The effect of ellipticity of wool fibres on handle assessment

A dissertation

submitted in partial fulfilment

of the requirement for the Degree of

Bachelor of Agricultural Science with Honours

at Lincoln University

by

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Lincoln University

2020

Abstract of a Dissertation submitted in partial fulfilment of the requirement for the Degree of Bachelor of Agricultural Science with Honours

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Wool is the most commonly used animal fibre, with clothing considered the high-value end-use. The mean fibre diameter (MFD) is the most important attribute in determining the value of a wool lot. In apparel, the handle of a fibre or fabric can influence consumer satisfaction, and therefore it is an important attribute to consider when producing wool fibre that is 'fit for purpose' and in demand by the textile industry. However, the handle assessment of wool fibre is subjective, and there is no objective measurement available. The MFD is known to account for some, but not all, of the variation in wool handle assessment. Consequently, there is a research focus on other fibre attributes that influence the handle of wool fibre, such as fibre shape. Wool fibres are not often circular in cross-section, and the degree of ellipticity of a wool fibre cross-section is called the fibre contour. This research was undertaken to see if fibre contour affected the fibre handle or the diameter distribution for Merino and NZ Romney ram wool samples. A greasy wool measurement system called FibreScan was used in the commercial testing of all the wool samples, but only the Merino wool samples were used in the handle assessment analysis. The results suggest there is a weak correlation between the contour ratio of a Merino wool sample and the handle assessment, but that it was not significant at a 95% confidence level. The MFD was the only variable included in a regression model that could be used to predict handle assessment of a fibre sample, and MFD explained 34% of the variation in handle assessment. Variation in the handle assessment by assessors highlighted the complexities of trying to produce an objective measurement to predict the handle of wool fibres for consumers. High contour ratios for NZ Romney ram wool samples produced fibre diameter distribution histograms that were bimodal in appearance, but the Merino samples did not. The absence of bimodality for Merino sample fibre diameter, suggests that as MFD decreases, it influences the visual distribution of fibre diameter around the mean. Overall, the results suggest that contour ratio has a minor effect on handle assessment of fine wool. Contour ratio affects the distribution of fibre diameter in strong wool samples but not fine wool, suggesting that MFD has an overriding effect on the results of this experiment.

Keywords: Wool fibre, mean fibre diameter, ellipticity, contour ratio, fibre diameter distribution, mean fibre curvature, handle, softness, comfort, electron microscopy.

ACKNOWLEDGEMENTS

Firstly, I owe my gratitude to Jon Hickford for supervising my honours project this year. Without your efforts of sourcing wool samples, getting them tested and ensuring they made it around Auckland during lockdown, this project would not have been possible.

To Catherine Hobbis, I am indebted to the work you put in to take the EM photos of all 34 wool samples. I am very grateful for the efforts that you went to, to ensure that the EM imaging was completed, even as Auckland bounced in and out of COVID alert levels! I would also like to thank you for offering to show me how the EM imaging was completed in the lab.

To John and Mary-Liz Sanders, thank you for supplying the Merino wool samples for this project. I hope that you have benefited from your involvement with this project as without your help it would never have got off the ground.

To Don Morrison and Pastoral Measurements Limited, thank you for taking the time to show me the FibreScan instrument and how it works. Thank you for testing all of the wool samples and for supplying the NZ Romney wool samples that were included in the project.

To Andrea Hogan, thank you for scouring all the wool samples and making sure they made their way around the country safely.

I owe a huge thanks to all the family, friends, flatmates and Lincoln University staff who willingly (or not!) completed the handle assessments for my wool samples, as without your contribution this project would not have been possible.

I also owe a huge thanks to Lily and Lauren, my two honours buddies, as without you to complain to, bounce ideas off or celebrate with, I’m not sure how I would have got this project done. I would also like to thank all my friends who I have made some awesome memories with over my time at Lincoln.

And lastly, I would like to thank my family who have supported me over my last four years at Lincoln University.

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1 INTRODUCTION

Wool is the most commonly used animal fibre in the textile industry and is experiencing renewed demand as it becomes popular for new end uses, such as next-to-skin clothing (Sneddon *et al.*, 2012b). It is valued by its 'fit for purpose', and the main wool trait that determines this is the mean fibre diameter (MFD) of a wool lot (Cottle and Baxter, 2015). Fine-wool, less than 21 µm, can be used in next-to-skin clothing, mid-micron wool is commonly used in outer-wear, and strong wool is used in insulation and carpet manufacturing. The International Wool Textile Organisation (IWTO) is responsible for upholding standards in the global wool textile industry. The IWTO produces test methods that have been used to standardise the testing of wool fibre around the globe.

In the clothing industry, the 'handle' of the fibres is the most important attribute as the consumer prefers clothing that is soft and pleasant against the skin (Sneddon *et al*., 2012b; Tester *et al*., 2015; Sun, 2018). Wool handle is inherently subjective in its assessment, as individuals have differences in what they consider pleasant or soft to touch. The wool industry has recognised the negative connotations that some consumers identify with wool, such as the itchy or 'prickly' sensations felt when wearing a woollen garment (Sneddon *et al.,* 2012a). A consumer's preference to purchasing an item is largely influenced by previous experience (Sneddon *et al*., 2012b), and if the garment does not satisfy the consumer's requirements, they are unlikely to purchase it again.

Literature suggests that the MFD and mean fibre curvature (MFC) of a wool sample can explain a proportion of the variation in the handle of wool products (Naylor *et al*., 1992; Cottle and Baxter, 2015; McGregor *et al*., 2015a). However, there is still variation in the handle assessment of wool samples when these characteristics are accounted for (Preston *et al.,* 2013), with this suggesting that there are other wool fibre characteristics that influence the assessment of handle. The MFD and MFC can be objectively measured using commercially available wool testing instruments, but one assumption made in the measurement of wool fibre with these instruments, is that wool is cylindrical and exhibits a circular cross-section (Cottle and Baxter, 2015). In reality, wool fibres are more commonly elliptical, and the degree of ellipticity is termed the 'contour' of a fibre (Lang, 1952; Mercer, 1954).

There is limited research exploring the influence of fibre ellipticity in wool or its relationship to handle. This project uses electron microscopy to analyse the shape of wool fibres obtained from 28 Merino ram and five NZ Romney ram wool samples. The handle of the Merino ram wool samples were subjectively assessed for handle by students and staff from Lincoln University, so as to enable a comparison of the mean contour ratio and the mean handle. The NZ Romney ram wool samples were tested to produce a fibre diameter distribution histogram, and this was compared with the mean contour ratio of the NZ Romney ram wool samples. Research into the effects of fibre characteristics on wool handle will provide insight for the industry on how to better produce wool that is ‘fit for purpose’.

The aim of this dissertation was to:

- Identify whether a difference in the mean contour ratio could be found between wool samples for the Merino and NZ Romney breeds using electron microscopy images.

- Identify whether untrained assessors could obtain a difference between the mean handle assessments of Merino wool samples.

- To ascertain whether there was a correlation between the mean contour ratio of a Merino wool sample and the mean handle assessment of that wool sample.

2 REVIEW OF THE LITERATURE

Introduction

Wool is a natural fibre that is used in many everyday textile products. The main value proposition of the wool fleece is its suitability for the desired end-use, whether that be for use in carpet, insulation, outerwear or next-to-skin clothing. Clothing is considered to be a high-value end-use.

One of the main attributes of wool influencing its 'fit for purpose' in clothing is the 'handle' of the wool or how the wool fibres are perceived when touched. This property can have lasting impressions on the consumer and in the past has led to the idea that wool is 'prickly' or itchy to wear (Sneddon *et al.,* 2012a; McGregor *et al.,* 2015b). However, advances in wool research and textile development mean there is now far less variation in the type of wool used in clothing, particularly in 'next-to-skin clothing'. One of the major advancements for the manufacture of next-to-skin apparel is a greater understanding of how the human body perceives prickle sensations, and how the MFD influences the ability of wool fibres to evoke a prickle sensation (Naylor *et al.,* 1992; Mahar *et al.,* 2013; McGregor *et al.,* 2015a; Naebe *et al.,* 2015). Consequently, the majority of next-to-skin wear is made from fine-wool, being that where the MFD is less than 21 µm (Cottle and Baxter, 2015).

The biggest obstacle to producing wool textiles that continuously meet individual consumer's requirements, for softness and comfort, is the assessment of 'handle' (Chen *et al.,* 2000). Currently, handle assessment is a subjective evaluation of the textural and compressional properties of the wool fibres or fabrics (Postle, 1990; Luible-Bär *et al.,* 2007). Research has been conducted to develop an objective measurement for fabric handle assessment (Kawabata and Niwa, 1991; Shishoo 2000; McGregor *et al.,* 2013), with less focus being placed on the development of an objective measurement for the handle properties of greasy wool. This emphasis is perhaps misplaced, as if the raw wool going into a fabric does not have a good handle, then the handle of the fabric itself may be compromised.

In raw greasy wool form, a handle assessment is conducted by a wool classer at shearing, but there is minimal consistency in the assessment methods used across the wool industry as a whole (Preston *et al.,* 2013). What-is-more, the development of objective measurements for both fabric, and greasy wool is hindered by the many conflicting ideas around which textural or compressional attributes are the most important in producing an instrument to objectively measure something that will ultimately be subjectively assessed by every individual contacting the finished woollen product (Sneddon 2012a).

There is some consensus in the literature that the MFD and MFC are two attributes that should be included in the objective measurement of wool handle (Liu *et al.,* 2004; McGregor *et al.,* 2014). However, there is little consensus in the literature as to what other attributes should be included in an objective measurement. Accordingly, there is increasing focus on fibre attributes that may be influencing the handle of a fibre, and in an attempt to increase the number of consumers that are satisfied with the handle of a woollen garment (McGregor *et al.,* 2014; McGregor and Quispe Peña, 2018).

Like all animal fibres, wool has a degree of non-uniformity that will always be present. One characteristic that underpins this non-uniformity is fibre shape. In commercial wool testing systems, wool fibres are assumed to be cylindrical (AWTA Limited, 1999), even though the literature suggests that wool fibres are more often elliptical (Lang, 1952; Anderson and Benson, 1953; Mercer, 1954). Variation in the shape of fibres is often ignored for ease of measurement, with the degree of error often assumed to be negligible if a large number of fibres are assessed (Cottle and Baxter, 2015). Given that fibre shape is a characteristic that can influence the compressional and textural behaviour of a fibre (McGregor and Lui, 2017), it may ultimately affect an individual's perception of wool handle as well.

Defining wool handle

Many descriptions have been constructed over time in an attempt to define the term 'handle' as a wool attribute. Research was being conducted as early as 1930 to establish a description for the handle of fabrics. Peirce (1930) defined handle as the combination of the sensations of "stiffness or limpness, hardness or softness, and roughness or smoothness" when one touched a fabric. However, subsequent research has used variations of this initial description. Hoffman and Beste (1951) defined fabric handle as, "the impressions which arise when fabrics are touched, squeezed, rubbed, or otherwise handled". Specific studies and organisations have related the term handle to a description of raw wool fibres. For example, the Australian Wool Testing Authority (AWTA) defines handle as, "the quality of fabric, yarn or fibre assessed by the reaction obtained from the sense of touch. Comprising the judgement of roughness, smoothness, harshness, pliability, thickness, softness, etc." Preston *et al.* (2014) described the handle of wool fibre as "the assessment of surface and structural features of the wool through a tactile evaluation". For this review, wool handle will be defined as the tactile assessment of the wool, relating to the smoothness, thickness, softness, stiffness and pliability, which aligns with the AWTA definition.

Use of subjective measurement in the textile industry

The textile industry is responsible for the development of yarn, cloth or clothing from raw materials. Traditionally, the textile industry has used subjective assessment to evaluate fibre and fabric by hand (Kawabata and Niwa, 1991; Behera and Hari, 1994; Luible-Bär *et al.,* 2007). However, the use of subjective assessment reduces the uniformity of the final product (Sülar and Okur, 2008). Botha and Hunter (2010) state that the world has moved away from subjective evaluation methods due to the demand for objective evaluation of products. With the increasing automation of the textile industry, the need for the objective assessment of fibre and fabric attributes has become increasingly important.

The development of new technology has enabled the textile industry to objectively measure many fibre and fabric attributes (Botha and Hunter, 2010), and the industry has recognised that to produce fabrics that consistently meet market demand, the use of objective measurements is required (Postle, 1990; Behera and Hari, 1994). There is increased demand for fibre and fabric by the textile industry when the product specifications are clearly defined within the supply chain (Cottle and Baxter, 2015). However, the appraisal of many fibre and fabric attributes has remained subjective as a consequence of the complexity of the action required to develop a quantitative value. The 'handle' of a fibre or fabric is one attribute that has remained a subjective evaluation.

Today's textile industry is global. Measurements that can be interpreted between countries and cultures are becoming increasingly important (Mahar *et al*., 2013). Objective specifications provide a common language between different positions along the supply chain in the textile industry (Cottle and Baxter, 2015). In contrast, a subjective appraisal can be influenced by cultural norms and language barriers (Mahar and Wang, 2010).

Fibre characteristics of importance to fibre handle

Fibre diameter

The most important attribute, when determining the value of wool, is the diameter of the fibres in a wool sample (Cottle and Baxter, 2015). Wool fibre diameter is measured in microns (one-millionth of a metre). The MFD is used to classify the fineness of wool, but three other measures can be used to describe fibre diameter distribution in a wool sample. These are:

a) The standard deviation of fibre diameter from the mean,

b) The coefficient of variation of fibre diameter (the standard deviation expressed as a percentage of the mean) and,

c) The coarse edge (the percentage of fibres within a sample that are greater than 30µm in diameter).

Diameter distribution histograms can also be created to visually illustrate the distribution of the individual fibre diameters in a sample, and it is a simple procedure to calculate MFD from a diameter distribution histogram (AWTA Limited, 1999).

In the apparel industry, the coarse edge of a wool sample can also be presented as the 'comfort factor'. However, comfort factor refers to the percentage of fibres that are less than 30µm (McGregor *et al.,* 2015a). A coarse edge greater than 5% (i.e. 5% of fibres over 30 µm) is considered undesirable in next-to-skin clothing, as it has been found to cause a prickle sensation when worn next to the skin. A prickle sensation is the result of the stimulation of cutaneous nerves in the skin (Naylor *et al*., 1997). Wool with an MFD greater than 21µm has an increased chance of having a coarse edge > 5% (McGregor *et al*., 2015a), and consequently, most wool used in next-to-skin clothing is less than 21 µm in MFD (Cottle and Baxter, 2015).

Wool fibres are considered to follow the phenomenon explained by 'Euler's Buckling Theory' when worn next to the skin (Naylor *et al*., 2004). 'Euler's Buckling Theory' states that the force (***F***) required to bend a fibre is proportional to the fourth power of the diameter (Naylor *et al.,* 1997) (Equation 1).

Equation 1 $$\boldsymbol{F} = \mathbf{E}\boldsymbol{d}^{\mathbf{4}}/\boldsymbol{l}^{\mathbf{2}}$$

Where,

E = the Young's Modulus

d = diameter of the fibre

l = the protruding length of the fibre

The Young's modulus is used to describe the elasticity of a tensile material and is related to the ability of that material to withstand changes in length due to compression or extension. When a fibre buckles, it will not stick into the skin and thus will be unable to evoke a prickle sensation. The larger the diameter of the wool, the greater the force it can sustain before it bends. As the diameter is to the fourth power, a small change in the diameter of the fibre can induce a substantial change in the force required to buckle a fibre. As the force required to buckle increases, a fibre is more likely to cause a prickle sensation against the skin (Wilson and Laing, 1995). The force that a fibre needs to withstand to cause a prickle sensation is 0.75 mN (Naylor *et al.,* 1992).

In fabric, the protruding length of the fibre from the material can influence the buckling behaviour of the fibre (Naebe *et al.,* 2015). If the length of the protruding fibre is short enough, even a fine fibre (≈ 10 µm), with the support of the surrounding fabric, may be capable of evoking a prickle sensation (Naebe *et al.,* 2015), as the support of the surrounding fibres increases the value of the Young's modulus of the fibre (Figure 2-1).

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Figure 2-1: The lines indicate the threshold at which a fibre will buckle when a fibre of a given diameter protrudes by a given length above the surface of the fabric. For fibre which the value falls below the line, the fibre exceeds the buckling threshold and will provoke a prickle sensation. The buckling load used is 0.74 mN, as determined by Euler's principle. The dotted line indicates Young's modulus of 5.4 GPa and the solid line indicates Young's modulus of 3.5 GPa.

The wool industry is limited in the number of methods it can use to quantify fibre fineness. Theoretically, there are four ways by which the fibre fineness can be obtained (Sommerville, 1998a). These are by assessing

1) The area of the fibre cross-section,

2) The width of the 2-dimensional projected image,

3) The area of the 2-dimensional projected image or,

4) The area of the fibre surface.

There are three instruments approved by the International Wool Textile Organisation (IWTO) that are commercially available to determine the diameter of wool fibres in a sample.

Fibre curvature

Curvature is the degrees of rotation around the middle axis of a fibre, expressed in degrees of rotation around the axis per millimetre of length (°/mm; IWTO units) (Fish *et al*., 1999). Like fibre diameter, fibre curvature is a three-dimensional characteristic, and it incorporates the curvature (bending) and torsion (twisting) of the fibre (Fish *et al*., 1999). The curvature of a wool fibre results from the variation in the type and the distribution of the different cortical cell types along the length of the fibre (Harland *et al*., 2018). In this respect, the paracortical cells are always situated on the inside of the curve of the fibre, whilst the orthocortical cells are located on the outside (Figure 2-2).

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Figure 2-2: The summary of findings using a model of intrinsic fibre curvature caused by the difference in length of paracortical and orthocortical cell types within a wool fibre. Sourced from Harland *et al.* (2018).

Harland *et al.* (2018) demonstrated that it was the difference in the relative length of paracortical and orthocortical cell types that caused the curvature for Merino wool fibres. The cells located on the outside of the curve of the fibre are longer than the cells located on the inside of the curve ($p < 0.01$) (Figure 2-3).

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Figure 2-3: Distribution of cell lengths from all cells located in 50 snippets (n = 344). Cells located on the inside of the fibre curve are shorter than cells located on the outside of the fibre curve ($P < 0.05$). Sourced from Harland *et al.* (2018).

The positioning of these cells within the fibre is the reason why, when unstressed, a fibre returns to a specific curvature (Figure 2-4). It is essentially an intrinsic fibre property.

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Figure 2-4: Diagrammatic representation of the curvature and formation of crimp, relative to the elliptical shape of the fibre. P: paracortex, O: orthocortex. Sourced from Mercer (1954).

The ‘waves’ along the length of a wool fibre are referred to as crimp. Wool crimp is the physical expression of the curvature of fibres within a staple, and fibre crimp and curvature are reported to be highly correlated characteristics ($r^2 = 0.77$) (Madeley and Postle, 1999) (Figure 2-5).

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Figure 2-5: Fibre curvature plotted against staple crimp frequency in Merino wool. Sourced from Madeley and Postle (1999).

Variation in fibre ‘curviness’ can influence the ability of a fibre in a garment to evoke a prickle sensation for the wearer, but there are contrasting ideas suggested in the literature as to how fibre curvature affects handle. Tester *et al*. (2015) suggested a highly curved fibre will buckle more easily at a higher MFD than a fibre with lower curvature, reducing the chance of prickle sensations from the fibre. However, Lui *et al.* (2004) suggested that a reduction in fibre curvature decreases the bending rigidity of a fibre, which ultimately produces a fibre that is easier to compress, and therefore will be perceived as softer.

Fibre shape

The cross-sectional shape of a wool fibre is unlikely to be circular and is more commonly elliptical (Lang, 1952; Mercer, 1954; Downes, 1975). The ratio between the major and minor axis is termed the ‘contour’ of the fibre (Lang, 1952; Anderson and Benson, 1953). A cylindrical fibre has a contour ratio of 1.0, and whilst there is a large range in the possible upper limit of contour, ratios for wool fibres don’t often exceed 2.0 (Lang, 1952). Anderson and Benson (1953) reported that the average contour value for wool fibres was 1.22 (CV = 13.3%) but found no correlation between MFD and contour ratio. They suggested that finer fibres tended to have lower contour ratios.

Wool fibres are a keratin protein fibre and are constructed from an internal cortex covered by an external cuticle layer (Popescu and Wortmann, 2010). The cuticle is constructed from four layers; the epicuticle, the a-layer, the exocuticle and the endocuticle (Figure 2-6).

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Figure 2-6: Layers of the cuticle of a wool fibre. EPI: epicuticle, a: the a-layer, EXO: exocuticle, ENDO: endocuticle. Adapted from Popescu and Wortmann (2010).

The internal cortex is constructed of cortical cells and the cell membrane complex (Popescu and Wortmann, 2010). Cortical cells are classified into three types, the paracortical, the orthocortical and the mesocortical cells (Deng *et al*., 2009) and are differentiated by the arrangement of microfibrils within the cell (Munro and Carnaby, 1999). Orthocortical cells have a whorl-like arrangement of microfibrils, whereas the microfibrils in paracortical cells run parallel along the length of the cell (Figure 2-7) (Munro and Carnaby, 1999).

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Figure 2-7: Image showing the microfibrillar cross-sectional structure in orthocortical cells (a), and paracortical cells (b), within a wool fibre. Sourced from Munro and Carnaby, 1999.

Mesocortical cells are suggested to be an intermediate type of cell (Orwin *et al.,* 1984). Mesocortical cells range in similarity between ortho- and para-cortical structure and are located between the ortho- and para-cortical cell types in the fibre.

The arrangement of the cortical cells is suggested to be a factor influencing the shape of the keratinised wool fibre (Deng *et al.,* 2009). Changes in the arrangement of cortical cells are suggested to be responsible for the variation in fibre diameter along its length (Deng *et al*., 2009). Cortical cell shape is influenced by changes in sheep nutrition (Hynd, 1994).

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Figure 2-8: Transmission electron microscope image showing a cross-section of a wool fibre. Adapted from CSIRO Science Image (n.d.).

The orthocortex and paracortex of the fibre have a bilateral arrangement within the fibre, with each cell type covering around half of the cross-sectional area (Figure 2-8) (Horio and Kondo, 1953; Harland *et al.,* 2018). Mercer (1954) found that in approximately 80% of elliptically shaped wool samples, the major diameter of the fibre cross-section was located between the surfaces of the ortho- and para-cortex regions of the fibre. The location of the major radii, relative to the distribution of the orthocortex and paracortex within the fibre, suggests that it is the relative distribution of these irregular shaped cortical cells that determines the cross-sectional shape of the fibre.

Commercial wool testing

The IWTO provides Test Methods for the analysis of wool lots around the world. There are four approved test methods available to analyse the diameter of wool fibres. These are the projection microscope (IWTO-8), SIROLAN^{TM}-LASERSCAN (LASERSCAN) (IWTO-12), Airflow (IWTO-28) and the Optical Fibre Diameter Analyser (OFDA) (IWTO-47). In New Zealand there is a fourth instrument, the FibreScan, which is commercially available for the analysis of the fibre diameter of wool samples. However, this technology is not currently approved by the IWTO.

The projection microscope was the original method used to determine the fibre diameter of wool. The fibres are cut into 'snippets' of 0.8-2.0 mm in length and positioned on a microscope slide. The magnified projection from the microscope allows for the width of individual snippets to be measured and therefore, the mean fibre diameter calculated. A minimum of 600 snippets must be measured, by two different people, from two different microscope slides to meet the IWTO test method standard. These specifications make the use of a projection microscope a labour-intensive and time-consuming task. Care must be taken so that each snippet, from a random sample, is only measured once.

The introduction of automated machines has reduced the use of the projection microscope in the commercial evaluation of fibre diameter. The AIRFLOW instrument is an indirect method of analysis, using the assumption that a bundle of wool fibre ends behaves similarly to the arrangement of a porous bed to calculate the MFD of a wool sample. The LASERSCAN and OFDA instruments are both direct methods of analysis (Cottle and Baxter, 2015), using the cross-sectional area of a fibre end to calculate the diameter of the fibre. The MFD calculated by each of these instruments is dependent on the assumption that fibres have a circular cross-section.

These automated instruments require calibration using measurements taken with the projection microscope method. The calibration procedure for AIRFLOW, LASERSCAN and OFDA uses measurements from eight 'calibration tops'. A calibration top is a uniform, blended wool sample, of which the MFD, the MFC and the coefficient of variation of fibre diameter of each top are known from projection microscope analysis. These calibration tops are used to ensure that all wool testing laboratories around the world have standardised measurements (NZWTA, 2018). The IWTO endorses Interwoollabs (International Association of Wool Textile Laboratories) to produce the calibration tops that meet the IH calibration standards (Baxter and Teasdale, 1992).

Wool fibres respond to the surrounding environment, so all testing must be completed after the wool has been exposed to a conditioning atmosphere. For wool testing, the conditioning atmosphere is set as an equilibrium temperature of 20 ± 2°C and a relative humidity of 65 ± 3%.

Airflow

The AIRFLOW instrument was the original mechanical method used to determine the fibre diameter of wool samples and was endorsed by the IWTO in 1975. The AIRFLOW method uses the known density of wool fibre to determine the fibre diameter. The process involves passing a current of air through a mass of fibres, compressed into a set volume. The ratio between the rate of flow of air through the wool sample and the pressure differential is primarily determined by the surface area of the wool sample. The method is an indirect method using equation two below. From equation two, it is possible to calculate the mean fibre diameter, based on the assumption that all wool fibres are a cylindrical shape and are of uniform density (Sommerville, 1998b).

Equation 2 $$\boldsymbol{Q = K_b \cdot \frac{A_c}{L_c} \cdot \frac{\varepsilon^3}{(1-\varepsilon)^2} \cdot \Delta P \cdot d^2}$$ (Sommerville, 1997)

Where,

Q = average flow (cm^3/sec)

K_b = the Konzey constant

A_c = the cross-sectional area of the fibre bed

L_c = the depth of the bed

ε = the porosity of the bed (free space/unit volume)

ΔP = the pressure differential across the bed

d = the mean diameter

The accuracy of the Airflow instrument is reduced when analysing wool samples that have a large coefficient of variation, medullated fibres or lamb's wool. These factors each alter the density of the fibres, introducing a greater level of error to MFD calculations from equation two.

SIROLAN^{TM}-LASERSCAN

The LASERSCAN method for fibre analysis was developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and was accepted by the IWTO in 1995 with the Test Method IWTO-12. The LASERSCAN technology can calculate the MFD, the MFC plus the fibre diameter standard deviation around the mean (FDSD), the coefficient of variation of fibre diameter (CVFD), the coarse edge of the sample (NZWTA Limited n.d). The LASERSCAN instrument works by immersing fibre snippets in a transport solution (isopropanol-water or pure water solution) (Mahar, n.d.) and having them flow through a measurement cell. In the measurement cell, the snippets intersect a laser beam which is directed at a measurement detector (Figure 2-9) (AWTA Limited, 1999). When the snippet intersects the laser beam the incident of light on the detector, and therefore the electrical signal produced, is reduced by an amount that is directly proportional to the cross-sectional area of the fibre (AWTA Limited, 1999).

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Figure 2-9: Diagrammatic representation of the SIROLAN^{TM}-LASERSCAN instrument. Sourced from AWTA Limited (1999).

By comparing the electrical signals of unknown wool samples with those from a sample of known fibre diameter, the MFD of the unknown sample can be calculated. The LASERSCAN instrument can measure 1000 snippets in approximately one minute, making it more efficient than projection microscope method.

Optical Fibre Diameter Analyser (OFDA)

The OFDA is the only IWTO approved image-processing method of fibre diameter measurements (SGS Wool Testing Services, 2014). The instrument scans a microscope slide, capturing an image that is then analysed by the computer to determine the widths of the fibres in the sample. The OFDA100 was the original instrument approved by the IWTO in 1995, but it has now been superseded by the OFDA2000. The OFDA2000 allows for measurements to be conducted on-farm and in the laboratory (SGS Wool Testing Services, 2014). The OFDA system can also calculate the distribution of fibre diameter in the sample, including the comfort factor, the FDSD and the CVFD (Mahar, n.d.). The OFDA can measure up to 20,000 snippets in a minute (OFDA, n.d).

FibreScan

The FibreScan instrument was developed in New Zealand for use on greasy wool samples. It uses a scanning electron microscope to produce a video recording of a sample of wool fibres. The instrument analyses the wool fibres every 19 µm along the length of the fibre by scanning the width of the fibre using megapixels. One megapixel is equivalent to 2.15 µm in size (pers. com. Don Morrison, PML, 30th July 2020). The number of megapixels required to produce the measurement across the width of the fibre is used to calculate fibre diameter at that point. As the size of the megapixel is known, there is no requirement for calibration of the instrument against IH Interwoollabs calibration tops.

The mathematical definition of area

The assumption used by IWTO-approved instruments that determine MFD is that wool fibres are cylindrical and therefore have a circular cross-section. However, wool fibres are not regular in shape and more commonly resemble an ellipse (Lang, 1952). By assuming the regularity of a wool fibre, the cross-sectional area ($\boldsymbol{A}$), and therefore the fibre diameter can be calculated from equation three.

Equation 3 $$\boldsymbol{A = \pi r^2}$$

In this equation, $\boldsymbol{A}$ represents the area and $\boldsymbol{r}$ represents the radius of the circle. When regularity is assumed the diameter can be determined by solving equation three for $\boldsymbol{r}$, as the diameter of the circle is equal to $2\boldsymbol{r}$. If the fibre is not cylindrical and is instead elliptical, equation four would be required to accurately determine fibre diameter because if the MFD is calculated using the assumption of shape regularity, it is unlikely to be an exact representation of the diameter of the fibre cross-section.

Equation 4 $$\boldsymbol{A = \pi r_1 r_2}$$

In this equation, $\boldsymbol{A}$ represents the area, $\boldsymbol{r_1}$ represents the major radius, and $\boldsymbol{r_2}$ represents the minor radius of an ellipse. When the radii differ in length, it is not possible to solve the equation and receive a diameter measurement that accurately represents the shape of the ellipse, as $\boldsymbol{r_1}$ and $\boldsymbol{r_2}$ can be equal to any combination of numbers, that when multiplied to together equal the cross-sectional area. This makes it impossible to accurately identify the diameter of the fibre cross-section from the cross-sectional area alone.

Limitations to the subjective measurement of wool handle

Physiology of tactile perception

The tactile appraisal of a fibre or fabric is a physiologically complex phenomenon as tactile sensing does not occur at a localised sensory organ like the other four senses do (Mahar *et al.*, 2013). The skin is the organ that receives the feeling of touch (Lederman and Browse, 1988). The skin responds to pain, temperature, vibration and pressure through the stimulation of different tactile units (Lederman and Browse, 1988). The main tactile units are mechano-receptors. These cells are located throughout the skin and are sensitive to the mechanical stimulation from external stimuli (Svechtarova *et al*., 2016). Mechano-receptors are responsible for the conversion of external stimuli to electrical signals, which are then transmitted through neurons to reach the brain.

It is rare that the perception of touch occurs in isolation. Auditory, olfactory or visual cues can also influence how the human body perceives the sense of touch at any one time (Gallace and Soense, 2014). The evaluation of fabric or fibre 'handle' is a subjective assessment, created from the combination of two separate components. The first is the stimuli from the physical properties of the fabric, and the second is the perception of the individual who is judging the sample (Winakor *et al*., 1980). This highlights the complexity of the use of a subjective tactile assessment to consistently analyse the handle of a fibre or fabric.

Mahar *et al.* (2013) reviewed the research that has been undertaken to increase the understanding of the human body's perception of touch and the implications for the textile industry. The driver for this research has come from the development of robotics and the requirement to understand the physiological drivers of tactile perception. From this review, Mahar *et al*. (2013) concluded that greater understanding of the physiological pathways involved in tactile appraisal would provide opportunities for improvement of the measurement and appraisal of fabric or fibre in the textile industry.

Repeatability of assessment

Subjective assessment is, by nature, prone to more sources of variation than an objective measurement (Sommerville, 1998a). The subjective evaluation of handle is a tactile appraisal, but the visual aspects of the wool have been shown to influence an assessor's perception of the tactile attributes of a wool sample (Preston *et al*., 2014). Unconscious bias, such visual appearance, influences subjective appraisal, reducing the repeatability of handle assessment between assessment events and between individual assessors. This finding is not surprising given the complex process by which the human body perceives the sense of touch.

Preston *et al*. (2017) analysed the repeatability of textural wool handle. This study was conducted using a subjective evaluation and assessing Merino wool at different stages of processing. The sheep used for the trial were mixed-sex Merino animals, which had been classed depending on the wool type of their sire, into either ultra-fine/fine, fine/medium or medium/strong. The wool was assessed on the live animal, as a greasy mid-side sample, and subsequently as a scoured mid-side sample. The assessments of four assessors were recorded for each stage of the trial. Each of the assessors had different levels of repeatability within their assessments. The trial concluded that the scoured mid-side sample provided the greatest repeatability of assessment for all assessors, with the live-animal assessment being the least repeatable. Each processing stage removes a greater number of covariates from the assessment, potentially reducing variation in assessor response. The main limitations to the scoured mid-side assessment are the time required and cost incurred to complete this form of assessment. These limitations make it uneconomical for a large proportion of farmers.

A handle assessment of raw wool is performed in fine-wool sheds at shearing. A wool classer subjectively assesses the visual and tactile characteristics of the fleeces before separating individual fleeces into separate lines for baling. The purpose of using a wool classer is to reduce the variation in wool fineness, colour and length within a bale (New Zealand Wool Classing Association, 2016). The findings of Preston *et al*. (2017) do, however, suggest that the repeatability of these assessments throughout the industry would only be moderate if completed by the same assessor, or low-moderate when using different assessors.

There is limited research on the repeatability of tactile appraisal of raw wool, but there are many studies which explore the level of agreement between assessors and within an individual's assessment for the appraisal of fabric handle. Mahar and Wang (2010) compared the results from 12 experienced assessors on their perception of seven tactile attributes, and their overall perception of the handle of fabric samples. The trial used the degree of correlation between the average of the assessment results, plus each assessor's individual results, as a measure of the agreement between the assessor's tactile appraisals. The average correlation between the average and the individual assessor's results was 0.75 (Table 2-1). This suggests a high level of agreement between the assessor's tactile appraisals ($p < 0.05$). However, there was a range of 0.36 between the minimum and maximum correlation values for assessors and the mean values, with this indicating that there is a level of variation between individual assessors for the assessment of overall handle.

Table 2-1: The average, minimum and maximum correlation coefficients for the relationship between individual assessor's scores and the average scores of all 12 assessors for each fabric attribute and the overall handle preference. Sourced from Mahar and Wang (2010).

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The lowest degree of correlation occurred for the 'warm-cool' (0.54) and 'greasy-dry' (0.59) tactile attributes. The lower degree of correlation between these assessments may be because there is greater influence by external stimuli that affect the tactile assessment of these particular attributes. The attributes with the greatest correlation are 'rough-smooth' and 'hard-soft'. Unlike the previous two attributes discussed, the assessment of these two attributes is less likely to be influenced by the other senses, as they are more likely to be perceived by ‘touch’ alone.

Of the seven tactile attributes assessed, it is unlikely that any of these are assessed in complete isolation from other attributes in the trial. Wang *et al*. (2013) suggested that primary ‘hand values’ are not independent of each other, which can have a confounding effect on the tactile appraisal of a fibre or fabric. This reinforces the complications that arise when attempting to quantify human tactile perception. Using the same seven attributes as the trial completed by Mahar and Wang (2010), Wang *et al*. (2013) attempted to identify which of these seven attributes were most important in determining the overall tactile preference of lightweight knitted fabrics. This study revealed that 92.6% of the total variance in overall tactile preference was explained by the first three principal components (Figure 2-10).

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Figure 2-10: Total variance of the descriptive tactile attributes explained by principal components. Sourced from Wang *et al.* (2013).

These three principal components (PC) were simplified into different perceptions of the tactile attributes. Principle component 1 was simplified to be a representation of the fabric luxury, which comprised predominantly from the perception of the ‘hard-soft’ and ‘rough-smooth’ attributes. Principle component 2 was simplified to be a perception of fabric tightness, comprising predominantly from the attribute ‘loose-tight’, and PC3 was identified as fabric weight, which was primarily comprised from the fabric attribute, ‘light-heavy’. Three of these tactile attributes corresponded to the tactile attributes that were identified to have the highest correlation between individual assessors and the average score described by Mahar and Wang (2010). This suggests that the lower correlation of the attributes ‘greasy-dry’ and ‘warm-cool’ between assessors and the mean of the assessment, as suggested by Mahar and Wang (2010), may not have a significant effect on the repeatability of an overall handle assessment.

Assessment site

<u>Wool fibre characteristics</u>

A major influence on the subjective assessment of raw wool handle is that as the MFD decreases, the handle of the wool improves. On an individual animal, the MFD can vary along fibres, between fibres in a staple, between staples in a position and between positions on a fleece (Scobie *et al*., 2015). The percentage change between the MFD at different locations influences the severity of this variation on handle assessment. When the variation in MFD is large, the chance of variation in subjective assessments also increases.

Summer and Craven (2000) compared the variance in MFC and MFD across eight sites on the body of six Perendale ewes (Figure 2-11). The study found that the sample site had a significant effect on all fleece characteristics measured, except for fibre diameter standard deviation (FDSD). The neck and belly samples (1 and 8) had the most significant difference compared to the other sample sites. The finest wool was found for the neck and shoulder (1 and 5) site samples, whereas higher MFD wool was located on the rump (4) region.

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Figure 2-11: Location of the eight sample sites used in the analysis of wool characteristics of the six Perendale ewes. Adapted from Summer and Craven, (2000).

There was no fibre curvature or fibre diameter gradient evident across the body of the sheep in the samples analysed, but further research has detected gradients in the variation of MFD and MFC across the body of sheep. Fish *et al*. (2002) investigated variation in MFD, the FDSD and the MFC between nine positions across the body of a sheep (Figure 2-12).

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Figure 2-12: Sample sites on the 150 Merino ewes analysed for variation in fibre characteristics across the body of the animal. Sourced from Fish *et al.* (2002).

The experiment used two different testing processes, the LASERSCAN and OFDA100, to analyse three different classes of Merino wool: fine, medium and broad. The OFDA100 measured a higher MFD on all three fibre classes, while the LASERSCAN had a slightly higher measurement of MFC in all three classes. The MFD increased from the anterior (fore) to posterior (hind) positions. A decrease from dorsal to ventral positions occurred in most samples for MFD. The MFC increased from the dorsal to ventral positions, a relationship that was expected, as previous research had shown that as MFD decreases, MFC increases (Fish *et al*., 1999). However, this relationship was not found along the anterior-posterior gradient, with MFC increasing with MFD. When both the compressional (MFC) and textural (MFD) attributes increase along the same gradient, a wool sample will have both high curvature and high diameter, potentially causing a deterioration in handle.

Once the relationship between site and mean fibre diameter was established, Fish *et al.* (2002) analysed which of the sites recorded the fibre diameter and curvature most closely related to the mean of the fleece (Table 2-2).

Table 2-2: Location of the sample site that produced an estimate most closely related to the mean value for the measurement of individual traits by OFDA100 and LASERSCAN. Sourced from Fish *et al.* (2002).

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The broad wool was most accurate for MFD and FDSD at sites A1 and C3, respectively, for both evaluation programs. In medium wool, site B1 was considered the most accurate for the MFD in both evaluation systems, but the FDSD did not have a site of assessment common to both evaluation systems. In the fine wool samples, site A1 was common between the two evaluation systems for accuracy of FDSD, but the MFD did not have a site of assessment common to both evaluation systems. None of the three wool categories had a common location for the evaluation of MFC between the two processing systems.

<u>Wool handle assessment</u>

As the handle of wool is suggested to be related to the textural and compressional attributes of the fibres, it is conceivable that wool handle would vary in assessment across the body of a sheep as MFD and MFC do. Preston *et al*. (2014) completed a study that analysed the relationship between the mean greasy wool handle assessment of a fleece and the greasy wool handle at selected sites on the fleece. The wool handle groups were developed from an in-field assessment by two assessors, with the Group 1 indicating a very smooth fleece, and Group 5 indicating a rough feeling fleece. However, no Group 5 sheep were identified, and this group was removed from further analysis. Nine sites across the body of the sheep were identified (Figure 2-13), and the wool was shorn from these areas.

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Figure 2-13: Location of sample sites across the right side of the body of the animal. T1: hip bone, T2: centre top side, T3: shoulder, M1: where the mid-side and hip intersect (the stifle), M2: the mid-side (centre of the last rib), M3: where the shoulder and mid-side intercept, B1: below the hip and above the hock, B2, lower mid-side, B3: below the shoulder. Sourced from Preston *et al.* (2014).

A group of assessors subjectively evaluated three staples from each location for the tactile attributes. The site 'M2' was found to be very close to the median textural greasy wool handle across all four wool handle groups (Figure 2-14).

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Figure 2-14: Box plot of the textural greasy wool handle across the fleece compared with the textural greasy wool handle groups. Vertical dotted line indicates the median value, median value for each site denoted by (*). Sourced from Preston *et al.* (2014).

When the variation in wool quality attributes was included in the analysis, the site of assessment was not significant. However, sire-code and textural group handle were significant variables affecting textural greasy wool handle. Sire-code indicated whether the ewe had descended from a sire classed as ultrafine/superfine, fine/fine-medium or medium/strong wool types. The ewes that descended from the ultrafine/superfine sires had texturally softer wool than the ewes from the other two sire types. As these wool types are classed from the average fibre diameter of the bloodline this finding was not unexpected as the heritability of fibre diameter is high and finer wool is generally perceived to be softer ($r^2 = 0.77 \pm 0.02$; Huisman *et al.,* 2008).

The site 'M2' was suggested as the most accurate location to determine median greasy wool handle. The location of the staple assessed was deemed an important factor to reduce variation in greasy wool handle evaluation between assessment events and between individual assessors. Further testing, which analysed the handle groups independently of each other, has since been completed. In the harsher handle Group 4 samples, the site of assessment remained significant, even when covariates were included in the analysis.

Preston *et al*. (2014) suggested that the differences found between textural greasy wool handle groups requires research. The variation between handle groups will impact on the reliability of the handle assessment across an entire flock, especially if there is considerable variation in the breeding lines, but the use of a common assessment site between individual animals will reduce some of this variation.

Objective measurements of wool handle

It has been hypothesised that the handle of a wool sample is a result of the relationship between the compressional and textural characteristics of a wool sample (Schlink, n.d.). The compressional properties of wool fibre or woollen fabric can be explained using the objective measurement of resistance to compression (Preston *et al*., 2015). Resistance to compression (RtC) is defined as the force per unit area required to compress a fixed mass of wool into a fixed volume (AWTA Limited, 2002). The RtC is related to the compressional fibre attributes, curvature and crimp, as well as fibre diameter. The compressional attributes of a group of fibres are referred to as wool bulk (Sumner *et al.,* 2009). Madeley *et al*. (1998) suggested that RtC is the best objective measurement of the raw wool form to predict the subjective assessment of handle of scoured wool, with staple crimp frequency and MFD found to be the main variables influencing the RtC of the lamb's wool. Preston *et al.* (2014) found that RtC had a significant effect on the handle of wool and that as the RtC increased for a wool sample, the handle of the sample decreased in desirability.

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Figure 2-15: Alpaca (●) and Merino wool (▲) fibres mean fibre curvature plotted against resistance to compression (A) and fibre curvature plotted against resistance to compression (B). Sourced from Liu *et al.* (2004).

The RtC decreases with an increase in MFD or a decrease in MFC (Figure 2-15). Liu *et al*. (2004) looked at the differences between the RtC of alpaca fibre and sheep wool. For wool, there was a strong relationship between the RtC and degree of curvature of fibres ($r^2 = 0.90$). There was also a correlation between the RtC and MFD, but this was not as strong ($r^2 = 0.55$). The MFC was highly correlated ($r^2 = 0.82$) with MFD (Liu *et al.,* 2004) (Figure 2-16).

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Figure 2-16: Alpaca (○) and Merino wool (■) mean fibre diameter plotted against fibre curvature. Sourced from Liu *et al.* (2004).

As the MFD decreases, there should be an increase in the perceived softness of the wool handle, through a change in the textural properties of the wool. However, as the MFD decreases, the MFC increases, which simultaneously changes the compressional qualities of the wool fibre. Madeley and Postle (1999) suggested that a reduction in fibre curvature and crimp should, theoretically, be as effective at increasing the softness of a fabric as a reduction in MFD. However, data collected subjectively from the assessment of woollen woven flannel did not support this suggestion. A preference for low MFD (18 µm) – high crimp fibre, over high MFD (19.3 µm) – low crimp fibre was demonstrated in the trial undertaken by Madeley and Postle (1999). This finding is supported by Lui *et al.* (2004), who suggested that resistance to compression was a poor indicator of the softness of fibre samples with varying MFD, because of the considerable effect that fibre diameter can have on the appraisal of the softness of loose wool.

Objective measurements of fabric handle

Most research has focused on the development of methods to objectively determine the tactile properties of fabrics, as opposed to the raw fibre. Traditionally, forearm tests or wearer trials were used to obtain subjective assessments of fabric handle. Forearm tests are used to determine the prickle factor of different garments as they have demonstrated a high degree of correlation with wearer trials (Naylor *et al.,* 1992).

To conduct a forearm test, a piece of fabric is placed on the forearm of the assessor. The assessor is instructed to place pressure on the other side of the fabric and press it against the forearm (Naylor *et al.,* 1992). The assessor is asked to describe how the fabric feels against the forearm. A lower score represents that a garment should have a lower incidence of prickle (AWTA Limited, 2014). Forearm tests and wearer trials are time-consuming, and they require a large number of test subjects to be precise (McGregor *et al.,* 2013) consequently, objective methods of handle evaluation are becoming more desirable.

Two commonly used fabric evaluation systems are the Kawabata Evaluation System for Fabrics (KES-F) and the Fabric Assurance by Simple Testing (FAST). The KES-F was developed through the Hand Evaluation and Standardisation Committee (HESC) in association with the Textile Machinery Society of Japan in 1981 (Sun, 2018). This system allowed the quantification of mechanical properties of a fabric. The Commonwealth Scientific and Industrial Research Organisation (CSIRO) developed the FAST method for use by tailors and worsted finishers (Li and Dai, 2006). It was designed to be simple to use and inexpensive to include in a fabric evaluation system (Thilagavathi and Viju, 2013).

The Wool ComfortMeter (WCM) and Wool HandleMeter (WHM) systems were developed by the Co-operative Research Centre for Sheep Industry Innovation (Preston *et al*., 2015), and became available for commercial use in 2013 (AWTA Limited, 2014). Both systems allow the manufacturer to assign a quantitative value to a garment that the consumer can equate to the degree of comfort they are likely to experience when wearing the garment. The WHM measures the seven core attributes of handle described by Mahar and Wang (2010) (Table 2-1) and assigns an overall value for the handle of the fabric. The WCM method assesses the prickle factor by passing a wire across a fabric. Any protruding fibres touch the wire and cause a vibration. The size and number of vibrations have been calibrated against the subjective evaluation of the same fabrics through forearm testing (Wang *et al*., 2016), and they have shown to be strongly correlated with the average prickle scores from wearer trials (McGregor *et al.,* 2013).

Conclusions

- Handle is an integral attribute of fibre and fabric destined for use in the textile industry. The chance of a consumer repeating a purchase can often be predicted by the first experience they have with a textile or item of clothing.

- The shift from a subjective appraisal of handle to an objective measurement is difficult due to the numerous wool traits that influence handle and the lack of understanding around how the human body perceives touch. This is further complicated by the variation in the sensitivity of touch by individuals.

- Several wool characteristics can be objectively measured by instruments that are IWTO approved and commercially available. However, there is variation in wool fibre characteristics across the fleece, between staples, within staples and within fibres.

- An assumption in the objective measurement of wool fibres is that they have a circular cross-section, but literature indicates that this is not true. There is limited knowledge of what causes the ellipticity of wool fibres and limited understanding of the effects of ellipticity on objective fibre measurements and the overall appraisal of fibre handle.

3 MATERIALS AND METHODS

Sample collection

This trial was conducted on the wool samples of 28 Merino and five NZ Romney rams. Twenty-nine Merino wool samples were collected from 28 rams at Matangi Station located in Central Otago, New Zealand. Eight wool samples were collected from full length, show fleeces shorn in August 2019. The remaining 21 wool samples were mid-side clips, collected from the rams in July 2020, four months after shearing. One ram had a sample from both August 2019 and July 2020 included in the analysis. The five NZ Romney wool samples were supplied by Pastoral Measurements Limited.

Commercial wool testing

Pastoral Measurements Limited used the FibreScan instrument to collect measurement data from the wool samples. The MFD, FDSD, CVFD, MFC, the percentage of medullation, the coarse edge (percentage of fibres in the sample over 30 μm) and staple length in millimeters were recorded. The FibreScan instrument also produced a histogram showing the distribution of the fibre diameter in the wool sample and a line graph showing the change in fibre diameter along the length of the fibre.

Wool scouring

The wool was scoured prior to the electron microscope photos being taken. Mesh baskets were used to hold the wool samples during the scouring process. The baskets containing the wool samples were placed into 50 °C water with detergent. The samples were periodically agitated over a 10-minute interval. This hot water agitation process was repeated twice using fresh water. Following the detergent wash, the wool samples were rinsed with hot water twice to remove any residues.

Electron Microscopy

To prepare the wool samples for electron microscopy (EM) a small lock of wool fibres was obtained from each wool sample and pulled through a rivet with a copper wire. The sample was then sliced against each edge of the rivet (Figure 3-1).

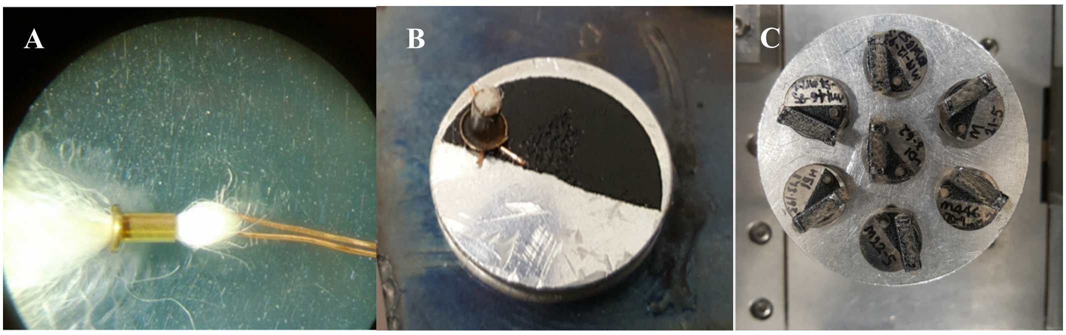

Figure 3-1: A) a lock of wool fibres being pulled through the rivet with a copper wire, B) the placement of the rivet on the pin stub, C) a group of pin stubs after being coated in Platinum. Images provided by Catherine Hobbis, University of Auckland.

The rivet was then placed onto a standard pin stub and covered with double-sided tape. The samples were then coated in platinum (Pt) for 120 seconds to reduce any charging effects. Samples were analysed using an FEI Quanta ESEM (environmental scanning electron microscope model: FEI Quanta 200 F) operating in variable pressure mode. Water was used as the imaging gas. The operating conditions are shown in Table 3-1. Each photo contained approximately 50 – 150 fibre ends.

Table 3-1: Operating conditions of the FEI Quanta ESEM operating in variable pressure mode to create imagery for analysis of fibre shape.

Operating Conditions	
Magnification	1000 x
Detector type	LFD
Spot size	3.0
Voltage	10.0 kV
Water vapour pressure	0.48 – 0.58 torr
Working distance	10.1 – 10.6 mm

Electron microscope image analysis

One electron microscope photo was analysed for each wool sample using IMAGE-J software. The Image-J software measures the distance in pixels between two points that have been identified on the screen. For the image analysis in this trial, one μm was equivalent to 7.47 pixels. Fibres that did not show an entire fibre end, either because of their location on the edge of the image or where other fibres obscured the end of a fibre, were removed from the analysis. If fibres were deemed not to show an 'end-on orientation', they were also excluded from the analysis. Once a fibre end was selected, the major and minor diameters of the fibre end were identified and measured using the Image-J software. From these measurements, the ratio (fibre contour) between the major and minor diameters was calculated and expressed as a percentage. Using Microsoft Excel, the percentage of fibres from the sample that had a major and minor ratio greater than 1.4, and the average ratio was calculated from these measurements.

Handle assessment

Each of the Merino wool samples was subject to a subjective handle assessment by 30 students and staff from Lincoln University. The assessors were asked to rate the softness of each wool sample on a scale of 1 – 10 (Table 3-2). A rating of 1 indicated a wool sample that was unpleasant to the skin, and a rating of 10 indicated a wool sample that was extremely soft and pleasant to touch.

Table 3-2: The scaling given to assessors to use to evaluate the handle of individual wool samples.

Scale	Feeling
1	hard or grainy to touch, unpleasant against skin
2	mostly grainy/hard feel
3	grainy/hard feel, some fibres still soft to touch
4	grainy/hard obvious but areas that are soft
5	slightly grainy or prickly to the touch
6	mostly soft but can definitely feel some grainy fibres
7	soft to touch, small percentage of fibres are prickly/grainy
8	soft to touch but few fibres feel harder
9	soft to touch
10	extremely soft and pleasant to touch

Statistical analysis

All data were analysed using Minitab 19. One-way ANOVA were conducted on both the handle assessment data and ratio measurement data, to determine whether there was a difference between individual ram samples. Correlations were run to determine whether there was a relationship between different fibre characteristics and the handle assessment of wool. Independent variables that were correlated with the mean handle assessments were included as explanatory factors in a multiple linear regression model. Independent variables that were not considered significant at a 95% confidence level were excluded from the models.

4 RESULTS

Analysis of data distribution and identification of outlying values

To analyse the distribution of the mean contour ratio and the percentage of fibres with a contour ratio greater than 1.4, the Merino ram wool samples were presented in a boxplot distribution graph. The box plot distribution suggested that one Merino wool sample did not fit the normal distribution model and was an outlier to the data set. Due to the small sample size ($n = 29$ Merino) this Merino ram (LD1-3-8) was removed from further analysis. The NZ Romney ram data were not included in the distribution model as no handle assessment was undertaken.

There was significant variation in the mean handle assessment of individual assessors ($p < 0.05$). However, none of the assessors were considered to have produced outlying handle assessment values. Due to the subjective nature of the task, the results of all assessors were included in the analysis.

Descriptive statistics of fibre characteristics

The mean fibre diameter ranged from 17.5 to 22 µm for the Merino samples (Table 4-1). The mean fibre curvature ranged from 88 to 118 °/mm. The percentage of fibres that exceeded a contour ratio of 1.4 ranged from 3% to 39% for the Merino ram wool samples included in the following analysis.

Table 4-1: Descriptive statistics of Merino and NZ Romney ram samples as measured with the FibreScan instrument by Pastoral Measurements Limited.

Tag Number	MFD	MFC	SDFD	Fibre Count	% of Sample Contour ratio > 1.4	SD Contour Ratio
Merino						
ALF1-11-18	17.5	105	3.2	128	13%	0.14
H42-143	22.0	118	4.2	69	25%	0.18
H42-167	18.3	116	3.2	84	39%	0.19
H51-173-193	20.5	100	3.9	67	24%	0.19
LD1-3-62	19.8	88	3.8	100	36%	0.21
LD1-3-8	19.8	96	3.5	66	50% *	0.25
M14-152	21.6	104	4.0	76	22%	0.22
M14-152-2	21.7	110	4.1	91	29%	0.18
M14-152-49	18.8	104	3.3	86	19%	0.16
M152-49	19.9	95	3.2	80	18%	0.14
M19-12-93	17.6	95	3.9	85	18%	0.19
M21-5	17.5	107	3.7	57	19%	0.17
M21-17	20.4	93	3.4	100	37%	0.17
M21-2-150	19.1	106	4.3	106	25%	0.17
M22-5	19.4	103	3.1	109	3%	0.11
M307-68-155	19.2	110	3.9	89	16%	0.16
M446-170-81	18.0	103	3.2	121	23%	0.18
M446-170-9	17.6	113	3.7	136	13%	0.15
M446-19-100	18.9	107	3.8	77	31%	0.17
M446-85-54	17.7	111	3.0	123	13%	0.14
MDP-4	18.1	104	3.1	123	12%	0.14
MDP3-68	18.8	118	3.9	101	10%	0.13
MVP1-5	20.0	109	3.3	107	13%	0.15
RP1-9-9-6	21.8	104	4.0	89	18%	0.16
SHC-177	18.6	115	3.2	111	9%	0.14
SHC-26-43-140	18.1	103	3.8	83	22%	0.15
SHC-26-43-6	18.1	118	4.0	74	23%	0.15
SHM-42	18.0	117	3.9	162	7%	0.12
SHM-42a	18.0	116	3.6	101	28%	0.19
NZ Romney						
R-719	33.6	62	13.6	25	58%	0.24
R-686	32.3	68	12.5	30	40%	0.27
R-820	33.5	58	8.9	25	26%	0.20
R-789	32.2	85	7.8	45	19%	0.18
R-652	25.4	80	4.5	59	3%	0.12

**Sample identified as an outlying value and removed from further analyses.*

The mean fibre diameter ranged from 25.4 to 33.6 µm for the NZ Romney ram samples (Table 4-1). The mean fibre curvature ranged from 58 to 85 °/mm. The percentage of fibres that exceeded a contour ratio of 1.4 for the NZ Romney ram wool samples ranged from 3% to 56%.

Analysis of variance of mean contour ratio of wool samples

At a 95% confidence level there were differences in the mean contour ratio calculated from the samples collected from individual Merino rams. The mean contour ratio for the Merino ram wool samples ranged from 1.20 to 1.37 (Table 4-2).

Table 4-2: Results of a Tukey post-hoc test following a one-way ANOVA of the mean contour ratio of fibres in individual Merino ram wool samples**.**

Tag Number	No. of Fibres Assessed	Mean Contour Ratio	Grouping*					
H42-167	84	1.37	A					
LD1-3-62	100	1.35	A	B				
M446-19-100	77	1.33	A	B	C			
M21-2-150	100	1.32	A	B	C			
M14-152-2	91	1.31	A	B	C	D		
SHM-42a	101	1.30	A	B	C	D	E	
M21-5	106	1.29	A	B	C	D	E	
M14-152	76	1.29	A	B	C	D	E	
M446-170-81	121	1.29	A	B	C	D	E	
SHC26-43-6	74	1.29	A	B	C	D	E	
M21-17	57	1.28	A	B	C	D	E	F
H42-143	69	1.27	A	B	C	D	E	F
RP1-9-9-6	89	1.27		B	C	D	E	F
H51-173-193	67	1.27	A	B	C	D	E	F
M307-68-155	89	1.26			C	D	E	F
M19-12-93	85	1.25			C	D	E	F
SHC-26-43-140	83	1.25			C	D	E	F
M152-49	80	1.25			C	D	E	F
M14-152-49	86	1.24			C	D	E	F
M446-170-9	136	1.24				D	E	F
M446-85-54	123	1.24				D	E	F
MDP-4	123	1.24				D	E	F
MVP1-5	107	1.23				D	E	F
ALF1-11-18	128	1.23					E	F
SHM-42	162	1.23					E	F
SHC-177	111	1.22					E	F
MDP3-68	101	1.22					E	F
M22-5	109	1.20						F

**Means that do not share a letter are significantly different.*

There were differences in the mean contour ratio calculated from the measurements collected from the NZ Romney ram wool samples. The mean contour ratio of the NZ Romney rams wool samples ranged from 1.21 to 1.48 (Table 4-3).

Table 4-3: Results of a Tukey post-hoc test following a one-way ANOVA of the mean contour ratio of fibres in individual NZ Romney ram wool samples.

Tag Number	No. of Fibres Assessed	Mean Contour Ratio	Grouping*		
R-719	25	1.48	A		
R-686	30	1.40	A	B	
R-820	25	1.28		B	C
R-789	45	1.28		B	C
R-652	59	1.21			C

**Means that do not share a letter are significantly different.*

There was a strong positive correlation between mean contour ratio and the percentage of fibres with a contour ratio greater than 1.4 ($r = 0.948$, $p < 0.05$).

Analysis of variance of mean handle assessment of wool samples

At a 95% confidence level there were differences in the mean handle assessment of the different wool samples (Table 4-4).

Table 4-4: Results of a Tukey post-hoc test after a one-way ANOVA revealing the differences in mean handle assessment for individual ram wool samples.

Tag Number	Mean Handle Assessment	Grouping*								
SHC-26-43-140	8.4	A								
SHM-42	8.2	A	B							
M14-152-49	8.2	A	B							
M22-5	7.9	A	B	C						
M446-85-54	7.8	A	B	C	D					
M152-49	7.8	A	B	C	D	E				
SHM-42a	7.8	A	B	C	D	E				
MDP-4	7.6	A	B	C	D	E	F			
LD1-3-62	7.6	A	B	C	D	E	F			
M21-17	7.6	A	B	C	D	E	F			
SHC-177	7.4	A	B	C	D	E	F	G		
MDP3-68	7.2	A	B	C	D	E	F	G		
H42-167	7.2	A	B	C	D	E	F	G		
SHC26-43-6	7.0	A	B	C	D	E	F	G	H	
M446-170-81	6.8		B	C	D	E	F	G	H	I
ALF1-11-18	6.7		B	C	D	E	F	G	H	I
RP1-9-9-6	6.7		B	C	D	E	F	G	H	I
M19-12-93	6.7		B	C	D	E	F	G	H	I
M446-170-9	6.5			C	D	E	F	G	H	I
M307-68-155	6.4			C	D	E	F	G	H	I
MVP1-5	6.3			C	D	E	F	G	H	I
M21-5	6.3			C	D	E	F	G	H	I
M446-19-100	6.3				D	E	F	G	H	I
H51-173-193	6.2					E	F	G	H	I
M21-2-150	6.2						F	G	H	I
H42-143	5.9							G	H	I
M14-152	5.6								H	I
M14-152-2	5.3									I

**Means that do not share a letter are significantly different.*

The handle assessment only included the Merino ram wool samples, so as not to bias the handle assessment with the harsher handling NZ Romney wool. The mean handle rating ranged from 5.3 (slightly grainy or prickly to touch) to 8.4 (soft to touch, but a few fibres feel harder).

Analysis of variance of individual assessor handle assessment

At a 95% confidence level there were differences in the average handle assessment across the wool samples given by each assessor (Table 4-5).

Table 4-5: Results of a Tukey post-hoc test after a one-way ANOVA revealing the differences in the mean handle assessment of individual assessors across the wool samples.

Assessor	Mean Handle Assessment	Grouping*							
Assessor 13	8.3	A							
Assessor 16	8.3	A							
Assessor 5	8.2	A	B						
Assessor 4	8.1	A	B						
Assessor 2	8.1	A	B						
Assessor 20	8.1	A	B	C					
Assessor 22	8.0	A	B	C	D				
Assessor 29	7.6	A	B	C	D	E			
Assessor 3	7.5	A	B	C	D	E	F		
Assessor 1	7.4	A	B	C	D	E	F		
Assessor 21	7.4	A	B	C	D	E	F		
Assessor 27	7.3	A	B	C	D	E	F		
Assessor 23	7.2	A	B	C	D	E	F		
Assessor 12	7.2	A	B	C	D	E	F		
Assessor 28	7.1	A	B	C	D	E	F	G	
Assessor 7	7.0	A	B	C	D	E	F	G	
Assessor 9	6.7		B	C	D	E	F	G	
Assessor 26	6.6		B	C	D	E	F	G	
Assessor 24	6.5			C	D	E	F	G	
Assessor 17	6.4				D	E	F	G	H
Assessor 11	6.4				D	E	F	G	H
Assessor 6	6.4				D	E	F	G	H
Assessor 30	6.3					E	F	G	H
Assessor 18	6.3					E	F	G	H
Assessor 15	6.1					E	F	G	H
Assessor 8	6.1					E	F	G	H
Assessor 19	6.0						F	G	H
Assessor 25	5.9						F	G	H
Assessor 14	5.6							G	H
Assessor 10	4.9								H

**Means that do not share a letter are significantly different.*

The mean handle assessment of the individual assessors ranged from 4.9 to 8.3 across the individual wool samples and followed a normal distribution pattern.

Correlation Coefficients

There is a weak negative correlation between mean handle assessment and the percentage of fibres with a contour ratio greater than 1.4, but this correlation is not considered significant at a 95% confidence level ($r = -0.335$, $p > 0.05$) (Figure 4-1).

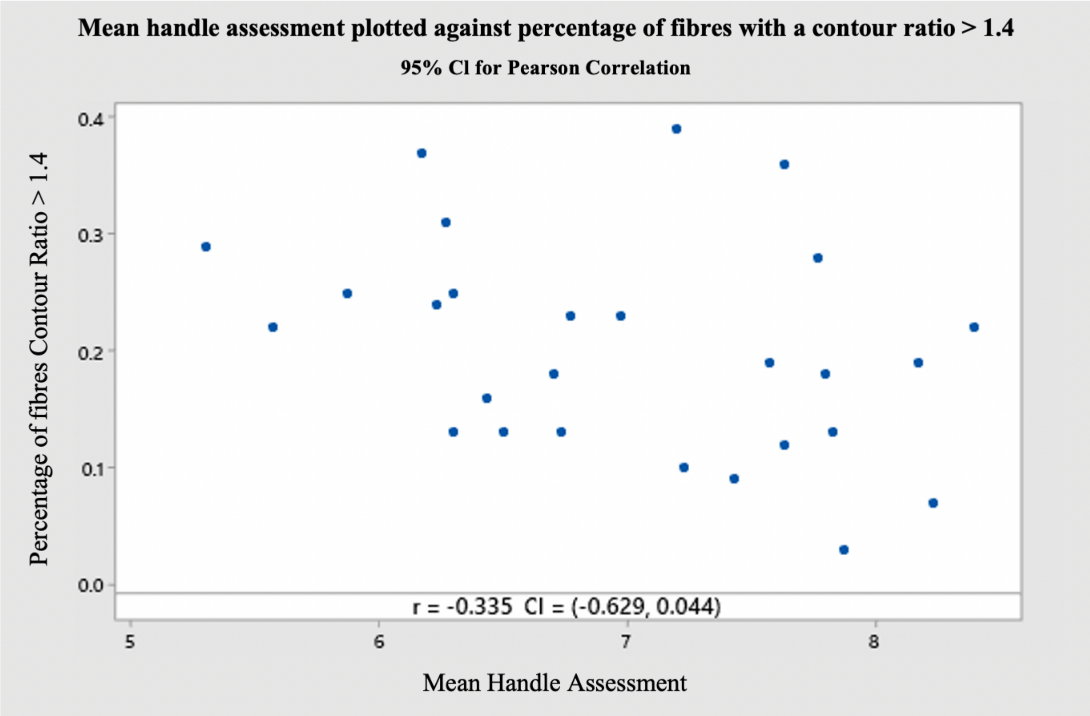

Figure 4-1: Scatterplot revealing the correlation between mean handle assessment and the percentage of fibres with a contour ratio greater than 1.4**.**

There was a moderate negative correlation between the mean handle assessment and mean fibre diameter of the wool sample ($r = -0.586$, $p < 0.05$) (Figure 4-2).

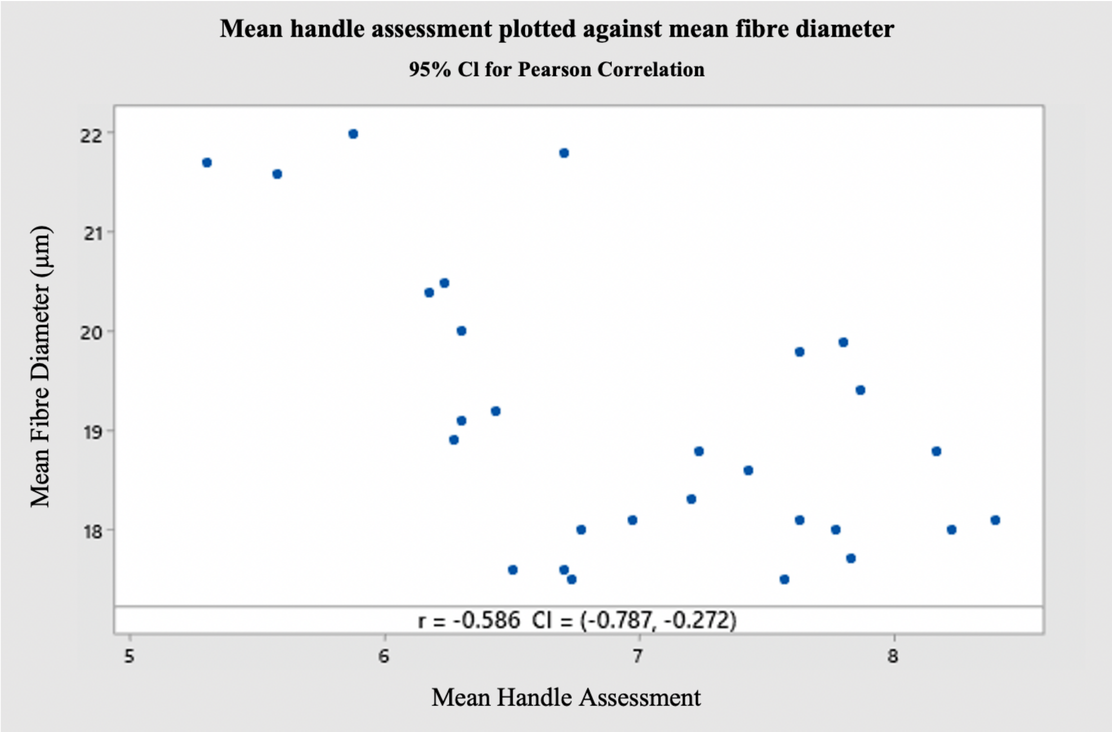

Figure 4-2: Scatterplot revealing the correlation between mean handle assessment and mean fibre diameter.

There was a moderate negative correlation between the standard deviation of fibre contour and the mean handle assessment ($r = -0.481$, $p < 0.05$) (Figure 4-3). As the variation around the mean contour ratio value increased there was a decrease in the mean handle assessment calculated from the data collected from the 30 assessors.

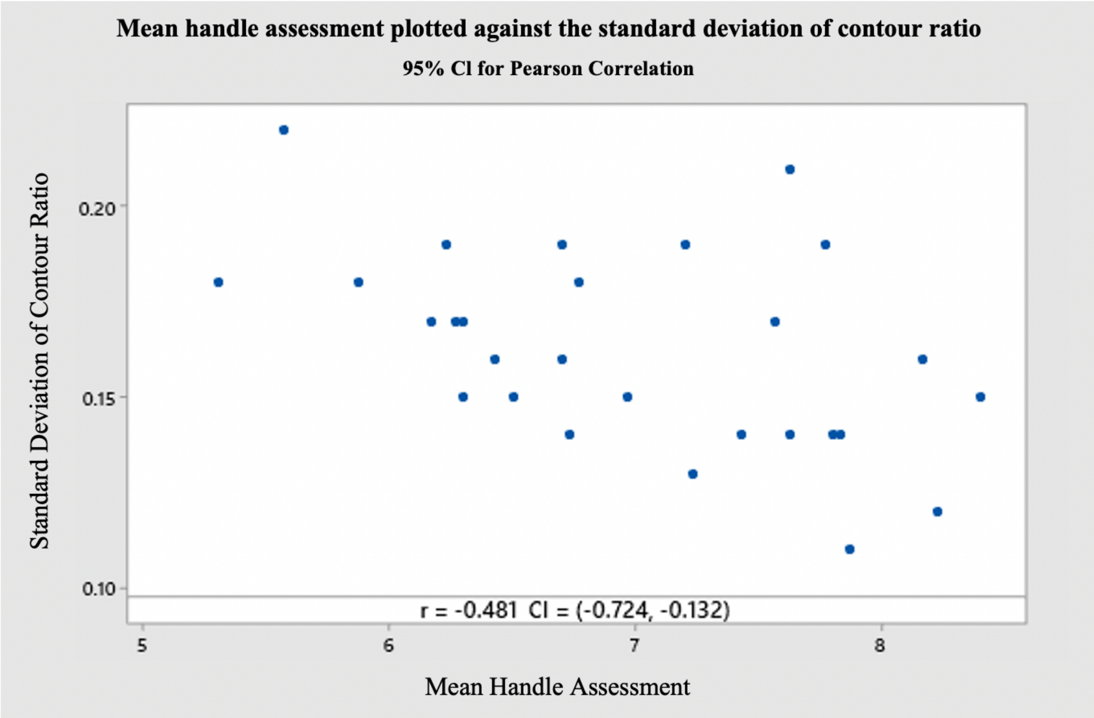

Figure 4-3: Scatterplot revealing the correlation between mean handle assessment and the standard deviation of contour ratio**.**

There was a moderate negative correlation between mean handle assessment and the FDSD ($r = -0.470$ $p < 0.05$) (Figure 4-4).

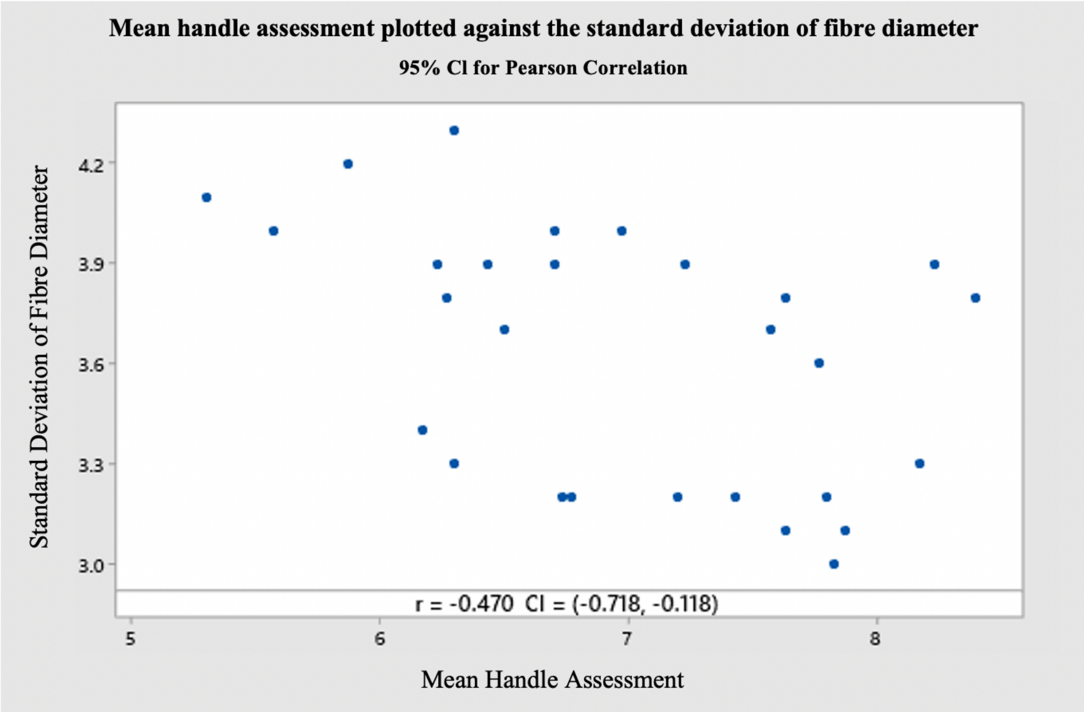

Figure 4-4: Scatterplot revealing the correlation between mean handle assessment and standard deviation of fibre diameter (FDSD)**.**

There was no correlation between MFC and mean handle assessment ($r = 0.01$, $p > 0.05$). There was no correlation between MFD, MFC or SDFD and the percentage of fibres with a contour ratio greater than 1.4 ($p > 0.05$).

There was a moderate positive correlation between the FDSD and the standard deviation of contour ratio ($r = 0.387$, $p < 0.05$) (Figure 4-5). As the FDSD increased, the variation in contour ratio also increased.

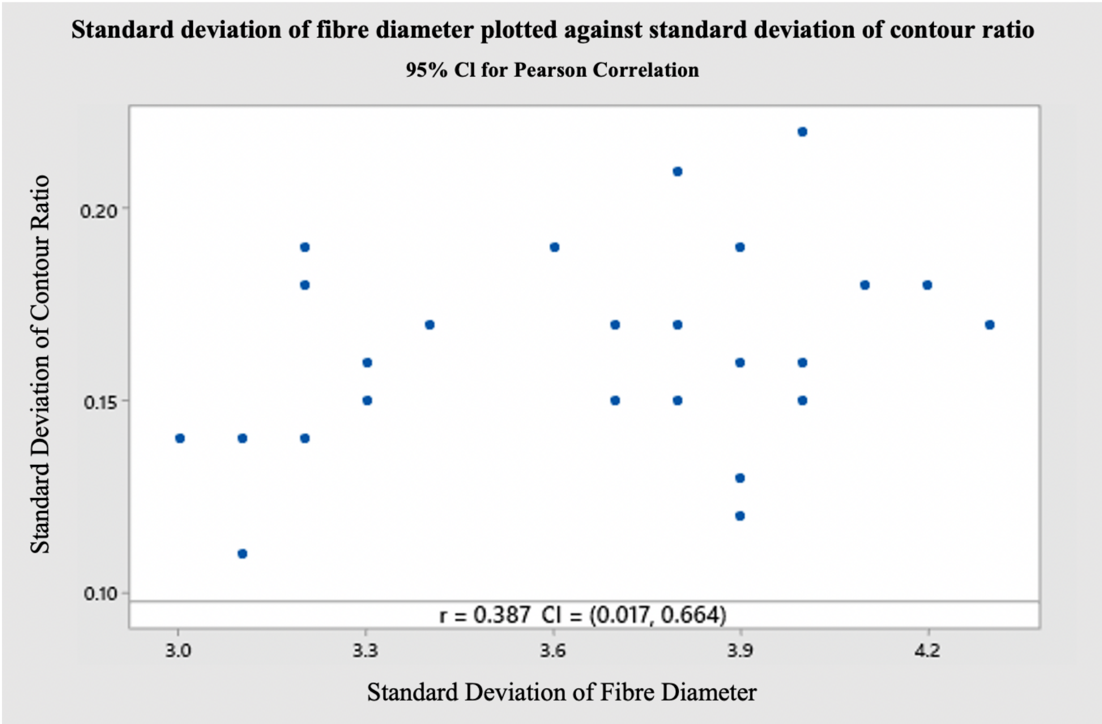

Figure 4-5: Scatterplot revealing the correlation between standard deviation of fibre diameter and the standard deviation of contour ratio of Merino ram samples**.**

There was a strong correlation between the standard deviation of handle assessment and the mean handle assessment ($r = -0.764$, $p < 0.05$) (Figure 4-6). There was greater variation in handle assessment of the wool samples perceived to be of harsher handle, than of the samples perceived to be of softer handle.

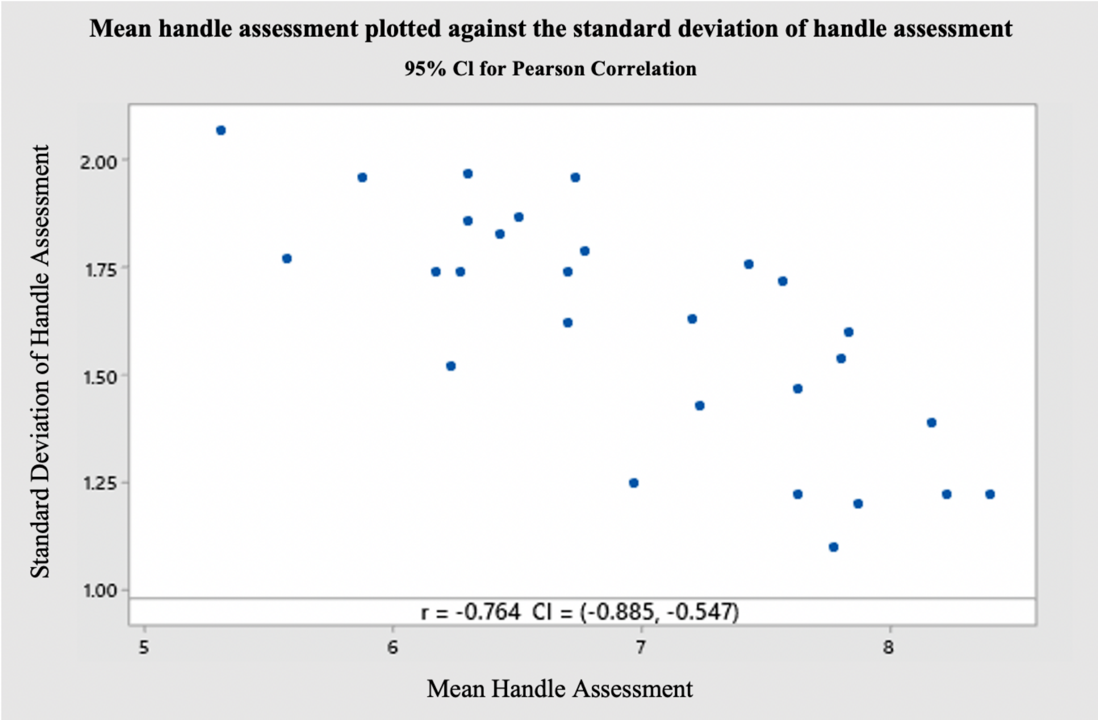

Figure 4-6: Scatterplot revealing the correlation between the mean handle assessment and the standard deviation of handle assessment.

Linear regression model

The mean fibre diameter was revealed to have an effect on the mean handle assessment when all the variables were included in a linear regression ($p < 0.05$). However, the standard deviation of fibre contour, the percentage of fibres with a contour ratio greater than 1.4 and FDSD did not have a significant effect on the mean handle assessment at the given confidence level (Table 4-6), hence they were removed from the regression analysis.

Table 4-6: Linear regression of MFD, FDSD, % of fibres contour ratio > 1.4 and standard deviation of contour to explain variation in mean handle assessment.

Analysis of Variance					
Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Regression	4	8.7442	2.18605	5	0.005
MFD	1	2.5895	2.5895	5.92	0.023
FDSD	1	0.5725	0.57255	1.31	0.264
% fibres contour ratio > 1.4	1	0.0383	0.03834	0.09	0.77
Standard Deviation of Contour	1	0.6904	0.69043	1.58	0.221
Error	23	10.0543	0.43714		
Total	27	18.7985			
Model Summary					
		S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**
		0.661168	46.52%	37.21%	24.85%

Mean fibre diameter remained a predictor of mean handle assessment ($p < 0.05$) with the other variables removed from the linear regression (Table 4-7). This suggests that variation in MFD accounts for 34.33% of the variation in mean handle assessment of the wool samples.

Table 4-7: Linear regression of MFD to explain variation in mean handle assessment.

Analysis of Variance					
Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Regression	1	6.453	6.4533	13.59	0.001
MFD	1	6.453	6.4533	13.59	0.001
Error	26	12.345	0.4748		
Lack-of-Fit	19	9.392	0.4943	1.17	0.441
Pure Error	7	2.953	0.4219		
Total	27	18.798			
Model Summary					
		S	**R-sq**	**R-sq (adj)**	**R-sq (pred)**
		0.689067	34.33%	31.80%	24.41%

5 DISCUSSION

The aim of this investigation was to ascertain whether a difference in fibre contour (cross-sectional shape of the fibre) could be found between individual Merino ram wool samples, and whether this difference was correlated with the handle assessment of samples, as perceived by untrained assessors. The working hypothesis was that samples with higher average fibre contour ratios (less circular in cross-section), would be of harsher handle than those with a more circular cross-section.

At a 95% confidence level there were differences between the mean contour ratios of wool samples. There were also differences between the mean handle assessments of the different wool samples, but there was no correlation between the percentage of fibres with a contour ratio greater than 1.4 and the mean handle assessment of the samples. There was also no correlation between the percentage of fibres with a contour ratio greater than 1.4 and the MFD, MFC and the FDSD. A regression model suggested that the MFD of a wool sample was the only variable that could be used to predict the mean handle assessment of a sample; as when MFD increased, mean handle assessment decreased (i.e. the handle worsened).

Fibre characteristics correlated with contour ratio

There was no correlation between the percentage of fibres with a contour ratio greater than 1.4 and MFD. This was an expected finding as no significant correlation between mean contour ratio and MFD has been demonstrated previously (Bailey, 1940; Anderson and Benson, 1953). Bailey (1940) demonstrated that whilst contour ratio tended to increase with increasing MFD, this only occurred in 50% of fleeces from Hampshire, Rambouillet, Shropshire and Southdown sheep, increasing to closer to 70% in crossbred sheep. It was also notable that when comparing within individual breeds, a low MFD did not often indicate a low contour ratio of fibres in the fleece. The study completed by Anderson and Benson (1953) also suggested that there was no correlation between MFD and mean contour ratio (MCR); but as MFD decreased, MCR tended to decline. In this study the authors used blended tops rather than the fleeces of individual animals, thus individual sample variability was not observed.

In comparison to sheep, a study of rare animal fibres found that ellipticity increased with increasing fibre diameter ($p < 0.001$) for alpaca, cashmere, mohair, qiviut, vicuña and bison fibres (McGregor and Quispe Peña, 2018). This suggests that some animal fibres might have a correlation between these two traits.

There was no correlation between the percentage of fibres with a contour ratio greater than 1.4 and the MFC of the wool sample. This suggests that the elongation and distribution of cortical cells types within a fibre does not influence the contour ratio. Wool fibres are considered to be the most cylindrical of animal fibres (McGregor and Quispe Peña, 2018), and as a result, there is limited literature about the influence of cortical cell morphology on the ellipticity of wool fibres.

In goats, McGregor and Liu (2017) suggested that changes in the thickness of the cuticle scales, not variation in cortical cell morphology of a fibre, affects the ellipticity of a cashmere fibre ($p < 0.05$). They further suggested that cuticle scale morphology was influenced by animal nutrition and that well-fed goats have greater cuticle thickness and a more elliptical fibre cross-section, than goats fed at maintenance or below. Champion and Robards (2000) suggested that nutrition influenced the ellipticity of Merino, Romney and Australasian speciality carpet wool breeds (Carpetmaster, Drysdale, Elliotdale and Tukidale), with increased ellipticity of fibres coinciding with increased seasonal nutritional levels for the animals. Their study did not differentiate between the cell components and their correlation with nutritional levels and fibre ellipticity. As the study did not differentiate between the cell components, it limits the conclusions that can be drawn. Wool fibres have thicker cuticle scales compared to cashmere, and whilst variation in the cuticle scale thickness may influence the ellipticity of wool fibres, other research suggests that this does not hold true for alpaca fibre (McGregor and Quispe Peña, 2018). It may therefore be a species-specific trait.

There was no correlation between the percentage of fibres with a contour ratio greater than 1.4 and the FDSD. This was an unexpected result as higher ellipticity was expected to increase the variability in fibre diameter (McGregor and Liu, 2017). However, FDSD was moderately correlated with the standard deviation of contour ratio ($r = 0.387$, $p < 0.05$). This suggests that the variation in fibre diameter around the mean value does indicate variation in the contour ratio of individual fibres within a sample. Greater variation in the contour ratio of fibres may contribute to the bimodal distribution of wool fibre diameter observed for some wool samples, with the influence of contour ratio on FDSD decreasing as MFD decreases. This idea has not been explored in any of the literature.

The lack of correlation between the percentage of fibres with a contour ratio greater than 1.4 and the MFD, MFC and the FDSD suggest that it is impossible to estimate the contour ratio of fibres from current objectively measured wool fibre attributes. The lack of correlation would suggest that the factors which influence the contour of a fibre are not strongly related to the factors that influence MFD, MFC or FDSD.

Fibre diameter and curvature

The results obtained in this study did not indicate a correlation between MFD and MFC. This was an unexpected result as the literature suggests that for Merino wool as fibre diameter decreases, fibre curvature increases (Fish *et al.,* 1999; McGregor and Toland, 2002; Liu *et al.,* 2004). The highest correlation coefficient between MFD and MFC was suggested by Liu *et al.* (2004, r^2 = 0.81). However, McGregor and Toland (2002) only demonstrated a weak correlation between MFD and MFC (r = 0.26, $p < 0.001$). Fish *et al.* (1999) also demonstrated a correlation between MFC and MFD of Australian wool lots, but the authors gave no correlation coefficient. They did demonstrate that there is a large variation in the fibre curvature of a group of fleeces of given fibre diameter.

The Merino rams in the present study had a small range of MFDs (17.5 µm to 22.0 µm), and hence the variation in fibre curvature for multiple samples of any given fibre diameter may have influenced the strength of the relationship between the MFD and the MFC.

Predictors of mean handle assessment

At a 95% confidence level, there were differences in the mean handle assessments of different Merino wool samples. Mean handle assessment was not correlated with the percentage of fibres with a contour ratio greater than 1.4. However, there was a moderate correlation between the mean handle assessment and the standard deviation of contour ratio (with the mean handle assessment decreasing as the standard deviation of contour ratio increased). This suggests that variation in the contour ratio of fibres in the sample has influenced the human tactile perception of individual wool samples.

Cylindrical fibres have a uniform radius, whereas elliptical fibres have both a major and minor radius. The minor radius requires less inertia to induce a bend in a fibre than the major radius. For example, a human hair is often elliptical in shape, and it has been demonstrated to preferentially bend along the minor radii (Wortmann and Schwan-Jonczyk, 2006). McGregor and Liu (2017) queried whether this concept may hold true for cashmere fibres and that the greater relative softness of cashmere fibres, compared to superfine Merino wool, could be because of the greater ellipticity of the cashmere fibres.

In the present study, there was one outlying Merino wool sample. This sample (LD1-3-8) was considered an outlier in a box plot distribution of the mean contour ratio data. The wool sample from this ram had a mean contour ratio of 1.41 and 50% of fibres with a contour ratio greater than 1.4. The original hypothesis of the experiment suggested that this sample should have a harsher handle, but the mean handle assessment of LD1-3-8 was 6.8/10, placing it in the 3rd quartile for mean handle assessment. This finding suggests that the original hypothesis did not hold true and that this sample may be preferentially bending around the minor radius of the fibre, increasing the perception of softness by the assessors.

To increase the softness of handle overall, a certain percentage of the fibres in a sample would need to have a contour ratio large enough to induce bending around the minor radius. This concept would only improve the handle assessment for a specific range of MFDs, as at a given point the minor radii would exceed the micron threshold at which the assessor can observe a prickle sensation from the fibres.

The mean handle assessment of the wool samples was moderately correlated with MFD, with a regression analysis suggesting that 34% of the variation in mean handle assessment could be explained by variation in MFD. As the MFD increased, there was a decrease in the mean handle assessment of the wool fibre sample (i.e. they felt rougher). The correlation between MFD and mean handle assessment was an expected result because as the diameter of a fibre decreases the effort required to induce a bending or compression of a fibre decreases as explained by 'Euler's Buckling Theory' (Naylor *et al.,* 1992).

There was a moderate correlation between the mean handle assessment and the standard deviation of handle assessment of a wool sample. In this experiment, as the mean handle assessment of a wool sample decreased, the variation in the handle assessment of individual assessors increased. This would suggest that people have different thresholds for considering a fibre sample to be prickly, but it also suggests that there may be a threshold of MFD at which the human hand is incapable of discerning differences between samples of wool with varying MFD. This was not an unexpected finding as the MFD of a wool sample is known to influence that perception of prickle factor by individuals, and it is conceivable that overall softness of handle would demonstrate a similar threshold concept.

Variation in assessor response

At the 95% confidence level, there were differences between the mean handle assessments from individual assessors across the wool samples. This was an expected finding as literature has stated that there are differences in the thresholds at which an individual perceives something to have an unpleasant sensation against the skin (Gwosdow *et al.,* 1986; Peters *et al.,* 2009; Cottle and Baxter, 2015).

One source of variation in these thresholds is the gender of an assessor. Gender been demonstrated to influence the perception of handle by the fingertips but only as a consequence of the relative difference in the size of human digits (Peters *et al.,* 2009). Females are likely to have smaller digits, and it has been suggested that smaller digits have a denser arrangement of tactile receptors per unit of area. This enables them to perceive finer tactile stimuli more easily (Peters *et al.,* 2009). Given this, an assessor with smaller fingertips would have a lower threshold at which they could distinguish the feeling of grainy or prickly sensations against the skin when compared to someone with larger fingertips. This supports the finding that the variation in the mean handle assessment increased as the mean handle assessment of the wool samples declined.

This trial collected handle assessment data from 17 male assessors and 13 female assessors. To the reduce variation in the handle assessment, as a consequence of hand size, it could either be conducted with just one gender or be analysed to see if there was an effect of gender or hand size on the handle assessment results. Age may also have affected the variation in handle assessment, as the ability to discern touch decreases with increasing age (Skedung *et al.,* 2018). To remove this variable from influencing the handle assessment there would need to be a reduction in the age range of assessors, as in this study, the age range was greater than 40 years.

Cottle and Baxter (2015) suggested that the micron at which most people will not perceive a wool sample to be prickly is 21 µm or less. McGregor *et al.* (2015a) suggested that at 17.5 µm is the threshold at which prickle sensation is generally not distinguishable by an individual. However, these micron thresholds are averages and are reliant on ‘normal conditions’. Normal conditions were described by Stanton *et al.* (2014) as being representative of an air-conditioned office, with a temperature of 23 °C ± 0.5 °C, a relative humidity of 45% ± 5%, and that the assessor was not undertaking physical activity.

Increases in temperature and moisture, as a result of climatic conditions or changes in physical activity, are known to influence how the human skin perceives touch, and therefore unpleasant prickle sensations from a fibre (Cottle and Baxter, 2015; Hollies *et al.,* 1979). Moisture on the skin surface increases at higher temperatures, at higher relative humidity and at an increased level of physical activity because humans sweat to dissipate heat from the body. Gwosdow *et al.* (1986) suggested that an increase of skin wetness correlates positively with a decrease in the perceived handle of a fabric. Increased wetness of the skin increases friction between the skin and the fabric, increasing the perception of roughness (Gwosdow *et al.,* 1986). Variation in the sensitivity of the human tactile receptors, as a consequence of changes in the assessment conditions, may explain some of the variation in the assessment of handle by assessors.

In the present study, the wool handle assessments were completed over a series of days and were not conducted under standardised conditions. There was variation in the temperature at which the assessments were completed, reflecting the climatic conditions and the time of day at which the assessment was conducted. Research suggests that temperature, relative humidity and wetness of skin all influence an individual's perception of handle at any one time (Hollies *et al.,* 1979; Gwosdow *et al.,* 1986; Cottle and Baxter, 2015).

Influence of non-wool constituents

In the present study, the wool samples were scoured by hand using a non-IWTO approved method. As a result, there was a risk of increased variation in the efficacy of the scouring process to remove all non-wool constituents. This was evident with a visual inspection of the wool samples following scouring, as there was still vegetable matter (VM) present in some of the wool samples. The EM images provided closer detail of the possible grease content of the wool samples following scouring. The wool samples that were perceived to still have higher grease content after scouring produced EM images that were 'gluggy'.

Roberts (1956) completed a study that compared the handle of sheep wool (18.0 – 27.2 μm, breed not stated) in both the greasy and scoured states as perceived by 10 assessors of varying experience. Whilst no significant effect of yield or non-wool components on the handle assessment was found, Roberts (1956) suggested that the relative amount of wax, dirt and suint in the wool was influencing individual handle assessment to varying degrees. Roberts (1956) hypothesised that increased suint content would mask the feel of the fibres from the assessor and that dirt content would influence the tactile assessment of the grainy feeling perceived by the assessor. This concept was supported by the findings of Preston *et al.* (2017), who suggested that when assessing greasy wool handle, non-wool constituents negatively impact on the consistency of an assessor's appraisal of handle, when compared with assessing scoured wool.

The climatic conditions under which the assessments were conducted in the present study could also have magnified the influence of non-wool constituents on the perception of handle. When a greasy wool sample is warm, the grease will appear smoother to touch and may mask an assessor's perception of handle of the wool fibres. This creates a confounding effect on the assessment of handle by an individual as warm conditions also increase the sensitivity of an assessor's sense of touch (Gwosdow *et al.,* 1986; Stanton *et al.,* 2014). Whilst it is impossible to isolate the two factors from each other, it is possible to minimise their effect on the handle assessment by changing how the experiment was conducted. The trial would need to be completed under standardised climatic conditions, and preferably for all assessors to undertake the survey at the same time.

Wool yield is the percentage of a greasy wool sample that remains after all impurities, such as suint and vegetable matter (VM), have been removed from the wool sample and it is a strongly heritable trait ($r^2 = 0.58$; Wuliji *et al.,* 2001). Some of the 28 Merino rams included in the present study were related through having a common sire or grand-sire. This increases the likelihood that pedigree might be affecting the results. For example, both samples with the sire H42 had gluggy looking images (H42-143 and H42-167), even after the scouring process had been completed. It was concluded that 'gluggy' wool samples were a potential source of error in this study as the higher grease content prevented the fibre ends from presenting a distinct circumference in the EM images (Figure 5-1).

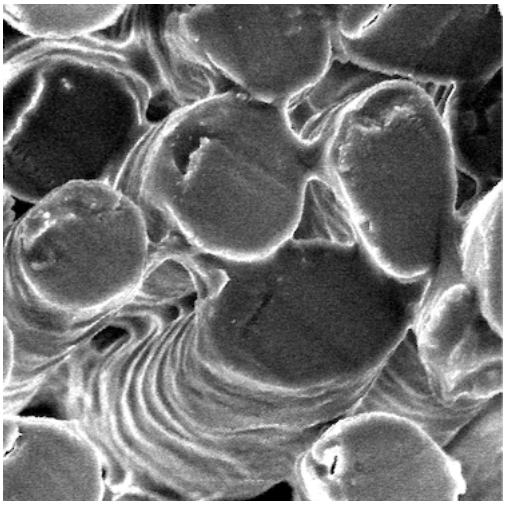

Figure 5-1: 'Gluggy' appearance of Merino wool fibres as seen on the EM image of ram H42-143.

Since all wool samples were subject to the same scouring conditions, a wool sample that had more grease or suint content prior to scouring may not have scoured as well as a wool sample that had a lower grease or suint content prior to scouring. Future studies may also benefit from repeating the scouring process to remove more grease from the wool samples, with this hopefully reducing variation in grease content across the wool samples.

Limitations to the electron microscope analysis

Wool fibre cross-section

Wool is a hard α-keratin protein, and consequently, it is difficult to cut a wool fibre. When fibres are hard to cut, it can damage the fibre, potentially limiting the ability to discern the true fibre cross-sectional shape. Hard to cut fibres can be identified in the EM images as they do not present a 'clean' cut fibre end (Figure 5-2).

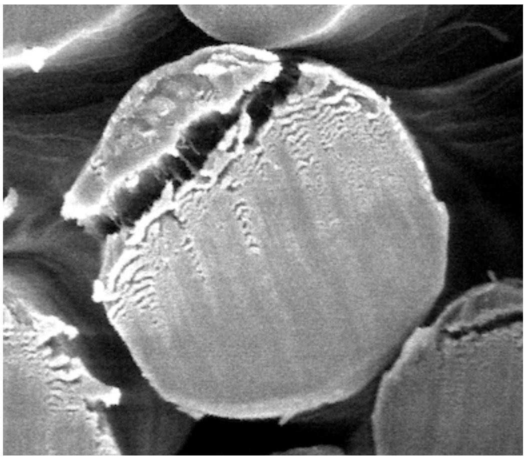

Figure 5-2: Damage to a NZ Romney wool fibre during the EM preparation process as seen on the EM image

Failure to cut fibres cleanly could have affected the measurement of the cross-section of the fibres (Champion and Robards, 2000). In the present trial, fibres that were visibly damaged were not measured, but there is a chance that fibres that were only slightly damaged would not be picked up by eye, introducing a human error into the analysis of the EM images. The occurrence of damaged fibres was most common in the NZ Romney wool samples, a likely consequence of their larger fibre diameter compared to the Merino wool samples. Increased ellipticity of the wool sample could be the result of the fibre cross-section not being cut perpendicular to the length of the fibre (Figure 5-3). These fibres were also excluded from the analysis if they were detected.

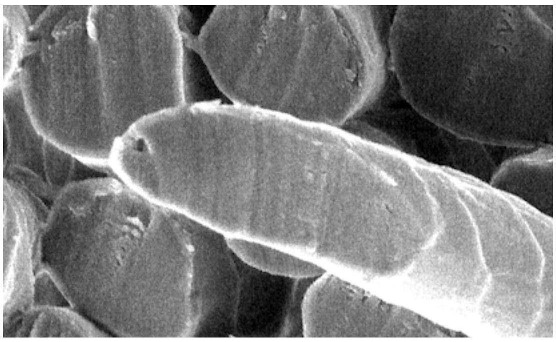

Figure 5-3: A Merino wool fibre that was not cut perpendicular to the length of the fibre during the EM preparation process as seen on EM image.

Identification of minor radius

Wool fibres are generally considered to be elliptical rather than cylindrical, but there is still considerable variation in the shape of many fibres (Sommerville, 2001) (Figure 5-4).

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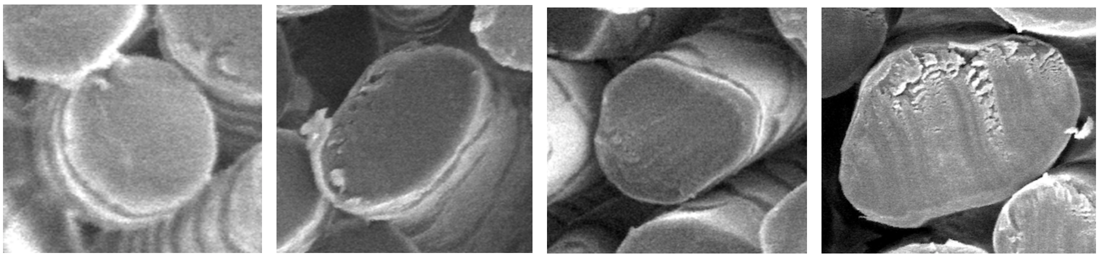

Figure 5-4: Variation in the cross-sectional shape of wool fibres presented in diagrammatic form (Sommerville, 2001), with the variation in cross-section shapes found in the Merino wool fibres in the present study.

EM image analysis of the wool samples found fibres that conformed to all of the shapes suggested by Sommerville (2001) (Figure 5-4). Whilst the identification of the major radius is straightforward, the variation of fibres from an elliptical or circular cross-section makes it hard to determine what the minor radius of the fibre is. Ideally, the minor radii should still pass through the centre of the fibre cross-section, but for some fibres, this would not produce a measurement representative of the fibre cross-section. However, if these fibres were removed from the analysis, then the results would be non-representative of the variation in shape found in the wool sample.

Future analysis of wool fibre shape may benefit from creating a set of measurements orientated for each of the fibre shapes presented in figure 5-4. This should be undertaken before commencing analysis to try and decrease the variation in the measurement of the fibres, producing a more accurate representation of the overall contour ratio of a fibre. Overall, this will always be problematic because wool is a natural fibre, and hence fibres that are variations of these basic cross-sectional shapes will likely always exist.

Differentiation of cell types

The electron microscope images analysed in this experiment were taken at a magnification of 1000x. This magnification did not allow for the differentiation of cell components, instead only producing an image representative of the overall shape of the fibre. Research has suggested that variation in the thickness of cuticle cells is what drives the elliptical shape of cashmere fibres (McGregor and Liu, 2017). McGregor and Liu (2017) suggested that cuticle scales were sensitive to levels of nutrition, with well-fed animals having thicker cuticle scales and more elliptical fibres.

If the EM images did allow for differentiation of cell components, a correlation between variation in cell components and the ellipticity of a fibre may have been found.

Diameter distribution histograms

The Pastoral Measurements Limited analysis of the wool samples using the FibreScan instrument produced diameter distribution histograms for each wool sample. In the NZ Romney wool samples, four of these histograms (R-686, R-719, R-789 and R-820) were bimodal in their distribution. A bimodal distribution suggests that there is considerable variation in the diameter of individual fibres within the sample. This variation could be the consequence of some fibres within the sample having large contour ratios. However, other possible sources of variation in fibre diameter are the change in diameter along the length of fibres or the ratio between primary and secondary follicles on the skin.

Carter and Clarke (1957b) suggested that primary follicles tended to produce fibres that were of a higher mean diameter than secondary follicles in an assortment of mid-micron and strong wool breeds. The Romney Marsh included in Carter and Clarke's study were suggested to have a secondary to primary follicle ratio (s/p ratio) of 4.1 – 8.2 and the fibres produced from their secondary follicles were finer than fibres produced by primary follicles (28.8 – 39.2 µm and 29.5 – 46.8 µm, respectively). Dick and Sumner (1995) found that in Perendale ewes, fibres grown from primary follicles had a higher MFD than fibres grown from secondary follicles (37.4 µm and 31.9 µm, respectively; $p < 0.001$).

The bimodal distribution of the NZ Romney wool sample histograms may be a result of the differences in fibre diameter between the two fibre types. The lower fibre diameter of secondary fibres, compared to primary fibres, would suggest that the left-hand peak (lower fibre diameter) would be higher than the right-hand peak due to the greater number of secondary fibres suggested by the s/p ratios reported by Carter and Clarke (1957b). However, this was only observed for R-719 (Figure 5-5), and not for R-820 (Figure 5-6).

The rams R-686 and R-719 had mean contour ratios of 1.40 and 1.48 respectively, and also had the most pronounced bimodality (Figure 5-5; ram R-719).

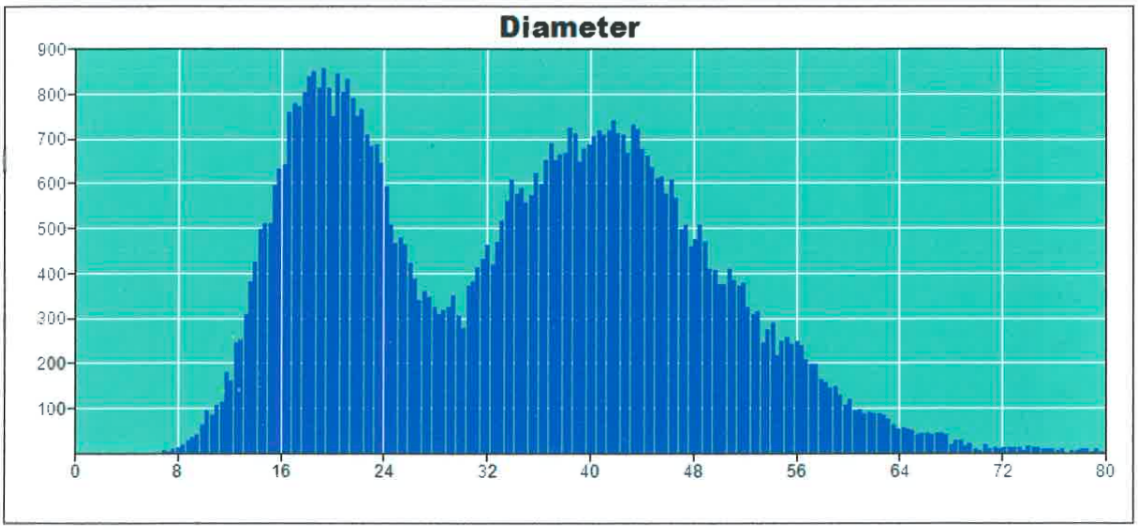

Figure 5-5: Diameter distribution histogram for the wool sample of NZ Romney ram R-719, as produced by Pastoral Measurements Limited with the FibreScan instrument.

The two NZ Romney rams (R-789 and R-820) each had a mean contour ratio of 1.28 and did not present with as strong bimodal distributions (Figure 5-6; ram R-820).

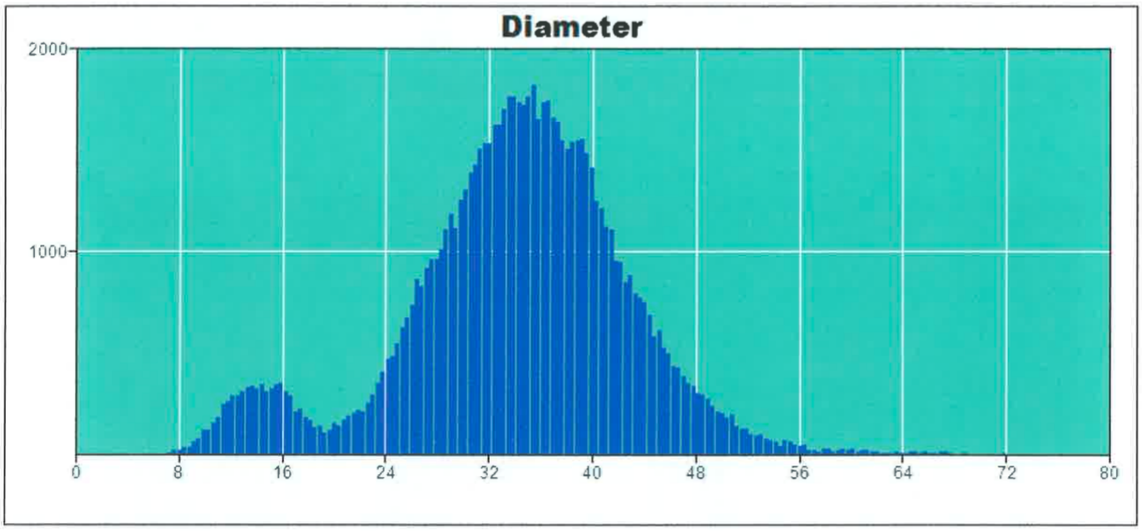

Figure 5-6: Diameter distribution histogram for the wool sample of NZ Romney ram R-820, as produced by Pastoral Measurements Limited with the FibreScan instrument.

As the mean contour ratio of a fibre decreases the difference between the major and minor radii of the fibre also decreases. This suggests that a fibre diameter distribution histogram of a wool sample with a low mean contour ratio should not present with such a strong bimodal appearance when compared with a sample with a high mean contour ratio. In this respect, the bimodal appearance of the graph for R-820 that demonstrated a contour ratio of 1.28, had a smaller low fibre diameter peak. Two NZ Romney samples, R-789 and R-820, still had a percentage of fibres that demonstrated a contour ratio greater than 1.4. However, the larger peak in the unevenly distributed bimodal graph (Figure 5-6) still has a very broad range of values within it. This suggests that the bimodality could be a result of both fibre contour ratios and secondary follicle derived fibre numbers.

It is important to note that this bimodality of diameter distribution was not obvious in the diameter distribution histograms produced for the Merino wool samples. As the MFD decreases towards zero, there will be a point at which there can no longer be a difference in the major and minor radii of the fibre. The difference between the length of the major and minor radii will decrease in value, and it will have less of an effect on the FDSD. The wool sample is then unlikely to present with a bimodal distribution in the diameter distribution graphs produced by the FibreScan instrument. For example, the Merino ram wool sample from LD1-3-8 has a mean contour ratio of 1.41, and 50% of the fibres demonstrated a contour ratio greater than 1.4. However, the diameter distribution histogram of this ram wool sample did not present with an obvious bimodal distribution (Figure 5-7), although there were small numbers of fibre diameter measurements extending to in excess of 60 μm.

Primary and secondary follicles and fibres may also influence the diameter distribution of the Merino wool sample. There is less variation between the MFD of primary and secondary follicles of Merinos compared to mid-micron and strong wool breeds (Rogers, n.d.). The ratio of secondary to primary follicles is also much higher in the fine wool Merino breed (Fine Merino s/p ratio: 11.2 – 32.8; Carter and Clarke, 1957a). These factors may influence the distribution of fibre diameter in the histograms, with the lack of bimodality illustrated in the Merino wool sample (Figure 5-7), being a consequence of the smaller difference in fibre diameter of the two fibre types, and the higher s/p ratio.

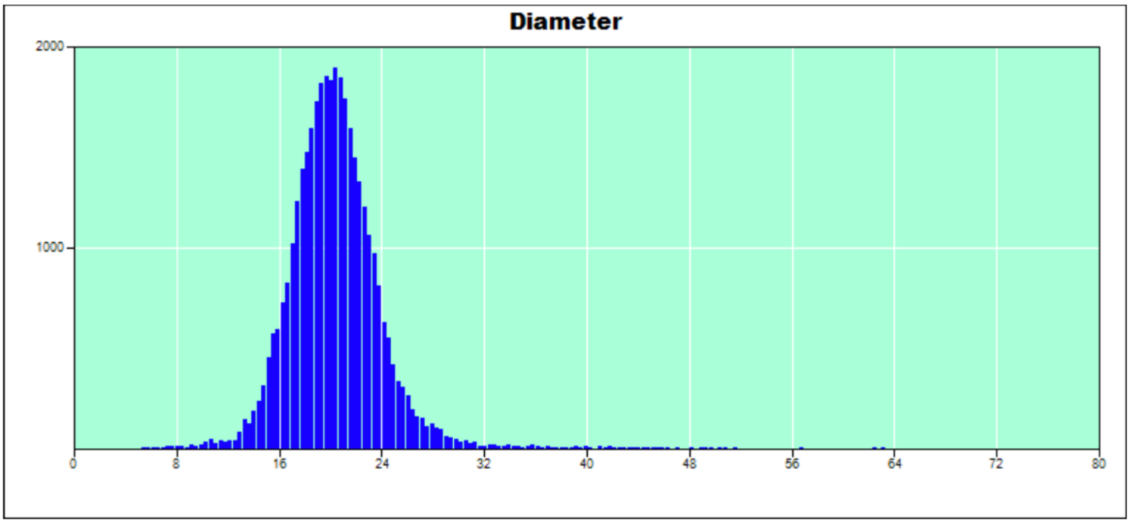

Figure 5-7: Diameter distribution histogram for the wool sample of Merino ram LD1-3-8, as produced by Pastoral Measurements Limited with the FibreScan instrument.

Decreasing the intervals between the numerical values on the x-axis may enable a bimodal distribution to be visualised, but it is more likely that as a consequence of the lower MFDs compared to the NZ Romney wool samples, the bimodal distribution may not be observed in the Merino wool samples. With the lower MFD of Merino wool fibres, the relative difference in the major and minor radii is sufficiently small not to cause an obvious bimodal fibre diameter distribution histogram.

At an MFD of 33.6 µm, a contour ratio of 1.4 could produce a difference of 9.5 – 13.5 µm between the major and minor radii, but at an MFD of 19.8 µm, this difference is reduced to between 5.7 and 7.9 µm. This suggests that as the MFD declines, the variation in diameter will also decrease, decreasing the bimodality of the diameter distribution histogram and the FDSD of the wool sample. However, when MFD of the wool sample decreases, the difference between the MFD of primary and secondary fibres tends to decrease, and the s/p ratio tends to increase, potentially influencing the shape of the diameter distribution histogram as well.

6 GENERAL DISCUSSION AND CONCLUSIONS

Considerations for future research

In the present study, the mean handle assessment was only completed with fine wool samples (i.e. samples had an MFD of less than 22 µm). Using fine wool samples limited the scope of the project as the majority of the wool samples fell below the threshold of 21 µm for use in next-to-skin clothing. At a micron below 21 µm, there is unlikely to be substantial variation in the handle assessment of the samples across the general population, hence why it can be used in next-to-skin clothing.

A future research opportunity would be to repeat this experiment but to use mid-micron fleeces such as Corriedale wool for the analysis. Arguably, mid-micron is the wool class that would benefit the most from research into wool handle. Mid-micron wool is not used in next-to-skin clothing, but it is used in outerwear so, at times, it will come into contact with the skin. If contour ratio could be used to predict the handle of mid-micron wool, it would help to reduce the variation in the handle assessment of mid-micron wool sold for clothing, increasing its 'fit for purpose' in the textile industry.

Analysis of the fibre diameter distribution histograms suggests that contour ratio may affect fibre diameter distribution in strong wool but does not visually affect the diameter distribution of fine wool. As wool fibre gets finer, it approaches an asymptote, at which the diameter distribution will not be affected by contour ratio. The inclusion of mid-micron wool samples into a study may provide a better understanding of the micron at which bimodality ceases to visually affect the diameter distribution of a wool sample.

General Discussion

The results of this project suggest that the contour ratio of Merino wool fibres cannot be used to predict the handle of Merino wool samples. The only variable included in the analysis that could be used to predict the handle of wool samples is the MFD of the wool sample. There was no correlation between the percentage of fibres with a contour ratio greater than 1.4 and the MFD, MFC or FDSD of the samples, suggesting that there are no current objectively measured traits that can be used to predict wool fibre contour. All of the wool samples used in the analysis were between 17.5 µm and 22 µm, which limited the variation in handle assessment. One Merino wool sample (LD1-3-8) had a high mean contour ratio (1.41) but also presented with a mean handle value of 6.8/10, suggesting that highly elliptical of wool fibres may induce preferential bending around the minor axis of the fibre, producing a sample perceived as softer than average for a given MFD.

The variation in assessor responses across the range of wool samples presented highlights the complexity of developing an objective measurement, for something that will ultimately be subjectively measured by the consumer. Variations in the gender, the climatic conditions or end-use of a garment by the consumer will all have a substantial influence on the perceptions comfort, suitability or softness of the garment. The influence of cultural norms or previous experience with wool products on handle assessment must also be taken into consideration, further complicating the ability to measure handle objectively.

Ideally, this experiment would need to be repeated with mid-micron wool samples to obtain a wider range of values in handle assessment. There would be little benefit of using the NZ Romney strong wool samples in handle research as they are not used in clothing, and in general, will all be perceived as grainy, prickly or rough against the skin. The NZ Romney wool samples were used in this project to determine if contour ratio may visually affect a fibre diameter distribution histogram. The findings of this study suggest that in NZ Romney wool samples, bimodality decreases with decreasing mean contour ratio of the wool sample. However, variation in fibre diameter along the fibre profile and differences in the diameter of primary and secondary fibres may also be driving the bimodality of the diameter distribution histograms.

The benefit of obtaining an objective measurement that can be used to help predict the handle of wool fibre is not to achieve 100% consumer satisfaction of woollen garment handle, but it is to decrease the percentage of consumers that are not satisfied with the feel of a garment against their skin. Increasing the number of satisfied consumers increases the demand for future products.

Conclusions

- Handle assessment of fibre, or fabric is an important attribute in the development of next-to-skin clothing as it can influence consumer purchasing behaviour.

- Handle is a complex phenomenon to assess, and consequently, there is a large variation in the assessment of handle by individuals, with this likely influenced by temperature, humidity, age, gender and cultural behaviours. This limits the success of employing objective methods to determine fibre handle.

- The MFD accounts for 34% of the variation in handle assessment of wool fibre samples (CL = 95%). The MFD often dictates the handle assessment by a consumer because of its effect on the textural and compressional attributes of a fibre, with lower MFD wool samples perceived as softer.

- Contour ratio may be visually affecting the distribution of fibre diameter around the mean value in a diameter distribution histogram in NZ Romney wool samples, suggesting a correlation between FDSD and contour ratio in NZ Romney wool samples. However, differences in the number of primary and secondary fibres within the wool sample may also be producing this effect.

- Contour ratio had a minor effect on the handle assessment of fine wool samples (i.e. samples with an MFD of less than 22 μm). However, high fibre contour may induce preferential bending around the minor axis of the fibre, producing a wool sample that is perceived as softer by an assessor compared to others of the same MFD.

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APPENDICES

Appendix A – Handle assessment of individual assessors for each Merino wool sample.

Individual Assessor Handle Ratings																														
	Assessor no.																													
Tag Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
ALF1-11-18	9	7	6	8	8	7	7	6	8	6	9	10	9	4	3	10	7	4	3	8	8	8	4	5	6	4	7	8	7	6
H42-143	7	8	7	7	8	3	6	4	6	2	3	6	8	6	3	8	7	5	5	8	5	8	8	4	2	4	7	6	8	7
H42-167	9	9	9	10	9	6	8	3	8	3	7	7	8	8	8	8	5	9	7	8	6	8	7	6	6	7	7	6	7	7
H51-173-193	7	8	7	8	7	3	5	5	6	5	6	6	6	4	6	10	6	7	4	6	5	8	4	6	6	6	7	7	9	7
LD1-3-62	9	8	8	8	8	9	8	9	9	8	7	9	10	3	8	9	8	5	6	8	8	9	8	7	5	6	7	8	7	7
LD1-3-8	8	8	6	9	8	5	5	7	7	2	5	8	9	5	5	7	5	6	7	7	8	8	7	7	8	9	7	8	7	6
M14-152	5	6	6	6	7	3	4	3	4	2	6	8	8	5	4	8	5	6	6	8	7	4	8	3	4	4	6	7	8	6
M14-152-2	5	7	6	8	7	7	5	5	3	2	4	5	9	2	3	8	5	3	4	6	7	7	5	9	2	3	3	7	6	6
M14-152-49	8	9	8	9	10	7	10	9	10	8	7	7	9	9	7	8	5	7	9	7	9	10	10	7	9	9	7	7	9	5
M152-49	8	8	9	9	9	5	10	9	9	3	8	8	9	8	8	10	6	8	7	9	7	8	8	5	8	9	8	6	8	7
M19-12-93	6	8	9	9	7	8	6	7	6	7	7	8	8	3	5	7	8	5	4	7	6	8	7	8	3	4	7	8	8	7
M21-17	8	9	10	9	10	9	7	9	9	3	8	4	7	8	6	9	6	6	7	7	8	9	8	5	6	7	10	7	8	8
M21-2-150	8	8	7	8	8	6	8	5	8	3	7	7	7	3	3	7	7	7	5	6	6	7	8	5	3	4	4	8	7	5
M21-5	8	8	6	7	7	7	5	8	5	2	5	7	8	4	3	7	5	5	4	10	7	4	3	8	7	9	8	8	8	6
M22-5	8	8	8	9	8	6	7	8	8	6	6	7	9	9	9	9	8	8	7	10	9	10	8	6	6	7	9	7	9	7
M307-68-155	7	8	8	7	7	6	3	4	4	4	4	8	10	4	4	9	7	5	6	10	7	8	6	7	6	7	7	6	8	6
M446-170-81	7	9	8	7	9	3	8	4	7	6	5	9	8	2	6	7	6	6	6	9	8	7	7	7	5	6	10	6	8	7
M446-170-9	8	9	7	9	9	2	8	4	6	6	6	7	8	4	7	7	7	6	3	6	6	8	8	9	3	6	6	7	8	5
M446-19-100	7	6	4	8	6	8	3	3	6	2	6	6	8	6	6	9	8	6	6	9	8	7	6	6	5	6	9	7	6	5
M446-85-54	8	10	9	9	8	10	9	7	3	7	5	8	9	6	9	8	6	7	9	8	7	10	9	7	10	7	8	8	8	6
MDP-4	6	9	6	6	8	7	8	5	7	7	7	9	8	9	6	9	7	8	8	9	9	8	10	8	8	8	9	7	6	7
MDP3-68	8	8	7	6	9	7	6	7	7	3	7	4	9	8	7	9	7	8	8	9	8	9	7	6	7	8	8	8	7	5
MVP1-5	6	7	8	8	10	5	8	8	10	5	8	5	8	3	4	8	6	6	3	7	6	7	7	6	3	4	6	6	6	5
RP1-9-9-6	6	8	8	9	7	7	8	7	4	3	6	8	7	3	6	6	6	4	7	10	8	7	9	8	6	6	4	7	8	8
SHC-177	9	7	7	9	8	9	7	3	5	9	8	8	8	6	7	9	7	6	4	8	10	10	4	7	8	8	9	8	9	6
SHC-26-43-140	9	10	9	9	10	8	9	7	9	7	7	8	9	9	10	9	7	6	8	10	10	9	9	7	8	10	8	7	8	6
SHC26-43-6	7	8	8	7	7	5	6	6	5	9	5	7	8	8	8	9	6	7	6	8	5	9	8	6	7	7	7	7	8	5
SHM-42	7	10	7	9	9	10	9	6	9	6	9	8	9	7	9	8	6	9	8	7	9	9	10	8	9	10	8	7	7	8
SHM-42a	8	8	9	9	9	9	10	8	6	6	9	7	9	7	7	8	8	7	6	9	8	8	7	6	6	7	8	8	8	8