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CRITICAL LITERATURE REVIEW OF FABRIC HANDLE

CRC SII Project 2.3.1

MILESTONE REPORT

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Critical Literature Review of Fabric Handle

Abstract

In this report, literature of fabric handle since 1990 was critically reviewed with aim of guiding decisions within the Cooperative Research Centre for Sheep Industry Innovation (CRC SII) project, Project 2.3, Handle of Merino Wool Fabrics. Technical and commercial gains can be made through the application of known fabric handle technologies to light weight (<200gm^{-2}) wool knitted fabrics. Investigations can be directed to isolation of the orthogonal fabric handle characteristics, e.g., coolness to touch, stiffness, for selected markets applicable to light weight wool knitted fabrics, e.g. sports active leisure wear, lingerie. Subjectively assessed orthogonal handle characteristics can be related to physical properties of fabrics which can be measured. KESF testing represents a benchmark in technically interpreting any new subjective handle characteristics. The PhabrOmeter instrument, which uses the pulling force method, is cheaper, faster, and simpler than the KESF and is recommended for measurement of fabric properties for the Handle of Merino Wool Fabrics project.

There are a number of wool fibre properties other than diameter and curvature which could influence fabric handle, notably fibre surface friction. Quantification of the variation in these properties amongst the Australian Merino clip may provide a basis for genetic improvement of these properties.

The physiological mechanisms by which fabric handle sensations are perceived involve the interaction of complex muscular manipulation and perception by different mechanoreceptors. A better understanding of these mechanisms would lead the way to improved development of fabrics with desirable handle.

1 Background

1.1 Why Study Fabric Handle?

Apparel purchasing behaviour uses two main human senses, sight and touch, while occasional use is made of hearing and smell. Touching using the hand is termed by the industry as 'handle' or hand feel. Decisions about fabric handle are made at a number of stages in the wool apparel supply chain. In particular fabric designers and manufactures, fabric agents, garment designers and retailers all influence the handle of fabrics available to the consumer. Retailers recognise the importance of handle for its sensory aspect as well as formability, aesthetics, drapability and tailorability, and strive towards putting appropriate handling garments on their shelves (Philippe et al., 2003). However, retailers lack confidence in assessing fabric handle as they lack a stable testing system to screen garments for handle attributes before a garment is put on the shelf.

Since fabric handle can be modified by changes to fabric finishing, fabric structure, yarn structure and fibre characteristics, fabric manufacturers have the equipment and raw materials to produce fabrics with great variation in fabric handle. However, retailers, clothing designers, fabric agents, fabric manufacturers and their suppliers can experience difficulty in communicating about fabric handle, particularly when they are not in a face-to-face meeting, and require a more comprehensive set of tools that can improve communication about fabric handle.

Provision of these 'tools' would:

- provide these supply chain partners with a clearer statement of consumers' desires in relation to fabric handle;
- give fabric designers access to improved tools for product development; and,
- offer manufacturers a more objective means of quality control.

1.2 Fabric handle and the development of objective measurement

Quality and performance of fabrics are commonly assessed subjectively by experienced fabric experts for quality control in manufacturing and by consumers in apparel market. Fabric handle, or fabric hand, is one of the major attributes in the assessment of fabric quality and is briefly "the human tactile sensory response towards fabric" (Pan, 2006) or "a psychological reaction obtained from the sense of touch" (Raheel and Liu, 1991b). The assessment involves a complex process (Peirce, 1930, Pan, 2006) which combines influences from:

- o Physics;
- o Physiology;
- o Psycho-physics; and,
- o Personal experience and cultural background

The development of objective measurement of fabric handle (OMFH) is based on an essential assumption that fabric handle attributes can be predicted based on measured fabric properties. In order to establish reliable methods for quantifying subjective judgments, Postle (1989a) precisely defined OMFH such that "a necessary and sufficient set of instrumental measurements be made on fabrics in order to specify and control the quality, tailorability, and ultimate performance of apparel fabric."

Intensive research of fabric handle has been conducted since early 1980s, not only on men's suiting but also on other fabrics including knitted and non-woven fabrics. There were the following critical international symposia and seminars devoted to the technology of fabric handle in all related areas:

- The First Japan-Australia Symposium on Objective Specification of Fabric Quality, Mechanical Properties, and Performance, Kyoto 1982. (Kawabata et al., 1982)
- The Second Japan-Australia Symposium on Objective Evaluation of Apparel Fabrics, Melbourne, 1983 (Postle, 1984).
- The Third Japan-Australia Symposium on Objective Measurement: Applications to Product Design and Process Control, Kyoto 1985 (Kawabata, 1986).
- A seminar on "Fabric Objective Measurement Technology: Application in the Textile and Clothing Industries", Hong Kong, 1989 (Curiskis, 1989, Harlock, 1989a, Harlock, 1989b, Postle, 1989a, Postle, 1989b, Postle, 1989c)
- The First Bradford International Clothing Conference on "Textile Objective Measurement and Automation in Garment Manufacture", 1990, Bradford, England (Stylios, 1990).
- The Second Bradford International Clothing Conference on "Objective Measurement Technology in the Textile and Clothing Interface" , 1992, Bradford, England (Stylios, 1992).

The major achievements both in knowledge of and instrumentation for fabric handle evaluation include that:

- Benchmark samples were established for men's and women's woven fabrics suiting.
- The components of subjective fabric handle were quantified for men's and women's suiting.
- The measurable fabric mechanical and surface properties related to fabric handle were quantified for certain types of fabrics.
- An objective measurement system called Kawabata Evaluation System for Fabrics (KESF) was developed under the auspices of the Textile Machinery Society of Japan.
- The second objective measurement system called Fabric Assurance by Simple Testing (FAST) was developed by CSIRO of Australia.
- A prototype of the fabric extraction objective measurement system called PhabrOmeter has been developed and is being marketed by NU Cybertek of USA.

1.3 Subjective evaluation of fabric handle

Subjective evaluation of fabric handle (SEFH) is the evaluation of fabric handle and quality by people without using any testing instrumentation. There are two processes involved in SEFH: the first is the psychophysical evaluation to the individual object; the second is the hedonistic choice (ranking) of the objects. Alternatively, Na and Kim (2001) particularly separated the complex process into two steps, hand and sensibility, in the handle evaluation of woven silk fabrics.

Successfully specifying and quantifying the SEFH components are essential to develop an OMFH system. Based on psychophysical evaluation of fabric handle for a certain type of fabric, SEFH should provide consistent results from individual judges from the viewpoint of statistics. Therefore, before doing SEFH, the following elements should be clearly defined:

- Fabric type
- Judges
- Assessment conditions
- Protocol of handling fabric
- Criteria of judgment and scales of the assessment
- Analysis and presentation of the results

1.4 Objective measurement of fabric handle

Since fabric handle is a comprehensive psychological concept, it cannot be defined by a simple fabric property. Peirce (1930) firstly proposed to measure fabric handle using a series of objective measurement data. Since then, tremendous effort has been made in the development of OMFH systems. A very first successful system, KESF, was developed in Japan, from which the fabric primary and total handle values can be predicted from the 16 tested mechanical and surface parameters of fabrics. Following the KESF system, the FAST system was developed by CSIRO, from which fabric tailoring performance and the appearance of garments in wear can be predicted. This system can also be an alternative of the KESF system in fabric design, quality control at various processing stages, and buying quality control for garment makers.

Under consideration of the disadvantages of both KESF and FAST systems, a simple OMFH system called PhabrOmeter was developed, from which the majority of the key parameters tested by the KESF system can be predicted by a simple fabric extraction test. Moreover, this system was claimed to be able to evaluate a wide diversity of products using a selected reference fabric for different purposes (Pan, 2006).

1.5 Application of objective handle measurement

Postle (1989a) has defined the following main application areas for OMFH:

- Measurement of fabric handle and quality.
- Design and production of high quality yarns and fabrics.
- Quality control and assurance of textile processing, particularly in finishing.
- Evaluation of fabric tailorability and quality assurance in garment making.

1.6 Potential for the Next Generation Wool Quality project

Previous research has laid very sound foundations in knowledge and applications of fabric handle. The following resources are useful and valuable for the current Cooperative Research Centre – Sheep Industry Innovation (CRC SII) handle project:

- Experts available in all relevant areas, such as wool, textile, testing, psychophysical evaluation etc.
- Established and newly developed OMFH systems, such as KESF, FAST and PhabrOmeter.
- New technologies developed in human tactile, instrumentation, and information systems etc.
- New markets for wool products of high quality.

1.7 Summary

Fabric handle is one of the major attributes in the assessment of fabric quality and performance. The subjective assessment of fabric handle involves a complex process. However, the human psycho-physical perceptions are quantitatively assessable under certain well defined circumstances. The KESF, FAST (and potentially PhabrOmeter) are relatively successful OMFH systems which are commercially available for assistance in fabric handle research.

Fabric handle is not a new research concept, rather it has been investigated for several decades, particularly for men's and women's suiting. Australian researchers have made significant contributions to this area over a long time and have built up both knowledge of fabric handle and its application. Previous resources in fabric handle evaluation are worthwhile for the current CRC SII handle project and may be largely enriched through the project as well.

A focus of the Project 2.3 is to characterise handle for knitted fabric types using objective and subjective evaluation systems. These systems will provide retailers with confidence in correctly placing garments on the shelf, that exhibit desirable handle characteristics for consumers.

1.8 Aims of review

The aims of this review are to:

- Source critical achievements from previous research in fabric handle evaluation in all relevant areas;
- Summarise the advantages and disadvantages of the techniques used in the previous research;
- Recommend potential techniques which may benefit to the CRC SII handle project; and,
- Recommend follow up strategy for the CRC SII handle project.

2 Tactile perception of fabrics

2.1 Features of human tactile perception

Tactile sensors in human beings are distributed all over the skin. Tactile sensing is defined as "a system that can measure a given property of an object or contact event, through physical contact between the system and the object" (Dargahi and Najarian, 2004). When describing the tactile sensing abilities and sensors in human beings, Dargahi and Najarian (2004) in their review paper pointed out that:

- "Contrary to the visual and auditory senses, the tactile sensing does not possess any localized sensory organ. In fact, the sense of touch operates all over the skin like a distributed phenomenon."
- "Tactile sensing has a complex nature" which is "not simply the transduction of one physical property into an electronic signal, because the sense of touch assumes many forms", including "the detection of temperature, texture, shape, force, friction, pain, and other related physical properties. The relationships amongst these different tactile features are not clearly understood."
- "Unlike the visual and auditory senses, the tactile signal is not a well-defined quantity."
- The rate of adaptation is an important characteristic of tactile sensors. That is "a change in the external stimuli, such as, pressure or temperature, is responded by most human mechanoreceptor cells." "In effect, the rate of adaptation is the rate at which the mechanoreceptor pulse rate returns to normal after a change in stimulus."

2.2 Anatomy of human hand sense

Anatomical analysis of the human hand showed that (Dargahi and Najarian, 2004):

- There are three different receptors functioning in the subsystem of the somatosensory system which is associated with the skin: mechanoreceptors for pressure/vibration, thermoreceptors for temperature and nocioceptors for pain/damage.
- "Tactile receptors are located in clusters around the human skin and they look like a jelly material. When they are stimulated or squeezed in some way, the layers rub against each other causing an electrical nerve pulse to be generated."
- As Figure 1 shows the skin mechanoreceptors are comprise of Meissner's corpuscles, Merkel Disks, Ruffini Organs, and Pacinian corpuscle. The function and location of these most important mechanoreceptors are listed in Table 1.

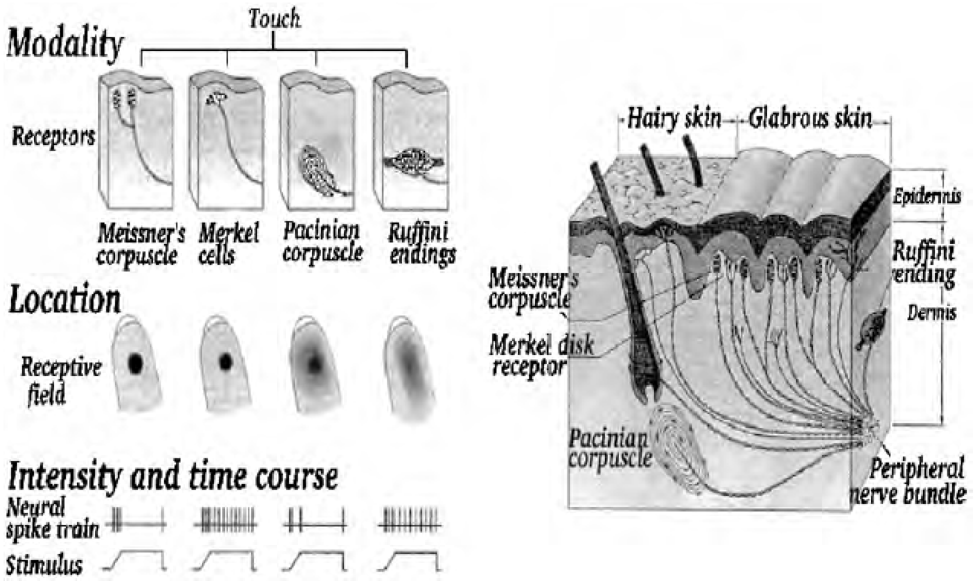


Figure 1. Mechanoreceptors distributed in human skin (Dargahi and Najarian, 2004)

Table 1. The location and function of various skin mechanoreceptors **(Dargahi, 2004)**

Name	Location	Function
Hair follicle ending	Hairy skin areas	Responds to hair displacement
Ruffini endings	Dermis of hairy and glabrous skin	Responds to pressure on skin and skin stretch
Pacinan corpuscle (PC)	Deep layers of dermis in hairy and glabrous skin	Responds to vibration
Meissner's corpuscle	Dermis of glabrous skin	Respond to motion and vibration
Free nerve endings	Throughout the skin	Different types of free nerve endings respond to mechanical, thermal, or noxious stimulation
Merkel disk	Epidermis of glabrous skin	Responds to pressure of the skin and texture

2.3 Categories and specification of hand mechanoreceptors

According to the size of receptive field or adaptation speed, the mechanoreceptors can be categorised as (Dargahi and Najarian, 2004):

- Type I: with small receptive field, and
- Type II: with large receptive field

or

- Rapid adaptors (RA),
- Moderate adaptors (MA), and
- Slow adaptors (SA).

It was also shown that "the SA I system is the primary spatial system and responsible for tactual form and roughness perception". "The PC system is responsible for the perception of external events". "The RA system is responsible for the detection and representation of localized movement between skin and a surface as well as for surface form and texture when surface variation is too small to activate the SA I afferents effectively." The electromechanical properties of the skin are related to the transduction of these stimuli in the form of electrical discharges into the central nervous system for further processing.

The features of these mechanoreceptors are listed in Table 2 (Dargahi and Najarian, 2004). In particular, the sensitivity and resolution of the human fingertip are summarised in Table 3.

Table 2. Characteristics of skin mechanoreceptors

Receptor	**class**	**Receptive field (mm^2)**	**Frequency range (Hz)**	**Receptors per (cm^2)**
Pacinian corpuscle	RA	10-1000	40-800	21
Meissner's corpuscle	MA	1-100	10-200	140
Ruffini endings	SA II	10-500	7	49
Merkel disk	SA I	2-100	0.4-100	70

Table 3. Sensory specifications of the human fingertip (Dargahi and Najarian, 2004)

Parameter	**Range**
Frequency response	1-11 Hz
Response range	0-100 g/mm^2
Sensitivity	~0.2 g/mm^2
Spatial resolution	1.8 mm
Signal propagation	Motor neurons 100 m/s Sensory neuron 2-80 m/s Automatic neurons 0.5-15 m/s

Li (2001) reports that there are a number of unknown questions that still exist about the human sensory system. Some of these questions include:

- What are the active touch movements of the hand?
- How do the active touch movements of the hand generate various types of mechanical stimuli to the touch receptors?
- How do the four types of mechanoreceptors respond to the mechanical stimuli?
- How are the neurophysiological responses from the receptors coded and transferred to the brain?
- How does the brain process the information and formulate various subjective hand perceptions?

These final two allude to the psycho-physiological and psychological aspects of perception of fabric handle.

2.4 Psycho-physiology of tactile perception

Dargahi and Najarian (2004) discussed some typical psycho-physiological stimulations in their paper. The findings are summarised in Table 4.

Table 4. Some typical psycho-physiological stimulations and mechanoreceptors

Stimulation	Status	Receptor
Force	If stimuli are held stationary	PC units; RA units SA I might code both normal and shear forces SA II units are very sensitive to tangential forces For the individual receptors, Merkel Disks responds to both compression and shear forces, and free endings are sensitive to slight pressures.
Position and size	Position Size	RA units SA I
Softness / Hardness	Vertical motion	RA units
Roughness and texture	Lateral movement: High frequency Low frequency	PC units RA units

2.5 Psychological

Psychological processes are the “processes of the brain which form subjective perception of sensory sensations from the neurophysiological sensory signals and then formulate subjective overall perception and preferences by evaluating and weighing various sensory perceptions against past memorable experiences and internal desires” (Li, 2001). Pontrelli (1990) introduced the concept of "Comfort's Gestalt" to discuss the various stimuli which result in comfort or discomfort but the same principal can also be applied to fabric handle (Barker, 2002). The psychological factors that Pontrelli considered important for comfort were state of being, end use and occasion of wear, style-fashion, fit and familiarity. Pontrelli also described factors that the mind stores which modify the psychological decision. These include past experiences, bias, expectations and lifestyle. The mind also has current factors, as opposed to the stored factors, that influence subjective perception. These include mood and outside environment (climate) (Howorth and Oliver, 1958b).

Li (2001) states that how the mind processes information from touching a fabric is unknown. However, Risvik (1996) hypothesised that human minds never perceive a product as a sum of attributes. Our minds may focus on key attributes, aggregate attributes into concepts, perceive holistic forms, or make up an iterative process with mixtures of the aforementioned. Some form of aggregation of information takes place in our information processing. Risvik’s conclusion formed that basis for Dowling and Stanton (2005) using a regression decision tree to understand consumer decision making about fabric handle as opposed to several other studies which use linear equations to represent the perception of fabric handle (Chen et al., 1992, Barker, 2002).

3 Subjective evaluation of fabric handle

The sensory methods using the human being as a subjective measurement tool fall into two main groups: hedonic analysis and sensory analysis. Hedonic analysis is the expression of a consumer preference or choice for one fabric or another. Hedonic analyses take into account fabric end use or application, and the "like" or "don't like" comments of the consumers. Although the expression of preference may subconsciously be based partly on an instinctive evaluation and integration of many fabric attributes, it must also contain elements of the individual's background and experience. Sensory analysis is the examination and quantification of sensory attributes by the sense organs, whatever the end-use domain may be and is described as a psychophysical measurement. These two approaches can be correlated in order to link the obtained sensory profile and the consumer preference 14 Philippe, F. 2003; 21 Bishop, D.P. 1996}.

3.1 Fabric type or end use

The ultimate criteria by which fabric handle is assessed vary according to the specific apparel end use. The desired set of primary handle attributes of a fabric may change from one fabric application to another. Hence fabric handle researchers clearly define the end use, or market, for a fabric before asking judges to assess handle, e.g. Kawabata distinguished between winter and summer suiting fabrics (Kawabata, 1980b).

3.2 The judges

The choice of judges used for SEFH is very important and dependent on the response required to address the aim of the study. The influence on the SEFH results from the judges may include:

- Physical conditions, including age, gender and skin type etc.;
- Knowledge in handle/experience;
- Communication and self-expression skills;
- Living region and cultural background; and,
- Tactile sensibility.

From the literature, three types of judges have been used for subjective evaluation: experts; trained; and, untrained consumers.

Experts are defined as people who reside in the fabric industry and constantly handle fabrics. Experts are used in SEFH to capture their knowledge and gain a precise estimate about fabric handle attributes of different fabrics. The knowledge of experts has been used by researchers in different ways. Kawabata (1980b) used fabric experts for his testing to determine differences between attributes of fabrics. Chen (1992) used expert knitters to develop a list of 12 primary sensory attributes which were then assessed using consumers. Gong (1995) used three experts to subjectively assess fabrics using the same criteria that they would use to assess fabrics in their factories. Gong (1995) found large inconsistencies between the three experts; however, he did not define the terms of evaluation. Howorth and Oliver (1958b) recognised from the work of Binns that skilled observers can be strongly biased by wool content of fabrics. Howorth also noted that it is very difficult to obtain a sufficiently large panel of experts that can be used on a recurring basis. This problem was also encountered by Philippe (2003, 2004).

A large amount of subjective work has been done on men's winter or summer suiting fabrics. The underlying reason is probably that suiting fabrics are relatively expensive and are of high quality. Handle properties appear to be of more importance in the market and in the manufacturing sector for suiting than for other fabrics. As a result, a significant number of experts at SEFH have expertise in assessing woven fabric handle.

Trained panels have also been commonly used in SEFH and can be defined as people who have undergone hours of training, such that they are all scoring the same attributes and are aligned in their scores of those attributes. The University of Mulhouse spent hours training ordinary people to become part of an trained panel such that all panel members were calibrated and precise in both language and hand movements (Philippe et al., 2003, Cardello et al., 2002, Philippe et al., 2004). Wang et al. (2000) used this model by fully explaining the scale and defining descriptors to the participants before testing. This method brings people onto a level knowledge set while not training them to become experts (Cardello et al., 2002).

Harlock and Ramkumer (1997) pointed out that while using an expert or trained panel delivers a procedure with good quality control, the final judges of a fabric are consumers and he thought it logical to undertake fabric evaluation using consumers. Barker(2002), Stanton et al. (2004), Thompson et al. (2005), Chen et al. (1992) and Fritz (1990) have all used untrained consumers to evaluate fabrics. Bishop (1996) believed that consumers use a process that they know best and are capable of making objective, quantitative and repeatable assessments of fabrics. Barker (2007 personal communication) also believed that by using consumers an accurate retail result can be interpreted from the fabric evaluation.

The selection of the type of judge to use for a trial depends on the objective of the trial. In the work contemplated for CRC Project 2.3 the aim is to improve the communication amongst the partners in the supply chain, and so expert judges are likely to be a main focus of subjective trials. There is also evidence that consumer judging panels are more diverse in their assessments of fabric handle than are expert panels. The results of comparing the fabric handle preferences of expert and untrained judges has, at least in one study, demonstrated that while the average handle ratings of each group were in good agreement the consumer panel exhibited much more scatter in their assessments than did the expert panel(Mahar and Postle, 1983).

Marketers understand that all people have an inherent behaviour which is their predetermined, innate set of value-based judgments, excluding stored past experiences and cultural influences, which dictate their approach to all decision making (Mayne, 2007). Inherent behaviour can be common across a wide range of genders, generations and cultures. It is this inherent behaviour that determines our consideration set, that is, the attributes that form part of the decision process for fabric handle. Understanding this inherent behaviour with respect to handle is the secret to better predicting a consumer decision to purchase.

In the analysis of fabric handle preferences for men's suiting fabrics, correlation analysis showed a significant, relatively high correction coefficient within each national group, even the untrained consumer judges (Pan et al., 1988a). This result indicated that the psychophysical perception and the preference to a certain type of fabric handle had good agreement for a certain group of people in the defined market. Mahar et al. (1987) reported the correlation coefficient between groups from five countries (Japan, Australia, New Zealand, India and USA). The results showed that for the same set of fabrics, the preferences of judges from different counties were generally the same but can also be different. In particular, the Japanese panel showed significantly different performance for the summer fabrics (Table 5).

Table 5. Correlation coefficients between international panels of fabric ranking scores

Winter / Summer	Japan	Australia	New Zealand	India	USA
Japan		0.85	0.76	0.82	0.80
Australia	-0.34		0.86	0.91	0.87
New Zealand	-0.30	0.82		0.83	0.83
India	-0.40	0.78	0.76		0.86
USA	-0.33	0.81	0.74	0.76	

Some problems existed between the judges when they subjectively evaluated fabric handle, such as the difficulty in communication between the judges, large difference in cultural preferences, and low assessment sensitivity of certain primary hand descriptions (Raheel and Liu, 1991b).

3.3 Defining descriptors

In every testing situation it is vital to define the fabric end use or application such that appropriate language can be used and appropriate judges can be tested. Language could potentially change for each class or type of fabric. Language barriers exist in several forms; between countries, between different cultures, between genders and between different generations. Before fabric handle can be assessed by different people, language differences need to be determined between these different groups of people. Li conducted a survey across three countries to develop a list of descriptors and found some differences between countries for summer wear descriptors but no difference between countries for winter or sportswear. Li also found no difference between male and female assessors. However, it is not clear how he dealt with translation of languages or whether he explored the definitions of each descriptor between countries. Kawabata was famous for his development of objective instruments and subjective evaluation. However, the subjective descriptors were developed in Japanese and hence translation to English is required (Wheelwright et al., 1985). Bishop (1996) described research by David (1986) that different judges were allowed to use different word sets as it was recognised they were still assessing the same fabric attribute.

Over the years language descriptors have been derived by researchers in different ways. Some researchers have used fabric experts to derived general descriptors and bipolar descriptors(Kawabata, 1980b, Chen et al., 1992), while other researchers have used consumers or participants to develop the descriptors (Hollies et al., 1979, Li, 2001, Howorth and Oliver, 1958b, Fritz, 1990). Howorth and Oliver refined the descriptor list using a factor analysis. Philippe (2004, 2003) refined the descriptor list by removing terms that were non-pertinent, redundant, noisy and visual, hedonic and non-understood terms. Fritz(1990) argued that the correct method of determining descriptors is using consumers because they have their own internal scale and concepts in evaluating fabric quality and hence researchers should try to discover the consumers' desires in the performance of products (Bishop, 1996). In contrast to the scales that have been developed by the above researchers, Hollies (1977) believes that the most meaningful psychological scale work has resulted from studies in which the observer is permitted free use of the language they considers appropriate to describe the fabric under study.

Kim collected approximately 144 English words which could be used in SEFH (Kim and Vaughn, 1979). Howorth and Oliver (1958a) examined the frequency of the descriptors used in SEFH as listed in Table 6. However, relatively few words were frequently used by the panel for a specific range of end-use products. It was found that approximately 86% of all decisions were made in a combination of the nine frequently used descriptors in Table 6 (Bishop, 2003, Ellis and Garnsworthy, 1980).

Table 6. Frequency of descriptors used (Howorth and Oliver, 1958a)

Term used	Frequency	Frequency (%)
Smoothness	82	28
Softness	64	22
Firmness	23	8
Coarseness	22	7
Thickness	16	5
Weight	15	5
Warmth	12	4
harshness	12	4
Stiffness	9	3
Body	8	3
liveliness	6	2
fullness	4	1.3
'wool-like'	4	1.3
'Quality'	4	1.3
Crispness	3	1.0
Paperiness	3	1.0
Greasiness	3	1.0
Weave	3	1.0
Boardy	2	0.7
Creasability	1	0.3
Drape	1	0.3
Total	297	100

The correlations between the rankings and further factor analysis suggested a set of seven descriptors for the fabric handle of suiting fabrics. They were (Howorth and Oliver, 1958a):

- Smoothness
- Softness
- Coarseness
- Thickness
- Weight
- Warmth, and
- Stiffness

The use of bipolar descriptors was sometimes favoured in SEFH. David *et al.* (1986) generated a list of bipolar descriptors that contributed most to the judgments of 'total handle'. The bipolar descriptors were:

Coarse	Fine
Stiff	Pliable
Rough	Smooth
Harsh	Soft
Cool	Warm
Hard	Soft (in squeezing)
Rustly	Quiet

However, Bishop (2003) indicted that the use of these bipolar descriptors did not add value over single descriptors, but had disadvantages when correlation analysis was performed between the descriptors or between SEFH and OMFH parameters.

Similarly, Jacobsen et al. (1992) developed a semantic differential grid with twenty-one bipolar descriptors in the evaluation of hand knitting yarns and the resultant fabrics. The bipolar attributes were:

Heavy	light
Even	uneven
Airy	dense
Drapable	stiff
Bulky	delicate
Stiff	pliable
Fine	thick
Body	limp
Coarse	fine
Insulating	conducting
Irritating	comfortable
Drab	elegant
Luxurious	cheap
Soft	harsh
Distorts	maintains shape
Prickly	smooth
Maintains appearance	matts, pills
Smooth	fluffy
Difficult to use	workable
Static	nonstatic

Lustrous dull

The correction analysis between these descriptors and the objectively measured parameters of the products showed that the semantic differential grid was an excellent means to define consumer perceptions in the handle evaluation.

Fabric softness is one of the most frequently used terms in describing fabric handle by consumers. Fabric softness has multiple meanings that can be related to compression, smoothness and flexibility of fabrics, depending of the fabrics being handled and end-uses or fabric application (Li, 2001). Softness is a good example of a descriptor that may need defining or using in the context of the fabric application for its sensory evaluation to be understood.

3.4 Protocols in SEFH

3.4.1 Fabric hand techniques

There is no a universally agreed method which should be used when handling fabric in SEFH. However, there are facts shown to affect SEFH.

3.4.2 Fabric conditions: Conditioning/un-conditioning

The conditions of assessment are important to provide a useful link to objective evaluations of fabric handle. The atmospheric conditions under which the SEFH was conducted were not clearly emphasised in most papers. It is preferable that the standard conditioning be used particularly when the SEFH results are used for quantitatively analysis.

3.4.3 Environmental conditions

If a consumer preference is being sought then one may consider the testing of fabrics in a shopping environment. It may also be relevant to test fabrics in a similar environment to that which their purpose is, for example, summer fabrics in a summer environment. It is also important that the testing environment be as plain as possible such that visual cues do not influence the testing. This may include:

- plain curtains pulled across all windows to block the outside environment
- no pictures that made induce certain moods or memories of the judge

Although a person is being tested in a standard environment outside conditions can impact on the testing being undertaken and hence it is important to note the outside conditions on the day of testing.

3.4.4 Visual sense: Appearance: sight/unsighted; coloured/undyed; lustre; drape

Fabric appearance usually influences the preference decision of the judges. Kawabata (1975) showed that the appearance of fabric surfaces made an important contribution to the judgements of the Japanese expert panel. However, sight will alter the assessment so it needs to be noted if tests are performed sighted or not (Bishop, 1996). In sighted testing by Bishop (1996) the relative importance of tactile attributes changed and different attributes relating to fabric construction, surface detail, and fabric lustre became dominant. Bishop (1996) concludes that in practice in attempting to establish an effective fabric objective measurement system, objective measurements may need to be correlated to subjective assessments made using sight and touch together. Dowling and Stanton (2005) and Stanton et al. (2004) performed unsighted handle assessments to get an understanding of the contribution of sight sense to fabric handle assessment. They found that sighted assessment best predicted the overall consumer result followed by unsighted comfort rating and then by unsighted handle rating(Stanton et al., 2004). Unsighted testing was performed by Howorth and Oliver (1958b), Chen(1992), Philippe(2003) and Sular and Okur (2007). Howorth and Oliver used unsighted testing because they had noticed in previous testing the sighted assessment strongly influenced results. Chen commented that sighted assessment tends to be less sensitive than unsighted assessment. It is argued that sighted assessment is more appropriate to predict the retail assessment.

3.4.5 Olfactory sense: Fabric odour

Fabric odour generally does not affect fabric handle features, unless the fabrics have undergone some special treatment to add an odour, e.g. microencapsulation of lavender fragrance, and the odour is strong enough to stimulate the judges' olfactory senses. If it is the case, the odour could well affect the preference decision of the judges.

3.4.6 Auditory sense: Fabric sound (noise)

Some handle descriptors such as "quiet" and "rustly", are used by the judges refer to reactions from our auditory sense. However, there is not much discussion in the literature about the specification or the relative importance of the auditory input to fabric handle evaluation.

3.4.7 Temperature sense: Fabric warm/cool feel

The sensation of temperature to fabric handle is determined by contact area and hence the surface character of the fabric has great influence on this sensation. A rough fabric surface tends to reduce the area of contact between the skin and the fabric, while a smoother surface increases this area of contact. The area of contact directly influences the heat flow between skin and fabric, thereby creating a cooler feeling fabric (Barker, 2002, Li, 2001) in the most common case of the fabric being at a cooler temperature than the assessor's skin. Green et al. (1979) investigated the effect of skin temperature on the perception of roughness and found that apparent roughness declines as skin temperature falls below normal (32 deg) and that apparent roughness tends to be enhanced as skin temp rises above normal, although the effect of warming is smaller and less predictable than the effect of cooling.

3.4.8 Protocol of handling fabric

Technically there is a list of core movements or exploratory procedures that the hand uses to allow the brain to convert and describe its perception when handling fabrics. Lederman (1998) describes these core movements as:

- Lateral motion – texture

- Pressure – hardness
- Static contact – temperature
- Unsupported holding – weight
- Enclosure – global shape, volume
- Contour following – global shape, exact shape

From these core movements our brain computes different combinations which we describe using descriptors. Over time, researchers have used many different descriptors (Table 6) which are in some way determined based on the core movements.

For those researchers that have used trained panels for SEFH, generally the panel have been asked to handle the fabrics using a certain protocol. Bishop (1996) describes that judges instinctively know how to manipulate fabric in their fingers to assess different attributes. However, instincts vary. For this reason Bishop states it is necessary to define the manner in which fabrics are handled for each descriptor. In development of a SEFH protocol it may be necessary to study core hand movements and construct a link between these movements and the associated words for use in testing.

3.4.9 Criteria of judgment and scales of assessment

Psychological scaling is the process of making judgments from perceptions that we have about fabric handle and the language we use to express these perceptions to one another. It is important to obtain from the prospective fabric handle evaluators the words and language of perception before deciding on the psychological scales of measurement and their appropriate intensity ranges (Hollies, 1977).

Different types of psychological scales can be used depending on the research aim and statistical analysis that are needed. Li (2001) details the four types of psychological scales that can be used and the purpose for using each scale. The following table is extracted from Li and demonstrates the different scales and the usage of each:

Table 7. The four types of psychological scales

Scale	Rules	Usage
Nominal	Determine equality	Categorisation, classification
Ordinal	Determine equality, relative position	Rank
Interval	Determine equality, relative position, magnitude of difference	Index numbers, attitudes measures, perceptions
Ratio	Determine equality, relative position, magnitude of difference with a meaningful zero	Sales, costs, many objective measurements

Nominal scales are used to categorize fabrics with the number serving as a label for a class category. Cardello (2002) describes those authors who have used nominal (category) scales. Some of the best known nominal scales include Hollies Subjective Comfort Rating Chart and the McGinnis category scale of comfort (Hollies, 1977). The advantages of using this type of scale include; simplicity, versatility, ease of use by judges and good reliability. However, there are significant disadvantages of using this type of scale. It is often assumed that the points on the scale represent equal subjective intervals, and this is not always the case. In this situation subjects tend to use the word labels rather than the number scale and this means the scale can only be used as an ordinal scale rather than an interval scale, restricting the statistical power of the scale. Another common problem is that subjects tend not to use the extreme ratings for fear that they may receive a worse fabric and hence this restricts the scale and hence subjects tend to overuse the "safe" categories (Cardello et al., 2002).

Ordinal scales comprise numbers used to rank fabrics according to their characteristics and relative position in terms of their characteristics. Ordinal scales indicate the relative position of fabrics but not the magnitude of differences between fabrics (Li, 2001). Howorth and Oliver (1958b) decided to use a ranking method and forgo the magnitude to avoid complications in the comparison of different judges' scales of rating. Howorth also preferred using ranking to avoid the scale migrating during testing. Stanton et al (2004) also used a ranking method in their original work before changing their protocol. The use of paired comparison tests is another example of ordinal scales. Howorth and Oliver (1958b) describes the paired comparison procedure as all possible pairs are presented to the judge in random order. This makes it possible for inconsistent choices to be recorded and used as an indication of the ability of the judge to distinguish differences between fabrics. This method assumes that a decision can always be made between two fabrics. This is not always the case but one would assume that if a decision was forced it would be random and the final scores would not be in serious error. This technique has been used by Harlock and Naylor et al. (Harlock and Ramkumar, 1997, Naylor et al., 1997). Bishop (1996) warned that paired comparisons are not appropriate when evaluating objective measurement as a magnitude rather than ranking is required.

Interval scales consist of numbers used to rank fabrics in such a way that numerically equal distances on the scale represent equal distances in characteristics being measured. Interval data can represent both the relative position and the magnitudes of differences between fabrics for the characteristics being measured (Li, 2001). Wang (2000) has used an interval scale to evaluate how fabrics performed. The scale moves from 0 to 10 and over a range of 5 words as illustrated in Table 8. Interval scales can also be represented as a "magnitude estimation" which is a line between two characteristics and the judge is asked to mark the line where appropriate. The data is collected by measuring the line using a ruler.

Table 8. Scale used by Wang (2000)

Grade	0	1,2,3	4,5,6	7,8,9	10
Warm feeling	Extremely cool	cool	neutral	warm	Extremely warm
Sticky feeling	Not sticky at all	Slightly sticky	sticky	Very sticky	Extremely sticky
Prickle	No prickle at all	Slight prickle	Prickle	Very prickle	Extreme prickle
Absorbency	Not absorbent at all	Slightly absorbent	Absorbent	Very absorbent	Extremely absorbent
Softness	Extremely stiff	Not soft	soft	Very soft	Extremely soft
Mugginess	Extremely muggy	Slightly muggy	Muggy	Very muggy	Extremely muggy

Roughness	Not rough at all	Slightly rough	rough	Very rough	Extremely rough
Total comfort	Extremely uncomfortable	Uncomfortabl e	Slightly uncomfortable	Comfortable	Extremely comfortable

Ratio scales also consist of numbers used to rank fabrics in such a way that numerically equal distances on the scale represent equal distances in characteristics being measured. However, this scale differs from the interval scale because it has a meaningful zero value.

3.5 Analysis and presentation of the results

Throughout the SEFH literature some common analysis techniques have been used. Table 9 shows a comprehensive summary of analyses of both subjective handle components and the relationship between subjective and objective fabric handle parameters. These analyses are grouped according to the type of statistical analyses performed, and brief comments are included on each analysis.

Correlations have been used to explore relationships and similarities between different SEFH attributes, between subjective and objective attributes and between individual judges on a panel. Linear regression has been used to predict certain handle attributes. For example, objective measurements have been regressed to predict total Fabric Handle and handle attributes have been regressed to predict total Fabric Handle. Analyses of variance have been performed to determine the significant differences between fabrics, panel members and SEFH attributes. More recent literature has described Principal Component Analysis being used to reduce the number of SEFH attributes that are used in regression analyses. Lastly, regression trees have been used in place of linear regression to better estimate the order of importance of different SEFH attributes. All of the described analysis methods are valid and depending on the hypothesis, any of the describe analysis techniques may be used for SEFH.

Table 9. Summary of analyses used for SEFH and OEFH

Method	Process	Reference	Results	Comment
Weber-Fechner Law (Linear /log function)	Translate fabric mechanical properties into hand parameters	Matsuo et al (1971)	Psycho-physical model	o Linear; o Simple; o Suitable for sensory data
	Each SEFH attribute related to the sum of the different contributions from OMFH	Hu et al (1993)	Larger errors than using Stenens's law	
Stevens's Power law	each SEFH attribute (magnitude estimation) related to single OEFH parameters	Elder et al. (1984, 1985)	Psycho-physical model Single relationships o Softness – compression (sig.) o Stiffness – drape coefficient (sig) o SEFH is fabric-type dependent	o Linear; o Simple; o More accurate than Weber-Fechner law o Suitable for sensory data.
	Each SEFH attribute (linear scaled) related to the sum of the different contributions from OMFH	Hu et al (1993)	Less errors than other methods o Ln(HV1 stiffness) – -Ln (WC), Ln(B), Ln (MIU), LN(MMD), Ln(LC) o Ln(HV2 smoothness) – -Ln(T0), -Ln(SMD), -Ln(B), Ln(LC), Ln(WT), Ln(W), -Ln(HB), Ln(WC) o Ln(HV3 softness and fullness) – Ln(T0), Ln(MIU), Ln(RT),	

			Ln(SMD), Ln(WC)	
Linear regression (inc. transformed (logarithmic and exponential) linear)	Stepwise linear regression	Kawabata (1982, 1994)	Standard calculations for HV's and THV	o Linear o Simple o Possible Collinearity between variables o Less fitting than nonlinear regression
		Hu et al (1993)	Larger errors than using Stevens's law	
		Jeurissen (1991)	A large fabric database used o Using average values of warp and weft o Linear regression model was not adequate for a large database	
		Cardello (2002)	Linear regression to predict subjective comfort rating using SEFH attributes	
		Stanton et al. (2004)	Prediction of consumer preferen ce using sensory attributes	
	Discriminant analysis: establish discriminant function by stepwise regression	Lai et al (2002)	For discrimination of cotton, linen, wool and silk fabrics The model based on KESF data is better than on FAST data.	
		Jimmy and Postle (2007)	58 lightweight wool and blend fabrics Regression performed on six fabric block properties.	

			o Stiffness/firmness – bending, shear and tensile blocks. o Smoothness – surface and shear blocks. o Fullness/softness – compression and surface blocks. o Crispness – surface weight and compression blocks. o Hardness – bending, surface and tensile blocks.	
	Basic Linear Regression	Peykamian and Rust (2000)	Using yarn parameters to predict fabric softness	
		Mehrtens (1962)	Determine the linear regression coefficients for each fabric	
		Chen (1992)	Physical properties used to predict SEFH of handle. SEFH attributes were used to predict Handle.	
	Regression tree Regression tree (minimize variance and develop level of importance)	Dowling et al. (2005)	Classification of Objective characteristics	o Use linear equations to develop different levels of the tree o Recognises a non linear relationship between different

				tree branches o Uses a decision making process that happens in a stepwise process rather than as an index like a ordinary regression model o Easy to perform with a good statistics package
Probability Model	Classification of consumer perceptions	Pleasants (2005)	Probabilistic model of consumer perception based on sensory scores. Classification (3 grades), linear function	o Suitable for random phenomenon, compared to mathematic models
Nonlinear regression	Nonlinear optimisation technique (MINOS programme)	Postle and Dhingra (1989) Peykamian and Rust (2000)	214 winter suiting fabrics The validity of the solution is dependent on the accuracy of both the objective function and constraint equations. Using yarn parameters to predict fabric softness	o Nonlinear o Better fitting than linear regression o Possible collinearity between variables o complicated
Correlation	Canonical correlation	Dreby (1941,1942,1943)	SEFH stiffness – OMFH stiffness by the Planofex SEFH smoothness – OMFH surface friction by the Friction Meter	o the early stage of regression analysis o simple o suitable for the

			OEFH compressibility – OEFH stiffness by the Compression Meter	selection of parameters
		Abbott (1951a, 1951b); Sudnik (1972)	Determining which objective methods gave the best fit with SEFH.	
		Gong (1995)	24 knitted fabrics Correlation between fullness ratings and KESF parameters: G, 2HG. 2HG3, B, 2HB, WC, -MMD and –SMD Bench mark of fullness is established based on B and G.	
		Merhtens (1962)	Determining which objective methods gave the best fit with SEFH.	
		Sular (2007)	Determined correlations between different SEFH attributes	
		Barker (2002)	Relationship between objective measurement & subjective rating	
		Harlock (1997)	Correlation between different objective measurements Also correlated objective	

			measurements with subjective ranks (paired comparison)	
		Wang (2000, 2003)	Relationship between sensory descriptors & total comfort	
		Chen (1992)	Relationship between SEFH & OMFH results for parameters wi thin fabric type	
		Cardello (2002)	Consistency of SEFH panel me mbers. Linking handle characte ristics with KESF measurement s	
		Thompson (2005)	Relationship between sensory scores tested on different muscle groups	
		Stanton et al. (2004)	Relationship between target (as determine by cluster analysis) and objective measurements	
Factor analysis (FA) / Principal Component analysis (PCA)	Multiple factor analysis	Howorth and Oliver (1958) Kobayashi (1944, 1974) Stearn et al (1984)	Men's suiting Stiffness, smoothness, and thickness Silk, wool, cotton, and nylon fabrics	o Multivariate analysis technique (advanced technique) o The numbers of variables can be largely reduced and the components are

		Gong and Mukhopadhyay (1993)	Reduce 18 parameters (KESF) to 10	orthogonally distributed (no collinearity). o Interpretation of the components are difficult o Complicated but with advanced software becomes easy. o PCA analysis has become very easy with modern statistical packages
	Discriminant functions	Lai et al. (2002)	For discrimination of cotton, linen, wool and silk fabrics 16 parameters are reduced to 4 components. Factor 1 consists of G, 2HG, 2HG5, 2HB, B and LT (or F, T2 W and E100 for FAST); Factor 2 consists of SMD, MMD, RT, and RC (or ST and STR for FAST); Factor 3 consists of W, MIU, and T (or G and B for FAST); and Factor 4 consists of WC, LC, and WT (or RS and HE for FAST). The fabrics made from different fibres are well discriminated.	
	Varimax rotation method (Rotated factor solutions)	Jimmy and Postle (2006)	58 wool fabrics and 20 cotton fabrics For wool fabrics: reduced 16 parameters to 8 components and explained 86% of the variance; For cotton fabrics: reduced 16 parameters to 5 components and explained 95% variance	
	Principal Component Analysis	Philippe (2003, 2004)	Highlight similarities between fabrics. Used to reduce the	

		Cardello (2002)	number of attributes that are important PCA to refine number of terms used in regression models	
Weighted Euclidean Distance (WD)	Select a reference fabric Matrix transformation of the eight fabric properties according to the Karhunen – Loeve (K-L) orthonormal - expansion theorem. Calculate WD referred to the reference fabric	Pan et al (1988); Pan (2006)	Eight fabric attributes were extracted from the force-displacement curve. Better for different markets and fabric types.	o Data preparation based on fuzzy technique o A reference fabric required for calculation of WD o Fabric feature attributes are orthogonal. o Easy interpretation
Fuzzy logic analysis	o Fuzzy comprehensive evaluation technique – using transformation matrix **R** to transform objective parameters to "grading levels (boundary levels are 0 for very poor and 1 for excellent). o Membership functions are used to establish the 'membership degrees' for any objective measurements on a 0-	Raheel and Liu (1991)	Light weight fabrics The model can quantitatively calculate fabric handle values and have good agreement with the results from SEFH	o Comprehensive o A membership function / a weight factor vector should be well established. o Large data base

	1 scale. o A weighting factor vector **A** was established through a panel of 25 judges for the relative importance of the contribution of each objective measured parameter. o **R** was used with **A** to give fabric handle value.			
	o Weighting factor vector **A** was determined by ANOVA and factor analysis. o Membership function was linearly assumed. o Fuzzy conversion matrix **U** was formed based on the membership function.	Chen et al (2000)	2 fabrics: Cotton /polymer and cotton treated with 8 recipes o Softness can be graded by fuzzy comprehensive evaluation, which has a strong correlation with the subjective grade.	
	Fuzzy cluster analysis o Building membership functions o Equivalisation of the fuzzy relation o Clustering o Determining the optimal number of groups	Pan et al (1988) Pan et al (1993)	20 fabrics (5 types and 4 members each) Sorting the fabric handle terms.	

		Stanton et al.(2004)	Development of membership gr oups and identification of an ap propriate target group which ha d high means and low variance for handle attributes.	
Neural Network	Back- propagation artificial neural network with three layers: input, hidden and output layers A resilient back-propagation artificial neural network with four layers: input, two hidden layers and output layer	Lai et al (2002) Hui et al (2004)	For discrimination of cotton, linen, wool and silk fabrics The model based on KESF data is better than on FAST data. 40 woven fabrics including wool, cotton and synthetic fibres 12 mechanical properties were used as inputs. 14 bipolar descriptors were used as outputs. Improved the prediction of consumers' sensory handle ratings.	o Comprehensive o Large data base o Model training required
Polar diagram	Selection of properties included on polar diagram Determination of the position of each radial axis Determination of length of each axis on polar diagram	Hallos et al (1990)	Double-jersey knitted fabrics; traditional testers Axis: Mass, thickness, specific volume, friction, tensile modulus, hardness, flexural rigidity, drape coefficient and stretch recovery	o Simple o Visually present results
Significance tests	Analysis of Variance (ANOVA) Determination of the importance of different	Philippe (2003, 2004)	Performed a 2 way ANOVA to d etermine the level of variance of fabrics, panel members and the interaction. Another ANOVA (D	o Simple for comparison of more than two means

	attributes		uncan's test) was used to deter mine significant differences bet ween fabrics for many different attributes. Results were presen ted in the form of a sensory prof ile.	o combined with regression analysis
		Hatch (1990)	Explanation of variance – perso n, fabric, time, error	
		Wang (2000, 2003)	Determine significant difference s between fabrics	
		Cardello (2002)	To determine the variance of ea ch SEFH attribute	
		Thompson (2005	Relationship between sensory scores tested on diff muscle groups	
	Wilcoxon Sign-Rank Test Determination of significance between fabrics that have been ranked in a paired comparison structure	Hollies (1979)	Able to determine if one fabric is significantly better than another fabric for a particular attribute that it has been ranked.	o Nonparametric analysis o Applicable only to paired comparisons
	Kendall's coefficients of con cordance Determination of consistency	Sular (2007)	Used to determine the consistency of different SEFH panel members	o Nonparametric analysis o Determine the agreement of two

				rankings
	Student Newman-Keuls Mul tiple Comparison Test	Wang (2000, 2003) Cardello (2002)	Establish differences between shirts at a significant level To determine significant subsets of SEFH attributes	o Post test following ANOVA o Find the difference between two groups o Does not control error and generate confidence intervals o Tukey test is more popular
	X^2 test Determine significance to the expected	Chen (1992)	Used to determine if fabric order in rankings was significantly diff erent to what was statistically ex pected	o Nonparametric analysis – count data o Common method for categorical data o Wide applications

3.5.1 Components of subjective fabric handle

Kawabata (1980a) suggested that a two-stage process was used in the assessment of fabric handle. In the first stage, the judges often used descriptors in the handle expression, which were called primary handle characteristics; in the second stage, the judges evaluated the overall fabric quality as a combination of the primary handle expressions. The primary handle expressions were summarised for specific end-uses as listed in Table 10.

Table 10. Primary handle expression used for different end-uses (Bishop 2003)

End-use	Primary handle descriptors
Men's winter suiting	Stiffness; Smoothness; Fullness and softness
Men's summer suiting	Stiffness; Crispness; Anti-drape stiffness
Women's light weight dress	Stiffness; Anti-drape stiffness; Crispness; Fullness and Softness; Scroop; Flexibility / softness
Wemen's apparel fabrics (all seasons)	Stiffness; Smoothness; Fullness and softness; anti-drape stiffness; Softness
Silk crepe fabrics	Stiffness; Crepe feeling

3.5.2 Analysis of fabric handle attributes

Correlation analysis was frequently used in establishing relationships between the SEFH components and OMFH parameters. Within SEFH, ranking and analysis of variance were often used to analyse variations between and within the judge groups. Principal component analysis (PCA) and fuzzy techniques were also employed by some researchers in sorting or grouping fabrics (Raheel and Liu, 1991b, Pan et al., 1988c, Byrne et al., 1993). Some results are summarised in the following section.

The importance of the descriptors was evaluated by Kawabata (1975) for men's suiting as shown in Table 11. Fabric stiffness, smoothness, and fullness and softness were employed in the correlations to the OMFH parameters for winter suiting. Crispness replaced smoothness in the analysis for summer suiting. Clearly, the relative importance of the descriptors is different in the winter and summer suiting markets.

Table 11. Importance of the descriptors for primary handle (Kawabata, 1975)

Descriptor	Importance (%)	
	Winter suiting	Summer suiting
Smoothness	30	-
Crispness	-	35
*Stiffness	25	30
Fullness and softness	20	10
Appearance of surface	15	20
Other	10	5

*Two types of 'stiffness' were isolated for summer suiting fabrics

Park and Hwang (2002) used fuzzy membership functions to derive weighted factors for knitted fabrics for winter outerwear in South Korea and New Zealand. The percentage of importance of each factor for knitted winter outerwear is listed in Tables 12 &13. The results showed that the rating of the fabric handle characteristic was different for the different markets, even when the same defined fabrics were used.

Table 12. Weighted factor of knitted winter outerwear in South Korea (Park and Hwang, 2002)

Characteristics	Rating	Percentage of importance (%)
Bulkiness	1	21.75 ± 8.63
Stretchiness	3	16.05 ± 5.53
Distortion	6	14.20 ± 3.87
Weight	5	14.85 ± 5.42
Flexibility	2	18.00 ± 5.48
Smoothness	4	15.15 ± 4.46

Table 13. Weighted factor of knitted winter outerwear in New Zealand (Park and Hwang, 2002)

Characteristics	Rating	Percentage of importance (%)
Bulkiness	1	28.20 ± 4.10
Stretchiness	3	18.50 ± 6.26
Distortion	4	9.50 ± 2.84
Weight	5	8.00 ± 6.75
Flexibility	2	25.80± 5.65
Smoothness	6	10.00 ± 3.33

3.6 Summary

The SEFH process involves two key stages: the judgement of fabric primary handle characteristics and the assessment of total fabric quality – total handle. The primary handle components are essential elements in finding out the measurable parameters of fabric which are associated with fabric handle. Successfully differentiating and scaling these components are critical to the development of an OMFH system.

Judges' natures have a strong impact on assessments of handle expressions, which in turn leads to large variability in the fabric handle. Single and bipolar descriptors of primary handle can be used for the judges to express their judgements. The importance of the descriptors should be examined in association with particular types of fabrics. Nevertheless, the difficulty in communication between the judges requires well designed and defined protocols in handle expressions, and an understanding of fabric handling techniques and testing conditions.

4 Objective measurement of fabric handle

4.1 Measurable components of SEFH

The investigation into the SEFH showed that fabric handle was largely determined by fabric flexibility, compressibility, foldability, stretchability, pliability and surface friction (Kim and Slaten, 1999, Pan, 1993, Alley et al., 1978). Effectively specifying these fabric attributes by instruments either individually or in combination is a critical step in objective evaluation of fabric handle. Pan (2006) summarised the in principle recommendations from Peirce (1930), Kawabata (1980c) and Postle (1989a) and suggested the following characteristics of fabric deformation should be specified in an OMFH system:

a) Low yet complex stresses at large deformation;
b) Nonlinearity;
c) Friction/hysteresis.

In summary, critical subjective components and their potentially related measurements are listed in Table 14.

Table 14. Critical subjective components and associated measurements

Subjective components	Associated measurements
Thickness	Thickness; Compression; Density; Weight
Softness	Bending; Tensile; Shear; Compression; Thickness
Stiffness	Bending; Shear; Compression; Thickness
Flexibility	Bending; Compression; Shear; Thickness
Smoothness	Friction; Roughness; Hairiness; Tightness
Fullness	Bending; Compression; Thickness
Warmth / Coolness	Thermal conductivity; Friction; Tightness; Hairiness
Crispness	Bending; Tensile; Shear; Compression; Friction

4.2 KESF System

4.2.1 KESF system and parameters measured

The KESF system consists of four instruments:

a) KES-FB1 Tensile and shear tester (Figure 2)
b) KES-FB2 Bending tester (Figure 3)
c) KES-FB3 Compression tester (Figure 4) , and
d) KES-FB4 Surface-friction and geometrical-roughness tester (Figure 5)

Figure 2. KES-FB1 (CSIRO TFT)


Figure 3. KES-FB2 (CSIRO TFT)

Figure 4. KES-FB3 (CSIRO TFT)

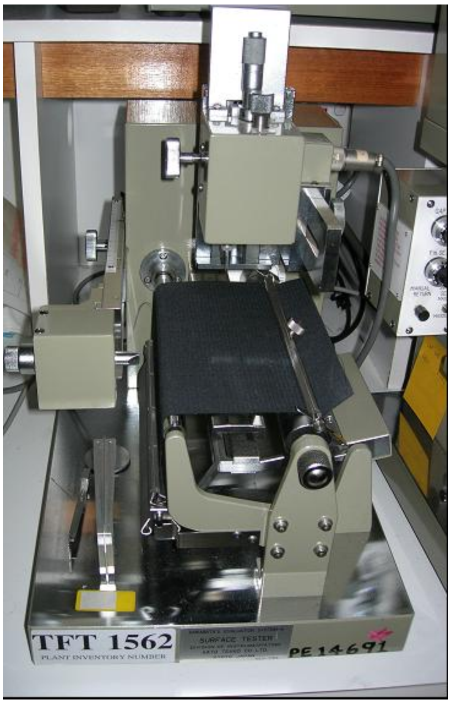


Figure 5. KES-FB4 (CSIRO TFT)

The parameters measured by the individual KESF instruments are listed in Table 15.

Mahar et al. (1987) reported the measurement precisions for the parameters tested in Table 15 based on an inter-laboratory trial conducted by seven international laboratories on approximately 200 pure wool or blend suiting materials. Recommendations were suggested for fabric testing based on the results of this trial.

Pan (2006) noted that the thermal property of the fibres should also be considered. The so-called effusivity of a material is highly related to contact transient in subjective assessment and, in turn to the sensation of warmth. The definition of effusivity is:

$$E = \sqrt{K \rho c_p} \qquad (1)$$

where, E is effusivity of material, K is the thermal conductivity (W/m K) of the fibre, ρ is the material density (kg/m^3) and c_p is the specific heat capacity (J/kg K) of the fibre.

A material surface with a higher effusivity value will feel cooler than a surface with a lower effusivity. Pan(2006) further pointed out that the small range of K for textile fibres cannot account for the difference in "coolness" sensation perceived by touching different fabrics made from different fibres. However, ρ and c_p are dependent on fabric structural parameters such as yarn and fabric construction. Therefore, the tested mechanical and surface properties dictate the fabric warmth sensation and the contribution of thermal conductivity, K, to the warm/cool sensation can be considered as negligible. The quantification of effusivity in the OMFH was unfortunately not mentioned in the 2006 paper(Pan, 2006).

Table 15. Parameters measured by KESF system

Instrument	Property block	Parameter	Description	Unit
KES-FB1	Tensile	EM (or EMT)	Fabric extension at 5 N/cm width	%
		LT	Linearity of load-extension curve	-
		WT	Tensile energy	N/m (gf cm/cm^2)
		RT	Tensile resilience	%
		EM	Extensibility, strain at 500 N/m	-
	Shear	G	Shear stiffness	N/m deg.
		2HG	Hysteresis of shear force at 0.5 degree of shear angle	N/m (gf/cm)
		2HG5	Hysteresis of shear force at 5 degree of shear angle	N/m (g/cm)
KES-FB2	Bending	B	Bending rigidity	10^{-4} Nm (gf cm^2/cm)
		2HB	Hysteresis of bending moment	10^{-2} N (gf cm/ cm)
KES-FB3	Compression	LC	Linearity of compression / thickness curve	-
		WC	Compressional energy	N/m
		RC	Compressional resilience	%
		T_0	Fabric thickness at 50 Pa pressure	mm
		T_m	Fabric thickness at 200 Pa pressure	mm
KES-FB4	Friction and Roughness	MIU	Coefficient of steel/fabric friction	-
		MMD	Mean deviation of MIU (frictional roughness)	-
		SMD	Geometric roughness	µm

4.2.2 Handle values

In the KESF system, fabric handle was evaluated on two levels:

- Primary handle
- Total handle

Different components of primary handle were identified and evaluated for different types of fabrics using the KESF system (Pan et al., 1988b, Kawabata, 1980b).

For Men's winter suiting fabrics, the primary handle components were:

- o stiffness (koshi),
- o smoothness (numeri), and
- o fullness and softness (fukurami).

For women's medium thickness fabrics, the primary handle components were:

- o stiffness,
- o smoothness,
- o fullness and softness, and
- o soft feeling (sofutosa).

Total handle was derived from the primary handle values as discussed later in this review.

4.2.3 Analysis and presentation of the results

In the KESF system, the calculation of primary handle values was based on an assumption that the primary handle components had a linear relationship with the relevant measured parameters. So the equation is:

$$HV_k = C_0 + \sum C_{ki} x_i \qquad (2)$$

where C_0 and C_{ki} are constant coefficients derived from the correlation analysis. HV_k is the kth primary handle value such that the index meaning is different for different fabrics as listed in Table 16 (Kawabata and Niwa, 1996).

Table 16. Meaning of k value in the equation

k value	For winter / autumn suiting	For summer suiting
1	Stiffness	stiffness
2	Smoothness	Crispness
3	fullness	Fullness
4		Anti-drape stiffness

The term x_i is the normalised ith (I = 1-16) mechanical parameter, normalised as

$$x_i = (X_i - M_i) / \sigma_i \qquad (3)$$

where X_i is the mechanical parameter measured. M_i and σ_i are the mean and standard deviation of X_i for the fabric population used to derive the original relationships.

Total handle value (THV) is evaluated based on primary handle of fabrics. However, the relationship between THV and primary handle components was assumed to be nonlinear. The equation is:

$$THV = C_0 + \sum Z_k \qquad (4)$$

where

$$Z_k = C_{k1}(Y_k - M_{k1}) / \sigma_{k1} + C_{k2}(Y^2{}_k - M_{k2}) / \sigma_{k2} \qquad (5)$$

Z_k is the contribution of the kth primary handle component to THV. The constants M_{k1} and σ_{k1} are population means and standard deviations of Y_k with the constant coefficient C_{k1}. M_{k2} and σ_{k2} are population means and standard deviations of Y^2_k with the constant coefficient C_{k2}. C_0 is a constant.

After the calculations, the HV and THV can be plotted in a control chart as shown in Figure 6 for handle and quality evaluation.

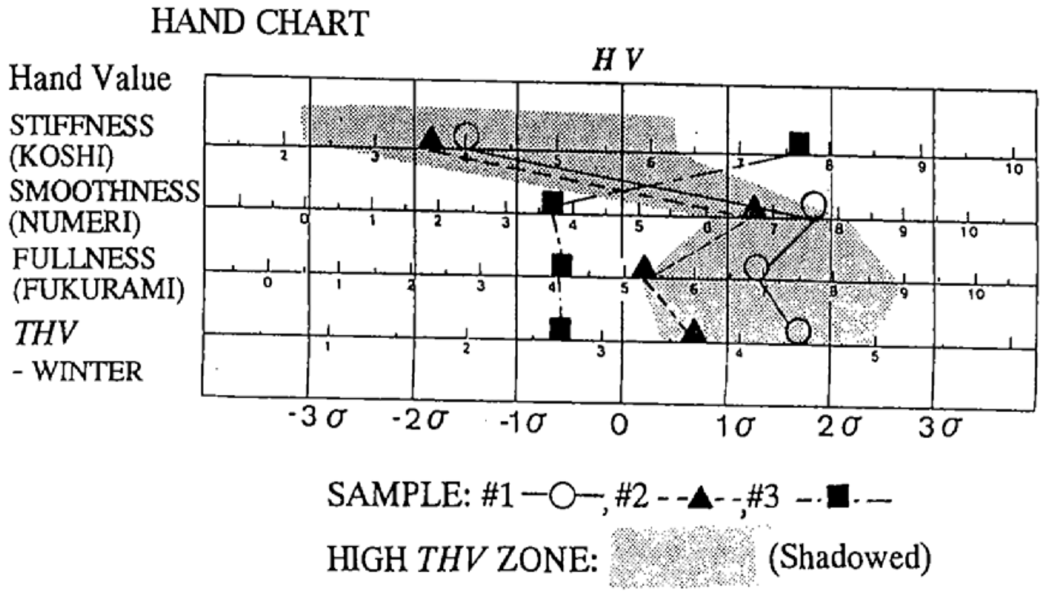


Figure 6. Handle control chart for winter / autumn suiting showing results for 3 samples and highlighting the region of high Total Handle Value (THV) (Kawabata and Niwa, 1996).

Postle and Dhingra (1989) employed 214 winter suiting fabrics to optimise the above calculations of HV and THV. The results of the nonlinear optimisation program suggested some specific design guidelines to maximise handle values for both heavy and light weight men's suiting materials.

Hu et al. (1993) used both Weber-Fechner and Stevens's Power laws to directly analyse the relationships between the KESF fabric parameters and psychophysical data for 39 worsted fabrics. The results were compared against those from the Kawabata's equations by using a paired-sample t-test on the relative sums of squares of deviation of the regressions. As a result, Hu et al. suggested that Stevens's law was a more appropriate model than the others. Furthermore, the KESF fabric parameters were selected for each primary hand component (stiffness, smoothness, softness and fullness) using a stepwise regression method. The parameters used in independent applications of Stevens's law for each measured parameter were then estimated. It is perhaps worth noting that the psychophysical data used in this research were obtained based on a linear scale of the SEFH, the same as in the Kawabata method, rather than on magnitude estimations. Bishop (1996) suggested in his comments to this approach that "the use of Stevens's law (or the Weber-Fechner law) is not appropriate unless the handle values are represented by the judges' estimates of their own responses to the fabric stimuli".

As in the KESF handle calculations, multivariate regression was used to analyse the results of SEFH obtained from the Japanese expert panel and the mechanical properties tested by the KESF system. From statistical point of view, the collinearity between the parameters measured from the KESF instruments influences the validity of the multivariate regression analyses (Pan and Yan, 1984, Pan, 1993). Therefore, Pan et al. (1988b) used 88 fabric samples to analyse the correlation between the values of primary handle for men's winter suiting fabrics and women's medium thick fabrics. The results showed that the values of some primary handle components were highly correlated. In particular, the correlation coefficient was approximately 0.74 – 0.90 between numeri (smoothness) and fukurami (fullness and softness), and 0.86 between numeri (smoothness) and sofutosa (soft feeling), so that the values of primary handle were not orthogonally spaced.

Following analysis of collinearity in Kawabata method, Pan and his co-workers (Pan and Yan, 1984, Pan et al., 1988b) employed weighted Euclidean Distance (WD_k) to differentiate fabrics from a reference fabric defined for a specific market. The larger the WD_k, the greater the difference in fabric handle between the fabric and the reference fabric.

PCA, factor analysis, fuzzy and neural networks were also employed by many researchers for the optimisation of the relationships between components from SEFH and OMFH (Pan et al., 1988c, Raheel and Liu, 1991a, Stearn et al., 1983, Na and Kim, 2001, Park and Hwang, 2002, Park et al., 2000, Shyr et al., 2004, Lam and Postle, 2006). Fuzzy techniques were claimed to be useful in classifying fabrics into different groups in the handle assessment process (Park et al., 2000, Pan et al., 1988c).

4.2.4 Applications

For fabric design, all the measured mechanical parameters can be plotted on a control chart as shown in Figure 7 (Dhingra et al., 1989, Gong, 1995, Kawabata and Niwa, 1996). The shaded area shows the ranges for each parameter for well-performed fabrics based on statistical analyses.

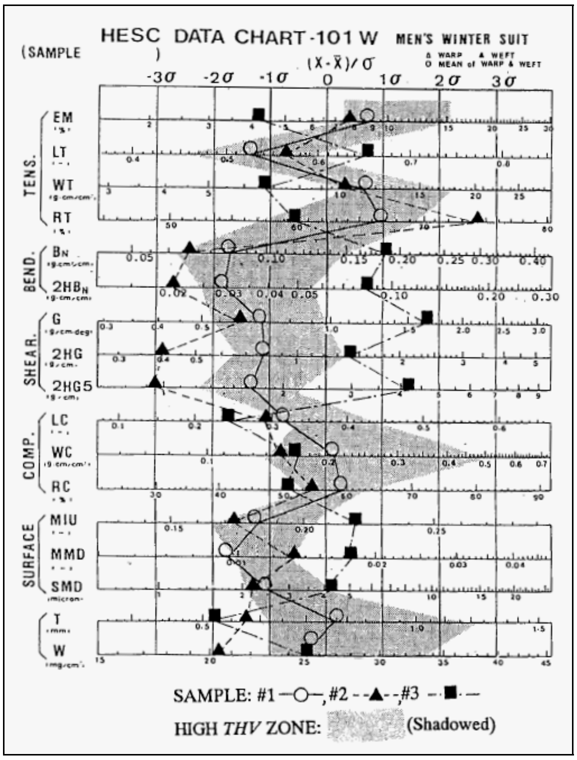


Figure 7. Application of KESF testing to process control (Kawabata and Niwa, 1996): KESF parameters for 3 samples and the zone of parameters for high THV fabrics.

For fabric performance in tailoring process control, the tensile and shearing properties were used in a similar control chart as shown in Figure 8 (Kawabata and Niwa, 1996).

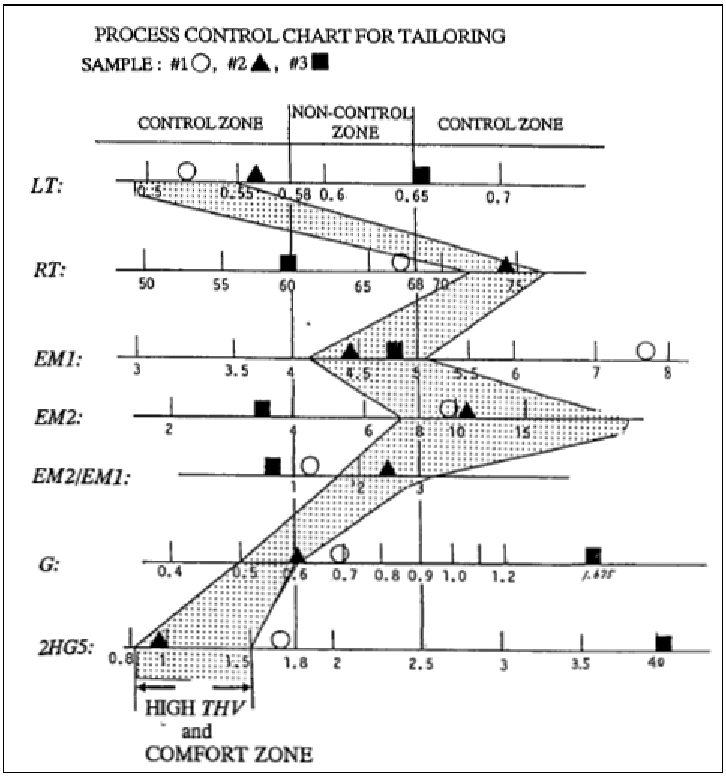


Figure 8. Processing control chart for tailoring and comfortable suit zone(Kawabata and Niwa, 1996).

The KESF technique was also applied to nonwoven fabrics (Kawabata et al., 1994, Yokura and Niwa, 2003, Yokura and Niwa, 2000, Fan and Ng, 2001). The methodology and techniques are almost the same as those used for woven fabrics. Some research showed that Kawabata's equation of THV for men's suiting was suitable for predicting THV of nonwoven fabrics, while the equations of HV needed to be modified (Yokura and Niwa, 2003).

4.2.5 Potential for the CRC SII handle project

The KESF is a very powerful OMFH system which could assist the CRC SII Handle in Merino Wool Fabrics project, particularly in selecting mechanical and surface properties of fabrics for a new OMFH system. It can play a 'benchmarking' role in the Fabric Handle project. However, the KESF instruments are very expensive, the test procedure is time-consuming and the interpretation of results is complicated. Therefore, the KESF system will not be the system used for the final commercial tests in the Handle in Merino Wool Fabrics project.

4.3 FAST System

4.3.1 FAST system and parameters measured

The FAST system is aimed to be a simpler, cheaper and quicker system for measurement of than is the KESF system. It is targeted for use in an industrial environment and is not designed as an instrument to measure fabric handle, though many of the FAST parameters are highly related to KESF parameters.

The FAST system consists of four instruments:

a) FAST-1 Compression meter (Figure 9)
b) FAST-2 Bending meter (Figure 10)
c) FAST-3 Extension meter (Figure 11), and
d) FAST-4 Ventilator (Figure 12)

Figure 9. FAST-1 (CSIRO TFT)

Figure 10. FAST-2 (CSIRO TFT)

Figure 11. FAST-3 (CSIRO TFT)

Figure 12. FAST-4 (CSIRO TFT)

The parameters measured by the individual FAST instruments are listed in Table 17.

Table 17. Parameters measured by FAST system

Instrument	**Property block**	**Property**	**Description**	**Unit**
FAST-1	Compression	T	Fabric thickness at 0.196Kpa (2 g/cm^2)	mm
		ST	Fabric surface thickness (difference between thicknesses measured at 0.196 and 9.81Kpa	mm
		STR	Released surface thickness (difference between relaxed ST (in water or steam) and ST)	mm
FAST-2	Bending	B-1 B-2	Warp (1) and weft (2) bending length or bending rigidity	mm µN m
FAST-3	Tensile	E_{100}-1 E_{100}-2	Warp (1) and weft (2) extensibility at 98.1 N/m (100 gf/cm width)	%
		E_5-1 E_5-2	Warp (1) and weft (2) extensibility at 4.9 N/m (5 gf/cm width)	%
		E_{20}-1 E_{20}-2	Warp (1) and weft (2) extensibility at 19.6 N/m (20 gf/cm width)	%
	Shear	G	Shear rigidity	N/m
FAST-4	Dimension	L1	Dried dimension	mm
		L2	Wetted dimension	mm
		L3	Redried dimension	mm
		RS-1 RS-2	Warp (1) and Weft (2) relaxation shrinkage: 100(L2-L3)/L3	%
		HE-1 HE-2	Warp (1) and Weft (2) hygral expansion: 100(L1-L3)/L1	%

4.3.2 Analysis and presentation of the results

In contrast to KESF, the FAST system records a single parameter at the limit of each fabric deformation being tested. The results from the FAST system were normally presented as ‘snake-chart’ without any complicated computation (Figure 13).

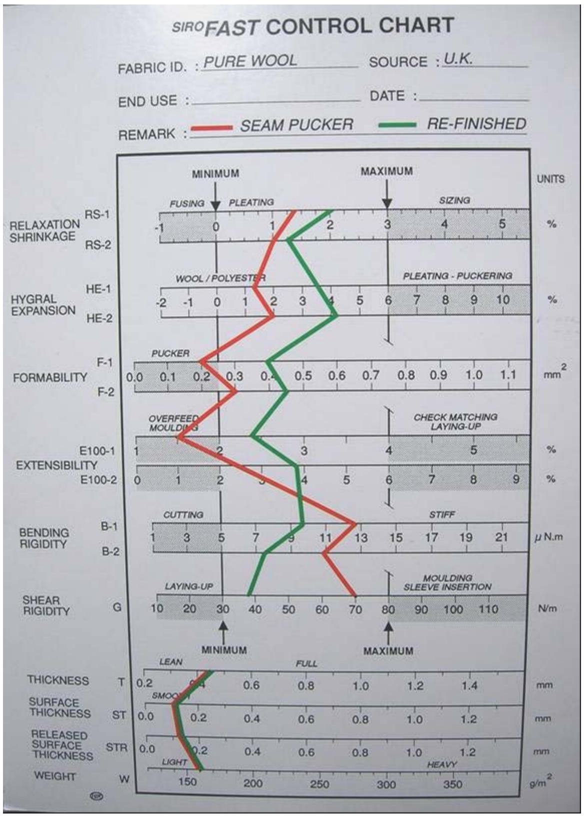


Figure 13. Quality control chart (CSIRO TFT)

4.3.3 Applications

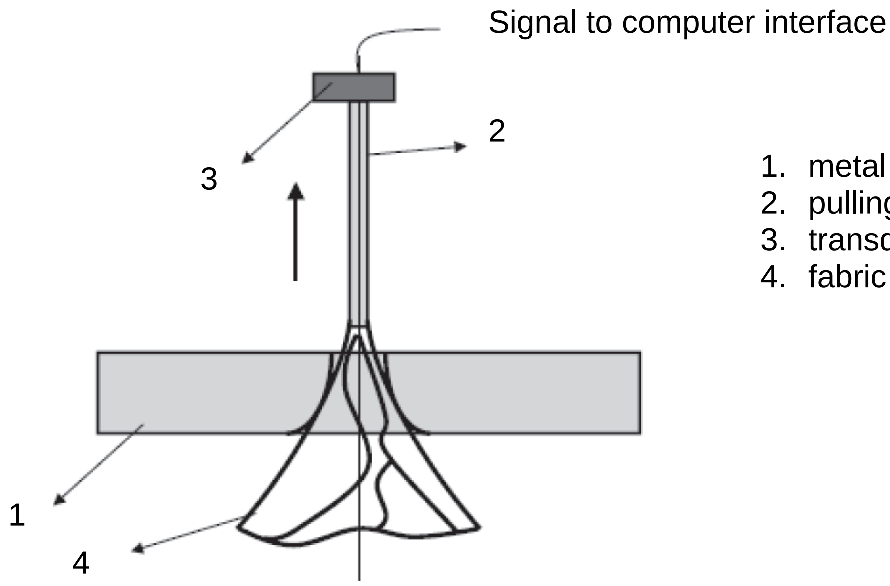
Strictly speaking, the FAST system is not an OMFH in the replacement of SEFH and may not be helpful in the interpretation of the relationship between SEFH and OMFH. However, it does aim to predict some fabric handle aspects and can be used in many applications as an alternative to the KESF system, such as in:

- Fabric development;
- Buying control for garment making;
- Quality control in garment making;
- Optimisation of processing, particularly fabric finishing;
- Evaluation of new process or technologies in processing.

4.4 PhabrOmeter – a prototype of the fabric extraction method

4.4.1 Parameters measured and evaluation of fabric handle

The fabric handle was objectively evaluated based on analysis of a force-displacement curve which was obtained by pulling a circular fabric sample (held at the centre) through a specially designed nozzle (Kim and Slaten, 1999, Alley et al., 1978). Research by Pan and his co-researchers laid sound technical foundation for this technique (Pan, 2006, Pan and Yen, 1992).The fundamental principle is shown in Figure 14. Based on this model, a prototype of the instrument called a PhabrOmeter is shown in Figure 15. The associated software graphic user interface (GUI) including the force-displacement curve is also shown in Figure 15.



1. metal nozzle
2. pulling rod
3. transducer
4. fabric sample

Figure 14. The technique of PhabrOmeter (Pan 2006)

Figure 15. PhabrOmeter (18kg; 9.5 in D x 14.25 in W x 20.5 in H) and software GUI (http://www.nucybertek.com/)

4.4.2 PhabrOmeter parameters

A feature vector Y with eight components was transformed from a data set X, which was discretised from the force-displacement curve. There was approximately 11% of information loss compared to the KESF system. The eight components in the Y vector were orthogonal and represented the human tactile sensory response space. Correlation analysis further showed that the first three components which explain the greatest proportion of variance in the data were highly corrected with the KESF Primary Handle Values as shown in Table 18.

Table 18. The first three feature components and their physical meanings

Component feature	Associated weight	Primary hand
Y_1	W1 = 0.252	Stiffness
Y_2	W2 = 0.195	Smoothness
Y_3	W3 = 0.144	Softness

Therefore, in the PhabrOmeter measurement, the first three Y's, Y_1, Y_2 and Y_3, were defined as primary handle components and the remaining five components were included in calculating an overall handle value based on the weighted Euclidean Distance to a reference fabric. The smaller the overall handle value, the closer measured the fabric was to the reference fabric.

4.4.3 Comparison with KESF and FAST

Compared with the KESF and FSAT systems, the PhabrOmeter has the following features:

- Testing is simple and fast;
- An estimate of fabric handle is extracted from one measurement;
- The system suits a much wider range of products; and
- The instrument is cheaper.

4.4.4 Applications

Equipped with the software called PhEs, the following applications of the PhabrOmeter were claimed by the developers (Pan 2006, www.nucybertek.com):

  - Handle evaluation of fabrics including nonwoven and paper products.
  - Fabric drapes evaluation.
  - Fabric wrinkle recovery evaluation.
  - Fabric stretch evaluation

4.4.5 Potential for CRC SII handle project

There was not much research work reported on knitted fabrics in the use of PhabrOmeters. In principle, however, the PhabrOmeter should be suited to testing knitted fabric handle once it is well calibrated for the defined fabrics in the CRC SII handle project. Using the PhabrOmeter in the Handle in Merino Wool Fabrics project will complement the applications of this technique as well.

4.5 Pulling force method

Zhang et al. (2005) reported a Pulling Force Method for evaluation fabric handle, particularly for fabric softness. This method was evolved from a similar test for the evaluation of fibre softness (Liu et al., 2004a, Wang et al., 2004). The basic set-up of the measurement is shown in Figure 16. A Lloyd tensile instrument was used to obtain a force-displacement curve as a fabric sample was pulled through a series of metal rods or pins.

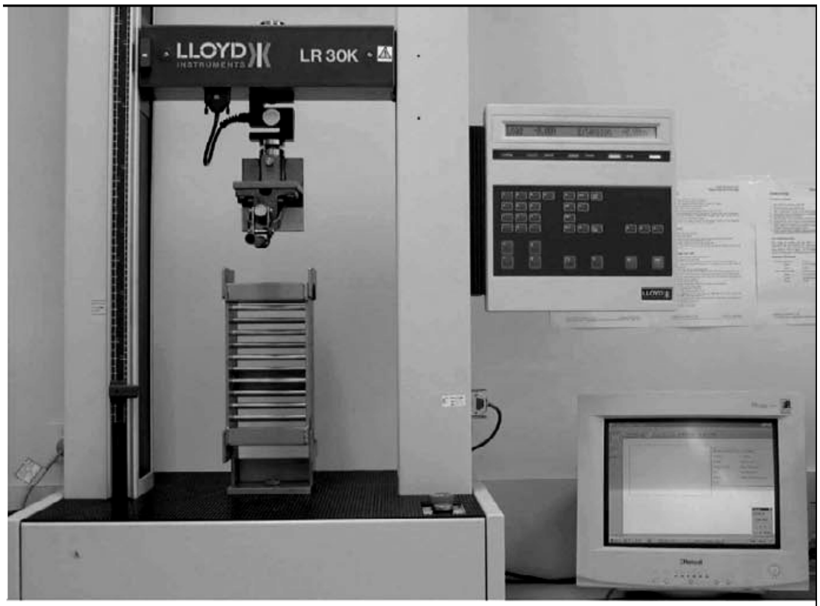


Figure 16. A Pulling Force Method for the evaluation of fabric softness (Zhang et al., 2005)

Due to the large difference in fabric attributes between woven and knitted fabrics, the different set-ups and testing conditions used by Zhang et al. (2006) are summarised in Table 19.

Table 19. Testing conditions for woven and knitted fabrics

Parameter	**Rig setting 1**	**Rig setting 2**		
Distance between pins (mm)	1.5 - 15	15	12.5	10
Pin diameter (mm)	3	5	7.5	10
Number of pins	10	12		
Test speed (mm/min)	400	400		
Preload (cN)	0 or 12	0 or 12		
Sample size	250 x 25	500 x 90		
Suitable fabrics	Woven	Knitted or heavy woven		

Figure 17 shows a typical pulling force curve. The average specific pulling force (the pulling force was divided by the fabric linear density (cN/ktex)) in between the two vertical dotted lines (approximately 60% of the full range) was used to correlate with the parameters measured from the FAST system. The definition of the dotted lines was not provided in the paper.

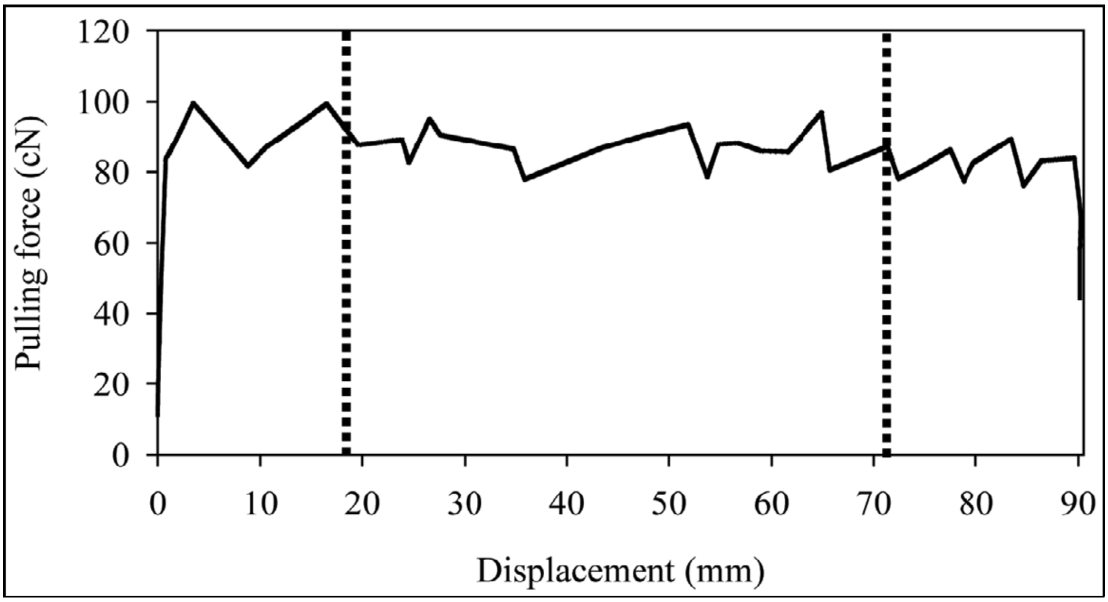


Figure 17. A typical pulling force curve of a fabric (Zhang et al., 2005)

The results showed that the specific pulling force was significantly correlated to parameters measured by the FAST system, such as thickness, bending length, bending rigidity and fabric stretch characteristics. Possibly due to the inaccessibility of the KESF system, no research was reported on the relationships between the specific pulling force and the parameters measured by the KESF system.

4.6 Summary

Each fabric objective measurement system examined in this review measured fabric properties at low-stress to predict some aspect or aspects of fabric performance related to handle. Effective specification of low-stress physical properties of fabric appears to be a critical step in the development of an OMFH system. The KESF and FAST are relatively successful fabric objective measurement systems. The KESF is a more comprehensive system than FAST. It will be a very powerful OMFH system in assistance of the Handle in Merino Wool Fabrics project, particularly in selecting fabric mechanical and surface parameters for any new OMFH system. It can also play a ‘benchmarking’ role in the fabric handle project.

However, the high cost and very significant commitment of time and experienced labour required to obtain reliable data are major barriers to intensive use the KESF in the fabric handle project. In contrast, the PhabrOmeter and the Pulling Force Method are simpler and cheaper. In each case an evaluation can be derived from a single test. In particular, the PhabrOmeter appears worthwhile for the fabric handle project, while the Pulling Force Method still needs much more fundamental research work to verify its feasibility for the evaluation of fabric handle.

5 Wool fibre properties relevant to fabric handle

5.1 Introduction

It is apparent that a complex interrelationship exists between fabric handle and the properties of the fibres, the structure of yarns and fabric and the finishing processes used to manufacture the fabric. Figure 18 gives a schematic representation of the interaction between fibre, yarn and fabric and handle. Much of the literature on fabric handle is devoted to the study of the effects of the processing parameters, such as spinning systems, yarn and fabric structures and finishing techniques on fabric handle and the assessment of fabric handle either subjective or objective using the KES-F system (Bassett et al., 1999, Alimaa et al., 2000a, Alimaa et al., 2000b, Brooks, 1991, Choi and Ashdown, 2000, Daukantiene et al., 2005, Radhakrishnaiah et al., 2005). Complex interactions exist between fibre assemblies and fibre properties and in 2002, Kawabata *et al* (2002) acknowledged that more details of fibre properties are required to understand the complex mechanical behaviours of fabrics.

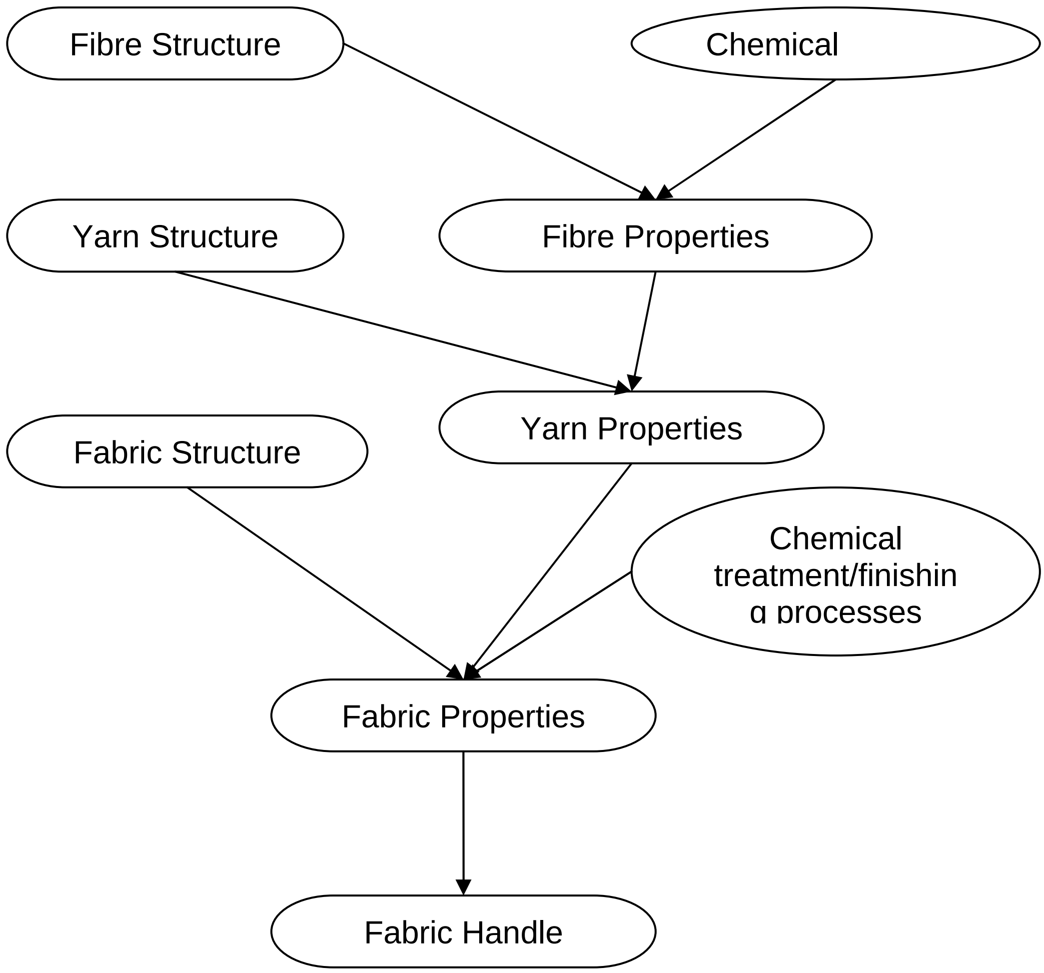


Figure 18. Interrelationship between fibre, yarn and fabric structure and properties on fabric handle

An extensive review published by Hoffman and Beste (1951) in 1951 has addressed the fibre properties relevant to fabric handle. They systematically identified the fibre properties relevant to fabric stiffness, compliance, liveliness, weight, leanness and bulk, compressibility and thickness, waxiness, friction, contact warmth, drape, smoothness and lustre, covering power, and contour retention and resilience. Behera and Shakyawar(2000) conducted a more general review of the fibre, yarn and fabric properties affecting fabric hand. More recently in a series of three papers, Madeley et al (Madeley et al., 1998b, Madeley et al., 1998a, Madeley and Postle, 1999) critically reviewed the fibre properties and handle of fine Merino lamb's wool, including the growth of wool in lambs and mature sheep, and the tactile appraisal of loose wool fibres, the effect of crimp on compressibility and handle and the effects of wool fibre curvature on the handle of woven fabric.

5.2 Fibre structure and properties

Unlike fabric, where the handle of fabric is described by terms smoothness, firmness, fullness, crispness and hardness (Liu et al., 2004b), the handle of fibre is described in terms of harshness and softness (Stevens, 1994) although the terms crisp, full and resilient are sometimes used (Shah and Whiteley, 1971). During subjective evaluation to grade the softness of fibre, wool classers rub staples of wool between their fingers and compress the wool to evaluate surface and compression properties of the fibre and grade the softness of the fibre (Stevens, 1994). Fibre softness was evaluated objectively by pulling a bundle of parallel fibres through a series of pins (Liu et al., 2004b). This study has shown that pulling force measurements can be used to detect differences in fibre softness.

What makes fibres soft? The softness of a wool fibre bulk is a result of a combination of characteristics, such as the ease with which fibres bend (bending rigidity), the fibre diameter and cross sectional shape, the intrinsic modulus of the material, the compressibility, resilience, crimp and fibre surface structure. Fibre surface friction strongly influences how easily fibres can slip past one another in fibre assemblies in response to stresses (Kirk-Othmer, 1998). Of these characteristics, mean fibre diameter is without doubt the major parameter effecting fibre softness, with the coarser the wool, the harsher the handle (Roberts, 1956, Shah and Whiteley, 1971, Hunter et al., 1982, Stevens, 1994). However it has also been reported that there have been marked deviations from this relationship particularly for the Down breeds (Shah and Whiteley, 1971). For a given fibre diameter, alpaca fibres are softer than wool fibres (Liu et al., 2004b) also indicating factors other than diameter contribute to the handle of a fibre bulk.

5.2.1 The morphological structure of the wool fibre

Wool is an α-keratin fibre grown by sheep. It is a complex material made up of several morphological components. Wool fibres can vary in diameter from about 6μm to more than 50μm depending on the breed of sheep (Kirk-Othmer, 1998), and generally have an elliptical cross-section, where the ratio of ellipticity which is usually between 1.1 and 1.3 (Postle et al., 1988). Coarse wool fibres are relatively straight and some have air filled cavities called medullae (medulla, sing.) (Postle et al., 1988). Fine wool fibres exhibit a regular crimp and are unmedullated (Postle et al., 1988). A schematic diagram showing the complex internal structure of a fine, unmedullated wool fibre is given in Figure 19 (Kirk-Othmer, 1998). Coarse wool fibres with diameters ranging between 25 µm to 70 µm are generally used in carpets, whilst fine Merino fibres with fibre diameters of 10 µm up to 25 µm are used in apparel because of their soft handle (Kirk-Othmer, 1998). Fibres from individual sheep also exhibit a range of fibre diameters and this fibre diameter distribution is also an important parameter particularly to the comfort and prickle properties (Kirk-Othmer, 1998).

The outermost layer of the wool fibre is a called the cuticle and consists of slightly overlapping layers of flattened cuticle cells (scales). The cuticle of fine wool fibres is normally one cuticle cell thick except where the scales overlap (Feughelman, 1997). The thickness of scales in Merino wool varies from 0.5 µm to 1.5 µm thick. This is in contrast to human hair where the cuticle is up to ten scales thick and each scale is about 0.5 µm (Postle et al., 1988, Feughelman, 1997). The exposed scale edges of the wool fibre point away from root end towards the tip of the fibre, with fibres being smoother in the direction of growth (MacLaren and Milligan, 1981). On the sheep's back, the scales are all aligned in the same direction, so fibre entanglement due to interlocking scales rarely occurs (Feughelman, 1997). The coefficient of friction of the wool fibre is different when measured in the with-scale or against-scale directions and is referred to as the directional effect (MacLaren and Milligan, 1981, Kirk-Othmer, 1998). More force is required to move the fibres in the against-scale direction than in the with-scale direction. Processing of wool randomises the orientation of fibres. When adjacent fibres are orientated in opposite directions, the scales form a ratchet-like structure. In water, the scales of a wool fibre project out further than in air and the ratchet mechanism causes irreversible fibre entanglement. This is the main cause of felting shrinkage of untreated wool fabrics. During felting the forces applied to moist fibres are insufficient to allow them to slide in the against-scale direction. Instead they move in the with-scale direction and tend to migrate towards their root ends (Feughelman, 1997, Huson, 1996).

The cuticle constitutes about 10% of a fine wool fibre and its main role is to protect the body of the wool fibre. In fine wool from Merino sheep, the cuticle cells are rectangular in shape with dimensions of about 20 x 30 x 0.5 µm (MacLaren and Milligan, 1981). Each cuticle cell is made of three layers, the endocuticle, exocuticle and epicuticle (MacLaren and Milligan, 1981). The exocuticle is a cystine-rich band that is enzyme resistant (MacLaren and Milligan, 1981) and forms about two-thirds of the scale structure (Feughelman, 1997). The endocuticle has a lower cystine content and is enzyme digestible and is mechanically the weakest component of the cuticle structure (MacLaren and Milligan, 1981, Feughelman, 1997). The endocuticle swells more than the exocuticle in water causing the scales to project out from the body of the wool fibre in water (Feughelman, 1997). This is due to the difference in their cystine content and the cross-linking of the protein structure (Feughelman, 1997). The exposed surface of cuticle cells is covered by a thin membrane called the epicuticle. It is a membrane-like proteinaceous band and is about 3 nm thick (Feughelman, 1997) and is thought to comprise of an outer layer of lipids bonded to a layer of cysteine-rich proteins through a thioester linkage (Maxwell, 2002a). The lipid has been identified as a saturated fatty acid called 18-methyleicosanoic acid (18-

MEA) (LaTorre and Bhushan, 2005b, Maxwell, 2002b). It forms a hydrophobic resistant barrier that affects fibre properties such as adhesion and dye uptake (Maxwell, 2002b, LaTorre and Bhushan, 2005b). The lipid and protein components of the fibre surface are the functional moieties of the fibre surface and are important in fibre protection and textile processing (Kirk-Othmer, 1998).

The cortex comprises of spindle shaped cortical cells that are about 95 µm long and 5 µm thick (MacLaren and Milligan, 1981). The cortical cells are cemented together by the intercellular cement, known as the cell membrane complex (CMC). The cell membrane complex also cements the cortical cells to the cuticle. The cell membrane complex is typically 25 nm thick and is chemically different to the cortical cells. Although the composition of the cell membrane complex is not known precisely, it is believed that the cell membrane complex both plays an important role in the penetration of water and chemicals into the fibre and also is the site affected by fatigue and abrasion (Postle et al., 1988).

Each cortical cell consists of macrofibrils that are about 0.3 µm thick and are as long as the cortical cell. The macrofibrils are oriented parallel to the fibre axis and consist of bundles of highly organised, rod-like, low sulphur protein microfibrils called intermediate filaments that are packed in a sulphur rich, amorphous matrix (MacLaren and Milligan, 1981). The intermediate filaments are about 10 µm long and 7.2 to 7.5 nm thick (MacLaren and Milligan, 1981, Postle et al., 1988)and have been resolved into pairs of α-helical ropes that are interlocked along their lengths (MacLaren and Milligan, 1981).

In wool there are two main types of cortical cells, namely the orthocortical cells and the paracortical cells. However in wool fibres of low crimp frequency and fibres such as cashmere and human hair may contain a third type of cortical cell called the mesocortical cell (MacLaren and Milligan, 1981, Caldwell et al., 2005, Popescu and Hocker, 2007, Plowman et al., 2007, Whiteley and Kaplin, 1977, Kaplin and Whiteley, 1978). Whiteley and Kaplin (1977) have also identified small numbers of mesocortical cells along the junction of the ortho- and paracortex in well crimped wool fibres.

Although in wool there is considerable variation in the number and distribution of the cell types both along the length and cross section of the fibre, orthocortical cells generally make up over 50% of the fibre cross-section and volume (Bendit, 1980, Plowman et al., 2007). The proportion of orthocortical cells increases as the fibre diameter increases (Orwin et al., 1984, Plowman et al., 2007). The proportion of mesocortical and paracortical cells decreases as the fibre diameter increases. Partial substitution of the paracortical cells for mesocortical cells also occurs (Plowman et al., 2007). Some hair fibres contain only one type of cell, usually the orthocortical cells (Popescu and Hocker, 2007). In low crimp wool fibres, the paracortical cells may occupy only 10% of the total cross-sectional area (Whiteley and Kaplin, 1977). They are clustered together within the mesocortex which occupies approximately 40% of the cortex in a loose bilateral arrangement with the orthocortex (Whiteley and Kaplin, 1977).

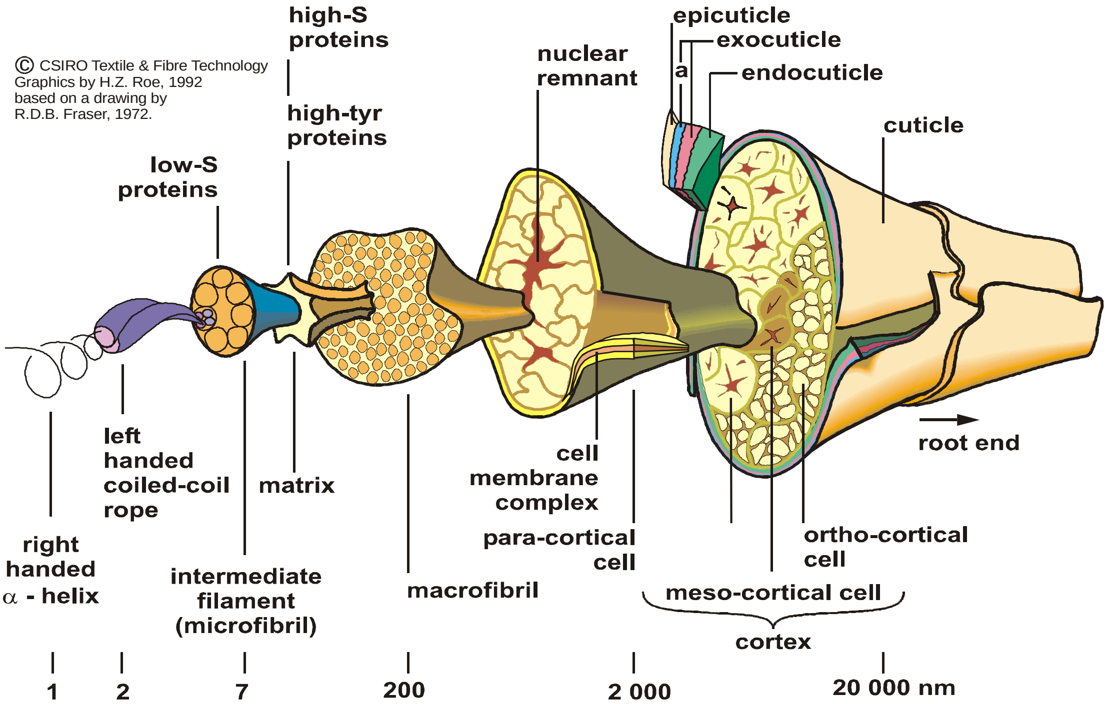


Figure 19. Schematic diagram of the structure of a wool fibre (Kirk-Othmer, 1998)

In the orthocortical cells, the intermediate filaments are more tightly packed than in the paracortical and mesocortical cells (Popescu and Hocker, 2007, Caldwell et al., 2005, Tester, 1987). In the ortho-cortex, the fibril-matrix composite forms a helical array (whorl structure) in macrofibrils whilst in the para-cortex, the fibril-matrix composite is oriented parallel to the fibre axis (Popescu and Hocker, 2007, Hearle, 2007). In the paracortical cells, the intermediate filaments (microfibrils) are more randomly arranged and the macrofibrils tend to fuse together (Tester, 1987). This fusing of the macrofibrils isolates areas of nonmatrix protein called the nuclear remnants (Tester, 1987). The mesocortical cells have a similar macrofibrillar structure to paracortical cells. However the intermediate filaments of the mesocortical cells are more ordered and hexagonally packed (Tester, 1987). The tightly packed orthocortical cells contain less matrix material than the paracortical and mesocortical cells (Whiteley and Kaplin, 1977, Tester, 1987). Mesocortical cells also contain less matrix material than paracortical cells (Tester, 1987).

Whiteley and Kaplin (1977) proposed the following descriptions of the three types of cortical cells found in wool :

> *Paracortical cells:* Microfibrils in a disordered configuration with occasional hexagonal or near-hexagonal areas. Macrofibrils extensively fused. Large nuclear remnants in most cells.
>
> *Mesocortical cells:* Predominantly hexagonal or near-hexagonal arrangement of microfibrils. Macrofibrils usually extensively fused as in paracortical cells. Large nuclear remnants in some cells.
>
> *Orthocortical cells:* Whorls of poorly resolved microfibrils forming small well-defined macrofibrils. Large nuclear remnants not common.

In fine Merino wool, the ortho and para cortical cells have bilateral structure with the orthocortical cells located on the outside of the crimp waves (Horio and Kondo, 1953). In some coarse wool fibres such as in Lincoln wool the cellular arrangement is annular or concentric cylinders, where the orthocortical cells form the core of the fibre surrounded by the paracortical cells (Kirk-Othmer, 1998). The cortical cells also contain cytoplasmic debris (nuclear remnants). The cytoplasmic debris is more abundant in the paracortical cells than the orthocortical cells (MacLaren and Milligan, 1981, Whiteley and Kaplin, 1977).
The cortex accounts for approximately 90% of the bulk of the wool fibre and determines many mechanical properties of wool fibres. The intermediate filaments have long been regarded as the basic mechanical unit of the wool fibre (Postle et al., 1988, Feughelman, 1959b). The cell membrane complex and the cuticle account for the remaining 10% of the wool fibre.

5.2.2 Mechanical properties of fibres

Wool fibres from different breeds of sheep show differences in their mechanical properties (Rao and Gupta, 1991, Carter et al., 1969, Collins and Chaikin, 1971). These differences have been attributed to biological aspects of follicle type and growth and histological structure of the cortex. Fibres rich in orthocortical cells have inferior mechanical properties. This is thought to be due to poor organization of the intermediate filaments in the matrix and differences in the amino acid composition (Feughelman and Haly, 1960).

The mechanical properties of wool fibres and other α-keratins fibres are dependent on moisture content, temperature and time (Feughelman, 1997). They are often referred to as viscoelastic fibres and the time, temperature and water dependence can be attributed to the viscoelastic properties of the matrix (Postle et al., 1988, Kirk-Othmer, 1998). The tensile and flexural properties of fibres are important mechanical properties that combine to determine the behaviour of the fibre in processing and to the handle properties of the final product. The longitudinal tensile characteristics are largely governed by the deformation characteristics of the crystalline helices of the intermediate filaments, whereas the stiffness in the lateral direction reflects the properties of the non-crystalline matrix (Rao and Gupta, 1991).

Early work by Cassie (1946), Khayatt and Chamberlain (1948) and Guthrie et al (1954) suggested that flexural properties of fibres namely bending and torsion are very important with respect to handle and wear. Khayatt and Chamberlain (1948) and Guthrie (1954) emphasized that bending properties of single fibres are more important than the tensile properties to the practical properties of fabrics, such as flexibility, draping qualities, handle, wrinkle recovery, creasing etc. Khayatt and Chamberlain (1948) also acknowledged that the determination of the flexural properties is more difficult than tensile properties because of the small forces involved in flexion. Chapman (1973b) found that most rheological studies on fibres were almost exclusively confined to tensile strains because of the unavailability of suitable commercial fibre bending apparatus and the difficulties in measuring bending experimentally. Kawabata *et al* (2002) have also acknowledged the importance of single fibre properties in understanding the complex mechanical behaviour of fabrics (Kawabata et al., 2002). They showed the five mechanical parameters responsible for describing the material property of a fibre as illustrated in Figure 20 and developed 5 testers called the ‘Micro-Measurement System’ to measure the properties of fibres:- simple extension, transverse compression, torsion, Poisson’s ratio and axial compression (Kawabata et al., 2002).

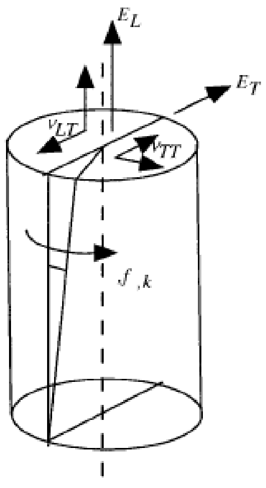


Figure 20. The mechanical properties of a fibre (Kawabata et al., 2002)

5.2.2.1Tensile properties

Of the fibre mechanical properties, the longitudinal tensile properties have achieved the most attention in the literature. The tensile modulus and other tensile properties have been extensively studied by many researchers (Feughelman, 1994, Chapman, 1969b, Meredith, 1945a, Meredith, 1945b, Speakman, 1927) and the typical stress-strain curves are reported in most fibre science text books. The stress-strain curves are most commonly obtained by testing fibres at a constant rate of extension on instruments such as the Instron Tensile Tester (Morton and Hearle, 1993). Speakman (1927) showed that for fibres equilibrated at fixed relative humidity and temperature, the longitudinal stress-strain curve of the fibre has three distinct regions of extension as shown in Figure 21 which has been reproduced from the Kirk-Othmer Encyclopaedia of chemical technology (Kirk-Othmer, 1998). Wool can absorb and desorb large amounts of moisture as the relative humidity surrounding the fibre changes. The saturated moisture level of wool is about 33% (Kirk-Othmer, 1998) and as shown in Figure 21, the three regions of the longitudinal stress-strain curve are most distinctly defined when the fibre is in water. The schematic shown in Figure 22 depicts the stress-strain curve of a wool fibre in water and shows the three distinct regions of mechanical behaviour. The slope of the stress-strain curve for the three regions, pre-yield, yield and post yield regions are in the approximate ratio of 100:1:10 respectively for fibres in water (Feughelman, 1997).

After stretching the fibre beyond the de-crimping region, there is a linear increase in load to about 2% strain. This region is called the pre-yield region (Feughelman, 1997, Bendit, 1980). Speakman referred to this region as the Hookean region (Speakman, 1927). For the wet fibre this is generally associated with the stretching of the α-helices of the intermediate filaments (microfibrils) and the deformation in the pre-yield region is completely reversible (Warner, 1995, Kirk-Othmer, 1998). At lower moisture contents, the matrix phase plays a more dominant role (Kirk-Othmer, 1998). The yield region occurs from 2% to 30% strain and is associated with progressive unfolding of the α-helices to form a β-pleat configuration (Kirk-Othmer, 1998, Postle et al., 1988). The post-yield region occurs above 30% strain and in this region the fibre stiffens and becomes increasingly resistance to further strain and eventually breaks as strain increases. When fibres are stretched into the post-yield region, the deformation becomes increasing irreversible and is associated with covalent bond breakdown (Feughelman, 1997). Provided that the fibres are not extended beyond the yield region, the mechanical properties of the fibre can be recovered by release of the fibre for one hour in water at 52°C (Feughelman, 1997). The reason for the stiffening of the fibre at high strains is still a matter of debate as conflicting models have been proposed (Kirk-Othmer, 1998).

Interpretation of the tensile stress-strain curve of wool in terms of structural mechanics has been debated for at least three decades. Hearle (2000) has reviewed the main three models that describe the stress-strain behaviour of wool fibres :- Wortmann and Zahn model (1994), the Feughelman (F94) model (Feughelman, 1997) and Chapman and Hearle's model (Chapman, 1969a). The models are based on Feughelman's two-phase composite model (Feughelman, 1959b) where the water impenetrable, intermediate filaments (microfibrils) are embedded in a water-sensitive matrix to form a fibre that is highly anisotropic. The mechanical relationships in the pre-yield and yield regions are generally agreed in the models, and it is generally believed that the stress-strain behaviour of wool fibres depends primarily on the response of the fibril-matrix assembly (Hearle, 2007). However the molecular explanations for the post-yield region are still conjectural. The Chapman-Hearle model assumes that the α ↔ β transition is controlled by a critical and equilibrium stress and that the matrix is rubber-like when the fibre is wet and the stress is transferred from the fibrils to the matrix as zones (Chapman, 1969a, Hearle, 2007). The Wortmann-Zahn's series-zone model assumes that the stress-strain curve in the yield and post-yield regions is dependent on the sequential opening up of two different and well defined portions of the monomer in the intermediate filament (Hearle, 2007, Wortmann and Zahn, 1994). Feughelman's (F94) model is based on a matrix of protein globules surrounded by water. It assumes that in the post-yield region the globules are jammed between the intermediate filaments as the fibre contracts laterally as it is extended (Feughelman, 1994, Hearle, 2007).

In normal apparel use the wool fibres are rarely strained to breaking point. Beste and Hoffman (1950) suggested that the practical limit of fibre deformation is approximately 11%.

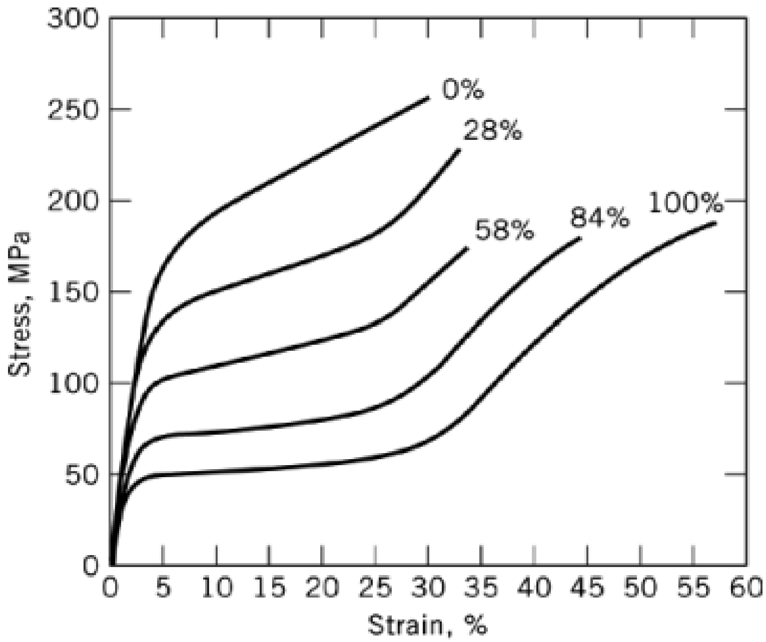


Figure 21. The stress-strain curves of a wool fibre at different relative humidities (Reproduced from the Kirk-Othmer "Encyclopaedia of Chemical Technology", 1998, (Postle et al., 1988)

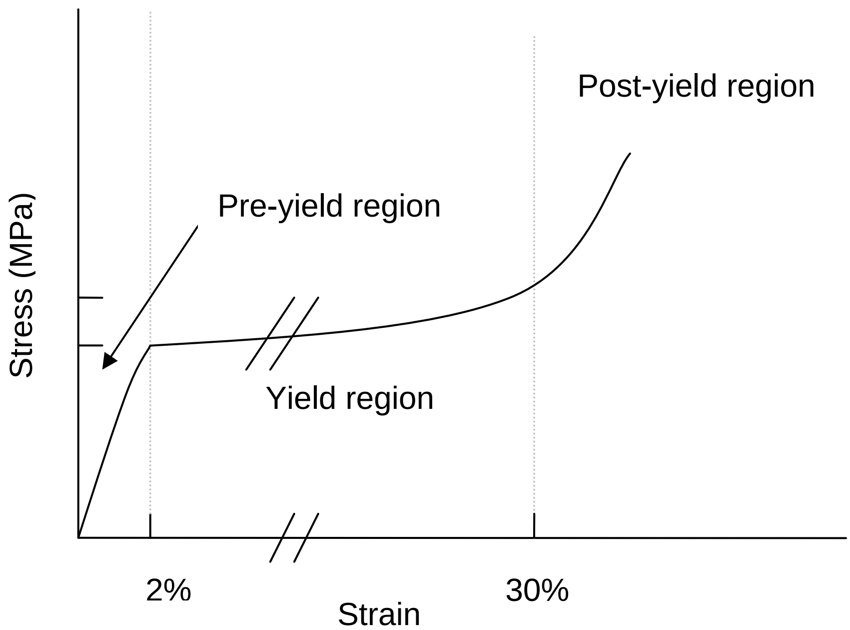


Figure 22. Schematic of a typical stress-strain curve for a wool fibre in water at 20°C (not drawn to scale)

5.2.2.1.1 Young's Modulus - tensile

The pre-yield or Hookean region of a stress-strain curve is the elastic region where materials recover completely from deformations. In the pre-yield region the stress and strain are linearly proportional, and for wool fibres this region occurs up to about 2% strain. The slope of the line is called the Young's modulus, *E*, also known as initial modulus or modulus of elasticity. The modulus is an important physical property of materials. It is an intrinsic property and provides information on the structure of the fibre. The modulus of fibres depends on the molecular arrangement as well as chemical structure (Warner, 1995). Increasing the molecular orientation along the fibre axis increases the modulus. Materials that have a high Young's modulus, such as steel, are hard, stiff materials that do not deform much in the presence of a stress. Materials that have a low Young's modulus, such as rubber filaments, are soft materials that deform easily in the presence of a stress (Warner, 1995). As can be seen from Figure 21, the tensile Young's modulus of wool fibre progressively decreases with increasing relative humidity. The tensile Young's modulus of wool fibre at 20 °C and 0% relative humidity is approximately 5 to 6 GPa and at 100% relative humidity the modulus is reduced to approximately 2 GPa (Feughelman, 1997, Postle et al., 1988).

Rao and Gupta (1991) studied the temperature dependence of the Young's modulus of Lincoln, Chokla and Merino fibres in water and found that the moduli decrease with increasing temperature. The slope of the Lincoln fibre was the greatest, followed by Chokla and Merino. The Young's modulus decreased with increased moisture content, and Lincoln fibres showed the highest values at all humidities. The wet-to-dry change in Young's modulus was a factor of 2.3 for the Lincoln fibres, 2.5 for the Chokla fibres and 3.1 for the Merino fibres. The Young's modulus has contributions from the oriented α-helices and the matrix, coupled in parallel. In the wet state, the Young's modulus is dominated by the α-helices because the matrix is highly compliant. Rao and Gupta (1991) attributed the higher relative change in modulus of Merino fibres as a function of humidity to be due to the high compliance of its helical structure.

Roberts was unable to demonstrate a relationship between Young's modulus and subjectively assessed handle of either greasy or cleaned loose wool (Roberts, 1956). Although he doubted the whether the accuracy with which the Young's modulus was determined was sufficient.

5.2.2.1.2 Compliance ratio

After the pre-yield region, the shape of the stress-strain curve suddenly becomes flatter and is associated with the unfolding of the α-helices (Kirk-Othmer, 1998). Where this curve changes is called the yield point and beyond this point the elastic recovery becomes less complete and permanent deformation starts to take place in the post yield region. Morton and Hearle (1993) suggest the shape or the flattening of the curve in the yield region has an influence on the fabric handle however they gave no experimental evidence to support this claim (Morton and Hearle, 1993).

Compliance is the reciprocal of the modulus (Morton and Hearle, 1993) and Hoffman and Beste (Hoffman and Beste, 1951, Beste and Hoffman, 1950) developed the term compliance ratio to describe the differences in the shape of the stress-strain curves in the yield region between 5% and 10% elongation. They expressed the compliance ratio (CR) as being equal to the (compliance at 10% elongation – compliance at 5% elongation) / 5. This was expressed mathematically as:

$$CR \equiv \frac{2}{L_{10}} - \frac{1}{L_5} \qquad (6)$$

where, L_{10} represented the stress at 10% elongation and L_5 represented the stress at 5% elongation. They found the compliance ratio of wool was typically 1.4 and silk 0.25, meaning that the compliance ratio of wool was more than 5 times greater than that of silk. They found the compliance ratio of nylon was -0.15. Nylon had a negative compliance value because the high orientation of nylon caused the stress-strain curve to curve upwards rather than downwards at higher elongations. They also demonstrated the relationship between the Young's modulus, compliance ratio and the harsh-compliant-limp aspects of fabric hand. For a fabric to be compliant or yielding, required a large compliance ratio and a low Young's modulus.

5.2.2.2Bending rigidity

When a fibre is bent into a curve or arc, the outside of the curve is in tension and is stretched while the inside of the curve is in axial compression. The bending or flexural rigidity (stiffness) of a fibre is defined as the couple required to bend the fibre to unit curvature (Morton and Hearle, 1993), and is a measure of the bending resistance of the fibre. This bending rigidity is the fibre property that dominates fibre softness (Warner, 1995).

The bending rigidity, B, of a fibre relative to an axis can be expressed as equation 1 (Bueno et al., 2004):

$$B = E \,.\, I \qquad (7)$$

where E is the Young's modulus of the fibre in bending and I is the moment of inertia of the cross section relative to the axis. The moment of inertia of the cross section relative to the axis is based on equation (2) where T is in tex, ρ is in g/cm^3 and η is the shape factor (Morton and Hearle, 1993):

$$I = \frac{1}{4\pi} \eta \frac{T^2}{\rho} \qquad (8)$$

And therefore bending rigidity is (Morton and Hearle, 1993):

$$B = \frac{1}{4\pi} \eta \frac{ET^2}{\rho} \times 10^{-3} Nmm^2 \qquad (9)$$

The bending rigidity of a cylindrical fibre, where η = 1, is also expressed as equation 4 (Warner, 1995):

$$B(Nm^2) = \frac{\eta E(Nm^{-2})\pi R^4}{4} \qquad (10)$$

From these equations it can be seen that the bending rigidity of a fibre depends on its shape, it's Young's modulus, its density and is proportional to diameter to the fourth power. The most important fibre parameter is undoubtedly the fibre diameter. Since the bending rigidity depends on the fourth power of mean diameter, only a very small change in diameter is required to produce a noticeable change in flexibility. Reducing the fibre diameter by a factor of 2 reduces the bending rigidity by a factor of 16.

For non-round fibres the bending rigidity is corrected by a shape factor. Table 20 which has been reproduced from Fibre Science (Warner, 1995), gives the shape factors for various fibres and their shapes. The more distant the shape is from the centre, the greater the shape factor becomes resulting in an increase in the bending rigidity. Figure 23 gives a schematic representation of how fibre shape influences the shape factor.

For an elliptical fibre, the bending rigidity can be expressed as equation 5 where a and b represent the radii of the two axies.

$$B(Nm^2) = \frac{b}{a} \times \frac{E(Nm^{-2})\pi \times a^4}{4} \qquad (11)$$

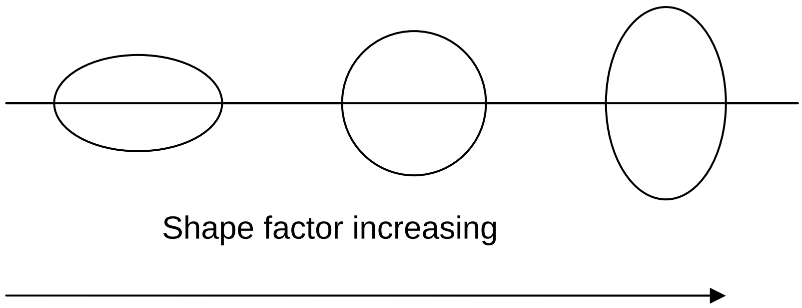


Figure 23. Relationship fibre shape and shape factor
Source: *Morton and Hearle (1993)*

Soft fibres have low bending rigidity. Therefore if one is selecting fibres for softness one should select fibres with low fibre diameter, low tensile modulus and have a more ribbon like cross sectional shape.

Hoffmann and Beste (1951) assumed the effect of density was negligible and expressed the bending rigidity of single fibres proportional to the square of the tex(T) multiplied by the Young's modulus (*E*) also known as the modulus of elasticity as (Hoffman and Beste, 1951) as in equation 6:

$$B \propto ET^2 \qquad (12)$$

They found that ET^2 was a reliable criterion of relative fabric rigidity (firm, crisp or soft fabrics) so long as the other variables were constant. Table 21 was reproduced from their report and shows that linen is a stiff fabric due to its high fibre bending rigidity. Although linen is a fine denier fibre, the bending rigidity of linen fibre is high due to its high Young's modulus. Other low denier fibres such as rabbit and silk have low fibre bending rigidity because of their low Young's modulus.

Table 20. Flexural rigidity of various fibres

Cross-sectional shape	Fibre	Shape factor
Circle	round	1.00
Crenulated	viscose rayon	0.74
Deeply crenulated	acetate	0.67
Elliptical (almost round)	wool	0.80
Pie-shaped	silk	0.59
Square	synthetic	1.05
Equilateral triangle	trilobal	1.21
Rectangle *b x 4b*	synthetic	0.26

Source: Fibre Science (Warner, 1995)

Table 21. Fibre rigidity

Description	Initial modulus of elasticity (M_i)	Denier (*d*)	Fibre Bending Rigidity ($M_i d^2$)
Firm Fabrics			**High rigidity**
Carpet wool	35	10	3500
Linen	208	2.3	1100
Crisp Fabrics			**Medium rigidity**
Suiting wool	20	5	500
Cellulose acetate	45	3	400
Soft Fabrics			**Low rigidity**
Angora rabbit fur	40	2	160
Cellulose acetate	45	1.5	90
Silk	90	1	90
Rubber monofilament	*0.04*	50	100

Source: Hoffman and Beste(1951)

Fibre bending properties are more difficult to measure than fibre tensile properties because of the low forces involved and consequently literature on bending is limited.

Roberts (1956) and Elder (1966) have assumed that bending behaviour may be predicted from tensile data, whilst Guthrie et al. (1954) felt that this was not the case for anisotropic materials.

Khayatt and Chamberlain (1948) developed a cantilever method of measuring the bending modulus of short, 1mm lengths of fibre. Their apparatus was built up on a stage of a microscope used in the horizontal position. The fibre was mounted so only a short 1mm segment of fibre projected onto the moving stage. The root end of the fibre was fixed in wax and the tip end was free. For elliptical fibres the major axis was horizontal to the plane of bending. The load was applied by pressing the fibre against a knife-edge attached to the arm of a torsion balance. The corresponding deflection was read off the eye-piece micrometer. Khayatt and Chamberlain (1948) studied the bending and tensile moduli of wool and hair at 65% relative humidity and 22°C. They found that the value of Young's modulus, as determined from bending was less than the corresponding tensile value obtained by stretching. The bending modulus was between 45% and 80% of the tensile modulus. Descaling the fibres reduced the bending modulus by 4% and reduced the tensile modulus by 10%. From this they concluded that the scale did not play any preferential role in bending.

Swift (1995) conducted a theoretical study of the mechanics of bending human hair. He modelled the bending behaviour of human hair using the cantilever model. He assumed hair was an isotropic structure and demonstrated how fibres always bend preferentially around the minor axis, concluding that the minor elliptic diameter had the more dominant effect on bending resistance. His model could be used to predict the stiffness of hair from different racial backgrounds and showed that Chinese hair, which had the greatest minor axial diameter, and was the stiffest. He also suggested that the cuticle might make a substantial contribution to bending resistance, even despite the relative thinness of the cuticle layer (Swift, 2000). Swift (1995, 2000, 2002) felt that there may be opportunities to soften or stiffen hair fibres by modifying the cuticle.

Guthrie et al (1954) used a similar cantilever method as Khayatt and Chamberlain (1948) and incorporated a dynamic measurement of bending modulus where one end of the fibre is vibrated transversely. This method requires at least 5mm of straight fibre of uniform diameter to make the measurement so measurements of wool and other natural fibres are difficult because of the crimp. Guthrie (1954) found that for fibres with round cross-sections, the tensile modulus fell between the static and dynamic bending modulus. The difference between the static and dynamic bending values was thought to depend on time effects (Guthrie et al., 1954). Elder (1966) used an Instron Tester to record the load and bending deflection of monofilaments. He found the bending moduli to be equal to tensile and compressive moduli.

Chapman (1973b) reported the cantilever technique of measured bending at strains of less than 0.5%. Other bending techniques such as the loaded loop method, Searle's double pendulum and the vibrating rod method also measured bending at strains of less than 0.5% (Chapman, 1973b). Chapman (1973b, 1971) developed an apparatus that could measure bending strains up to 20% because it was suggested that in creasing and wrinkling, fibres experience bending strains as high as 20% (Chapman, 1973b). Although it was not possible to bend the fine fibres to such large bending strains, similar stress-strain curves were obtained in bending and tensile testing. The modulus calculated from bending is nearly the same as that calculation from the fibre load extension curve (Chapman, 1973b, Postle et al., 1988). Chapman (1973a) found that the bending modulus was reduced with an increase in temperature and humidity.

Shah and Whiteley (1971) also used Guthrie's (1954) cantilever technique to measure bending properties of single fibres at 21°C and 65 % relative humidity. They found considerable variation in the bending modulus of the samples tested which was largely due to variability of fibre cross-sectional area along the length of fibre segments. They carried out subjective handle appraisals on 5g samples of scoured, carded loose wool from which the bending fibre samples were extracted. The handle appraisals were conducted in darkened rooms to remove visual bias. A partial regression of subjective handle on bending modulus proved non-significant and Shah and Whiteley (1971) were unable to demonstrate a relationship between subjectively assessed handle of scoured, carded loose wool and bending modulus. They concluded that their bending modulus results concurred with Roberts' (1956) Young's modulus and that a relationship between fibre substance and handle could not be established.

A new test developed to characterize the bending properties of treated or virgin hair Fibres is described by Baltenneck et al (2001) . The device consists of a pendulum that bends a sample made up of 39 parallel hair Fibres at each swinging stroke. Hair bending stiffness can be assessed by the number of strokes observed until the pendulum stops. Using this technique they confirmed that the mechanical behavior of natural hair Fibres is related to their geometric characteristics.

More recently researchers (Collier et al., 1991, Ramaswamy et al., 1995, Lombard et al., 1994) have measured the bending properties of fibres such as nylon and polypropylene fibres coated with rayon, milkweed and kenaf fibres with the Kawabata Pure Bending Tester, KES-FB2. Collier (1991) adapted the method for testing fabric bending behaviour to determine the bending behaviour of monofilament fibres. For each bending test, 20 single fibres were aligned and mounted in a parallel fashion on paper strips and were tested on the Kawabata Pure Bending Tester. All 20 fibres bear the bending stress during testing. Five replicates were tested so that for each test the results are reported as the average of 100 fibres. Collier et al (1991) showed that the precision of this test method was good and that the coating of nylon and polypropylene fibres with rayon did not increase the bending stiffness. Lombard et al (1994) used a combed fringe of fibres to evaluate fibre bending in the KES-FB2 tester.

Kawabata (2002) has included an axial compression tester to assess the bending properties of single fibres and fibre bundles in his 'Micro-measurement System'.

Yu and Liu (2006) have evaluated the softness of single fibres by calculating the equivalent bending modulus from force-displacement curves generated from axial-compression bending. They carried out fibre axial-compression bending on an instrument they developed called the compression bending analyser (FICBA). They found the equivalent bending modulus of wool, alpaca and silk to be 1.47GPa, 2.15GPa and 4.58GPa respectively. They attributed the high bending modulus of silk to the β pleated sheet structure of silk. On the basis of these results it would be expected that for an equivalent fibre diameter, wool would be “softer” than alpaca and silk. On the contrary it has been reported that for a given fibre diameter, a bulk sample of alpaca fibres are “softer” than an equivalent bulk sample of wool fibres (Liu et al., 2004b), and the apparent difference in subjective softness may be attributed to the smooth surface characteristics of the alpaca fibre, though difference in inter-fibre friction may also be responsible.

5.2.2.3 Torsional rigidity

Guthrie et al (1954) suggested that torsional properties of fibres are important with respect to handle and wear. Fibres are twisted and flexed to form yarns and fabrics and during handling or subsequent wear the fibres are further twisted and flexed. Twisting fibres applies shear stresses and shear strains to the fibre. The shear stress and shear strain in the fibre is proportional to the radial distance from the centre of the fibre and is maximum on the surface of the fibre (Warner, 1995).

Torsional rigidity of a fibre is its resistance to twisting and is defined as the torque to produce a twist of one turn per centimetre (Morton and Hearle, 1993, Guthrie et al., 1954, Robbins, 1994). The total torque is given by equation 13 (Warner, 1995).

$$torque = \frac{\pi R^4 G\theta}{2l} \qquad (13)$$

Where θ/*l* is the torsional displacement, G is the shear modulus and $\frac{\pi R^4}{2}$ is a geometric term. Rigidity in twisting is analogous to stiffness in bending and is proportional to fibre radius raised to the fourth power. Reducing the fibre diameter by a factor of 2 reduces the torsional rigidity by a factor of 16 (Warner, 1995). Ribbon shapes are flexible in twisting because the torsional rigidity is proportional to ab^3 where a is the larger and b the smaller dimensions of the fibre cross-section (Warner, 1995).

As with bending, torsional properties of wool fibres are difficult to measure and because they are not as important as tensile properties are in processing, they have not received as much attention in the literature (Nordon, 1962).

The torsional properties of wool fibres are important because they show a differentiation from the longitudinal properties caused by the two-phase morphological structure of wool (Nordon, 1962). The matrix and the intermediate filaments are considered to exhibit different mechanical and water sorbing properties and Feughelman (1959a) has suggested that at high humidities the longitudinal properties depend on the intermediate filaments while the torsional properties depend on the matrix (Feughelman, 1959a).

Although several methods for determining the torsional rigidity of fibres have been described in the literature (Robbins, 1994), they are related to the torsional pendulum method which is the simplest and is easy to use (Robbins, 1994, Warner, 1995). The torsional pendulum method involves suspending a small pendulum from a fibre that can be set into rotational oscillation. By determining the period (p) of oscillation (time of vibration), the fibre length (L), the fibre diameter (D) and the moment of inertia of the pendulum (I), the resistance to twisting or torsional rigidity (R_{twist}) can be calculated from equation 14 and the torsional modulus (G) can be calculated from equation 15:

$$R_{twist} = \frac{8\pi^3 IL}{p^2} \qquad (14)$$

$$G = \frac{R_{twist}}{JA^2} \qquad (15)$$

where, A is the fibre cross-sectional area and J is a shape factor. The shape factor is usually assumed to be 1 for wool and human hair fibres (Robbins, 1994). Dry wool fibres have a torsional modulus G of approximately 1.8GPa whilst wet wool fibres have a torsional modulus G of approximately 0.14GPa (Postle et al., 1988). The water sensitive matrix material is responsible for the change in torsional modulus from dry to wet. The matrix is considered to behave as an amorphous cross-linked polymer able to undergo a transition from a glassy state when dry to a rubbery state when wet (Phillips, 1987).

Phillips (1987) suggested that torsional measurements are a convenient and sensitive technique for observing changes to the matrix properties and used the pendulum method to examine the effect of ageing on torsional parameters. Phillips (1987) concluded that the torsional damping of wool fibres which increased with humidity and decreased with ageing was consistent with the model describing the matrix as an amorphous material characterized by glass transition behaviour.

Rao and Gutpa (1991) used the torsional pendulum method to compare the torsional modulus of Lincoln, Chokla and Merino wool and found that torsional modulus is reduced with increased moisture content. In the dry state, the torsional modulus was the highest in Merino fibres, followed by Chokla and Lincoln. This was the opposite of the Young's modulus findings for these fibres.

Robbins (1994) stated that the torsional behaviour of hair is more dependent than is the tensile behaviour on the cuticle or external layers of the fibre. Also torsional behaviour is more sensitive to water than tensile properties and waving (setting) and bleaching do change the torsional behaviour of hair (Robbins, 1994).

Poisson's ratio is a measure of the change in volume or density of a fibre subjected to a tensile deformation and is only measured in the Hookean or pre-yield region of the stress-strain curve (Warner, 1995). Poisson's ratio for fluids is 0.5 since their volume is invariant with deformation (Warner, 1995). The Poisson's ratio for isotropic polymers is between 0.3 and 0.4 (Warner, 1995). For isotropic solids, a relationship exists between the Young's modulus (E), torsional modulus (G) and Poisson's ratio (γ) as shown in equation 16 (Postle et al., 1988).

$$\frac{E}{G} = 2(1+\gamma) \qquad (16)$$

The ratio of E/G is a measure of anisotrophy in the fibre. The E/G of dry wool fibres is approximately 3.5 whilst the E/G of wet wool fibres is approximately 13 (Postle et al., 1988). Rao and Gupta (1991) calculated the E/G ratios for Lincoln, Chokla and Merino fibres at various moisture regains. For dry wool, the E/G's of Lincoln, Chokla and Merino were 3.9, 2.9 and 2.2 respectively. For wet wool, the E/G's of Lincoln, Chokla and Merino were 19.6, 17.9 and 12.5 respectively. Rao stated that the matrix is similar in Lincoln and Chokla fibres but different in Merino (Rao and Gupta, 1991).

5.2.3 Fibre shape

Fibre cross-sectional shape and cross-sectional area or diameter are important physical characteristics of fibres determining the mechanical properties, optical lustre and tactile properties of fibres (Warner, 1995). Fibre cross-sectional shape also affects the cohesion and bulkiness of fibre assemblies (Kyungwoo Lee, 2003). Wool fibres are generally elliptical to circular in shape whereas synthetic fibres can be manufactured in various shapes including hollow shapes and multi-lobal shapes (Warner, 1995). Table 20 describes the cross-sectional shape of common fibres. Merino fibres are more circular than carpet wool breeds such as Romney's which are considered to have high ellipticity (Champion and Robards, 2000). Ellipticity is a term often used to describe the deviation from the circular shape. It is measured as the ratio of the major axis to the minor axis of the fibre. During fibre growth, the level of ellipticity of fibres can vary depending on seasonal changes and level of nutrition, with peak ellipticity occurring during periods of increased feed availability and intake (Champion and Robards, 2000).

A process transforming the keratin structure of the wool fibre has been developed that changes the fibre cross section to a polygonal shape increasing the surface smoothness and reflectivity (Bhoyro et al., 1997).

Orwin et al (1983) studied a range of wools with different degrees of lustre by scanning electron microscopy. They found that in addition to staple-form or assemblage effects, the fibre shape and fibre diameter variability were important determinants of the degree of lustre within breeds.

Matsudaira et al (1993) examined the effect of cross-sectional shape of polyester fibre on the handle of 'Shingosen' fabric and concluded that the fabric mechanical properties and handle are predominantly affected by the fibre assembly structure rather than the fibre cross-sectional shape. The lack of effect on fabric handle of fibre cross-sectional shape is surprising and probably arises because the shapes were quite complex and fibre 'fineness' was allowed to vary (Bueno et al., 2004).

The effect of fibre shape on rotor spinning performance has been studied with polyester fibres (Alston et al., 2002). Multilobal fibres with aspect ratios greater than one had superior spinning performance to fibres with an aspect ratio of one. This was due to the lower torsional rigidity and lower fibre to surface contact.

Bueno *et al* (2004) showed that the cross section fibre shape also influences the surface characteristics of knitted fabrics. They studied polyester fibres of the same length but different diameters and four different cross sectional shapes: round, scalloped oval, cruciform (cross shaped) and hexachannel. The fibres were processed into fabrics under identical conditions. They measured surface roughness-friction using a multi-directional tribometer and used a measurement of transient heat conduction in a vacuum as an indirect measure of real contact area. They found that increasing the moment of inertia of the fibre (increasing bending rigidity) resulted in an increase in the fabric's surface roughness and a decrease in the real contact area. Of the fibres they studied, the scalloped oval shaped fibres had the smallest moment of inertia. However instead of observing a decrease in fabric surface roughness when fibre diameter and moment of inertia were reduced, they observed an increase in surface roughness and a slight decrease in real contact area. They explained this in terms of the higher level of hairiness associated with yarns containing coarser fibres.

Fibre cross-sectional shape is often determined by examining fibre sections using a light or a scanning electron microscope (Matsudaira et al., 1993). Image analysis enables the calculation of the cross-sectional area of the fibre and the lengths of major and minor elliptical axes (Gourdie et al., 1992). A Single Fibre Analyser (SIFAN) (Peterson, 1997) can also be used to estimate the fibre ellipticity of approximately circular fibres by measuring fibre diameter at different pairs of orthogonal orientations of the fibre(Wang et al., 2007).

As discussed above, the shape of a fibre is important in bending and torsion. Ribbon like fibres of similar cross sectional area are softer than round fibres by virtue of their lower moment of inertia. Although ribbon like fibres are easier to bend than round fibres, in a yarn arrangement it is not possible for all of the ribbon fibres to be arranged so that they can bend in the direction of their minor axis (Bueno et al., 2004).

5.2.4 Surface properties of the wool fibre

It is well known that surface properties of fabrics have a significant effect on handle (Kawabata et al., 2002, Ajayi, 1988). In particular the surface roughness and friction are deemed to be important and tests for these properties are included in the suite of instruments that make up the KESF system (Manual). The construction of the fabric heavily influences the surface properties and whilst surface smoothness generally correlates well with subjective assessment of handle the results for friction have been less clear (Ajayi, 1988). When a slider moves relative to a fabric or yarn surface, under a fixed normal force, Amontons's law of friction (equation 17) is generally not obeyed, with the coefficient of friction increasing or decreasing to a constant value as the normal load is increased (Ajayi, 1992, Morton and Hearle, 1993, Ajayi, 1988). The data is generally fitted with a modified version of Amonton's law (equation 18)

$$Ff = \mu\ Fn \qquad (17)$$

$$Ff = a\ Fnb \qquad (18)$$

Where:

Ff = frictional force
Fn = normal force
μ = coefficient of friction
a = frictional constant (= μ when b = 1)
b = frictional index

It follows that to compare the coefficient of friction of different fabrics the conditions (including Fn) must be kept constant. Using this approach Ajayi (1992) found no correlation between the frictional constant of fabric and subjective assessment of handle.

Similar problems exist for the measurement of the coefficient of friction of individual fibres (Morton and Hearle, 1993); however it is still useful to quote typical values, obtained under specified conditions. Roder (1953) measured the surface frictional properties of a single fibre laid over a rotating beard of fibres and showed that the difference between the static (measured at low speeds) and dynamic coefficients of friction was important. He investigated the effect of different finishing agents, level of application, increased tension, speed and humidity. Other workers have shown that the difference between the static and dynamic coefficients of friction affected the processability and feel of the material (Ajayi, 1988). A range of different methods have been employed to measure fibre friction and these are well summarised by Morton and Hearle (1993). A novel approach was used by Lombard et al (1994) who modified a KESF system to measure the coefficient of fibre friction of a fringe of fibres and showed a change in the frictional properties of milkweed fibres upon washing.

The surface of the wool fibre consists of slightly overlapping layers of flattened cuticle cells (scales). Thus both the friction of the surface between the scales and the friction due to the protruding scale edges of the wool fibre will be important. Olofsson and Gralen (1950) showed that the coefficient of friction is greater when the fibre is pulled against the scales. The directional effect is reduced when the scales are mechanically abraded or when the fibre is chemically treated (Morton and Hearle, 1993). Scale height is generally measured by SEM (Varley, 2006, Wortmann and Phan, 1999) although recently Wortmann et al (2000) used profilometry to show that Cashmere fibres have lower scale heights than wool. The frequency of scales may also be important, Onal et al (2007) showing a slight increase in frequency from cashmere to wool to Angora fibres. The friction of the surface between the scales has recently been measured on keratin fibres by Scanning Probe Microscopy (McMullen and Kelty, 2001, LaTorre and Bhushan, 2005a, LaTorre and Bhushan, 2006, Huson et al.). It was shown that under these conditions Amonton's law is obeyed and the coefficient of friction of the fibres was shown to be sensitive to damage, additives and chemistry of the surface.

5.2.5 Crimp frequency and fibre curvature

Crimp is defined as the natural wave formation in animal fibres. The crimped structure of wool Fibres is generally associated with a bilateral arrangement of ortho- and paracortical cells (Kaplin and Whiteley, 1978, Horio and Kondo, 1953). The most obvious difference between these cell types is in the arrangement and relative proportions of microfibril to matrix proteins that constitute the Fibre cortex. Kaplin and Whiteley (1978) reported a poorer expression of bilateral cortical asymmetry in the low-crimp wool fibres compared with the high-crimp wool fibres. Low crimp Merino wool fibres are comprised of approximately 40% mesocortical cells and 10% paracortical cells in a poorly defined bilateral arrangement with the orthocortex (Whiteley and Kaplin, 1977). It has also been suggested that there is a direct relationship between cysteine content and the curvature in wool (Plowman et al., 2007, Campbell et al., 1972).

Traditionally staple crimp frequency was used as an indicator of wool fineness (Robinson, 2000, Madeley and Postle, 1994), where highly crimped wools were normally fine and were expected to be soft. Therefore staple crimp and fabric quality were highly correlated (Behera and Shakyawar, 2000, Madeley and Postle, 1994). However Madeley et al (1995) confirmed that there is a poor correlation between mean fibre diameter and mean staple crimp frequency for fine to superfine Merino and lamb's wool. Wool staple crimp can be expressed by crimp definition and crimp frequency (Lamb et al., 1996). The crimp definition describes the degree of alignment of the crimp within the staple. Some staples have a sharp, clearly defined wave pattern whereas in others the staple crimp is barely visible (Madeley et al., 1998b). Crimp frequency is reported as the number of crimps per centimetre (Hansford, 1996, Lamb et al., 1996). Both crimp definition and crimp frequency are genetically controlled (Madeley et al., 1998b). Crimp frequency can vary with the availability of feed and during controlled feeding regimes or drought, crimp frequency can increase with an accompanying reduction in growth rate and diameter (Madeley et al., 1998b).

Wool on the sheep's back has a crimp frequency ranging typically between 3 and 7 crimps per centimetre (Robinson, 2000). Mechanical action during processing to top and yarn reduces the fibre crimps. Assuming that no permanent set has occurred, steaming the top releases the strains in the fibre and allows the fibre to return to an inherent state of crimp (Fish et al., 1999). The recovery of crimp in yarn or fabric will however be restricted by constraints imposed by the yarn and fabric structure and setting procedures (Robinson, 2000).

Swan (1994) reported that staple crimp frequency is an expression of curvature of the fibres within the staple. Fish et al (1999) defined fibre curvature as the space-filling properties of a mass of wool fibres. Swan and Mahar (2000) developed a technique to measure fibre crimp curvature, based on light microscopy and image analysis. The measurement of fibre curvature has been commercialized in the Optical Fibre Diameter Analyser (OFDA) and Laserscan and now allows the rapid assessment of fibre crimp (McGregor, 2003). Fish (1999) and McGregor (2003) reported that there is strong agreement between these two instruments. Fibre crimp frequency is highly correlated with Laserscan fibre curvature (Robinson, 2000). Smuts (2001) and Behrendt (1996) have reported that OFDA fibre curvature is highly correlated with fibre staple crimp frequency and Behrendt (1996) suggested that crimp frequency and crimp definition may be two raw wool parameters that are able to affect wool processing and final product quality. Fibre curvature is a useful measurement because fibre curvature measurements can be made at all stages of the wool processing pipeline, whereas staple crimp frequency measurements can only be made on greasy staples (Swan, 1994, Swan and Mahar, 2000). Fibre curvature has been included in the prediction of spinning performance and yarn quality in the YarnSpec software package (Lamb et al., 2000).

Brown (2005) studied the crimp, curvature and diameter of approximately 3500 wool samples from 15 Merino flocks. He found that within the flocks studied, crimp frequency and curvature were not significantly correlated with fibre diameter, genetically and phenotypically; however a significant negative relationship across all flocks was noted. Contrary to this finding, Liu et al (2004c) found a very strong negative correlation between the mean fibre diameter and curvature of wool.

Some studies have been devoted to evaluating the effect of staple crimp on processing performance. Lamb et al. (2000), Behrendt (1996), Stevens (Stevens and Crowe, 1994, Stevens, 1994) and Hansford (1996) found that wools with low crimp frequency and high crimp definition produced the longest Hauteur (mean fibre length) in top. Lamb's studies on superfine wools (Lamb et al., 1996, Lamb et al., 2000) found that for similar diameters, longer staple length, lower crimp frequency and lower CV_D produced longer Hauteur in top, less waste, better yarn evenness and fewer ends down and fabrics of similar or better softness.

McGregor and Postle (2002) produced knitted fabrics from single yarns spun from high and low curvature superfine Merino wool. They found that the low crimp wool produced top with fewer neps however the top Hauteur was shorter. This contradicts previous findings (Lamb et al., 1996, Stevens and Crowe, 1994, Hansford, 1996, Behrendt et al., 1996, Lamb et al., 2000) where low crimp wool produces longer Hauteur in top. They concluded that fabrics produced from low curvature superfine wool were thinner, more compressible, lighter and more permeable to air compared with fabrics produced form higher curvature superfine wool.

Wang et al (2006) found that for wool fibres of a given fibre diameter, yarns spun from high curvature wool fibres had lower yarn hairiness than yarns spun from low curvature wool. It is worth noting that the low curvature wool fibres produced shorter Hauteur top than the high curvature wool.

Stevens (1994) studied the subjective handle of raw and semi-processed wool fibres and reported an increase from soft to harsh with an increase in mean fibre diameter. For a given fibre diameter, handle of raw wool became harsher as the fibres became more crimped and their resistance to compression increased. Stevens (1994) reported on how appraisal subjective methods can affect the perceived softness. Differences in softness due to differences in diameter but not crimp could be detected by rubbing fibres between the fingers. Differences in softness due to differences in crimp but not diameter could be detected by squeezing the fibres with a gloved hand. Shah and Whiteley (1971) also suggested that during appraisal of loose fibre, samples are compressed and rubbed in between fingers and the diameter effects are detected when the sample is rubbed between the fingers. Stevens (1994) assessed the mechanical properties and subjective handle of woven twill fabrics produced from higher and lower crimp wools. For a given fibre diameter, the appraisal panel clearly preferred fabrics woven from lower crimp fibre. These fabrics were lighter weight, thinner, smoother, less stiff and less extensible. For a given crimp frequency, the panel preferred fabrics prepared from the lower diameter fibres. Again these fabrics were lighter weight, more extensible, smoother and less stiff. Overall Stevens found that the panel preferred fabrics produced from lower diameter and lower crimp wool.

Madeley and Postle (1999) concluded from their subjective assessments that for a given fibre diameter, the handle of light weight, wool flannel woven from high twist woollen spun yarn containing low crimp wool was no different to that containing high crimp wool. They reported that their objective data indicated that a reduction in crimp curvature is as effective as a reduction in mean fibre diameter in increasing softness.

Robinson (2000) reported that fibre curvature had an impact on the weight of knitted fabric. Knitted fabrics from high crimp frequency or higher curvature fibres tended to bulk up more during wet or steam relaxation, increasing the fabric weight and thickness (Lamb et al., 2000, Robinson, 2000). This effect however was dependent on whether the fibre was set in a straightened configuration during dyeing and finishing.

Shah and Whiteley (1971) obtained results that confirmed the importance of compressibility and concluded that, after diameter, it was the most important parameter affecting handle.

Madeley et al (1998b) used selected data points from Shah and Whiteley's research (1971) to plot fibre crimp frequency against fibre crimp amplitude and fibre bending modulus. They found that fibre crimp amplitude is inversely proportional to fibre crimp frequency. They also obtained a reasonable correlation between the fibre bending modulus and fibre crimp frequency. However they only used selected data points and when other points are used there is no correlation between bending modulus and fibre crimp frequency.

Hunter et al (1982) examined the effect of fibre diameter and crimp on the objectively measured (KES-F) handle of woven fabrics. They found that when evaluating fabrics as summer suitings, an increase in fibre diameter within the range covered, tended to have a beneficial effect on handle. However, when fabrics were evaluated as winter suitings, fabric handle appeared to be less dependent on fibre diameter and more dependent on fibre crimp and fabric thickness.

As the fibre resistance to compression is decreased, the subjective softness and objective compressibility of knitted fabrics increased (Madeley et al., 1995). Given the relationship between resistance to compression and staple crimp, it was reported that softness of knitted fabric increased with a decrease in staple crimp (Madeley et al., 1995). Knitted fabric bending (stiffness) decreased as fibre resistance to compression and staple crimp frequency decreased (Madeley et al., 1995).

5.2.6 Resistance to compression

Resistance to compression of loose wool is an objective test of the compressibility of a fibre bulk. Chaudri and Whiteley (1968) found extremely large variations in the compressional properties of bulk samples of wool fibres which they attributed to differences in the nature of the structure of the fibres. They found that 89% of the variation could be explained by crimp form and frequency as well as by the product of the fibre diameter and crimp frequency. Researchers (Fish et al., 1999, Slinger, 1965, Madeley et al., 1998a, Madeley et al., 1995, Chaudri and Whiteley, 1968, Brown, 2005) have found positive relationships between resistance to compression and crimp frequency. As staple crimp frequency is reduced, loose fibre resistance to compression is also reduced (Madeley et al., 1995, McGregor and Postle, 2002). The resistance to compression of lamb's wool is less than that of non lamb's wool because of the lower crimp observed in lamb's wool staples (Madeley et al., 1995).

Ali et al (1971) confirmed the greater the resistance to compression, the harsher is the handle associated with the fibre. They reported that crimp characteristics were significant through their influence on compressibility and suggested that predictions of fibre softness could be based on objective measurements of mean fibre diameter and specific volume. Madeley et al (1998b) also suggest that the resistance to compression and objective fibre diameter measurements would be useful for predicting softness.

As the fibre resistance to compression is decreased, the subjective softness and objective compressibility of knitted fabrics increased (Madeley et al., 1995). Given the relationship between resistance to compression and staple crimp, it was reported that softness of knitted fabric increased with a decrease in staple crimp (Madeley et al., 1995). Knitted fabric bending (stiffness) decreased as fibre resistance to compression and staple crimp frequency decreased (Madeley et al., 1995).

Madeley et al (1995) found a poor correlation between resistance to compression and mean fibre diameter and suggested that the spread of their data was the result of some other factor other than mean fibre diameter. Shah and Whiteley (1971) found that diameter played a significant although minor part in bulk compression.

Liu et al (2004c, 2004b) demonstrated profound differences in the resistance to compression properties of wool and alpaca fibres. They found a negative correlation between resistance to compression and the mean fibre diameter for wool fibre, whereas for alpaca fibre they found a slightly positive correlation between mean fibre diameter and resistance to compression. The resistance to compression of the wool fibres increased as the curvature of the wool increased whereas for alpaca fibres the resistance to compression was only weakly correlated with a narrow range of fibre curvature. They also found a negative correlation between mean fibre diameter and curvature for both wool and alpaca fibres. They have suggested that resistance to compression is a poor indicator of fibre softness, particularly for wool fibres of varying diameters. This conclusion was drawn from the relationships they observed between resistance to compression and fibre diameter, resistance to compression and curvature and curvature and fibre diameter. For alpaca fibres they observed a slightly positive correlation between resistance to compression and mean fibre diameter, suggesting that the coarser alpaca fibres may offer greater resistance to compression even though the fibre curvature is lower for coarser fibres.

Elder et al (1984) defined the softness as the ease of yielding to pressure. Judges assessed the softness of woven and non-woven fabrics and were restricted in their method of handling fabrics to focus their attention on the compressional aspects of softness. They found good correlation between the subjective finger-pressure assessments of softness and objective measurements of compression made on an

Instron Tensile tester. They concluded that it is possible for a person to detect fine differences in fabric compressional softness but suggested that there may be a limit to this sense of perception.

5.2.7 Settability

Wool fibres can be permanently set in water at temperatures above 70°C or at higher temperatures and lower regains. This process of setting forms an important part of the finishing operations of wool yarn and fabric. It is generally accepted that setting has a significant effect on fabric properties such as relaxation shrinkage, hygral expansion, extension, bending, shear and compression; all properties that influence the handle of fabrics (Kirk-Othmer, 1998, De Boos and Tester, 1994). It is thus likely that if fibres set at different rates and to different extents, that this could translate into differences in the handle characteristics of fabrics made from these fibres.

The protein molecules of wool, particularly those of the cuticle and matrix regions of the fibre, are stabilized by a number of covalent bonds and non-covalent interactions. The most important of these are disulfide bonds, which crosslink the peptide chains. A unique feature of the wool fibre is the ability, under suitable conditions, for these disulfide bonds to rearrange and form a new cross-linked polymer network. This occurs via a mechanism involving a thiol/disulfide interchange reaction (Caldwell et al., 1964) and results in strained wool fibres being set in a new configuration (Kirk-Othmer, 1998). Thus fibres in a curved configuration as a result of natural crimp, twisting in a yarn, or weave crimp become permanently set in this new curved state.

The rate and extent of setting is dependant on the concentration of thiol anions in the fibre (Feldtman and Fleischfresser, 1972, MacLaren and Milligan, 1981), as well as the mobility of the protein chains. Hence, the rate can be increased by increasing the pH, breaking disulfide bonds with a reducing agent to form additional thiol anions, or by increasing the regain (Feldtman and Fleischfresser, 1972) or temperature to facilitate molecular mobility. Kopke (1970a, 1970b), in an extensive study, has shown that moisture is the main rate-controlling parameter implying that mobility of the protein chains is very important. Mobility in turn is related to the glass transition temperature and Fig. 7 gives an indicative curve for the minimum temperature needed for imparting permanent set to wool at different regains. Note that the curve tracks the Tg-regain curve.

Different wool types, with slight differences in structure and composition (ortho/para ratio, disulphide content, crystallinity and equilibrium regain) are likely to set at different rates and to different extents. Differences have been shown between Lincoln and Merino wool (Feughelm.M and Mitchell, 1965) as well as between Cashmere and Merino (Tester and Foley, 1986). However to the best of our knowledge no study has been done to establish the full extent of the variability of setting between different wool fibre types. Garcia et al. (1995) showed that cysteine levels changed during dyeing and finishing of wool and that low stress fabric mechanical properties are related to cysteine levels. It remains to ascertain whether natural variation in structure and composition between fibres exists at a sufficient level to translate to significant differences in fabric handle.

The degree of set is readily determined in fabric using the standard crease angle test (Huson, 1992). After setting, snippets of creased yarn are carefully removed from each sample and allowed to relax in distilled water before measuring the angle of the crease. Relaxation is normally in water at 70^{o}C for 30 minutes; however other conditions can also be used if appropriate. The measurement of set on individual fibres is less common, however they can be set on glass or steel mandrels (Huson, 1992, Huson, 1993, Tester and Foley, 1986, Feughelman, 1989). The set fibres are then either cut into several fibre segments and treated as for yarns or released as a helix and the number of turns used to calculate the level of set (Feughelman, 1989, Tester and Foley, 1986). The hair care industry has also developed procedures for evaluating setting or “curl retention” in hair tresses and single fibres (Robbins, 1994). These are generally similar in principle to the methods used for single wool fibres. Where wool fibre bundles have been set on a mandrel potential exists to measure curvature on the bulk sample using either OFDA or Laserscan (Fish et al., 1999, van Rensburg, 2000).

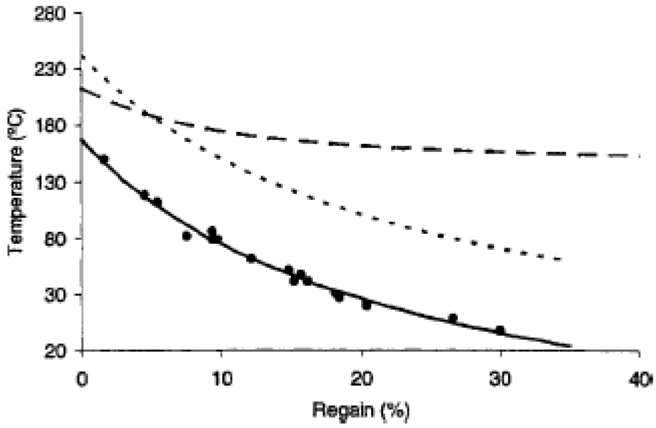


Figure 24. Glass-transition (—) (Wortmann et al., 1984), indicative minimum permanent setting temperature (----) and melting temperature (– – – –) of wool as a function of regain (Feughelman, 1989) (Reproduced from the Kirk-Othmer “Encyclopaedia of Chemical Technology”, 1998, (Postle et al., 1988)

6 Summary

- Fabric handle is a major attribute assessed when consumers evaluate the quality and expected performance of fabrics.
- The physiological mechanisms by which fabric handle sensations are perceived involve the interaction of complex muscular manipulation and perception by different mechanoreceptors. Tactile perception is not initiated by a single well defined quantity, such as light or sound, nor is one or two localised sensory organs involved. The tactile signal is not a well defined quantity, being the detection of temperature, texture, shape, force, pain and other related physical properties. It is perceived all over the skin. Both the distribution of the mechanoreceptors and the frequency of stimulation affect tactile perception.
- The fabric handle of lightweight (<200gm^{-2}) wool knitted fabrics has not previously been studied.
- There has been a number of successful studies of the subjective assessment of fabric handle for a range of fabric types, including fabrics for which a wool-like handle is desired, e.g. men’s suiting fabrics.
- Several studies of subjective assessment of fabric handle have highlighted the existence of orthogonal handle characteristics, e.g. fabric stiffness, fabric smoothness, which collectively describe the handle of a fabric. These orthogonal characteristics may be different for different fabric types.
- Subjectively assessed orthogonal handle characteristics have been related to physical properties of fabrics which can be objectively measured. These objective measurements can be of fundamental physical and mechanical properties, e.g. fabric bending rigidity, or the coefficient of surface friction, or of more complex deformations, e.g. fabric extraction.
- Wool fibre properties influence fabric handle. The major properties which influence fabric handle are fibre diameter and fibre curvature. Other fibre individual properties which may influence fabric handle include: fibre surface friction; fibre elastic moduli, especially in bending and torsion; fibre cross-sectional shape; and, fibre settability. The bulk fibre property of Resistance to Compression has also been shown to relate to fabric handle.

7 Conclusion

Technical and commercial gains can be made through the application of known fabric handle technologies to light weight wool knitted fabrics. Specifically, communication about fabric handle within the supply chain can be simplified and made less ambiguous.

Investigations can be directed to isolation of the orthogonal fabric handle characteristics for selected markets applicable to light weight wool knitted fabrics, e.g. sports active leisure wear, lingerie. Both expert (industry) assessors and consumers can be used to select the important handle descriptors for each market. Scaled single or bipolar descriptor grids are recommended to help the judges to discriminate fabric handle characteristics according to well-defined protocols. The relationship between these orthogonal characteristics and overall fabric handle preferences can also be determined. Analysis of these orthogonal fabric handle characteristics could assist in the development of objective measurement of fabric handle characteristics for the chosen fabric types.

There has been a number of approaches used to establish relationships between the subjective evaluation of fabric handle and objective measurement of fabric properties. While correlation analysis is simple and is often used, more sophisticated statistical analyses such as fuzzy logic and neural networks, principal component analysis and factor analysis offer scope for improved relationships between subjective and objective fabric handle data.

The KESF is a well developed system for measuring low stress properties of woven fabrics, while being relatively unproven on knitted fabrics. The KESF is expensive and uses complex testing and interpretation procedures. KESF testing represents a benchmark in technically interpreting any new subjective handle characteristics. The PhabrOmeter instrument, which uses the pulling force method, is cheaper, faster, and simpler than the KESF and may be a more appropriate candidate for measurement of fabric properties for the Handle of Merino Wool Fabrics project.

Research on the types, functions and sensibility of the mechanoreceptors in the human fingers will help to characterise and scale the primary handle components in the subjective evaluation of fabric handle and may lead to improved instrumentation and development of desired fabric handle characteristics.

There is a number of wool fibre properties other than diameter and curvature which could influence fabric handle, notably fibre surface friction. Quantification of the variation in these properties amongst the Australian Merino clip may provide a basis for genetic improvement of these properties.

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