed variables of dehaired and non dehaired fibres are usually measured in the laboratory. They can also be identified visually, as is in the case of medulla type fibres.

The threshold (cut-off) variables that panellists can detect when comparing dehaired and non dehaired fibres are: overall fibre diameter (1.01 µm in yarn and 1.55 µm in fabric surface), fibre diameter coefficient of variation (5.31% significative in yarn); fibres greater than 30 µm (7.66% in yarn and surface); coarse fibre by weight (3.23% in yarn and 4.57% in surface); coarse fibre mean diameter (3.5 µm in yarn and 3.2 µm in surface). These thresholds differences are explained mainly by: the lattice medulated fibre diameter (8.20 µm in yarn and 6.5 µm in fabric surface); non medulated fibre diameter (0.67 µm only in surface); and lattice medulated fibre frequency (1.6% only on fabric surface).

Differences detected by panellist between dehaired and non dehaired yarns and fabrics can be accounted as a minimal cut-off for each fibre-based variable when classifying fibres as objectionable or desirable fibres during the dehairing process.

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