Acoustics and friction of apparel and model fabrics, and consumer perceptions of fabric sounds.

by

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Abstract

To date apparel fabrics have been investigated in terms of their objective measurements (for example, friction, bending and compression) and subjectively using consumer and sensory panels. However, current research has expanded this by investigating the acoustics of fabric friction. Understanding the influence of the fabrics microstructure on frictional noise was investigated in terms of surface roughness for three multi-fibre apparel fabrics (denim, cotton and silk) and single-fibre polyester model fabrics. Surface roughness (R_a) (measured using Interferometry) correlated strongly with total noise emitted ($R^2 = 0.97$) and was attributed to the 'hairy' nature of multi-fibre fabrics. In terms of specific frequencies emitted within a fabric's sound spectrum, the microstructure of the model fabrics was strongly correlated ($R^2 = 1.00$) with the fundamental harmonic predicted, therefore enabling a 'fingerprint' theory to be proposed. Friction coefficients, measured using tribology, of apparel and model fabrics were established, and showed that the major impact on friction was R_a and fibre type, in terms of the hygroscopic nature whereby, the more hydrophilic a fabric the more easily wetted and more lubricated it became. Furthermore, friction was reduced via the lubrication of hydrocolloid fluid gel particulates, by means of reducing the surface roughness by filling in asperities and reducing the hairy nature of the fibres. Consumer perceptions of fabrics and fabric sounds were established with one-to-one interviews, and the influence of sound on sensory perception and liking was established by manipulating real-time fabric sounds, showing that by altering high and low frequencies, and overall noise, a significant difference in sensory attribute 'textured' can be observed.

In loving memory of my sister, Andrea.

May you always watch over and protect me.

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Nomenclature

Acoustics

E	Energy (W)
Δf	Frequency difference (Hz)
Hz	Hertz
ΔL	Level range (dB)
P	Power (W)
R_a	Surface roughness (μm)
T	Time (s)
λ	Wavelength (m)

Tribology

A	Area (m^2)
A_a	Apparent area (m^2)
A_r	Real area of contact (m^2)
σ_E	Engineering stress (MPa)
σ_T	True stress (MPa)
ε_E	Engineering strain
ε_H	True strain
F_f	Friction force (N)
F_t	Force transducer
κC	Kappa carrageenan
KCl	Potassium chloride
MTM2	Mini traction machine 2
μ	Friction coefficient (dimensionless) (W/ μ)
N	Newton
RH	Relative humidity (%)
SRR	Slide roll ratio [$(U_{disc} - U_{ball})/U$] (%)
T_{inlet}	Temperature at the inlet (°C)
T_{exit}	Temperature at the exit point (°C)

U_{ball}	Ball speed (mm/s)
U_{disc}	Disc speed (mm/s)
W	Normal load (N)
W_1	Wear of surfaces (μm)

Sensory Perception

σ	Standard deviation
F	F ratio
p	Significance value
r	Pearson's correlation coefficient
R	Effect sizes
$\bar{x}$	Mean values

Abbreviations

AFM	Atomic force microscopy
ANOVA	Analysis of variance
AUC	Area under curve
A.U.	Arbitrary units
BGN	Background noise
CFE	Extreme conditioning
dB	Decibel
DS	De-sized
FFT	Fast Fourier transforms
FG	Fluid gel
HF	High frequency
κCT_{40}	Kappa carrageenan temperature change 1
κCT_{56}	Kappa carrageenan temperature change 2
KES-FB	Kawabata Fabric Evaluation System
LF	Low frequency
LPT	Level pressure of total sound
M	Manipulation

MAFN	Measuring apparatus for fabric noise
MS	Manufacturers' sizing
OL	Overall level
PDMS	Polydimethyl siloxane
PI	Peak increase
PSD	Power spectra density
QG	Quiescent gel
RS_{1500}	Rotational speed 1 (Agar) 300rpm
RS_{300}	Rotational speed 2 (Agar) 1500rpm
S.B.A.T	Space between adjacent threads
SDS	Sled drive system
SEM	Scanning electron microscopy
SRR	Sound resistant rig
SPIP	Scanning probe image processor
SPSS	Statistical software
TAS	Thwing Albert sled
VAS	Visual analogue scale

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1 Introduction

Motivation and Background

The world of textiles encompasses many uses including, but not limited to, garments (apparel), upholstery for home interior and exterior purposes and linings within automobiles, which are interacted with almost every minute of every day within the modern world. It was reported in 2013 that the value of the apparel market, globally, was $1.7 trillion and employed 75 million people in the year 2011-12 (FashionUnited 2013). When understanding apparel consumption by Britain in terms of sales, it was reported that the British people spent €59 billion in the same year.

Fabric construction encompasses many industries such as: farming of raw materials, raw material suppliers, manufacturers, wholesalers, distributers and shops and supermarkets, however, it is imperative to account for the money spent on fabric care. Procter and Gamble's Annual Report on estimated sales for 2013-14 states that $27.4 billion has and will be spent on fabric care; including fabric conditioners, washing agents and after washing treatments such as fragrances and extra softeners (P&G 2013).

It can be summarised that the fabric industry, along with the fabric care industry, is extremely important to the social and economic climate in which we live, and therefore advancements in science are imperative to both consumers, to be able to deliver the most effective treatments and high quality garments, as well as being cost effect and profitable for the relevant industries.

Scientific measurements of textiles encompass a broad range of purposes and methods, both subjective (e.g. consumer panels and testing) and objective (e.g. mechanical properties) and is constantly expanding in knowledge. Currently, objective measurements of textiles and garments found in literature, and used within industry, focus mainly on the friction, bending and compression of fabrics in order to quantitatively assess fabric treatments. However, advancements in the design and construction of fabrics is proving to be beneficial, in terms of microstructurally modifying fabrics (composition, chemical structures and construction) in order to achieve consumers' ever expanding desires and demands. At present subjective testing of fabrics in terms of original materials or garments is carried out using time-consuming and costly sensory and consumer panels in order to gain a true insight into the thoughts and opinions of new fabric care products or a new range of apparel materials. However, fabric industries are moving towards relating the mechanical properties of fabrics (friction, bending and compression) with consumer opinions in two and three dimensional models with questions such as:

- Does a high friction coefficient correlate with/to consumer perceptions of toughness, roughness, unpleasantness?;
- Would the addition of a new fabric conditioner affect the mechanical properties of a fabric (e.g. stiffness) and does this then relate to positive consumer responses?

As advancements are being made to achieve this in terms of friction, bending and compression of fabrics, it was also thought that the sound that a fabric makes when in contact with other surfaces (i.e. frictional noise), could be an important/useful avenue to explore. Frictional noise of fabrics has been shown to be affected by the microstructure of the fabric, for example, increase in total noise with the increase of surface roughness, fibre count, and fibre type has been observed. However, the sound of specifically treated fabrics (i.e. with conditioners and additives) has not been fully explored. Therefore, understanding the frictional noise produced by everyday garments, in terms of how the sound is produced, how it is accurately measured and how it can be altered, is proposed as a way of advancing the already existing knowledge of the mechanical properties of fabrics.

Objectives

The aims of the study were:

- Investigate the frictional noise of everyday apparel fabrics in terms of total noise and specific frequency analysis, and relate the microstructure of the fabrics to frictional noise using a single fibre model system i.e. to enable the comparison between single and multi-fibre systems;
- Investigate the frictional properties of everyday apparel fabrics, in terms of frictional coefficients and wear, and how the friction can be altered via lubrication of specifically engineered hydrocolloid particulate systems. The effect that the microstructure of the fabrics has on friction is explored by comparing multi-fibre and single-fibre systems;
- Explore consumers' thoughts on the senses (sight, touch, smell, taste and sound) used to assess apparel fabrics and to gain an understanding of the importance of sound;
- Investigate whether manipulating real-time fabric sounds (to attenuate or enhance the whole spectra or specific frequencies) affects consumer ratings of sensory attributes.

Layout of thesis

The research carried out for this thesis aims to relate the mechanical properties of fabrics using novel techniques to achieve both friction and frictional noise, with consumer perceptions of fabrics in relation to sound. The thesis is laid out in such a way as to firstly address the engineering aspect of novel fabric measurements: sound and friction, and approaches to adapting friction, followed by consumer thoughts and perceptions of the novelty of fabric sounds, and the effect that manipulating sound in real-time has on perception of sensory attributes. The following chapter, Chapter 2, aims to give a comprehensive overview of many aspects of fabrics, acoustics and fabrics, and consumer perceptions which are relevant to the research carried out. Chapter 3 explains the materials, and standard methods, and method development for fabric sound capture via the construction and calibration of a sound resistant rig, sound manipulation software and sensory protocols and data analysis, used to establish all results gained. Chapter 4 aims to show the development of a method to capture sound of fabrics and by comparing how multi-fibre, apparel and single-fibre, model fabrics' microstructures affect frictional sound. Using the knowledge gained from Chapter 4 in which friction of fabrics can be emitted as noise or wear, Chapter 5 investigates the effect of microstructure on friction measured using an MTM tribometer, and to gain an understanding of the effect of lubrication, via a hydrocolloid fluid gel particulate system, has on friction for both apparel and model fabrics. Chapters 6 and 7 focus on consumer responses to fabrics. Chapter 6 explores consumer thoughts centred on senses used to assess fabrics through one-to-one in depth interviews and in particular how sound is regarded compared to other senses. Chapter 7 aims to investigate the influence of the manipulation of real-time fabric sounds produced by consumers themselves on their responses to sensory attributes. Finally, Chapter 8 contains major conclusions, which aim to bring both all results together and to establish future work that may be carried out.

Publications and Presentations

Cooper, C.J., Norton, J.E., Marshman, C. & Norton, I.T. The acoustics of friction noise of apparel and model fabrics. Textile Research Journal 2013.

Cooper, C.J., Norton, J.E., Mills, T.B. & Norton, I.T. An understanding of the frictional properties of apparel and model fabrics and the influence of fluid gel lubrication as measured by tribology – in progress

Scholarship Award to present at Eurosense Bern, 2012: Investigation into consumer perception of wardrobe fabrics with relation to friction sound. Cooper, C.J., Norton, J.E., Norton, I.T. & Oakes, A.

2 Literature Review

The purpose of this Chapter is to gain a comprehensive review of the background of four knowledge areas that are relevant and essential to this thesis: fabrics, sound, friction and sensory perception. All areas investigated within this thesis are interlinked throughout and therefore they layout of this literature review is also reflective of this nature. In order to guide the reader through the complex nature of the review, areas will be sign posted in terms of Chapter relevance.

The literature review will begin by explaining the history of fabrics, which is essential to all research carried out within this thesis, their construction and purpose, and how they are currently measured in terms of mechanical properties. The specific mechanical properties relevant to Chapters 4 and 5 are frictional noise and coefficients, respectively.

As the fundamentals of this research are focused around frictional noise (results presented in Chapter 4) and coefficients (results presented in Chapter 5) an insight into sound follows, with relevance to how sound is heard by humans and how it quantified and measured. With regards to frictional coefficients, an understanding of the laws of friction, how friction is defined and measured and the frictional properties of various materials will be discussed. It is important to note here that the study of friction by the use of tribology is understood within the following section; however, the use of tribology in terms of advancement in fabric systems enhanced by the literature relevant to the food industry is discussed at the close of the review. In order to combine the principle understandings with relevance to this thesis centred on fabrics, both sound and friction will be extensively reviewed with respect to how they are achieved, measured, the influence of material properties (e.g. surface roughness and fibre/fabric type) on the friction produced, and the influence of each principle on another in turn (i.e. the frictional influence on noise produced).

Following on from the insight into sound and friction of fabrics observed from research carried out within a laboratory, an understanding of consumer and sensory perception, as a whole and more specifically in terms of fabric sound, will be presented. All literature centres on the psychology (and in some research the physiological responses) of fabric sounds when conducted with the used of sensory and consumer panels. This literature is essential to the understanding of Chapter 6 and 7's results.

As previously discussed, this literature review will close with the understanding of food hydrocolloids fluid gel systems which have been shown to reduce friction (measured using tribology) which is related to the oral perception of semi-solid foods. The section will describe the two fluid gels used within this research (kappa carrageenan and agar) in terms of their structure and gelation, as well as their influence on friction coefficients produced.

2.1 Fabrics

Early fabric structures are thought to have been influenced by man weaving twigs and branches to form shelters and protection. Until the early 1700s, spinning and weaving by hand was the most commonly used method of creating fabrics for personal use. However, in 1733 a 'flying shuttle' was introduced into looms which doubled the production output of industrially made material, as did the introduction of steam engines during the industrial revolution. Fabrics are used throughout all aspects of everyday life: clothing, bedding, home furnishings, car interiors, and many are considered to be essential to the modern world. For all different uses of fabrics, construction varies vastly and must fulfil the requirements of the purpose.

2.1.1 Understanding fabrics

Fabrics are made of original fibres which are mainly sourced from animals: wool, silk; plants: cotton and flax; minerals: glass fibre and synthetic: nylon, polyester, acrylic etc. Synthetic or manmade fibres can be used to imitate natural fibres for a fraction of the production time and cost. For example, nylon and polyester are used to imitate silk, as natural silk is more expensive.

Natural fabrics are generally constructed by having various 'levels': at the smallest level individual fibres are collected from their natural inhabitant (e.g. cotton plants, sheep, silk worms etc.) and spun into threads in vast numbers. Both fibres and threads are considered to be on the micro scale. Threads can be woven into a multitude of patterns to form macro areas of fabric samples. For the purpose of this research, plain and twill weaves were investigated (see Figure 2.1), however, many more complex weaves are achieved by looms and, more often than not, are operated automatically via an in-built design (e.g. basket, satin, ribbed and pile weaves). All weaves are designed to have repeating units; however, as is the nature of natural fibres and threads; it is not possible to be identical.

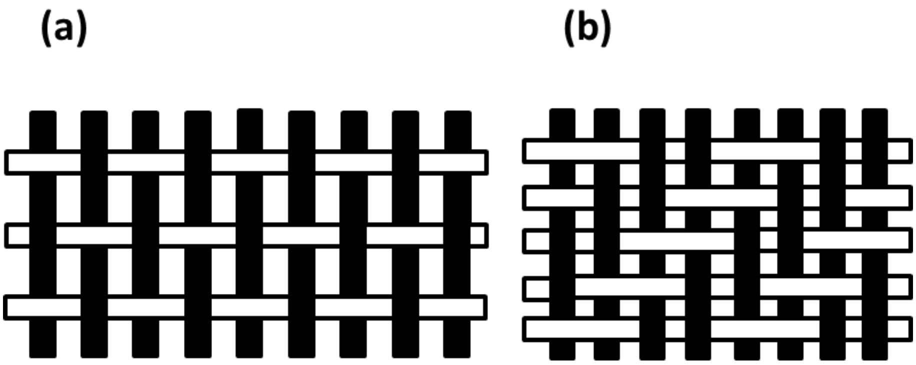


Figure 2.1 Schematics of (a) plain (b) twill weave construction of fabrics. Black threads represent weft and white warp threads.

Fabrics are woven with two main threads: threads in the vertical position are fixed and held taught against the top and bottom of the loom; these threads are named 'weft'. Other threads are woven in and out, as desired, of the weft threads and pulled tight to the bottom; these threads are known as the 'warp' (see Figure 2.1).

Dimensions of fabric samples consist of the following terms (see Figure 2.2 for a schematic):

- Aperture – the free space between adjacent threads. It must be noted that the aperture will have different dimensions in the weft and warp direction if fabric samples are designed to not be identically woven;
- Thread diameter – the cross sectional measurement of each thread;
- Fibre diameter – the cross sectional measurement of each fibre woven into a thread;

- Space between adjacent threads (S.B.A.T.) – more commonly referred to as 'pitch'; the measurement between the centres of each adjacent thread i.e. the peak of each thread.

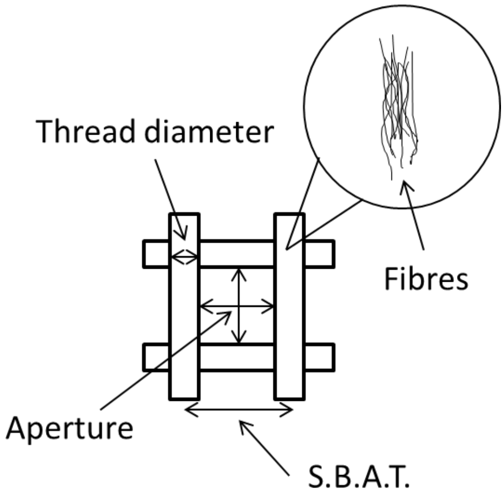


Figure 2.2 A schematic of typical fabric dimensions depicting the thread diameter, aperture size, individual fibres and space between adjacent threads (S.B.A.T.).

Most manmade fabrics are created from polyester and satin, for example and are formed using a non-woven technique in which individual fibres are generally bonded together using either heat, chemicals and solvents (Mahmoud *et al.* 2011).

Natural fabrics and manmade fabrics are available to consumers in varying forms and types, and in particular those fabrics which are used often in everyday life (e.g. cotton, silk and polyester), are widely investigated with both objective and subjective methods. According to the World Apparel Fibre Consumption Survey (2013), the amount of cotton within the world consumed by man was the highest of all the naturally occurring materials including wool, flax and cellulosic fibres and yet was approximately 3/5^{ths} of the amount of synthetic fibres consumed (see Figure 2.3). This level has increased throughout the years, from 1992 to 2010 (see Figure 2.4).

Figure 2.3 The consumption of apparel fibres in percentage in 2007 (left) and right in 2010 from the data collected by the World Apparel Fibre Consumption Survey in 2013. Fibres grouped into 5 categories: cotton, wool, flax, cellulosic fibres and synthetic fibres. (FAO 2013).

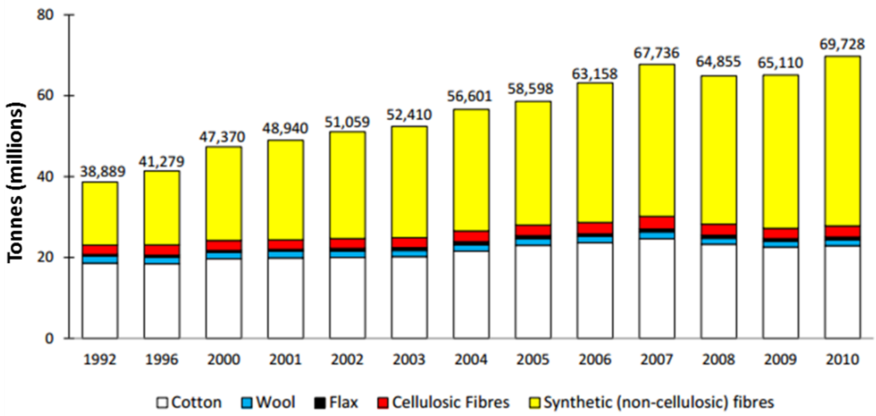


Figure 2.4 The consumption of apparel fibres in in million tonnes through the year 1992 to 2010 from the data collected by the World Apparel Fibre Consumption Survey in 2013. Fibres grouped into 5 categories: cotton, wool, flax, cellulosic fibres and synthetic fibres. (FAO 2013).

Cotton was investigated within this thesis, as previously mentioned, as it was the highest consumed naturally occurring fibre, and in order to have a contrasting fibre type, 100% silk was also chosen. The following section will explain the nature of each material chosen in terms of fibre type and usage.

Cotton material is constructed of threads/yarns spun from the naturally occurring fibres taken from the cotton plant, which is most often farmed for the world's large demands, and is 95% cellulose (with the majority of the noncellulosic being made up of waxes and proteins). Individual fibres are twisted in different directions along the length of the fibre which is essential to the interlocking behaviour of the cotton fibres within a thread. The hygroscopic nature of a cotton fibre is high due to the structure: a dry cotton fibre will collapse in on itself and will have expressed the majority of the water within its structure, and therefore an uptake of moisture from a humid atmosphere is rapid and without obstruction. It is thought that in natural environments the amount of moisture within a cotton fibre is between 7 and 10% (Grayson 1984; Mather & Wardman 2011b).

Silk is also a natural fibre. However, in contrast to cotton it is produced by insects and spiders, as opposed to a plant, and is excreted as a solidified viscous fluid. The construction of a silk fibre is that of an almost continuous filament, often measuring between 300 and 1200 m in length, and has a high tensile strength as well as being elastic in nature. Silk is considered to be highly hygroscopic in its nature with a moisture uptake in 20% relative humidity conditions of between 10-15% (Grayson 1984; Mather & Wardman 2011b).

Both the fibrous and hygroscopic nature of cotton and silk fibres are essential to the research carried out within this thesis as it is hypothesised that they will have an influence on friction in terms of acoustic noise, friction coefficients and wear of surfaces.

2.1.1.1 Mechanical properties of fabrics and their measurement techniques

A well-known and widely used standard method of investigating the mechanical properties of fabrics is the Kawabata Fabric Evaluation System (KES-FB) (Kawabata 1980) and encompasses measuring certain parameters including: tensile, shear, bending, compression, surface friction and roughness (in some systems fabric weight and thickness have also been measured (Sirkova 2012)). This method has been used in conjunction with other mechanical properties such as sound, and also has been related to sensory properties, which are further discussed within Section 2.7.1 (Cho & Casali 1999; Yi *et al.* 2002).

Fabrics are generally engineered to have a particular tensile strength, which can be measured in different ways depending on in which direction the bulk of the sample is stretched; when fabric swatches are pulled in either the weft or warp direction (uniaxial) or both (biaxial), tensile strength is considered to be higher than when pulled along the bias (in a diagonal motion) (Pan 1996). The tensile strength is measured by the KES-FB and has also been related to the bending and compression values, along with the original fibre and resulting thread and structure, and their elastic and plastic nature. Fabric strength is as a result of a combination of individual elements: individual fibres, threads/yarns and weave. For example, a fabric with a closely woven structure is more likely to have a larger tensile strength than fabric with a loose weave.

In order to ensure that all fabrics are aesthetically pleasing to both wholesalers and consumers, manufacturers of the original reels of materials treat their individual threads, and occasionally individual fibres, with 'sizing': a collective term for a number of chemicals and natural ingredients specifically designed for fabric treatment (Seydel & Hunt 1981). To achieve the most highly desirable fabrics, manufacturers tend to use an excess amount of sizing and therefore the actual softness and other properties of the material are not true at first. For further use of the material e.g. dyeing and further softening, purchasers of the original material (i.e. wholesalers and the garment industry), have to remove the sizing by a process of 'de-sizing'. De-sizing can be achieved by repeatedly washing and rinsing the material (generally via an industrially calibrated protocol). It is essential that as much sizing is removed as possible as many mechanical properties of fabrics such as friction, adhesion and also appearance will be greatly affected by such chemicals (Mather & Wardman 2011a).

2.2 Sound

2.2.1 Sound – A basic understanding

Sound is one of the five human senses and is relied upon daily in many situations. Sound is heard via sound waves travelling through a medium, but in more detail through vibrations of energy. These vibrations are caused by disturbances in, for example, air which then emit noise. Sound can be described with a combination of waves; transverse and longitudinal. Sound travelling as a transverse wave is where the disturbance causes the wave to oscillate in a perpendicular motion to the direction of the wave itself. For example, as the wave moves in an x direction, the individual waves will move along the y direction (see Figure 2.5).

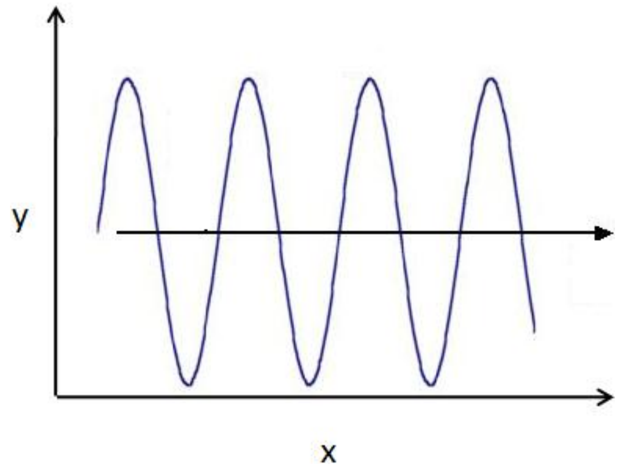


Figure 2.5 A simple sound wave illustrating how as the wave moves as a whole across the 'x' axis, it also moves individually along the 'y' axis.

To be able to understand the travelling and transfer of a sound, it can be described as a longitudinal wave. In the case of sound, the longitudinal wave exists when there is a disruption of pressure equilibrium in the air (or another medium) in which the sound is present. The sound's energy either disturbs the pressure by pushing or pulling molecules on to other molecules present, shifting their energy, and in doing so transfers the sound across the medium. When the molecules are pushed together it is known as compression, and when they are pulled it is termed rarefaction. It could be said that as the sound wave is going through compression, the energy of molecules is stored before being transferred. The pushing and pulling of molecules in the longitudinal wave move along the sound wave, in contrast to the transverse wave.

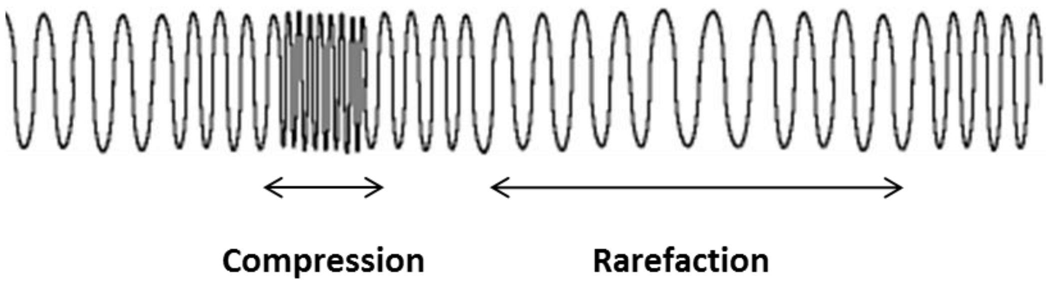


Figure 2.6 A sound wave showing the change in transfer of sound energy from compression to rarefaction.

Sounds can exist in different forms: a sinusoidal wave or a non-harmonic (or non-periodic) wave. A sound with a distinctive repeating cycle form is known as a sinusoidal (sine) wave (see Figure 4.2(a)). A sound with a tendency to have cycles that do not repeat over time is known as a non-harmonic or non-periodic sound and therefore do not have a distinctive pitch or amplitude (these terms are described fully in Section 2.2.2) (see Figure 4.2(b)).

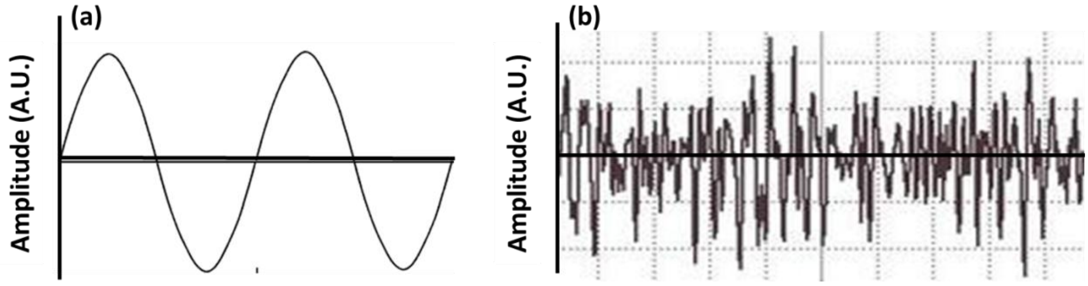


Figure 2.7 A schematic of (a) a periodic sine wave and (b) a non-periodic wave, showing amplitude (A.U.) vs. time (figure adapted from (Crowell 2011)).

2.2.2 Measuring, describing and displaying sounds

Sound waves can be described using many different terms as is schematically presented in Figure 2.8:

- Frequency of a period is the number of repeating occurrences per second and has the units of hertz (Hz). For example, a sound wave may have 5 repeating cycles in a second and therefore would emit at 5 Hz;
- Amplitude, generally on the y axis, when against frequency (Hz) or time, is the maximum displacement of the sound. Amplitude has arbitrary units;
- Wavelength (λ) is the distance between two points of the same phase in a sinusoidal wave i.e. the distance to complete a single cycle, either a peak, trough or along the x plane (units are often Hz or time (s)).

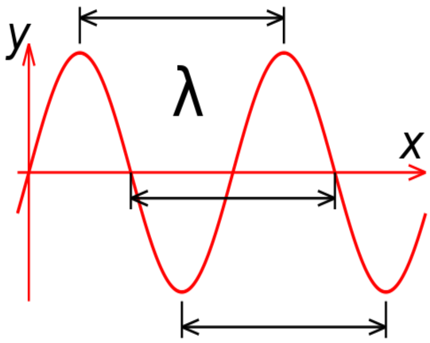


Figure 2.8 An example of a sound wave, depicting wavelength (λ) for the three available points on a cycle.

Amplitude of sound is relative to the recording or hearing system. A sound can be termed loud or quiet, but is ultimately a subjective measurement or interpretation; loud to one person is not necessarily too loud to another. The strength of a sound signal is what is objectively measurable by its intensity or power, where power (W) is the amount of energy (E) generated or dissipated per unit time (T):

Eq. 2.1

$$W = E/T \text{ (joules/second)}$$

The power of sound is generated by the initial vibration that pushes and pulls the molecules to transfer the energy along the sound wave. Amplitude, as previously stated it has arbitrary units (A.U.) and therefore is not defined, however, a frequently used unit for describing sound levels is decibels. A decibel originates from Alexandra Bell's first telephone and the level of sound it was able to emit. It describes the gains and losses of signal power within an audio system and has logarithmic base 10 progression of values. It has been suggested that a decibel is a useful form of analysis of sound "as an exponential change in power is perceived as a linear change in loudness" (Thompson 2005). The intensity of a sound is thought to be due to a greater amount of stored energy in compression mode of the wave, which is generated from a greater initial vibration. Where, intensity is the amount of energy, in this case sound power, passing through a specific area (m^2) during one second.

2.2.3 Human perception of sound

Consensus suggests that humans can hear between 20 and 20,000 Hz, and it is more likely that one can hear better and more consistently at the lower end of the frequency spectrum than that of the higher levels; very few humans can hear frequencies at 20,000 Hz and the most commonly heard range is between 50 and 10,000 Hz (Whittle *et al.* 1972). The aforementioned vibrations are responsible for how humans hear: a sound is created and travels through the air, is transferred via sound waves which enter the human ear and travels along the ear canal, vibrates on the ear drum within the outer ear. From here, the vibrations will enter the middle ear and cause the ossicles (three small bones) to vibrate to the inner ear in which fluid changes the hair cells which send electrical signals to the brain which is interpreted as sound.

2.3 Friction

Friction occurs between two contacting solid surfaces, when one is moving over the other, and in order to achieve said motion, the frictional force must be overcome. Friction follows two basic laws first discovered by Leonardo da Vinci:

(1) Friction force (F_t) is proportional to the load (*W)* and therefore the coefficient of friction is a fixed value for the two surfaces;

(2) Friction force (F_t) is independent of area of contact (A_r).

These laws were verified by Guillaume Amonton (1699) and a third law was later added by Coulomb, whereby friction is independent of sliding velocity (Howell & Mazur 1953; Howell *et al.* 1959). The two-term model of friction, proposed by Bowden and Tabor (1964), of two surfaces sliding over one another results in frictional forces arises from adhesive forces between the two surfaces and is a result of the breaking of these forces to ensure that the surfaces move across each other, which causes friction. The increase in frictional force is thought to be due to an increase of adhesive forces needing to be broken, which then dissipate as energy (for the purpose of this thesis, the energy is dissipated as both sound and friction) (Bowden & Tabor 1964). The relationship between the frictional force (*F*) and contact area (*A*) was also explained by Bowden and Tabor (1954) in which the real contact area (A_r) is influenced by the number of asperities, *a*, (e.g. surface roughness and in relation to this theses fabric micro- and macro-structure):

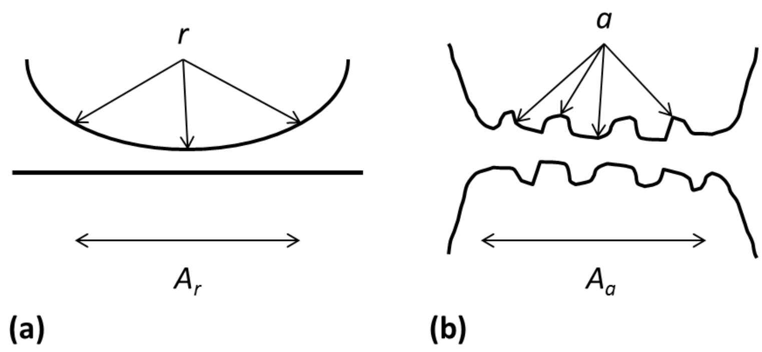


Figure 2.9 A schematic of Bowden and Tabor's theory of friction whereby, (a) shows an idealised surface roughness with only one asperity with a radius of *r*, and (b) the more realistic surface roughness with many asperities with a radius of *a* for each asperity. The frictional force is calculated using Eq. 2.2. Schematic and equation adapted from Howell (1959).

Eq. 2.2

$$A_r = \sum a$$

Bowden and Tabor (1964) also provided assumptions along with their theory of friction that in order for two surfaces to slide relative to each other:

(1) Asperities are plastically deformed;

(2) Interfacial stress component corresponds to shear strength of a soft material.

The measure of friction, for the purpose of this thesis, is the friction coefficient (μ), tangential frictional force (F_t) and wear of surfaces (W_1). The friction coefficient is dimensionless and is measured, within this research, by an MTM – Tribometer (see 2.3.1 for more details) and is calculated by the following equation (where load (*W*) and tangential friction force (F_t) are both measured in Newton's (N):

Eq. 2.3

$$\mu = \frac{F_t}{W}$$

Further understanding of the laws proposed by da Vinci, Amonton and Coulomb was provided by Archard (1957), whereby, although Amonton's 2nd law states that F_t is independent of contact area, however, when real contact area (A_r) is taken into account, asperity contact is increased linearly with W. Therefore friction is independent of contact area, but directly proportional to the real contact area (A_r), which is then proportional to W. Based on Archard's theory (now law), Amonton's 1st law is explained; F_t is directly proportional to W.

For the purpose of this thesis, friction is considered in two ways: 1) sound friction and 2) surface friction and is further explained in Section 2.4.1, and therefore the frictional energy is dissipated as noise and heat (with minimal wear).

2.3.1 Methods of measuring friction: Tribology

Tribology is the study of friction and wear of surfaces and was first introduced for the automobile industry and replicated moving car parts to assess the effect of lubricants on friction (Bartz 1978). Tribology for this thesis has been established using a tribometer (MTM tribometer, PCS Instruments (see Section 3.3.7 for methodology and schematic)) and consists of two surfaces: a ball rotating against a disc. Advancements to the technique have been made by the food industry, where friction is related to mouth feel and lubricants: food and liquids (see Section 2.8).

Lubricants are used within tribology, particularly at high speeds, to reduce friction by the process of entrainment: surfaces are separated initially, either partially or fully, and therefore the friction reduced by the lubricant is now measured, as opposed to the rough surfaces it separates. The mechanics of lubrication is such that the contact between the ball and the disc is at a minimum at the centre of contact and increases to the outer sides of the ball. This increase of free area around the ball is what initially pulls in the lubricant and it is the characteristics of the lubricant which enables or disables the movement into the smaller free space between the ball and disc, and an increased disc speed drags in the lubricant, also reducing friction. A typical display of tribology comes from assessing the influence of entrainment speed (*U*) on friction coefficient (μ) where three main regimes are observed: boundary, mixed and hydrodynamic (see Figure 2.10) and are commonly referred to as a Stribeck curve, created by Richard Stribeck in the early 1900s.

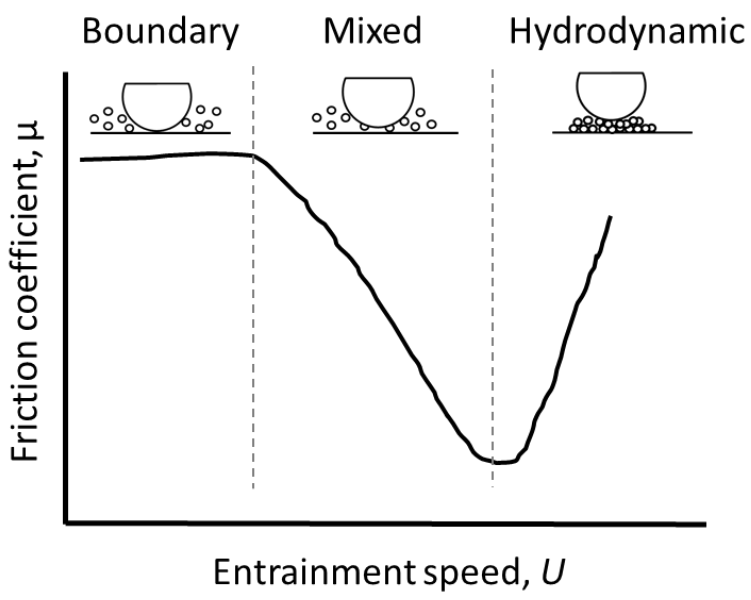


Figure 2.10 A schematic of a typical Stribeck curve depicting the three regimes of lubrication: boundary, mixed and hydrodynamic.

As can be seen from Figure 2.10, friction coefficient values change when increasing entrainment speeds, initially starting high within the boundary regime where the two surfaces are in constant contact, resulting in a plateau, with minimal influence of the lubricant on friction levels. On increasing speed, lubricants are drawn in between the two surfaces, as previously discussed, resulting in a lower coefficient. The hydrodynamic regime is as a result of full entrainment of the lubricant, however, as can be seen results in an increase in friction due to the increase in amount of lubricant which therefore increases the shear needed to keep the ball moving over the new lubricant surface. This latter regime is independent of surface roughness and is dependent on lubricant viscosity (Garrec 2013). However, it is related to bulk viscosity measured by rheology and therefore is traditionally measured by a rheometer and is often not reported within literature.

As tribology is concerned with the effect of lubrication on friction it is important to understand lubricants in all aspects of home and personal care. Advances have been made with regards to importance of tribology within the food industry, where tribometry experiments and methodology has been shown to correlate with mouthfeel and sensory properties of semi-solid foods (Malone *et al.* 2003). It is thought that results and methodology collected and developed by the food research can be replicated in fabric care as conditioners are essentially lubricants in processing, construction, within washing machines, during drying, folding and touching fabrics. To advance understanding of the lubrication of fabrics, the lubrication of food products on friction within the mouth is discussed in Section 2.8.

2.3.2 Fabric friction

Friction of fabric can be as a result of fabric-on fabric friction and fabric-on-skin friction. The following section describes the methods used to capture friction of fabric surfaces, skin friction and the relationship between friction levels (μ) and varying fibres and areas of the human body.

2.3.2.1 Fabric-on-skin friction

Discussing friction as a result of fabric-on-fabric and skin-skin/surfaces is essential to understanding the influence of each variable on the friction coefficients produced, and is imperative to overall fabric-on-skin friction. As this thesis is concerned with all aspects of fabric friction in terms of frictional noise, as well as friction coefficients reduced by lubricants where a silicone ball is used to mimic human skin, the influence of skin-on-fabric is discussed.

Within humid environments, friction coefficients are reduced when compared to dry conditions and is attributed to not only the wetting of the fabrics, but also the uptake of water by the skin, resulting in smoother, swollen surfaces (Kenins 1994; Gerhardt *et al.* 2008).

2.3.2.2 Fabric-on-fabric friction

Fabric friction arises from the asperities on the fabrics surfaces interacting and interlocking with the same asperities on the opposing fabric surface (Howell *et al.* 1959). As 'asperities' is a collective term for deviations in any given surface, as discussed within Section 2.3, in terms of fabric surfaces it encompasses fibres, threads and apertures (free space between adjacent threads, see Section 2.1 for more information) i.e. micro- and macro-structure. When considering interlocking fibres, friction is as a result of the 'hairiness' (free fibres) of both the fibres and threads. Fibres are able to possess varying levels of hairiness themselves due to their original fibre type e.g. cotton is spun from many bent, irregular and short fibres which create a larger surface area. However, when assessing the hairiness of silk it is known that due to its construction from single filaments therefore has a lower surface area. On increasing surface area of the fibre hairiness the level of interlocking that will occur also increases (Bueno *et al.* 1996; Das *et al.* 2005). As well as fibres exhibiting a larger surface area, threads of woven fabrics also influence friction as an increasing thread diameter (a thread which is constructed of a higher number of fibres, or those with more free space between fibres) will result in a larger surface area. In addition to thread diameter, aperture size also has a marked effect on surface area. The surface area of fabrics (e.g. fibres, threads etc.) is quantified by a fabrics surface roughness and, as is discussed within this Chapter, an increase in surface roughness leads to a higher level of friction (see Section 2.3.2).

Fabric-on-fabric friction has been known to be influenced by a number of parameters: sliding velocity (Hermann *et al.* 2004; Ramkumar *et al.* 2004b), normal load (Carr *et al.* 1988), fibre type (Arshi *et al.* 2012) and surface roughness (Ajayi 1992a) to name but a few. It is well known to have been measured using the KES-FB system explained in Section 2.1.1.1. However, when funding of research does not stretch to such an expensive piece of equipment, other methods can be used to establish friction measurements. An example of which is the Instron Tensile Tester has been used by a number of researchers and a schematic can be seen in Figure 2.11 (Ajayi 1992a; b; Ajayi *et al.* 1995; Ajayi &

Elder 1997; Das *et al.* 2005; Arshi *et al.* 2012). The method involves digitally recording the friction coefficient of fabrics tested by the load cell which gives signals corresponding to the frictional force acting on the fabric. It also, in real-time of the experiments, calculates the surface roughness of the material in question. The friction can be measured at varying loads, at different speeds and under different fabric tensions.

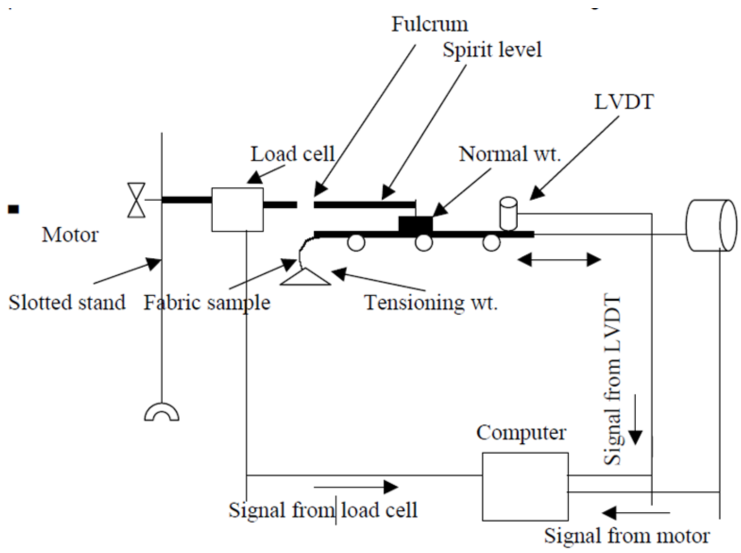


Figure 2.11 A schematic of the Instrom Tensile Tester used to capture friction of fabrics (Reproduced from Das *et al.* (2005)).

In the same way that skin friction deviates from Amonton's laws (see Section 2.3.2.3), fabric friction has also been shown to deviate, or commonly known at a failure of Amonton's laws. Ramkumar *et al.* (2004a) studied friction of polymeric materials and reported that the relationship between frictional force and normal load can be expressed by the following equation:

Eq. 2.4

$$\frac{F}{A} = C(\frac{N}{A})^n$$

Where *F* is frictional force, *N* the normal load, *A* the apparent area of contact, *C* the friction parameter and *n* the friction index.

With regards to the effect that increasing or decreasing speed has on friction, fabric friction is dependent on sliding velocity and has been seen to increase simultaneously (Taylor & Pollet 2000; Hermann *et al.* 2004; Ramkumar *et al.* 2004b). In contrast to this finding, Ajayi *et al.* (1992b) reported that on increasing sliding velocity kinetic frictional resistance was increased, however, their friction coefficients did not significantly differ. Kinetic frictional resistance was calculated using the following equation:

Eq. 2.5

$$Kinetic\ frictional\ resistance = F_s - F_k$$

Where F_s is the static friction and F_k is the kinetic friction. Their research is dependent on understanding frictional resistance taken from the stick-slip measurements, which is generally in contrast to literature of constant friction taking place. The increase in frictional resistance, which differs to other literature, is related to the understanding of stick-slip, that on increasing speed, the amplitude of stick-slip is also increased i.e. the force needed to overcome the resistance of each thread and move on. Although the research discussed differ in their approach and in the relationship between friction and sliding velocity, they both agree that for fabrics Amonton's law fails.

Ajayi *et* al.'s (1992a) research investigated the effect of increasing the density of fibres on frictional resistance measured which resulted in an increase of resistance on increasing fibre number. It is the effect of increasing number of fibres that then increases the 'hairy' nature that results in a higher level of interlocking and therefore force needed to overcome the adhesion between interlocking fibres increases.

When investigating the effect of load on dynamic fabric friction (Amonton's law states that friction is independent of load) research has shown that on increasing load, fabric friction, in varying measured parameters (coefficient, resistance, force etc.) differs as a result. Carr *et al.* (1988) reported that on increasing pressure, friction decreased. However, they do not relate their findings to any explanation, but state that their findings confirm that Amonton's law fails with respect to pressure.

Ajayi *et al.* (1992b) report that friction coefficient diminishes with increasing normal load and was observed for cotton samples with varying weave patterns and state that a linear relationship does not exist between the two factors, implying agreement with the failure of Amonton's law.

2.3.2.3 Skin Friction

As previously described, friction is concerned with the theory of two surfaces rolling over one another and in terms of this thesis the surfaces are a combination of fabrics and skin. It is important to recognise here that skin friction is essential to this research as within Chapter 5, the silicone ball used is designed to mimic skin and with respect to Chapter 7, where participants interact with fabrics using touch of their hand. Many studies have investigated the fundamentals of skin friction and, as with all surfaces, are affected by lubrication and wear. The mechanical properties of skin at the surface, and in particular the stratum corneum (the most outer layer of the skin); consist of hydration, elasticity and roughness. Hydration, elasticity and roughness are all influences on friction (μ) and skin is known to deviate from the above mentioned Amonton's laws, although studies throughout time have contradicted one another. A review written by Sivamani *et al.* (2003a) described how early research into skin friction by Naylor (1955) found that skin friction did conform to Amonton's law, whereby, μ was proportional to load, however, El-Shimi (1977) reported that μ was inversely proportional to load. This deviation was also reported in research by Comaish and Bottoms (1971) and Koudine *et al.* (2000).

2.3.2.3.1 Devices to measure skin friction

μ was initially measured using a basic linear pulley system, created by Comaish and Bottoms (1971): a sensory probe was pulled across the skin using weights in a pan with a supposed constant velocity. A schematic of the earliest measurement technique can be seen in Figure 2.12. μ was calculated by dividing the total weight in the pan by the normal load on the probe, however, doubts were cast over the control of speed of the probe and therefore the accuracy of μ measured.

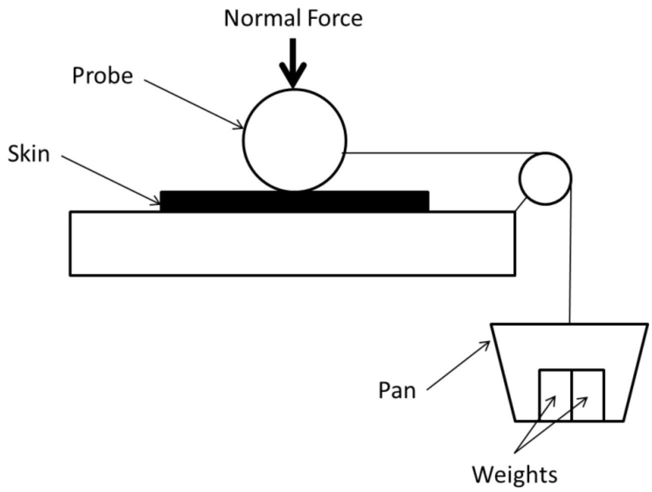


Figure 2.12 A schematic of Comaish and Bottom's early pulley system. Adapted from Sivamani *et al.* (2003a).

More complex measurements of skin μ were developed from Comaish and Bottoms (1971) initial technique which involved a revolving motor to ensure that all speeds were accurate and were combined with a strain gauge attached to the probe to measure friction. Other methods involve a rotating wheel with a known load onto the skin surface which relays μ measurements to a computer (Highley *et al.* 1977).

Derler *et al.* (2007) designed a method to measure the friction coefficients of a human finger across an interchangeable surface. A participant pulled their finger with varying loads (panels were firstly trained and practiced in applying certain loads) across a force plate which feeds back to the researcher the normal and two tangential forces to be used to calculate μ. Other surfaces were used within their research as skin models: textiles which had similar surface roughness measurements and structures to skin were used (artificial leather, fleece, silicone and three different glass surfaces etc.). The purpose of their research was to test different surfaces to establish a model for skin friction in combination with an objective friction measurement method in relation to a human finger. When comparing normal load produced by the participants, Derler *et al.* showed that μ decreased with hydrated skin and stayed constant with dry skin and the skin model (leather). Water was introduced within the skin model system to understand the effect of hydration on μ. It was concluded that more participants would be needed to conduct a full scale study on skin hydration, but that any differences seen between human skin and model skins would be due to the structure of human skin itself.

2.3.2.3.2 Influences of hydration on skin friction measurements

The effect of hydration on μ has widely being investigated, whether in-*vitro* or in-*vivo* (Naylor 1955; El-Shimi 1977; Highley *et al.* 1977; Kenins 1994; Dawson 1997; Sivamani *et al.* 2003b; Derler *et al.* 2007; Gerhardt *et al.* 2008). Consensus from literature, which is by no means exhaustive: as skin hydration increases, μ also increases, with the exception of fully wetted skin where Dawson (1997) reported that friction levels were decreased. A general trend was also shown within most skin friction research that as the skin is dried, and in some cases beyond the normal level of dryness, that μ is decreased.

Gerhardt *et al.* (2008) adapted Derler *et al.*'s research (2007; 2010) by investigating the frictional characteristics of the human forearm as opposed to the finger, whilst using the same set up, and expanded upon it to further investigate the effect of hydration on skin friction. Gerhardt *et al.* reported a linear relationship between epidermal hydration and μ, whilst further showing that varying the hydration of participant's skin had a marked effect on μ, whereby, as very dry skin resulted in the highest levels of μ, followed by dry and normal, respectively. These results were as a result of human skin being rubbed against dry fabric surfaces, however, when the fabrics were soaked the opposite in relationship between hydration and μ was observed.

It was thought that the increase in μ for damp skin was due to swelling of the epidermal layer, therefore creating a larger surface area in which friction levels would increase and in contrast, dry skin would produce areas of increased roughness and wrinkles and consequently reducing the areas of contact with the base surface decreasing friction levels (Sivamani *et al.* 2003a). When levels of water on the skin or surfaces are increased beyond which normally exists on wetted skin i.e. drenched or soaked areas, μ is observed to decrease (Derler *et al.* 2009), however, the opposite was seen for Gerhardt *et al.* (2008): when materials tested were fully soaked a two fold increase of μ was observed. However, fully wetting the skin or surfaces is still very minimal in terms of published research and a consensus has yet to be reached (Sivamani *et al.* 2003a).

Although skin friction deviates from Amonton's law, as previously discussed, in terms of load, research into his 2nd law: *friction force is independent of contact area* has not yet been critically analysed for skin friction. Varying areas on the human body have been investigated in terms of friction coefficients, including but not limited to: forearm (El-Shimi 1977; Gerhardt *et al.* 2008), finger (artificial or real) (Lederman & Taylor 1972; Lederman 1974; Kenins 1994; Sivamani *et al.* 2003b; Gee *et al.* 2005; Derler *et al.* 2007; Liu *et al.* 2008; Darden & Schwartz 2009; Derler *et al.* 2009; Zahouani *et al.* 2009; Derler & Rotaru 2013; Koç & Aksu 2013), edge of the hand (Derler *et al.* 2009) and back of the hand etc. For most literature, single separate areas of the body were investigated; however, Kenins (1994) researched the difference in resulting friction between fingers and forearms and observed that finger friction on fabric resulted in a slightly lower level of μ than the forearm and relate it to the contact area, thus questioning whether skin friction also deviates from Amonton's 2nd law of friction. Although μ changed with areas of the human body, the overriding difference in μ was when the fabrics and skin were wetted, agreeing with previous literature discussed. Cua *et al.* (1990) also investigated a change in μ measure from different areas of the body which resulted in the highest μ level at the forehead (0.34) followed by volar forearm (0.26), upper back (0.25), palm (0.21) and abdomen (0.12).

As well as varying the areas on the body, where only skin is the surface, some researchers have used different probes to measure friction levels: polyethylene (Naylor 1955), stainless steel (μ varied between 0.2 and 0.6 when stainless steel probes were either rough or smooth, respectively) (El-Shimi 1977; Sivamani *et al.* 2003b), glass (Koudine *et al.* 2000; Derler *et al.* 2009) and nylon (Highley *et al.* 1977). It is important to note that as tribology probes can be used to mimic skin that friction levels produced from varying materials will differ, and therefore all measurements designed to represent human skin must be taken with caution and care.

2.4 Roughness of materials

A vital part of all surfaces is the roughness measurements they exhibit, whether deliberately engineered or naturally occurring. There are many methods available to establish the surface roughness values. Within all literature there are differing nomenclature for surface roughness values, however, for the purposes of this section it will be referred to as R_a, unless otherwise stated.

R_a can be established through two major methods: either contact or non-contact. Where it is essential that samples are not damaged or contaminated a non-contact method is preferable, i.e. microscopy, interferometry etc. Different types of microscopy can be used, including scanning electron microscopy (SEM) to establish roughness values down to the nanometer scale. SEM is useful for qualitative roughness evaluation, imaging and currently is not accurate with quantitative measurements. However, Atomic Force Microscopy (AFM), when used with appropriate tips can quantify R_a values well, although the process does come into contact with the surface (XiaoMei & Hong 2009).

Diffraction methods are also non-destructive and are very accurate at measuring R_a on small scales. Instruments such as an Interferometer (see Section 3.3.3.1 for more information) are capable of producing 3D images of material surfaces and are therefore able to measure heights of surfaces and consequently roughness values. Interferometry is a method of light reflection from a surface by measuring the time taken for the laser to return to the original source and at what angle it returns at; from this, a map of the surface is reproduced. An advantage of using interferometry, particularly over microscopy, is the sample size able to be measured; interferometry can measured samples on a millimetre scale, and even up to a cm, however, the larger samples are, the longer imaging will take.

The earliest method of measuring surface roughness', to the best of the author's knowledge, is that of Butler *et al.*'s (1955) 'Cloth Profilometer' that primarily identified the faults in fabric samples. The proceeding method was that of the Surface Tester within the KES-FB and has been well documented

(Gong & Mukhopadhyay 1993; Chen *et al.* 2000; Eunjou & Cho 2000; Cho *et al.* 2001b; Yi *et al.* 2002; Cho *et al.* 2009). Ramgulum *et al.* (1993) used the KES-FB surface tester along with two other methods to compare surfaces: a non-contact laser scanner; similar to an interferometer with a laser technique to measure distance from the origin to the fabric sample and back again, and rotary roughness measurer (part of the KES-FB surface tester) to calibrate the new laser scanner with the well-established KES-FB. Results showed that their laser scanner was capable of measuring surface roughness values; however, they make their readers aware that contact methods are potentially more replicable to skin contact of roughness perception due to attractive forces and deformation as a result of pressure.

The R_a of surfaces that have been deliberately engineered are measured and reported only from the specifications from which they have been processed i.e. Lederman (1974) and Taylor and Ledermen (1975) investigated the perception of grooved surfaces and it was the spaces between each groove that was considered to be the R_a value; SEM images were used to display the nature of the grooves.

2.4.1 Relationship between surface roughness and acoustics of materials

A range of materials have been investigated within literature to understand the frictional noise they produce and how this is affected by changing certain properties of the materials e.g. surface roughness and weight. (Othman & Elkholy 1990; Othman *et al.* 1990; Aguilar *et al.* 2009; Le Bot & Chakra ; Akay *et al.* 2012).

Aguilar *et al.* (2009) devised a method for predicting the surface roughness of paper using dry frictional noises produced when a nylon brush was run over its surface. They identified that varying the surface roughness values, and types of paper, produce different sound spectra shapes and the power spectra density (PSD) (total noise emitted). The authors observed a positive relationship between surface roughness and PSD; however, the method in which surface roughness was measured was not disclosed in the literature.

Othman and Elkholy (1990) stated that there was a serious lack of understanding of the effect of frictional speed and surface roughness on frictional noise. Therefore the authors aimed to investigate this relationship by varying the surface roughness (R_a) of one material (the exact material was not disclosed within their manuscript). Material samples were machined to produce varying R_a values (0.025 μm and 100 μm) via grinding, turning, milling, drilling and shaping, and were established using a Talysurf 10 (Rank Hayler Hobson Ltd.): a stylus which physically reports the change in height over an area (i.e. a contact method of analysis). A strong positive relationship was established between R_a and sound pressure (dB), whereby, as R_a increased, sound levels also increased (see Figure 2.13); however, explanation for why this relationship was observed was not explained.

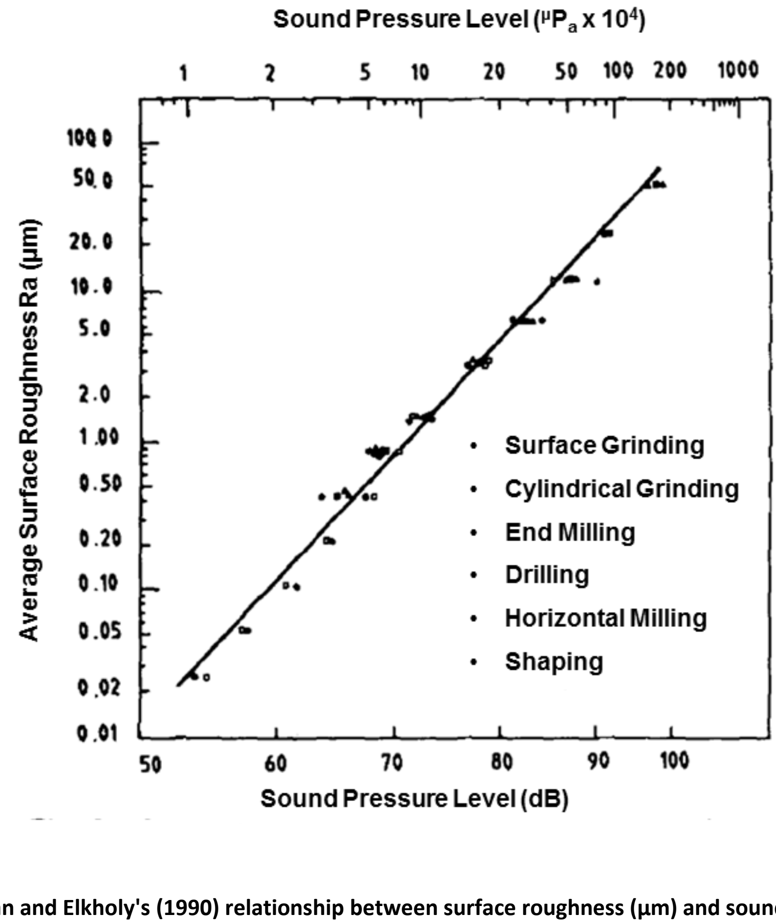


Figure 2.13 Othman and Elkholy's (1990) relationship between surface roughness (µm) and sound pressure levels (dB).

This research was further enhanced by the work of Othman *et al.* in (1990) where a range of surface roughness values for three metals (aluminium, steel and brass) were investigated and resulted in the same relationship: an increase of R_a leads to a larger sound pressure level emitted for all metals tested. The same method was used to establish both R_a and frictional noises produced (see Figure 2.14 (a)), however, this additional research also highlighted the effect of material properties on sound spectra shape (see Figure 2.14 (b)).

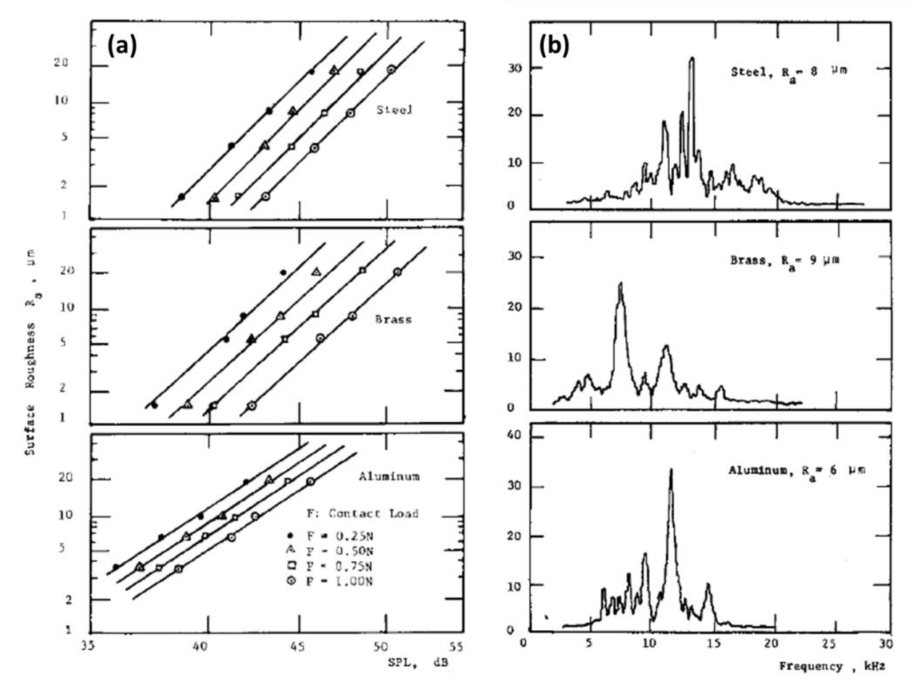


Figure 2.14 (a) Sound pressure level (dB) vs. surface roughness (μm) and (b) Frequency (Hz) vs. sound pressure level (dB) spectra produced by brass, steel and aluminium. (Othman *et al.* (1990).

An explanation for the relationship between R_a and total noise was presented by Le Bot *et al.* (2009) and is based on Akay's (2002) research which encompasses an asperity theory. Surface roughness of materials is a result of asperities i.e. deformities with an uneven nature, namely rugged and sharp edges of a surfaces, even at an atomic level, and when two surfaces with asperities come into contact with one another, it is these asperities which interlock causing an increase in friction due to adhesion and plastic deformation of said asperities. The adhesive forces are dependent on contact area (as previously discussed in section 2.3) and material type i.e. charges, hydrophilic/phobic nature etc. and the energy to overcome these forces is emitted as sound and therefore the larger the contact area of the asperities and material type the louder the sound it emitted.

Literature surrounding the frictional noise of contact on human skin is minimal, however, Zahouani *et al.* (2009) created a tribo-acoustical probe to capture the skin friction sounds. They firstly investigated the effect of changing the roughness of a model system (created from silicone replica skin and meshes with varying R_as) and reported a linear increase in sound pressure levels captured when R_a was also increased. From here they went on to investigate the frictional noises produced from skin in-*vivo* at two different sites: calf and cheek as well as friction coefficients, μ, measured by the multifunctional tribo-acoustic probe.

They reported that the cheek area (R_a = ~8 μm) produced a lower average sound level produced than the calf (R_a = 24 μm), however, in contrast produced larger μ than the calf area. Zahouani *et al.* explained these findings in such a way that the assessment of touch is a direct result of both friction coefficient and acoustic emissions, as frictional noise gives a signature of softness, whereas, μ and frictional force is an measure of adhesive forces and contact area of the skin.

2.4.2 Material frequency sounds

Stoimenov *et al.* (2007) investigated the effect of changing the surface roughness values (R_z) of stainless steel samples on the frictional noise produced when rubbed together and in particular the specific frequency values emitted. As well as a change in roughness values, Stoimenov *et al.* also investigated changing the speed (170 and 80 mms^{-1}) and load (25 N and 6 N) of the rubbed surfaces to understand if these too had an effect on frequencies and frictional noise. They reported that a subjective change in frictional speed resulted in similar spectra for each speed except for peak at 9.5 kHz, which they deemed to be electrical noise, and the faster speeds resulted in a high power spectral density (PSD) (see Figure 2.15 (a)). Figure 2.15 (b) shows the effect of changing load on frictional sound, and as can be seen the higher the load the broader the frequency peaks. In addition, some individual peaks seen in lower loads are combined into one with higher loads.

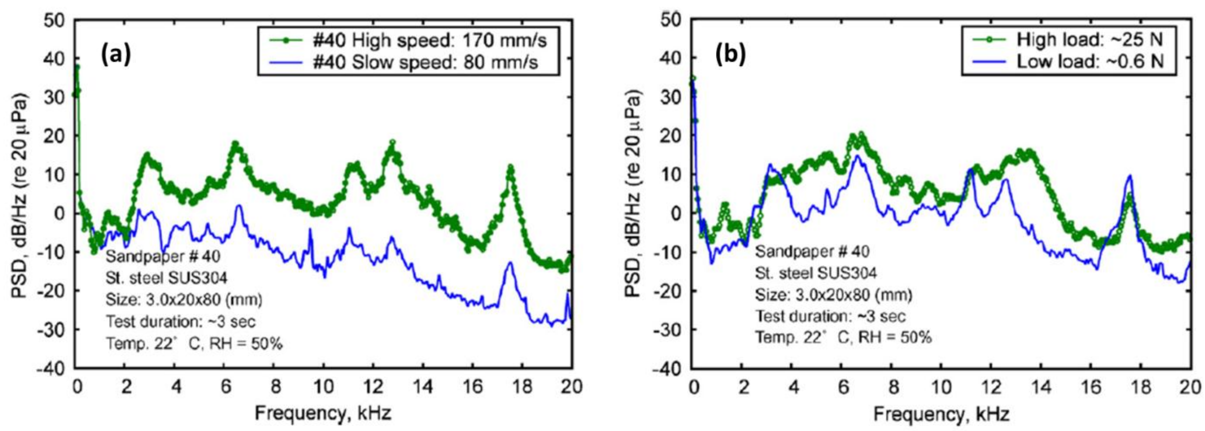


Figure 2.15 Frequency vs. power spectral density spectra produced by Stoimenov *et al*. (2007) showing the (a) change in frictional speed and (b) effect of changing load.

When investigating the effect of R_z on specific frequency peaks it was seen that a shift occurs to the higher end of the frequency spectrum as the roughness values are decreased. They reported that the sound spectrum was divided into five main peaks (‘P’) and that the lowest frequency peak was more sensitive to change in surface roughness. P_1: shifted from 3.0 to 4.5 kHz when max surface roughness changes from 10.9 to 3.4 μm. In addition, the location of peaks 1, 2 and 4 shifts to a higher frequency as surface roughness is reduced (see Figure 2.16).

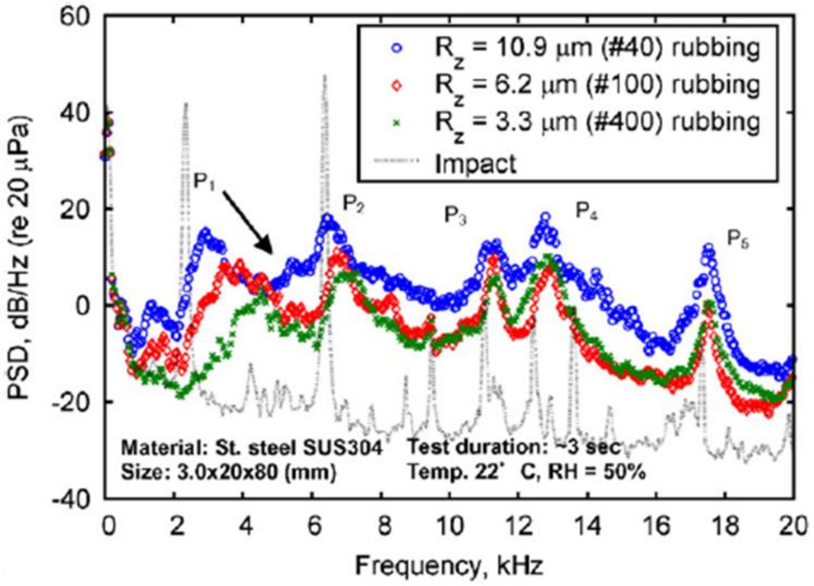


Figure 2.16 Frequency vs. PSD spectra produced by rubbing three pairs of different stainless steel samples together. Graph reproduced from Stoimenov *et al.* (2007).

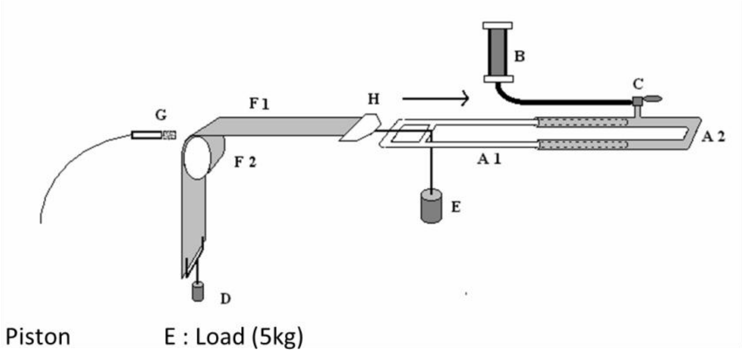
As well as reporting a change in specific frequencies, the overall sound levels emitted by the stainless steel samples increased with increasing R_z values (see Figure 2.16). This finding agrees with previous literature discussed.

Although these changes were observed, Stoimenvo *et al.* (2007) gave little in the way of explanation as to why these shifts in frequencies were occurring. However, to the authors knowledge is the only publication in the literature that explores the effect of roughness on specific frequencies within a sound spectrum. When critically analysing Stoimenov *et al.*'s (2007) research, it was apparent that a number of errors would have occurred when the frictional noises were produced due to the subjective nature of: speed, load and creating surface roughness values (researcher's used sandpaper to create varying R_z values and consistency could not be verified).

2.5 Relationship between fabric friction and sound

2.5.1 Sound of fabrics

In order to capture fabrics sounds, literature preliminary started with in-*vitro* investigations; whilst fabric samples were stationary within a laboratory and not when worn by humans, and a number of measurement techniques were developed. The group lead by Yi and Cho created a Measuring Apparatus for Fabric Noise (MAFN) in 1999 in order to capture frictional noise produced when one surface was pulled across another (Yi & Cho 1999). The MAFN was adapted from its first concept to ensure that fabric movement was consistent and did not involve stick-slip by replacing the weight mechanism with oil driven piston system (see Figure 2.17). The MAFN was used for many investigations on different fabrics, including but not limited to: wool, silk, polyester, flax and cotton (Cho & Casali 1999; Cho *et al.* 2001a; Cho *et al.* 2001b; Yi *et al.* 2002; Cho & Cho 2007; Park & Cho 2012), and for different uses i.e. to work with sensory perception as well as mechanical properties of the fabrics investigated.



A1 : Piston | E : Load (5kg)
A2 : Pipe | F1 : Fabric (15 cm width×75 cm length)
B : Cylinder | F2 : Fabric wounded on pulley (15 cm width×15 cm length)
C : Valve | G : Microphone
D : Load (500g) | H : Holder

Figure 2.17 A schematic of the MAFN created by Yi and Cho in 1999. (Schematic reproduced from (Cho *et al.* 2002))

In early work, the MAFN produced fabric sounds that were displayed in graphs of frequency vs. amplitude, after being fast Fourier transformed (FFT), from which three values were established: level pressure of total sound (LPT), level range (ΔL) and frequency difference (Δf) to enable comparison of the different fabrics measured.

Most literature centred on fabric sound has shown a relationship between surface roughness and total noise, whereby, the rougher the fabric the more total noise produced. As described in Section 2.4, there are many methods of capturing surface roughness for materials and research is now moving towards non-contact methods i.e. Interferometry.

Yi and Cho (2000) captured the sounds of 25 fabric samples with varying fibre type (cotton, wool, polyester, silk and nylon), along with different weave patterns (plain, twill and satin). Their results were presented in frequency vs. amplitude spectra and showed how varying both the weave and fibre type altered the resulting spectrum shape (see Figure 2.18). Yi and Cho reported that little difference was observed between each sound spectrum within the cotton or woollen groups, despite varying fabric types. They also showed a similarity between the spectrums produced by silk and polyester (both with satin weave) which then supported previous literature by Fujimoto (1986) and Fukuhara (1993) that manmade silky fabrics sound similar to natural silk materials.

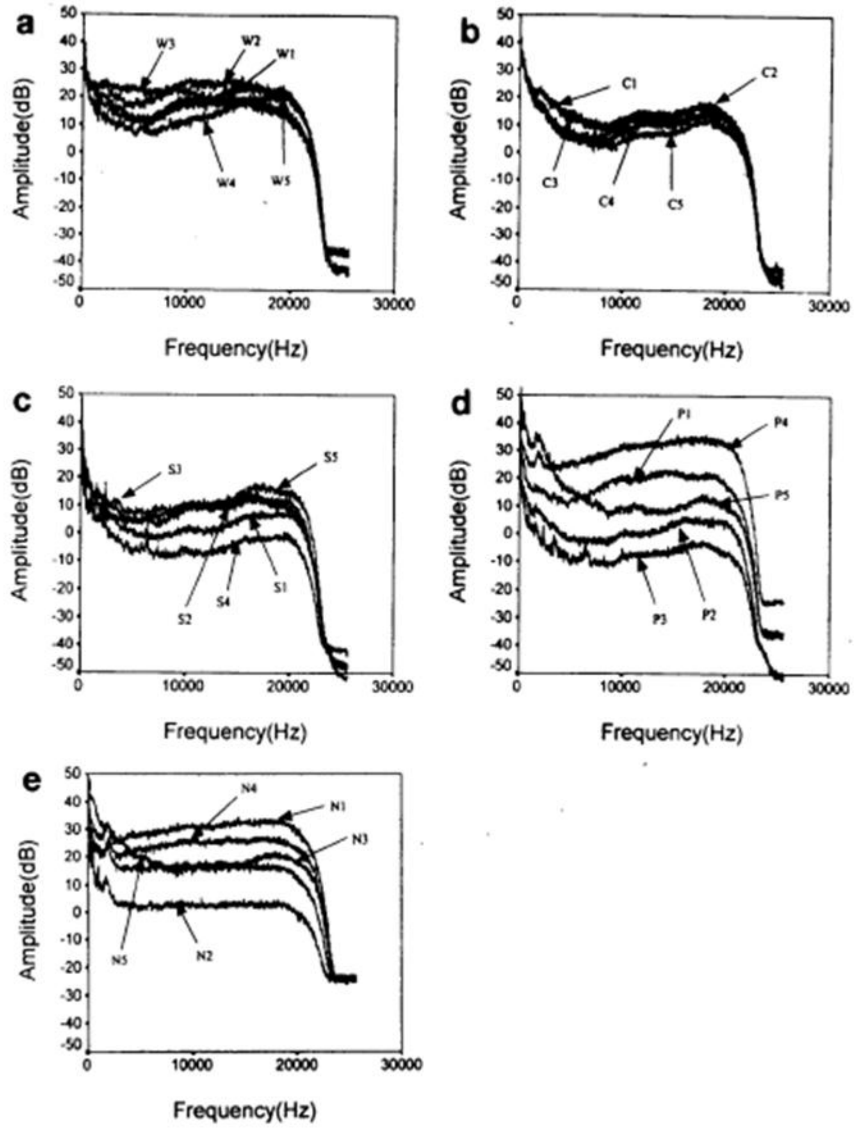


Figure 2.18 Frequency vs. amplitude spectra from Yi and Cho's research (2000) showing (a) wool (b) cotton (c) silk (d) polyester and (e) nylon.

As previously described in Section 2.1.1, fabrics are constructed using multiple different weaves and investigations into how a change in weave can affect frictional noise was investigated by Kim *et al.* (2002). They used silk fibres, spun into yarns, and engineered them to have four different weave patterns (seven were tested but only four are discussed here due to the interest in weave): one plain, two twill and one satin weave and ensured that all samples has the same density and thread count. Using the MAFN previously described to capture the frictional noise produced the results indicated that a significant change in spectral shape was not observed (see Figure 2.19), however, amplitude was affected by different weave patterns with TWL3 (a ½ twill weave) producing the loudest amplitude level.

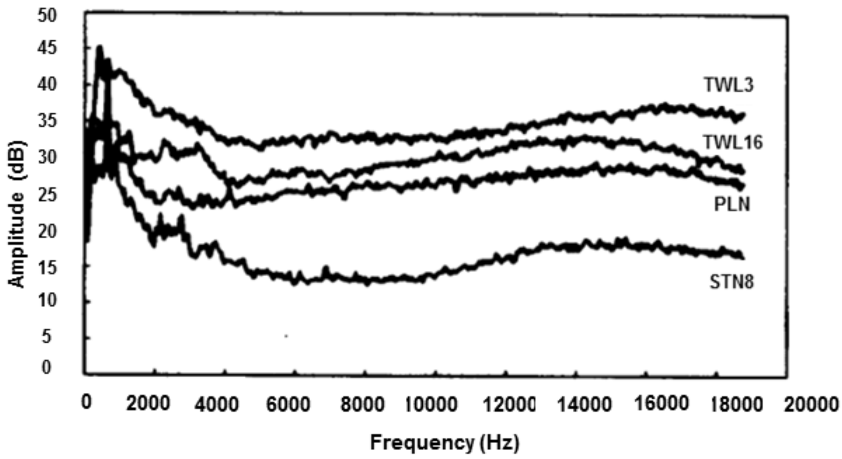


Figure 2.19 Frequency vs. amplitude sound spectra captured from four different silk weave patterns: STN8 (satin weave), PLN (plain weave), TWL16 (8/8 twill weave) and TWL3 (1/2 twill weave). Graph taken from Kim *et al.*'s manuscript (2002).

Kim *et al.* (2002) also related the mechanical properties (as measured using KES-FB) to the frictional noises produced, as well as Zwicker's psychoacoustic parameters (Zwicker's models involves roughness, sharpness, loudness and fluctuation strength and are most often used within literature to understand relationships with mechanical properties (KES-FB) and frictional noise produced (Fastl, H. and Zwicker, E. 2007)) and here they reported that the order of surface roughness from high to low was: PLN, TWL3, TWL16 and SN8 which as can be seen from Figure 2.19 did not relate to total noise produced. When relating Zwicker's roughness measurement to the level pressure of sound (LPT) produced by the four silk samples, it was reported that no relationship between roughness and LPT, however, Zwicker's loudness was increased depending on weave type. Kim *et al.* (2002) concluded that a change in loudness was as a result of interlacing connections between the weaves; where there were a higher number of connections in TWL3 than TWL16, a greater value for loudness was measured, along with LPT. However, this theory was then contradicted for PLN which had the highest number of interlacing connections but produced a lower loudness value than TWL16; this was explained due to the ruggedness of the twill weave.

2.6 Sound absorption of fabrics

Fabrics are more generally thought to absorb sounds, as opposed to emit sounds, in environments such as cars, homes and offices by the use of curtains, car seats and door frames etc. The engineering of fabrics has been investigated in literature to understand the most efficient and effective use when unwanted noise is required (Shoshani & Rosenhouse 1990; Tilak *et al.* 2007; Liu & Hu 2010; Brown *et al.* 2011; Mahmoud *et al.* 2011; Soltani & Zerrebini 2012; Yang & Li 2012).

Different material properties of fabrics have been known to alter sound absorption behaviour with an increase of levels such as; hollow fibres when compared with non-hollow fibres (Mahmoud *et al.* 2011), an increase of surface area of different denier fibres (Brown *et al.* 2011) and weave type (Soltani & Zerrebini 2012).

Shoshani and Rosenhouse (1990) investigated the effect of changing weft fibre type (acrylic, cotton and wool), whilst keeping the warp yarns constant with cotton, yarn count, as well as the influence of a change in air gap behind the fabric wall on the sound absorption capabilities. Specific frequencies were analysed for the change in amplitude by sound absorption as opposed to the whole spectrum available: 125, 250, 500, 1000, 2500 and 4000 Hz were measured and results observed that although a change in fibre and yarn type was not an influence on sound absorption at frequencies below 500 Hz, significant differences were observed at the highest frequency tested; 4000 Hz. Shoshani and Rosenhouse (1990) concluded that their work encouraged the awareness of woven fabrics as more effective sound absorbers.

A comprehensive and full investigation was carried out by Soltani *et al.* (2012), in which sound absorption capabilities of fabrics were measured, when varying parameters were changed. In particular reference to this thesis work, and the changing of fibre type, their research into the effect of changing weave patterns was examined. Soltani *et al.* (2012) concluded that higher levels of absorption were achieved by a plain weave, as opposed to twill and satin, respectively, at particular frequencies (as was observed within the previously mentioned Shoshani and Rosenhouse (1990)). It was reported that at both the extreme minimum and maximum frequencies measured (250 and 2000 Hz, respectively) sound absorption did not vary greatly with weave type, however, at frequencies around 1000 Hz a difference was observed. Soltani *et al.* (2012) explained that the difference between sound absorption properties of the varying fabrics was more influenced by porosity and density and therefore these three factors are of a combination of the fabrics ability and not weave alone.

Understanding the mechanism of sound absorption has been explained by 'hollow' areas and spaces between layers creating areas which will trap air which carries unwanted sound waves and it is an increase of these hollow areas which will influence a materials ability to absorb sound. Mahmoud *et al.* (2011) engineered fabrics for a car interior purpose to have specific hollow polyester fibres which were then cross-laid together (a non-woven technique) and tested on their ability to absorb unwanted outside and inside noise from automobiles. A number of variables were tested within their research: changing the ratio of hollow polyester fibres to solid polyester fibres, weight of samples and as a consequence the weight (g/m^2) of the fabric samples. When comparing the sound absorption coefficients (%) of all samples of hollow and complete polyester fabrics to 100% complete polyester fabrics it was consistently observed that a higher % was absorbed in the mixed samples, however, when the ratio was increased from 75% polyester/25% hollow polyester to 55% polyester/45% hollow polyester a significant difference was not observed. As well as observing strong correlations between % absorption coefficients and ratio types, the weight of the fabric samples was also well correlated; all ratios of fibre type were seen to have the largest level of % absorption at the highest weight 600 g/m^2, followed by 500, 400 and 400 g/m^2 respectively. As well as Soltani *et al.* and Shoshani and Rosenhouse, Mahmoud *et al*. (2011) measured the sound absorption as certain frequencies (125, 250, 500, 1000, 2000 and 4000 Hz) and it is these frequencies that may well prove to be influential within this research based on microstructure and weave type.

The behaviour of fabrics in terms of sound absorption has been discussed at length to understand if the counteracting sound emitting behaviour of similar fabrics is also observed, whereby, effect of weave, fabric density; weight, thickness, fibre type etc. will have an influence on the total noise levels emitted.

2.7 Sensory perception of fabrics and other materials

2.7.1 Sensory perception

As has previously been discussed, the method of objectively measuring fabrics has been advanced within recent years, however, although research is moving towards aiming to relate consumers' perceptions of fabrics using senses to mechanical properties, subjective evaluation of fabrics is essential for industry and will almost certainly always be required. Touch, sight, smell and sound are often used to describe and give opinions on advances in textile and textile preparation and care methods and are generally given by panels and interviews.

Aesthetics of fabrics, for garment, soft furnishings, and interior and exterior purposes, encompass many of the five senses used by humans; a fabric is considered aesthetically pleasing on many levels, including cognitive and emotional levels. Swan and Combs, in Chen-Yu *et al.* (1999), observed that consumer approval of apparel products is affected by the physical qualities, as well as the psychological, and is not only limited to the functional aspects, but also includes the aesthetics. A fabric can look soft, but if it does not feel soft, a consumer will not be inclined to use or buy it, and vice versa. A review by de Klerk and Lubbe (2004) explains, in depth, consumers' evaluations of apparel aesthetics and categorises perceptions into the following dimensions: sensory, emotional, cognitive and an interaction between the body and the apparel fabric in question. They explain how consumers' emotions have a vital role when buying apparel fabrics, as well as creating a product experience. However, they conclude that either unconscious or conscious, the role that emotions play in apparel selection and appreciation is still unknown.

Basic evaluation of fabrics is concerned with touch and feel, and is generally measured by trained or untrained panels within industry, and is more often than not concerned with the effect of adding chemicals to soften the surfaces i.e. fabric enhancer or conditioners.

2.7.2 Sound perception of fabrics

As mechanical investigation of fabric friction is expanding into the area of sound, it is imperative to understand the influence of sound on consumers' perceptions of fabrics. Literature is somewhat limited on basic perceptions and consumer thoughts on fabric sounds, as research has tended to focus on the physiological responses of participants. Physiological responses have been measured using EEG signals and monitored for changes in brain activity when participants are asked to interact with fabrics. Relationships and interactions between Zwicker's psychoacoustic parameters and physiological responses have been presented and found to correlate well (Cho *et al.* 2001b; Cho *et al.* 2005; Cho *et al.* 2006). Studies involving physiological responses to fabric sounds have been as a result of presenting participants with fabric sound which have been established using the MAFN, previously discussed in Section 2.3.2, and not in-situ fabric sounds, therefore all results should be taken with caution as the influences of real-time fabric sounds on EEG responses has not yet been observed.

Participant responses to changes in fabric sound with respect to sound pressure level (i.e. total noise), has been investigated and correlated with sensory responses (Cho & Cho 2007). It is known that an increase in 'loudness' of fabric sounds is the main Zwicker's parameter which is accountable for participant responses to fabric sounds, as opposed to sharpness, roughness or fluctuation strength, which are also measured. Cho and Cho (2007) presented 30 female participants with fabric sounds, captured using the MAFN, which were manipulated manually with three 'loudness' levels: 40, 50 and 60 dB. Participants were asked to rate the fabrics using a seven point Semantic Differential Scales (SDS) with the sensory attributes: hard vs. soft, quiet vs. loud, dull vs. sharp, obscure vs. clear, smooth vs. rough, low vs. high, unpleasant vs. unpleasant. The participant responses were correlated with Zwicker's psychoacoustic measurements of the same fabrics after having their SPL increased to each of the desired decibel levels. When fabrics sounds were at their lowest total noise, 40 dB, participants rated them as being more soft, quiet, clear, smooth and pleasant which would have been expected based on the relationship discussed throughout this thesis that the more rough a surface the more total noise emitted.

In similar methodology to the previously mentioned study by Cho and Cho (2007) with the use of the MAFN to capture fabric sounds, participants were also asked to feel the same fabric whilst rating the sensory attributes on the SDS of their opinions of both sound and touch/feel of fabrics. Here, sounds were not manipulated, however, were also not in real-time. Correlations were made between the participant responses to fabric sound and touch along with mechanical properties of the varying fabrics measured by the KES-FB (see Section 2.1.1.1 for more information), in addition to sound parameters, such as pressure of total sound, level range and frequency differences. Participant responses were explained with mechanical properties, and louder sounds were strongly correlated with increasing roughness perception.

2.7.3 Sound of consumed foods

A major area within the sensory perception of sound is concerned with the sound produced during consumption of food. Literature available can be divided into two sections encompassing all real-time sounds: those which are original and unchanged and those which have been altered, and it is this latter group which is of particular interest to this thesis.

Being able to quantify the sound of eating is very challenging, as most of the noise is generated within the mouth which is most often closed and therefore recording and measuring the resulting noise is not possible. To mimic eating researchers have used a form of textural analysis that then compresses the food in question (e.g. crisps, hazelnuts etc.) resulting in a measurement of the force required to break the product multiple times (Saklar *et al.* 1999). The mechanical properties measured by the textural analyser have then been related to sensory properties perceived by consumer panels. The relationship enables development of food products to be quicker and easier by reducing the number of sensory trials required to assess the products. Saklar *et al.* (1999) concluded that crispness and crunchiness of hazelnuts strongly correlated with the first fracture point measured by a compression device ($R^2 = -0.96$, $p < 0.001$).

Researchers recognised that as well as measuring the force required to fracture a food product, the sound that it emits when breaking is also of great importance. The method by which a food releases a sound on biting/eating is a direct product of the microscopic cell structure breaking down. Within dry foods the cell structures do not have contents, but it is the strength of the cell walls themselves when broken that causes vibrations, and within wet products, such as apples, it is the fluid within the cells, which create the sound (Duizer 2001).

In order to adequately and accurately research the effect of crispness of food products on sensory perception, using both acoustic and mechanical properties are more beneficial together than either used individually (Vickers 1987).

As suggested earlier, mechanical properties are extremely useful in determining predicted sensory perception and enable future product development. However, some researchers have expanded this further by questioning whether if acoustical properties of food products were manipulated whether consumers would have differing sensorial relationships with them. The first known research into real-time manipulation was by Jousmäki and Hari (1998) where they created an experimental method whereby participants listened directly to real-time sounds of their own skin which were both not manipulated and altered in dB level. Participants were asked to rate their perceptions of their skin in terms of roughness/moistness to smoothness/dryness. A three block design was created (a design which was then used in literature to assess several different product sounds e.g. toothbrushes (Zampini *et al.* 2003), crisps (Zampini & Spence 2004) and general food and drinks (Zampini & Spence 2010)) and is explained in Table 2.1.

Table 2.1 An example of the three block design created by Jousmäki and Hari to show results of participant responses when real-time sound of skin and other products are assessed and perceived. Table adapted from Jousmäki and Hari (1998).

	High frequency levels (dB)		
Attenuation (dB)	**-15**	**Normal**	**+15**
-40 **-20** **-0**		Average participant responses	

A significant effect of sound manipulation was observed: when participants heard an increased level of either the high frequency sounds and overall level (i.e. when the overall level was not attenuated), they perceived their skin to be both drier and smoother, and consequently the moistness and roughness of their skin was decreased. Jousmaki and Hari's research was replicated by Guest *et al.* (2002) by asking participants to rub their hands together and rate the roughness, confirmed the relationship between high frequencies and overall sound levels with perception of the attribute, and also reported that a larger number of participant gave better weighting to the significant results. Although these studies gave an insight into consumers' audiotactile responses to skin, the designed itself is flawed by the reasoning that a participant was asked to feel their own skin a minimum of nine times, with only sound being varied. It questioned why a participant would think their skin was more dry when only the sound was changed as opposed to, for example, an earlier test where the sound was quieter and they perceived it to be more moist, when they are quite obviously always feeling the same skin. This leads into thoughts that the participants may have been responding with answer that they believed the researcher wanted to have as opposed to being real perceptions i.e. demand characteristics.

Research into the audiotactile area was further enhanced by Charles Spence and his research group with many studies being carried out on different products and, unlike Jousmäki and Hari, participants were not privy to which samples were being tested by means of a screen, covered area or being handed individual products in the case of crisps and apples. The three block design was adopted; however, the decibel levels were slightly changed from +/- 15 dB to +/- 12 dB (see Table 2.2). In all cases, the products were always identical, and it was only the manipulation of the sound that was varied.

Table 2.2 An adaption of the three block design created by Jousmäki and Hari (1998) to show results of participant responses when real-time sound of skin and other products are assessed and perceived by Zampini and Spence (2003; 2004; 2010) and Guest et al. (2002).

	High frequency levels (dB)		
Attenuation (dB)	**-12**	**Normal**	**+12**
-40			
-20		Average participant responses	
-0			

As many variables were tested and multiple statistical analyses was carried out, in summary, the following results were observed from Zampini and Spence's research into perception of crisps (2004):

- A significant difference was observed between crispness ratings when overall sounds were not attenuated when compared to attenuation -20 dB and -40 dB (with significant difference being observed between the two attenuations also, as well as when compared to no attenuation). No attenuation was perceived as being the crispest, followed by -20 dB and -40 dB, respectively.
- When high frequencies were amplified, crisps were again perceived as being crisper respectively: +12 dB was crisper than no amplification and -12 dB attenuation (and significant differences were also observed between all three variables).
- The exact opposite effect was observed when staleness rating was analysed: with decreases in both overall sound and high frequency sounds, crisps were perceived to be staler, with significant differences also being observed between all variables.

Zampini and Spence went on to investigate the influence of changing real-time sounds of toothbrushes using the same design as in Table 2.2. They asked participants to rate their perceptions of pleasantness (unpleasant to pleasant) and it was observed that the most pleasant sounds were as a result of -40 dB attenuation and when high frequencies were attenuated by -12 dB. The same relationship was observed when participants were asked to rate smoothness to roughness, whereby, with an increase in high frequencies toothbrushes were perceived to be rougher than both no change in sound and -12 dB attenuation, respectively.

Both studies discussed previously claimed consumer ignorance to the manipulation of the audio feedback. However, it is difficult to relate this research to that of touch and sound perceptions due to the complicated nature of perception of eating sounds by the brain. Eating noises are a combination of factors such as the sounds heard when the mouth is open i.e. the first bite (as was assessed in Zampini and Spence (2004)) through sound waves into the ear. When the mouth is closed and food is being consumed by the back teeth air-bone conduction is responsible for the perception of sound. As food is being consumed the action in the back teeth produces vibrations which then send signals to the brain. This creates the challenges previously discussed in assessing, objectively, product sounds within the mouth.

In order to assess the audiotactile response in terms of touch a part of the three block design was employed by Guest *et al*. (2002) in which participants were asked to choose, out of two sandpaper samples which one was rough and which one was smooth, whilst no sound alterations were made in either the high frequencies or overall sound level. The interest in this research was the reaction times to assess samples in terms of rough and smooth and the errors inflicted upon each choice. Although, Guest *et al.* (2002) moved towards using the three block design to assess touch, an experiment was not carried out on investigating the effect of the real-time sounds whilst participants were handling any product, and therefore knowledge is limited within this area.

On reflection of the research carried out using Jousmäki and Hari's (1998) three block design, problems arise in terms of sound levels used to alter real-time sounds. Although, proceeding research lowered the attenuation and amplification levels from 15 dB to 12 dB, when considering the overall sound level, all literature attenuates by -40 dB regardless of the product used to achieve the sounds. It would be more prudent to have related the change in sounds with regards to the product i.e. a toothbrush within the mouth would more than likely produce a louder sound than a crisp. As well as taking into account the decibel levels of the real-time unaltered sounds for food products, attenuating the sound produced by touching surfaces by -40 dB would potentially reduce the sound to such a level that it would be difficult to hear. To give an insight into general sound levels, an environment within a library is recorded at a 40 dB level, with normal speech at 60 dB; therefore in order to attenuate any sound by -40 dB the original sound must be at least the sound recorded within a library for example. Taking these extreme approaches in attenuating and amplifying real-time sounds may well be a contributing factor to the sheer number of significant relationships previously discussed; it would be inevitable that participants would recognise a difference in samples as it would be hard to disregard the change in sounds. Again, demand characteristics may mean that participants either unconsciously, or consciously, change their behaviour (ratings) according to their interpretation of the study objectives.

2.8 Modification of surfaces using novel systems

It is widely known that the use of fabric conditioners when washing and preparing garments is to result in a softer, often cleaner, fragrant material and is commonly measured by consumer and sensory panels. In terms of mechanical properties, fabric conditioners are manufactured to reduce the friction of fabric surfaces by lubricating when wet and leaving a smoother surface after drying with a reduction in the number of hairy fibres. Using the knowledge discussed in Section 2.8, that a surface can be filled with specifically engineered hydrocolloid particulate systems to create a smoother surface which results in a lower friction coefficient, a major consideration for this thesis is if this methodology can be replicated for fabric friction. Hydrocolloids fluid gels, explained below, can be used to create a control system for fabric conditioners in order to understand the effect of particulates within a system on fabrics.

2.8.1 Hydrocolloids

Hydrocolloids that are generally used in food research are naturally occurring polysaccharides that originate from natural sources such as seaweeds, trees and plants and animals. They are hygroscopic in nature and due to their relatively high molecular weights bind well to water.

The hydrocolloids used within this research were kappa carrageenan (κC) and agar as they have been previously shown to reduce the friction levels produced within food research (Malone *et al.* 2003; Gabriele 2011; Garrec 2013).

2.8.1.1 Kappa Carrageenan

Carrageenan is a family of polysaccharides derived from red edible seaweed and are used within the food industry as gelling agents and thickeners. κC (an $(A–B)_n$ copolymer of O–b–D–galactopyranosyl–4–sulfate–(1–4)–O–3,6–anhydro–a–D–glactopyranosyl–(1–3) (Gabriele *et al.* 2009)) is a variety of carrageenan and is distinguishable by its one sulphate group on each disaccharide, as opposed to other forms of the polysaccharide: iota and lambda (see for the chemical structure of κC).

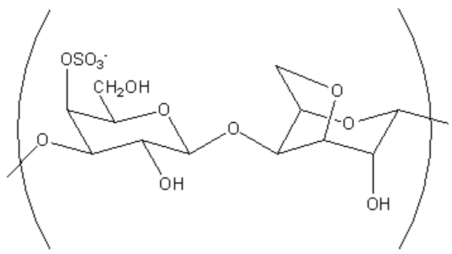


Figure 2.20 One repeating unit of kappa carrageenan. Image adapted from Garrec (2013).

The process of gelling for κC is proposed as a domain model by Morris *et al.* (1980) and can be seen in Figure 2.21. It is the addition of salts, namely potassium for this thesis, which forms stable gels where the double helices line up against one another, aggregate and form densely packed, thermodynamically stable gels.

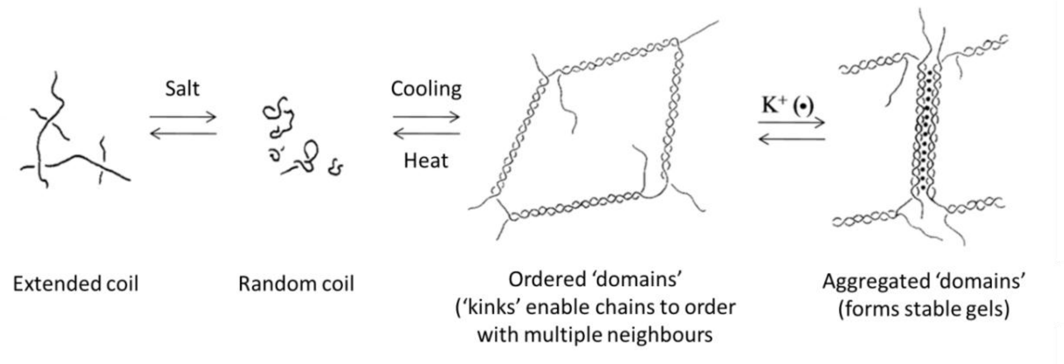


Figure 2.21 The gelation process of kC in the presence of K^+. Image adapted from Garrec (2013) of the domain model produced by Morris *et al.* (1980).

2.8.1.2 Agar

Agar is a mixture of two components: agarose and agaropectin and is derived from red algae. It is used commonly within the food industry due to it occurring naturally and therefore is edible in its agar form. As well as being natural its gelling properties are most valuable in food products such as semi-solids and desserts. The biopolymer, agarose, is responsible for the gelation of agar with the addition of heat via a helical conformation between the neutrally charged polysaccharides (formed of the basic disaccharide agarobiose: D-Galactose and 3, 6 Anhydro-L-galactose (see Figure 2.22)).

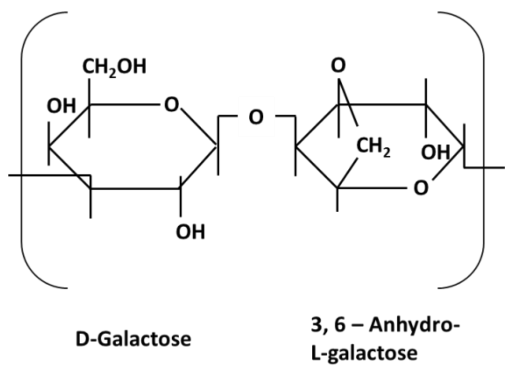


Figure 2.22 Schematic of the chemical structure of agarobiose: depicting the repeating unit including D-Galactose and 3, 6 Anhydro-L-galactose. Adapted from Gabriele (2011).

Agar gels in a similar manner to kC, where extended coils exist in solution and on heating, to approximately 40°C, it forms a first level of gelling where the extended coils join together to form double helices; however, it is on further heating ~70°C, where these join together producing a more kinetically and thermodynamically stable gel.

2.8.1.3 Fluid gel production

Both kC and agar will gel on heating, and with the presence of salt for kC, and therefore when left to cool without agitation, shear or processing will form quiescent gels: a strong network of helical aggregation and will take on the form of which ever vessel it is contained in. Quiescent gels are able to hold their shape and weight under gravity and, depending on concentration of both polysaccharide and salts, are able to withstand varying degrees of compression and mechanical testing (Garrec 2013). If, however, during cooling, the hydrocolloid solutions are processed by means of shear, fluid gels are formed which consist of a continuous medium that has not gelled, which carries in it smaller gelled particles. These particles are often suspended within the non-gelled medium (Cassin *et al.* 2000). In terms of basis appearance, quiescent gels are solid, whereas, the fluid gels are designed to flow, preferably under minimal shear/stress; however, it is dependent on concentration and a range of processing parameters.

Fluid gels can be processed in either small, potentially more controlled quantities, and in large batches for use in scale up or industry. A rheometer can be used to produce small quantities of fluid gel where by the hydrocolloid solution is placed between two surfaces (which in the case of kC and agar are heated initially to above their onset of gelling temperatures, discussed below) and shear is applied as uniformly as possible; different geometries will produce varying shears and stresses at different areas, and the surfaces are cooled to allow for the gelation process to occur. Two main geometries can be used to produce fluids; parallel plates and cylindrical vessels, where both shear the fluid gels in an approximately 1 mm gap at defined speeds. Although, the use of a rheometer is capable of producing evenly sheared fluid gels with accurate cooling rates, shear speeds and stresses, the amount that is produced is often not enough for further testing (e.g. tribology).

Processing fluid gels on a large scale has been achieved previously by Garrec (2013) and Gabriele (2011) with the use of a ‘pin-stirrer’, encompassing a vessel volume of 150 mL (see Section 3.3.6 for methodology), which is also a continuous process, therefore depending on flow rate, can result in quantities in the order of litres per hour.

For both systems: rheometer and pin-stirrer, the processing parameters can be related to each other as the rotational speed of the pin-stirrer has been measured to be running at approximately 200 s^{-1} when run on the highest level: 1500 rpm, and cooling rate is dependent on the vessel size, temperature change from pre to post processing and flow rate i.e. how fast the hydrocolloid solution is being passed through the system. Therefore, comparisons between large and small scale production of fluid gels is possible, in terms of material properties i.e. viscosity, yield stresses, elastic and plastic nature, and fluid/solid like properties etc.

2.8.1.3.1 Understanding processing parameters on the mechanical properties of fluid gels

Thorough investigations and understanding have been presented within literature on the processing, concentration and influence of addition of salt of fluid gels (Norton *et al.* 1999; Gabriele *et al.* 2009; 2010; Gabriele 2011; Garrec *et al.* 2013; Garrec & Norton 2013; Mills *et al.* 2013).

The temperature of the onset of gelation of all hydrocolloids must be known before processing in order to ensure that gelling does not happen prematurely before shear can be applied, failure to do this will result in a solution of non-gelled particles and quiescently cooled particles giving rise to a 'lumpy solution' (Garrec & Norton 2012d). Garrec *et al.* (2012d) presented the influence of temperature change between the inlet and outlet temperatures on the production of fluid gels within a pin-stirred unit. The outlet temperatures (named T_{exit}) chosen were between 40 °C and 5 °C with intervals of: 35-40 °C; 25-35 °C; 20-25 °C and less than 20 °C. It was concluded that when T_{exit} = 5 °C, gelation takes place under shear which forms a fluid gel; however, when T_{exit} = 40 °C, gelling takes place after exiting the pin-stirrer and on collection, therefore producing a quiescently cooled gel. In summary, Garrec *et al.* (2012d) made it known that in order that full gelation is achieved under shear, the inlet and outlet temperatures must be above and below the gelation onset temperature, respectively.

As well as effect of temperature on fluid gel production Garrec *et al*. (2012d) also established the influence of salt concentration, where it was found that the introduction of lower concentrations (<0.1 % w/v) resembled quiescent gels on storage after production due to bridging within the network, and 0.3% w/v KCl was considered to be optimum as it was also observed to result in a fluid gel particle size of ~1 μm which was effective in reducing the friction coefficients of food products (discussed within Section 2.8).

As discussed previously, the production of fluid gels can be altered on both the rheometer and pin-stirrer unit via the change in shear (s^{-1}) and rotational speeds (rpm), respectively. Gabriele *et al.* (2010) investigated the influence of varying the rotational speeds (1450, 750 and 350 rpm) on the particle size of a fluid gel constructed of the hydrocolloid agar. The authors reported the average particle sizes (measured using a High Performance Particle Sizer (Mastersizer, Malvern Instruments, UK)) 106.1 μm, 93.1 μm and 83.1 μm for the rotational speeds 1450, 750 and 350 rpm, respectively. Therefore, particle size was shown to be dependent on rotational speeds, which was also in agreement with other fluid gels created by Norton *et al.* (1999).

The hydrocolloid fluid gels discussed within this section were created as fat replacers within semi-solid food products and therefore, although the chemical and mechanical properties of the fluid and quiescent gels were acceptable, the influence on friction coefficients were also investigated in terms of relation to mouthfeel with the addition of lubricants. The following section described how fluid gel production alters the friction coefficients observed and how studies have correlated values to sensory perception of fluids within the mouth.

2.8.2 Tribology of fluid gels

The friction coefficients produced by fluid gels investigated within literature were observed to produce a typical Stribeck curve, where boundary and mixed lubrication regimes were entered, however, hydrodynamic lubrication was not often observed (Norton *et al.* 1999; Malone *et al.* 2003; Gabriele *et al.* 2010; Garrec & Norton 2012b; c; a; 2013; Mills *et al.* 2013).

The two surfaces within tribology, (as previously stated in order to achieve friction: two surfaces sliding along one another) to replicate mouthfeel, represent the human tongue and hard-palate, whereby food and viscous liquids are squeezed and sheared through the two surfaces. It has been shown that the receptors within the mouth relay information to the brain based on the forces needed to break down the foods, and relate to sensory attributes such as ‘smoothness’ and ‘thickness’ (Chen & Stokes 2012). As tribology is related to the lubrication of thin-films it is the breakdown of food by mastication which results in this thin-film and can be seen to reduce friction within the mouth between the tongue and hard-palate. Studies have also shown how tribology investigations have been correlated with in-mouth sensory attributes (Malone *et al.* 2003).

Recent studies have been carried out to relate the fat reduction in semi-solid foods, with the use of hydrocolloid particulate systems and changes in processing parameters, to alterations in friction, as measured using tribology. As has previously been discussed, the change in shear speed in the production of fluid gels has been shown to reduce the particle size (Gabriele *et al.* 2010), and when those fluid gels were used within tribology a reduction in friction was observed with a reduction in particle size (see Figure 2.23). The authors related the reduction to the increased ability of smaller particles to be entrained between the two contacting surfaces, therefore increasing lubrication. With this understanding it is beneficial to engineer an optimum particle size in order to achieve the ideal reduction in lubrication.

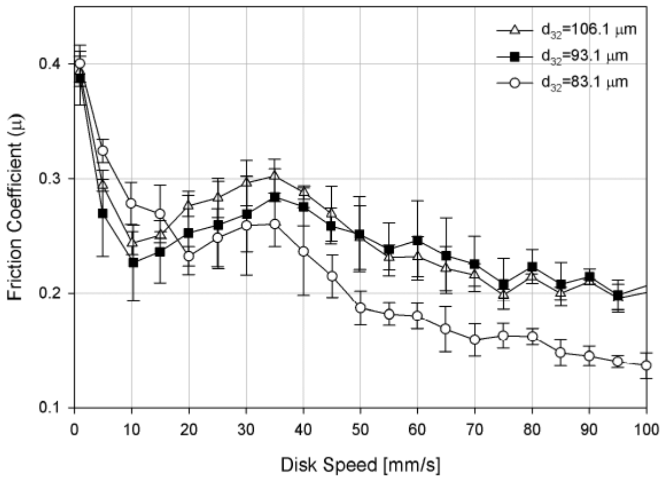


Figure 2.23 The effect of particle size on lubrication of 2% w/v agar fluid gel. Graph adapted from Gabriele *et al.* (2010). Symbols for rotational speed: 1450 (Δ), 750 (□) and 350 rpm (○).

The typical Stribeck behaviour observed within Figure 2.23 is different to that described within Section 2.3.1, where a ‘bump’ is present within the mixed regime; an increase in friction coefficient then leads to a decrease after a disc speed ~ 35 mms^{-1}. This ‘bump’ was attributed to the exclusion of particles with a larger size (i.e. the particle size distribution was a combination of larger and smaller particles, averaging the particle size explained previously), leading to a further entrainment of smaller particles therefore reducing friction further (Gabriele 2011).

Garrec (2013) executed comprehensive investigations into the influence of fluid gels on tribology, and observed a differing Stribeck behaviour to Gabriele’s previously discussed, whereby a more apparent boundary and mixed regime was present (see Figure 2.24 for an example).

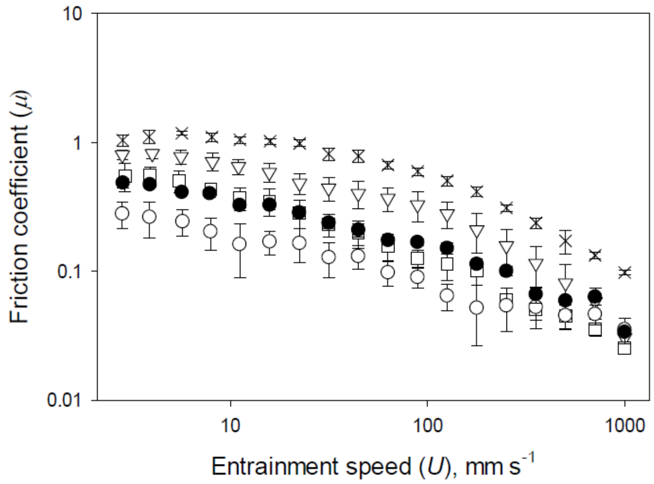


Figure 2.24 A typical Stribeck curve depicting the influence of volume fraction of kappa carrageenan fluid gels have on friction coefficients produced. (For the purpose of this thesis, the actual volume fractions are not required or disclosed). Image adapted from Garrec (2013).

Using the processing parameters discussed previously, Garrec *et al.* (2013) designed a kappa carrageenan fluid gel with a particle size of ~ 1 μm and reported that, a reduction in surface roughness of the elastomer disc used was achieved. Using interferometry, the authors visualised the surfaces roughness of the disc and reported an average of 2 μm in height the of the asperities, and stated that the inclusion of the fluid gel particles into said asperities resulted in a reduction of friction by means of creating a new semi-permanent, smoother surface.

Using the understanding gained within the literature of food hydrocolloids, it could be possible to replicate this reduction in surface roughness of other materials (e.g. apparel and model fabrics).

3 Materials, Methods and Method Development

3.1 Introduction

Presented within this Chapter are the materials and standardised and original methods used to capture and analyse results seen with Chapters 4, 5, 6 and 7, with particular focus on the method development of the sound resistant rig (SRR): essential to establish frictional sound, as previous to this work Yi and Cho developed a MAFN to capture frictional sound, however, efforts have been made to further develop this method, with the construction and calibration of the SRR, by creating a consistent and reproducible frictional noise as well as a easily accessible in-house method. Method development of the analysis of frictional sound, with respect to total noise, presentation of spectra, frequency analysis, is also presented within this Chapter. Finally, development of sensory protocols, sound software and analysis is discussed. All method development was essential to final working methods used in order to achieve results shown in Chapters 4, 5, 6 and 7.

3.2 Materials

3.2.1 Apparel fabrics

Three apparel fabrics were chosen; denim, cotton and silk. Both ‘denim’ and ‘cotton’ are constructed from 100% cotton fibres, woven into twill and plain weave respectively. The silk fabric is plainly woven from 100% silk. All fabric types were sourced from Fancy Silk Store, Birmingham, UK.

Microstructural images can be seen in Figure 3.1 (see Section 3.3.3.2 for details on microscopy technique) in two resolutions; providing an overall understanding of the surface structure of each fabric type (right) and a magnified image of individual fibres/threads (left). Specific microstructural measurements of the construction of each fabric type are presented within Table 3.1.

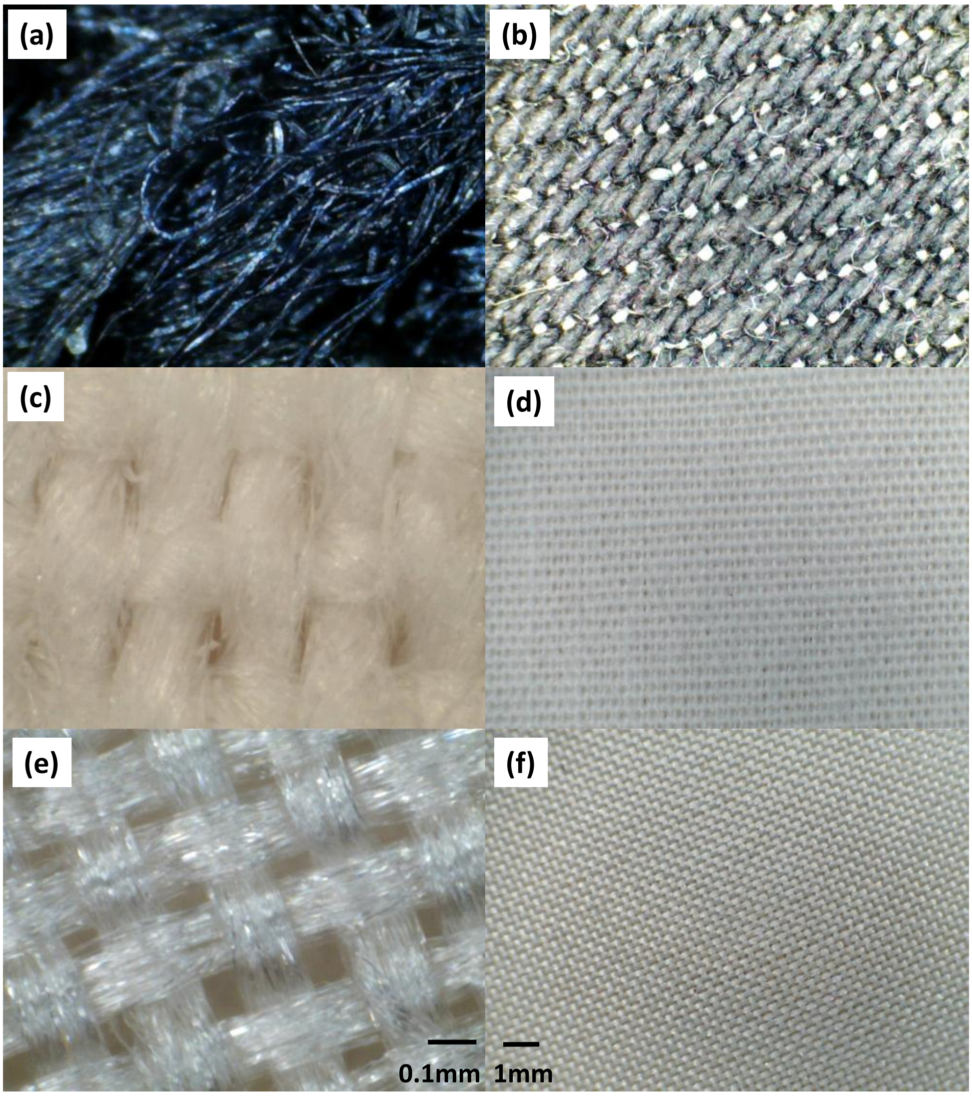


Figure 3.1 Microscope images of wardrobe fabrics measured using Veho portable microscope in two focal lengths; high resolution; (a) denim, (c) cotton, (e) silk and low resolution (b) denim, (d) cotton and (f) silk. Characteristics (including dimensions) of the apparel fabrics can be seen in Table 3.1.

3.2.2 Model fabrics

In order to have a control system for this research, model fabrics were sourced (G.BOPP, UK). The model fabrics are more commonly used for screen printing and were made from polyester and had a uniform, single-fibre structure which provided understanding of the influence of specific microstructures (e.g. weave dimensions, thread diameter etc.) on sound characteristics i.e. total noise and frequencies produced (Figure 3.3). Table 3.1 depicts the characteristics and structure of the polyester model fabrics in terms of aperture size (free space in between each weave) and thread diameter (the widest part of the thread (it is important to note that the thread diameter varies slightly due to distortion at crossings with other threads therefore averages were taken across a number of areas for accuracy); schematics of these can be seen in Figure 3.2.

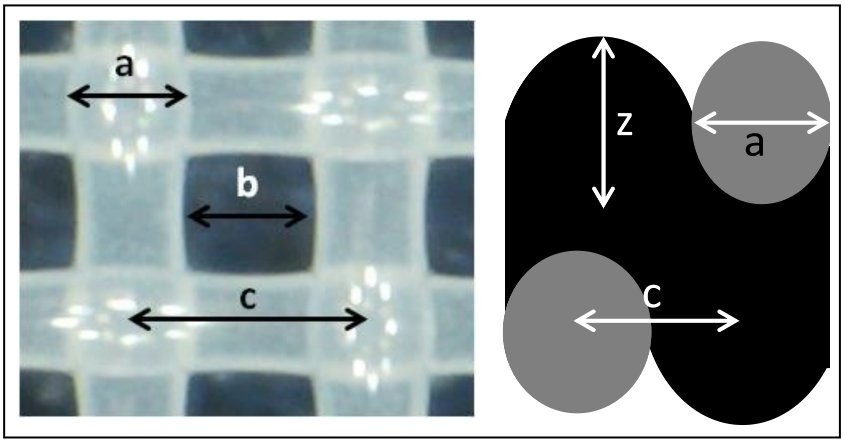


Figure 3.2 Left: Light microscope image of a polyester model mesh (imaged with Veho Microscope) and right: A schematic of fabric weave (both model and apparel) with white arrow showing the z direction (height) (referred to in Section 3.3.3). Both left and right indicating (a) thread diameter (mm), (b) aperture size (mm) and, (c) space between adjacent threads (mm).

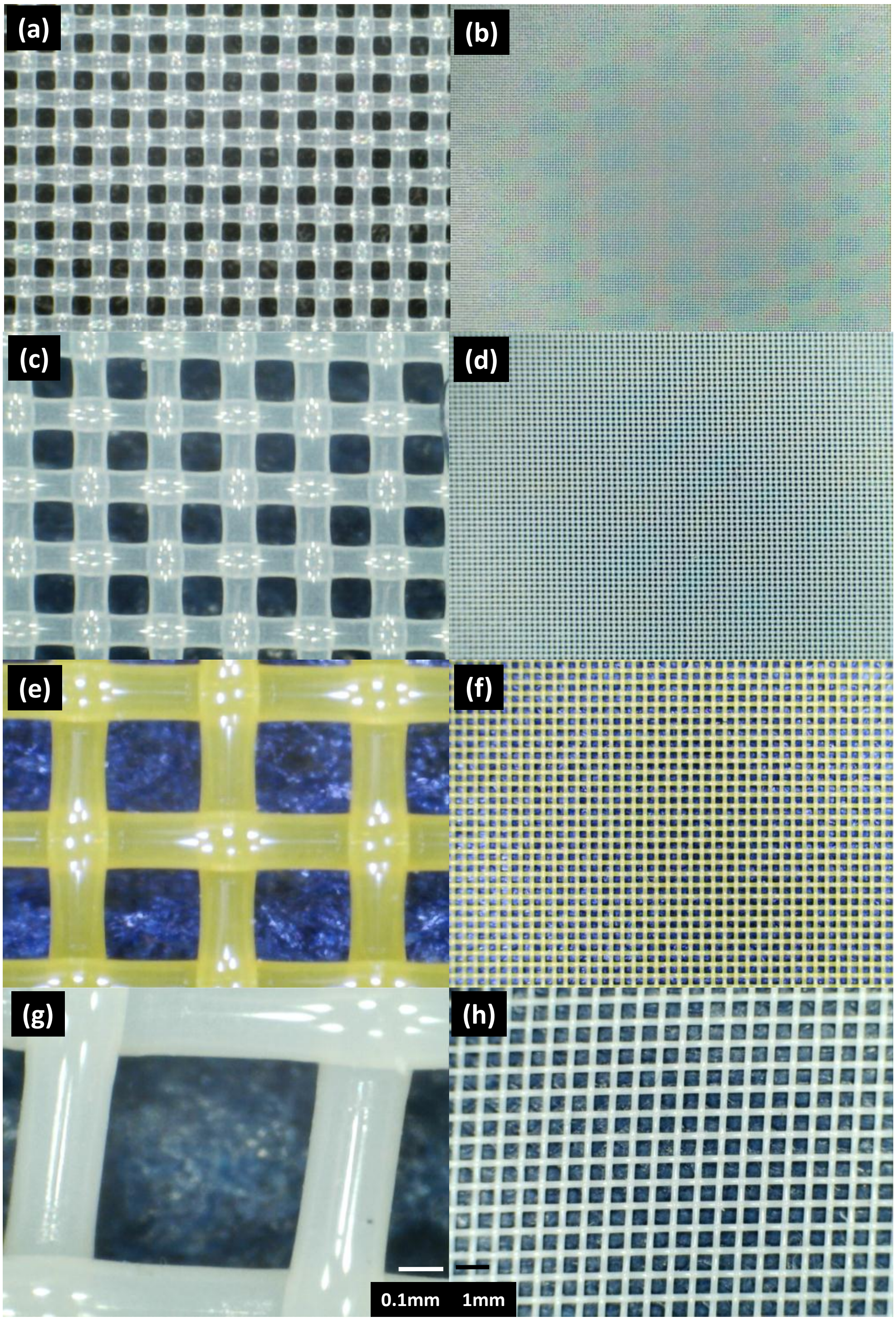


Figure 3.3 Microscope images recorded using Veho Portable Micrscope of Model Polyester Fabrics (a,b) Model Fabric A, (c,d) Model Fabric B, (e,f) Model Fabric C and (g,h) Model Fabric D. Focal Length '20' (left) and '400' (right). Characteristics (including dimensions) of the model fabrics can be seen in Table 3.1.

Table 3.1 Characteristics of fabrics, both apparel and model, used. Measured using light microscopy and software analysis using programme Image J.

	Material	Weave	Aperture Size (mm)	Thread Diameter (mm)	Thickness (mm)	Areal Density (kg/m^2)
Denim	Cotton	Twill	-	0.338	1.048	0.432
Cotton	Cotton	Plain	0.144x0.016	0.161	0.270	0.131
Silk	Silk	Plain	0.080x0.032	0.149	0.060	0.035
Model A	Polyester	Plain	0.042x0.042	0.038	0.055	0.034
Model B	Polyester	Plain	0.087x0.087	0.074	0.101	0.058
Model C	Polyester	Plain	0.211x0.211	0.120	0.212	0.101
Model D	Polyester	Plain	0.465x0.465	0.200	0.353	0.141

3.2.3 Apparel and model fabrics for tribometer surfaces

The same three apparel fabrics seen within Chapter 4 were used as disc surfaces: denim, cotton and silk (Fancy Silk Store, UK). The same model fabrics (G.BOPP, UK): model A and B, were used as the control systems for the same purpose as assessing the acoustics emitted which results can be seen in Chapter 4; to understand the effect of multi-fibre vs. single-fibre structures on the friction levels produced.

3.2.4 Hydrocolloids

Kappa carrageenan (κC) (Sigma Aldrich, UK) and Agar (Sigma Aldrich, UK) were used to create FGs under shear as supplied and were not further purified or altered before FG production.

3.2.5 Salts

KCl (potassium chloride, Sigma Aldrich, UK) was used in order to complete the process of gelation of κC.

3.3 Methods and Method Development

3.3.1 Sound resistant rig

In order to be able to only capture fabric friction noise, background noises such as laboratory users, equipment and in particular the motor used to pull fabric samples needed to be excluded and therefore a Sound Resistant Rig (SRR) was built to enable this. The following section describes the processes used to construct and validate the rigs ability to eliminate all possible noise.

3.3.1.1 Construction

The SRR was constructed using two different sound insulating materials sourced from Sound Reducing Systems, UK; a rigid outer shell, 'Maxiboard', (light grey) to provide stability coupled with a steel frame custom made to fit and two layers of sound absorbing foam, 'Acoustilay', (dark grey) which lined the outer casing. Initial experiments were carried out to test one layer of insulating foam; however, it was shown that a second layer eliminated an optimum amount background noise on testing. The final SRR can be seen in Figure 3.4 with both doors open (a) and doors closed (b).

Figure 3.4: Sound resistant rig with (a) doors open and (b) doors closed.

3.3.1.2 Calibration

As the SRR was developed in house, calibration tests on its ability to exclude background noise were essential. As can be seen with Figure 3.4, the SRR is extremely accessible with hinged doors which then were securely fastened when needed, and therefore provided an effective seal against the outside areas. A microphone (Marantz, UK) was chosen for all experiments (see 3.3.2.7 for calibration and further information), and therefore was used to aid calibration of the SRR. The microphone was placed within the centre of the SRR to accurately record all noise produced. The microphone recorded background noise when the doors were both open and closed with the sled drive system (SDS) (a common laboratory peristaltic pump (Watson and Marlow, UK)) (used to pull the fabric to achieve fabric noise; see Section 3.3.2.3) running. The SDS has speed settings from 1 to 100 which enabled it to run at faster speeds and in consequence produced a louder sound as the level increased; therefore, four interval sound recordings were made based on a method seen below:

1. The microphone was turned on and placed inside the rig with the doors wide open;
2. The SDS was turned on at the lowest level (1) and left to run for 15 seconds;
3. The doors were closed on the rig to exclude the sound of the SDS for 15 seconds;
4. Doors were opened again for a further 15 seconds, after which, the SDS was turned up to the next level and process repeated;
5. The levels chosen were 1, 25, 50, 75 and 100 (N.B. these are markers and not validated values);
6. The sound recordings were cut and edited into separate sections of background noise and SDS noise for comparisons using software (see Section 3.3.2.2);
7. Specific frequency points were selected and the corresponding amplitudes were measured using software. This enabled an average to be taken from three repeats and error bars to be calculated, which can be seen in Figure 3.5.

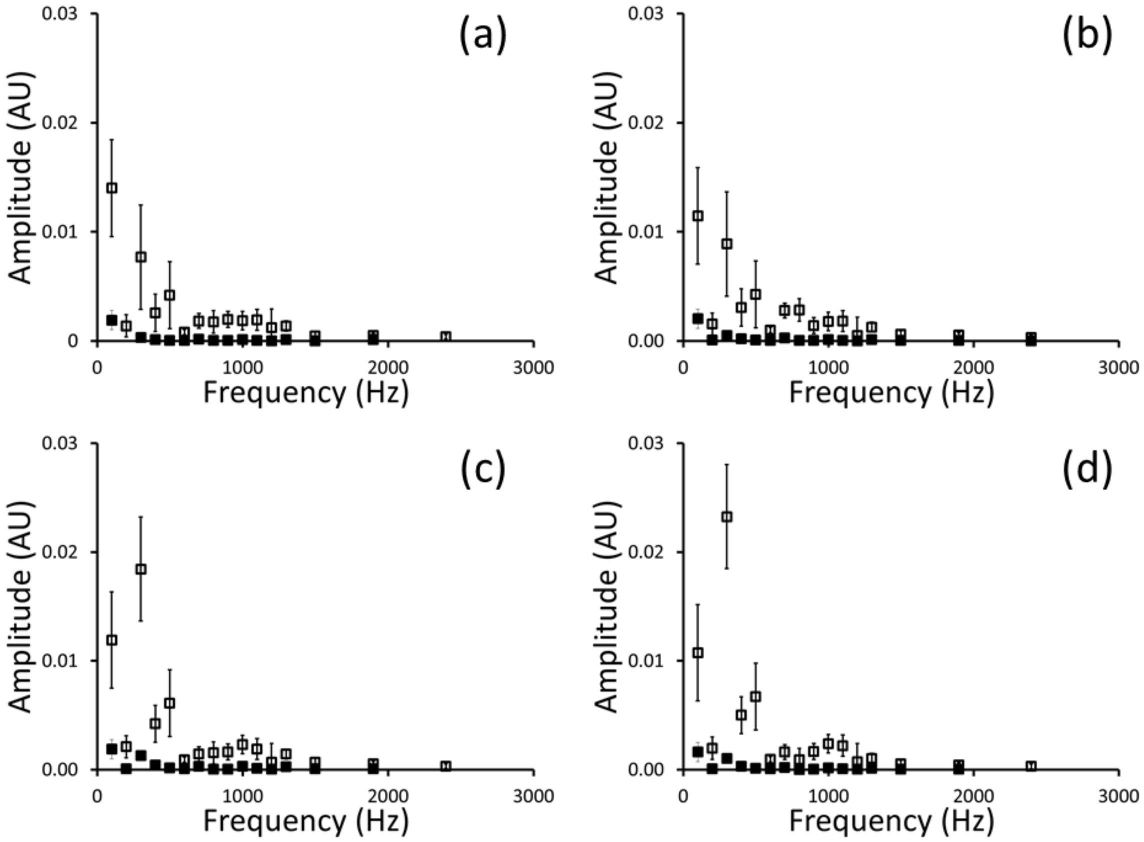


Figure 3.5 Amplitude vs. Frequency graphs depicting the sound insulating behaviour of the SRR by eliminating the background noise, including SDS at four intervals (a) 1, (b) 25, (c) 50 and (d) 100 along the speed capability of the SDS. Open symbols represent the sound recorded by the Marantz microphone when the doors of the SRR were open and the closed symbols when the doors are closed.

Figure 3.5 demonstrates the ability of the SRR to eliminate a high proportion of the background noise produced from the SDS; however, it was not possible to omit all frequencies with the sound dampening material chosen; when looking at the lowest frequencies (below 500 Hz), within Figure 3.5, there are two reoccurring peaks that produce a larger level of amplitude than higher frequencies. Figure 3.6 shows the two specific frequency peaks apparent (100 Hz and 312 Hz). It is unclear why these particular frequencies are present, however, they may be harmonics of the frequency at which mains electricity runs at (50 Hz). Due to the nature of the process chosen to edit the frictional noise, the background noise was unable to be taken away from each fabric sound, and therefore is consistently presented throughout results presented in Chapter 4. Doing this ensures that all levels of total noise and frequency analysis were occurrences of tested fabrics and not of the background noise.

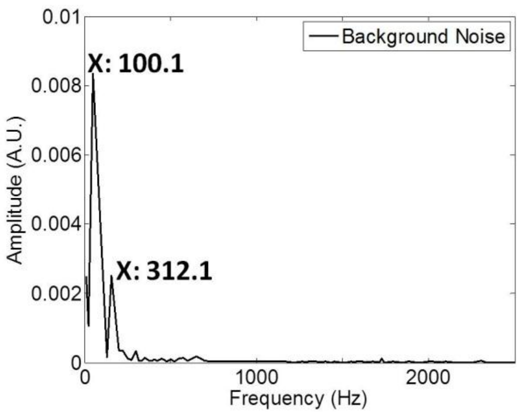


Figure 3.6 A Frequency vs. Amplitude sound spectrum of the background noise produced by the SDS and laboratory noise as measured from within the closed SRR.

3.3.2 Frictional sound capture

In order to successfully capture all frictional sound produced by both apparel and model fabrics, an experimental method was developed including, 1) software (sound editing method) and 2) hardware (a SDS, wires to pull the fabrics, fabric orientation (i.e. warp or weft)). A schematic of the experimental setup can be seen in Figure 3.7 and in order to show further understanding of each component, methods to optimise these will be discussed within this section.

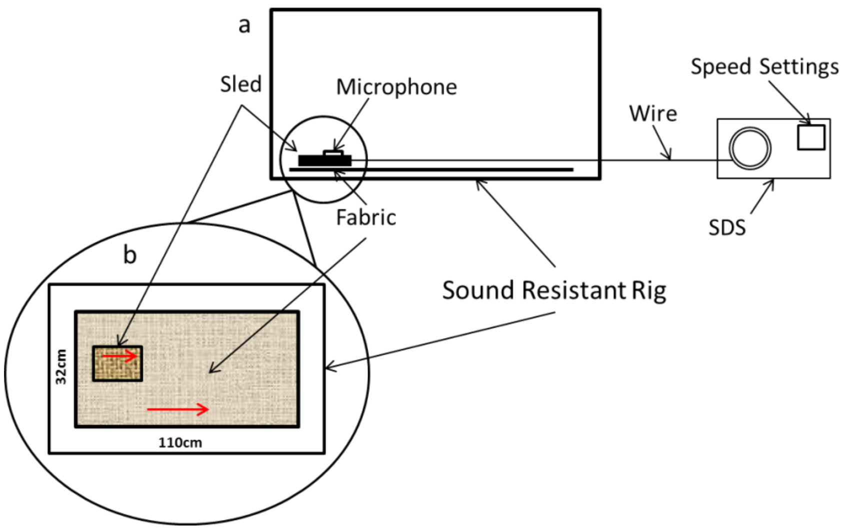


Figure 3.7 Schematic of the experimental setup for sound capture using the Sound Resistant Rig (SRR), showing a side view of the rig (a), and bird's eye view of the base fabric and the sled (b). During the experiment the sled (covered with fabric) is pulled by the sled driving system (SDS) along the base fabric, whilst the microphone captures the sound emitted. Red arrows depict the orientation (i.e. warp) of fabric sample; the schematic shows same orientation for both sled and base. The dimensions of SRR are H:620xW:1180xL:570mm. Schematic not to scale.

3.3.2.1 Fabric holding device

In order to produce frictional noise from an experimental fabric sample, it was established that both frictional surfaces must be the same type of fabric and the top surface is in constant contact with the base fabric surface. A Thwing Albert Sled (TAS) (usually used within the Coefficient of Friction Tester, Thwing Albert, US), presented in Figure 3.8, was donated by the sponsor Proctor and Gamble (UK) Ltd. as a standardised method to affix fabrics securely with optimum tension. The TAS dimensions are 62x64 mm and the microphone was attached to the front of the sled in order to capture all sounds emitted (see Figure 3.8).

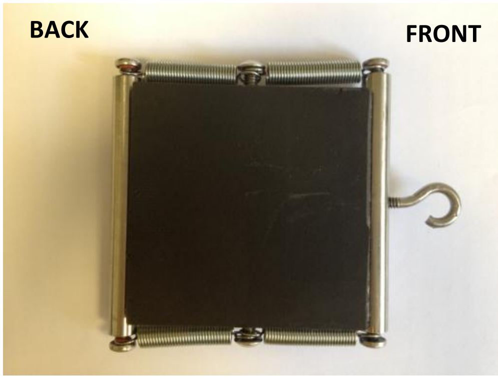


Figure 3.8 Fabric holding device (Thwing Albert Sled) designed to affix fabric samples securely for sound of friction experimental design (supplied by P&G).

3.3.2.2 Acoustic Analysis

After recording the frictional noise, the 2nd stage of sound analysis of frictional noise from all fabric samples was editing; Audacity (UK) was chosen as the software to carry this out. An example of the sound in a visual manner can be seen in Figure 3.9, showing the typical areas of sound produced. Firstly, a large area of ‘noise’ (blue lines) was produced when the doors of the SRR were opened, followed by the general background noise leading to the SDS being turned on; creating again an increase in noise but very minimally, the noise produced when the TAS was engaged with the fabric base sample and finally the doors were closed. Methodological limitations were seen initially with regards to what is known as ‘stick-slip’: where the top surface fabric gets stuck on the bottom sample causing an increase in tension along the SDS which then caused an increase in power to ensure that the TAS continues to move at the desired speed and which interrupts the continuous motion. This causes the TAS to 'jump' creating a break in frictional noise, as is demonstrated in Figure 3.10. It was essential to eliminate stick-slip as it would not be representative of the fabrics surface characteristics.

The visual nature of Audacity enables the fabric noise to be easily separated from all additional, redundant background noise and cut away, saved as a separate WAV files and then Fast Fourier Transformed in MATLAB.

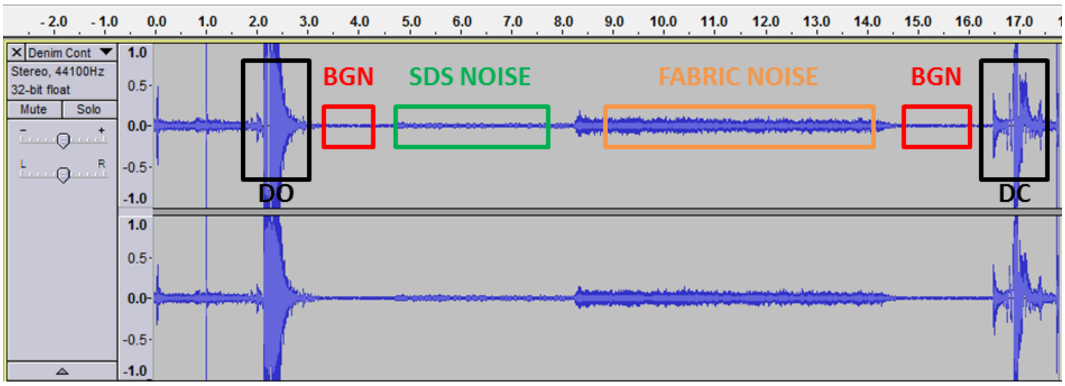


Figure 3.9 A visual example of all stages of noise produced from experimental methodology seen from left to right; doors of the SRR closing, background noise from laboratory, SDS noise, fabric noise, background noise and doors opening of the SRR.

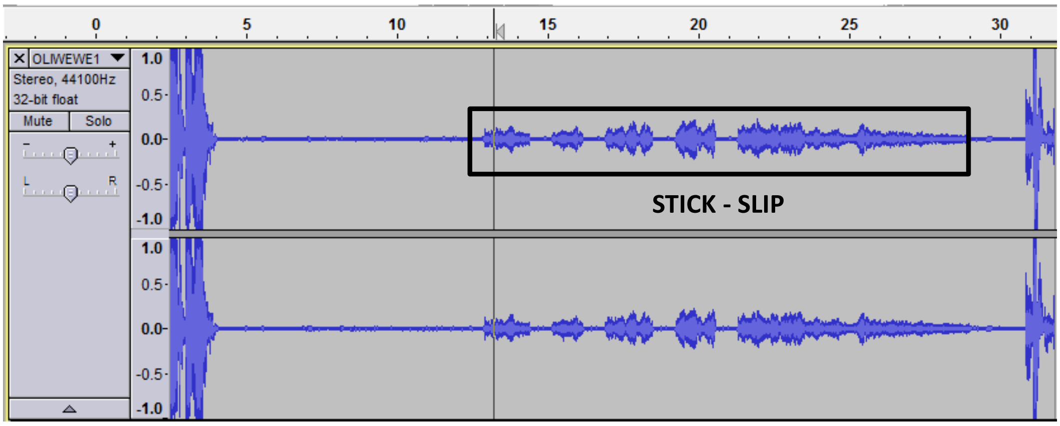


Figure 3.10 A visual example of stick slip for a fabric sample, larger noises are frictional noise and spaces are 'stick' turning into 'slip'.

3.3.2.3 Speed drive system (SDS)

As has previously been described within Section 3.3.1.2, the SDS was used to pull the TAS, which held each fabric sample, by means of a nylon wire of varying weights (see Section 3.3.2.4 for further information). The wire was thread through the outer casing of the SRR via a hole designed to be no larger than the wire diameter itself and was attached inside the SRR to the TAS and around the SDS. The wire was wound around the SDS, when in motion, until a marker was seen exiting the SRR to indicate when the sled was approaching the inner edge of the SRR (ensuring that the system was not broken by the increased tension and power of the SDS when it reached its limit within the SRR) and the SDS was turned off. Figure 3.11 (left) shows the SDS components, and the dial used to control the speed at which it ran. A range of appropriate speeds were chosen to pull along the TAS in order to investigate the effect of speed on the frictional noise produced and ultimately the optimum speed to run at when taking into account stick slip and operator requirements; e.g. if the SDS ran too quickly not only would the wire wind too fast for the operator to stop in time it would not produce a large enough amount of frictional sound to be FTT'd.

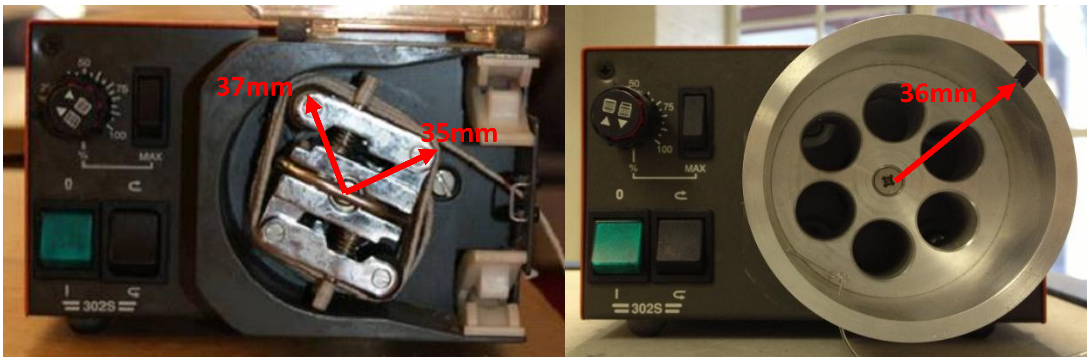


Figure 3.11 A photo of the SDS (left) the original winding mechanism and (right) modified showing different speed selections and radius measurements for calculating angular velocity

The nature of a SDS is to push through liquid under pressure and in order to achieve this, the part which moves the liquid has a shape similar to a diamond enabling a pulling and pushing motion (Figure 3.11 (left)). For this more typical purpose there are two different 'radii' to the winding mechanism (37 mm and 35 mm). However, to be able to pull the wire/TAS accurately (and also eliminating further stick-slip) a circular component was required. The original SDS was modified to create a circular surface (radius of 36 mm) which enabled more uniformed friction and more accurate speed calculations (seen in the right of Figure 3.11).

3.3.2.3.1 SDS speeds

The SDS speeds were calculated using revolutions per second to measure the distance travelled over time by the modified mechanism of the SDS, where,

$$\text{speed (mm}^{-\text{s}}) = \frac{\text{distance (mm)}}{\text{time (s)}}$$

Eq. 3.1

Using initial data from Table 3.2 the time taken for 1 revolution of the SDS to occur was entered in as time (s) and the distance was the circumference of the SDS wheel (226 mm - calculated using the radius of the SDS's winding mechanism).

Table 3.2 Speeds 1-3 of the SDS as calculated using the circumference of the winding mechanism.

Speed No.	**1**	**2**	**3**
10 Revolutions (s)	29.70	15.90	12.30
1 Revolution (s)	2.970	1.59	1.23
Speed (mm s^{-1})	76	142	184

All three SDS speeds were used to understand the effect on each fabric sample in both orientations of the fabrics structure i.e. warp and weft (see Section 3.3.2.6 for more information) and the resulting sound spectra can be seen in Figure 3.12. Speed 1 could not always be relied upon to eliminate stick-slip for all fabric samples and therefore was disregarded from further experiments. Speed 3 can be seen to produce more defined spectra (a combination of a broader main peak around 5000 Hz and more specific individual frequency peaks) for all samples, and in particular silk, which consistently produced the smallest level of amplitude. Due to the amount of data needing to be collected (speed 3 produced a higher level of efficiency due to less time spent pulling the TAS), it was decided that this speed would be used for further work.

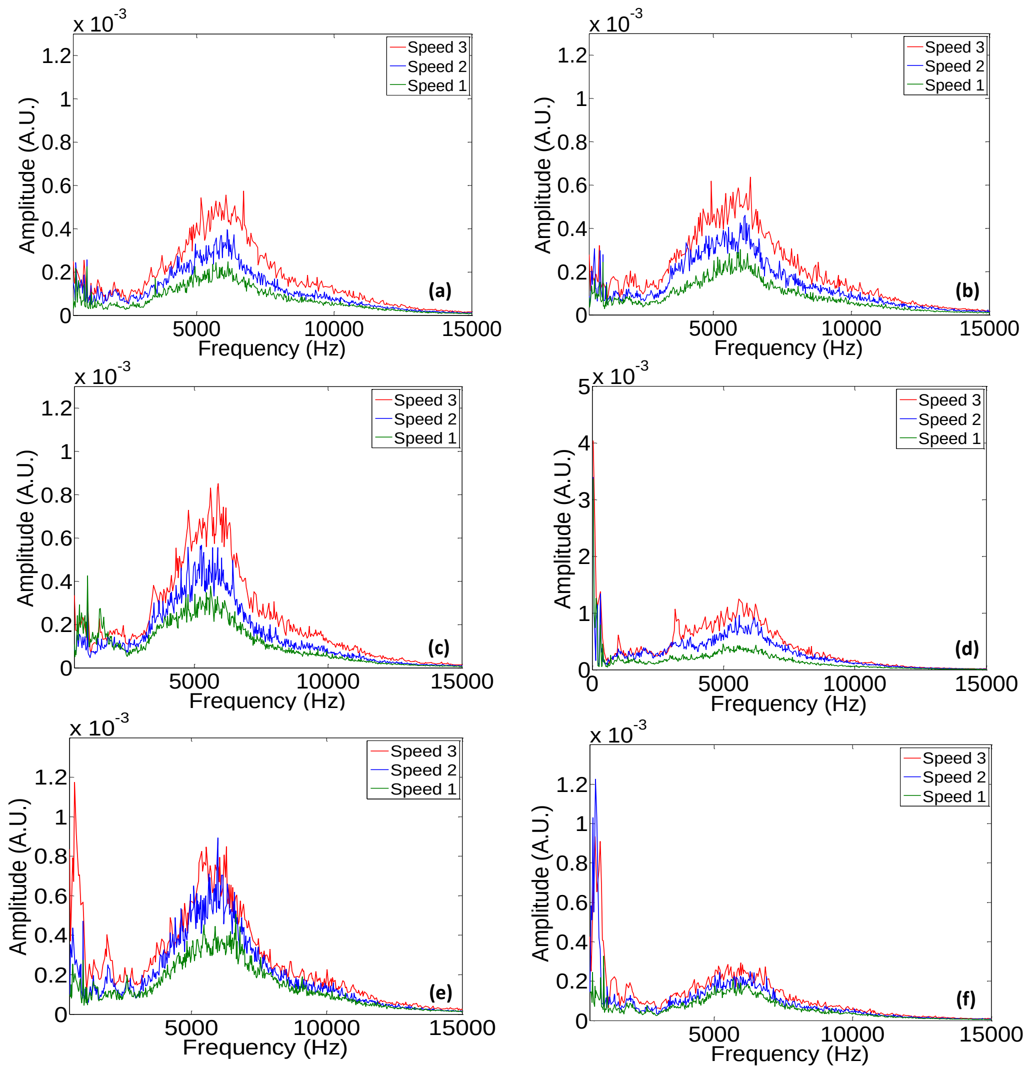


Figure 3.12 Frequency vs. Amplitude sound spectra produced by all three apparel fabrics, (a) cotton warp on warp, (b) cotton weft on weft, (c) denim warp on warp, (d) denim weft on weft, (e) silk warp on warp and (f) silk weft on weft with the three experimental speeds; Speed 1 (---), Speed 2 (---) and Speed 3 (---)

3.3.2.4 Effect of wear on friction noise

In order to determine the reproducibility of the fabric friction noise the sled was run over the same area of fabric 10 times. However, as can be seen in Figure 3.13(a) a slight difference could be seen between runs, and when looking more specifically at runs 1, 5 and 10 (Figure 3.13(b)) the difference could be seen more distinguishably; suggesting that there was wear occurring between repeats. It was essential to ensure that all repeats were individual and eliminated wear; therefore, all subsequent repeats were carried out on new samples of fabric, but within the same batch of original fabric.

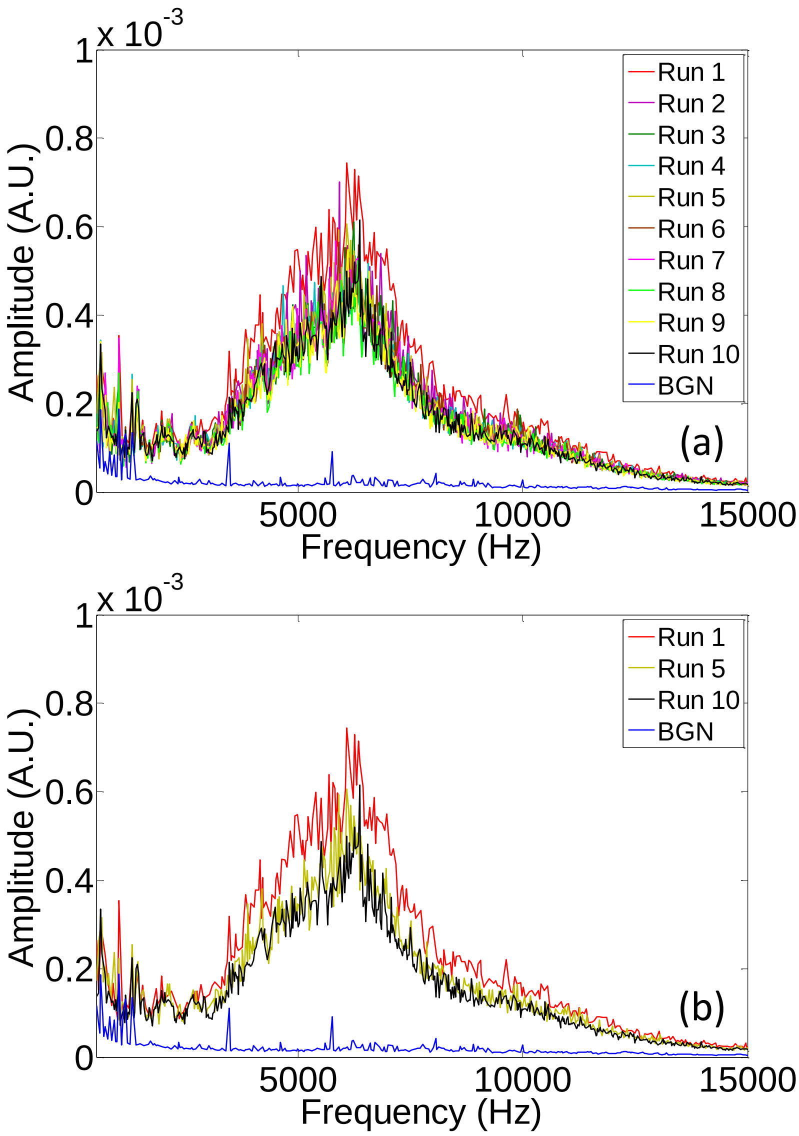


Figure 3.13 Frequency vs. Amplitude sound spectra produced by an apparel fabric showing (a) the effect of wear over 10 repeats and more specifically (b) runs 1, 5 and 10

3.3.2.5 Wire weights

In order to ensure that the only friction that was recorded was deduced from fabric-to-fabric contact nylon fishing wire was selected which, by nature of its original use, is assumed not to deform or spring under pressure created by the friction and run smoothly through the SRR. The wire is classified into weights; 40 lbs, 80 lbs and 100 lbs. Figure 3.14 shows that the relationship between wires used and frictional noise produced and that there was no noticeable difference between 40 and 80 lbs. *In-situ*, the 100 lbs wire was easier to work with, as well as more being capable of resisting kinks which could have ultimately affected the SDS ability to pull the sled accurately and without interruption. It was established that for all future experiments 100 lbs wire would be used.

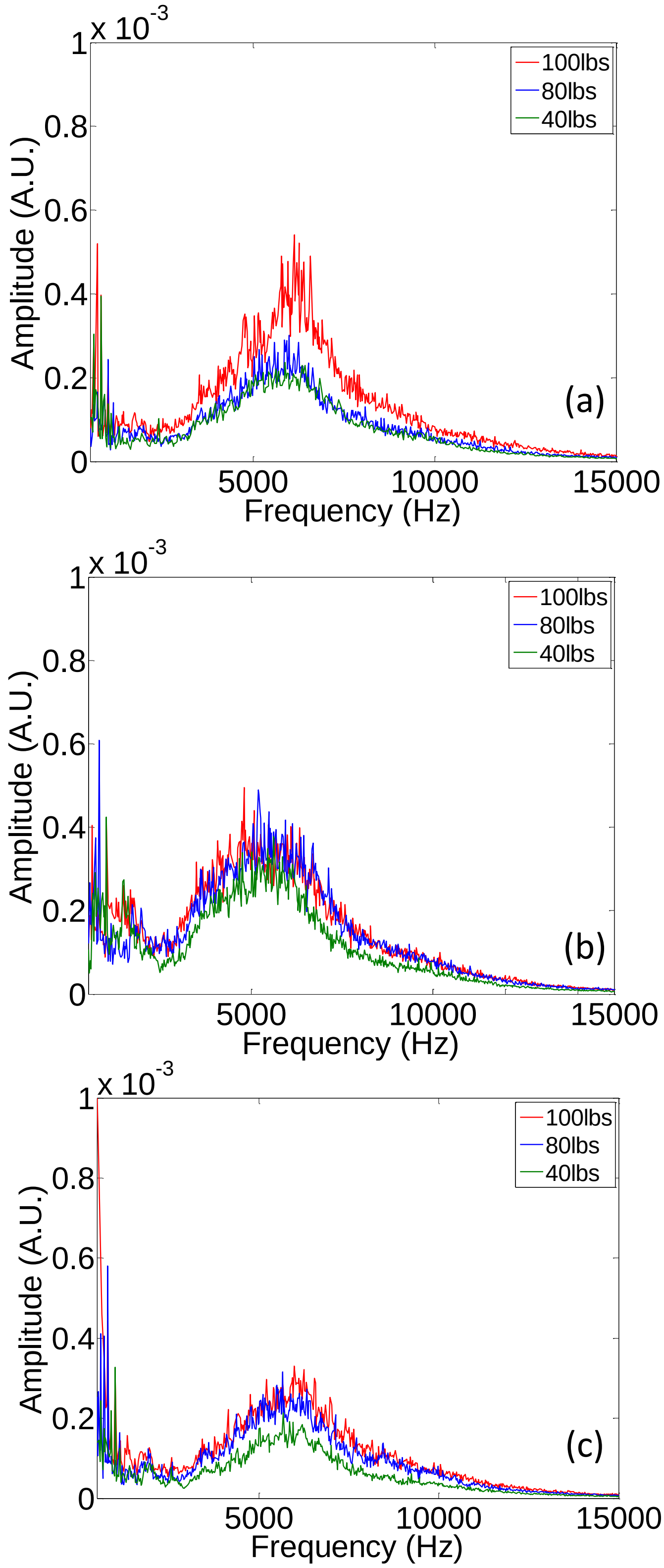


Figure 3.14 Comparisons of the selection of wires chosen with differing weights where (a) cotton fabric, (b) denim fabric, (c) silk fabric in Frequency vs. Amplitude FFT graph produced in MATLAB. 100 lbs wire (---), 80 lbs wire (---) and 40 lbs wire (---)

3.3.2.6 Orientation of fabric structure

As has previously been described within Section 2.1, all woven fabrics are constructed using a specific weave pattern and for this research plain (cotton, silk and model fabrics) and twill (denim) weaves were chosen for analysis. In order to establish which direction the warp runs on a particular fabric an individual thread was pulled from the side and the level of crimping (bends in the thread) was investigated. If a thread had a significant amount of crimping it was determined that it was a warp thread which had been woven between the taut weft threads. However, a thread with minimal or no crimping was pulled it was deemed to be a weft thread. If a fabric sample was taken from an original reel of material the weft threads are clearly defined as their parallel edge will have been bonded to stop further fraying.

Fabrics are made for specific manufacturing or requested purpose, which may have required a certain distance from one weft to another weft thread and then a different distance between the warp threads. As such, it could not be assumed that the apparel fabrics used in this research were uniform. The space between each adjacent threads i.e. warp or weft thread, was measured and can be seen in Table 3.3 (including standard deviation) and shows that although the dimensions of both cotton and silk are similar in the warp and weft directions they are not exactly the same. Due to these differences frictional noise was captured in both the warp and weft directions of each fabric sample to determine whether they had a noticeable effect on the noise emitted and also the effect of differing orientation of the base sample to the top sample was also investigated (see Table 3.4).

Table 3.3 Space between adjacent threads (S.B.A.T) (mm), of three apparel fabrics (denim, cotton and silk), as measured using a Veho Light Microscope and Image J (see Section 3.3.3.2 for more information). Average of 6 measurements.

	Silk		Denim		Cotton	
	Warp	**Weft**	**Warp**	**Weft**	**Warp**	**Weft**
S.B.A.T (mm)	0.228 (± 0.005)	0.350 (± 0.005)	0.531 (± 0.0006)	1.670 (± 0.009)	0.211 (± 0.012)	0.367 (± 0.025)

Table 3.4: Orientations of apparel fabrics for both sled and base samples

Orientation No.	Sled Orientation	Base Fabric Orientation
1	Warp	Warp
2	Weft	Weft
3	Warp	Weft
4	Weft	Warp

Figure 3.15 shows the method development of orientation of the fabric samples and as is shown there was no consistent pattern when the resulting sound spectra from each orientation was analysed, this was also seen in Das et al (2005); where by no noticeable difference was seen between warp and weft. Due to the dimensions of the apparel fabric reels, it was more efficient to select the orientation of warp sled on a warp base as a higher number of samples with the required length could be cut from the original batch.

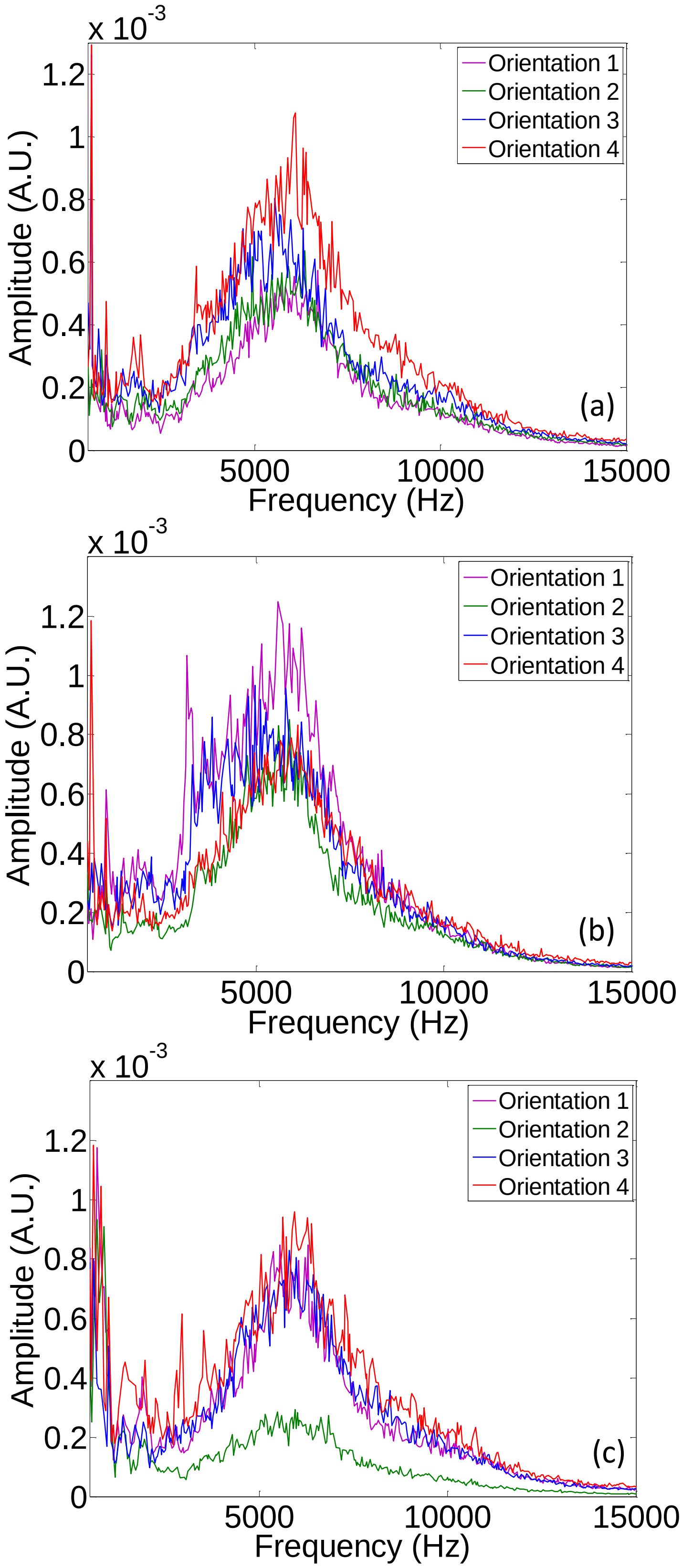


Figure 3.15 Frequency vs. Amplitude spectra for different orientations of the fabric samples weaving method and how it lies as the sled/base fabric – (a) cotton fabric, (b) denim fabric and (c) silk fabric at speed 3. Orientation no. 1 (---), 2 (---), 3 (---) and 4 (---). See Table 3.4 for orientation numbers.

As model fabrics are uniform in their structure it was assumed that their weft is the same as the warp (this was verified and can be seen within Table 3.1).

3.3.2.7 Calibration of microphone

A microphone (Marantz, UK) was used to capture all friction sound emitted, as has previously been described in Section 3.3.1.1, and as all results are presented in Frequency vs. Amplitude plots it was essential to ensure that the microphone was capable of capturing all aspects of the sound (all sounds were recorded using WAV format, which was selected on the solid state recording device attached to the microphone in order to be compatible with MATLAB). To achieve these, two experiments were carried out: 1) detection of specific frequencies and 2) the amplitudes of those frequencies.

A tuning fork calibrated at 440 Hz was struck on the side of a table and held on top of a solid surface enabling it to ring out whilst being recorded by the microphone. This sound was then subjected to MATLAB FFT function (see Appendix 1) and plotted as Frequency vs. Amplitude. Figure 3.16 shows the single specific frequency peak at 440 Hz representing the tuning fork. Therefore, from initial tests confidence in the microphone was instilled, however, 440 Hz is a relatively low frequency and overall frictional sound commonly emits at the higher frequency range, and therefore the microphone was subjected to recording specific engineered values (Table 3.5).

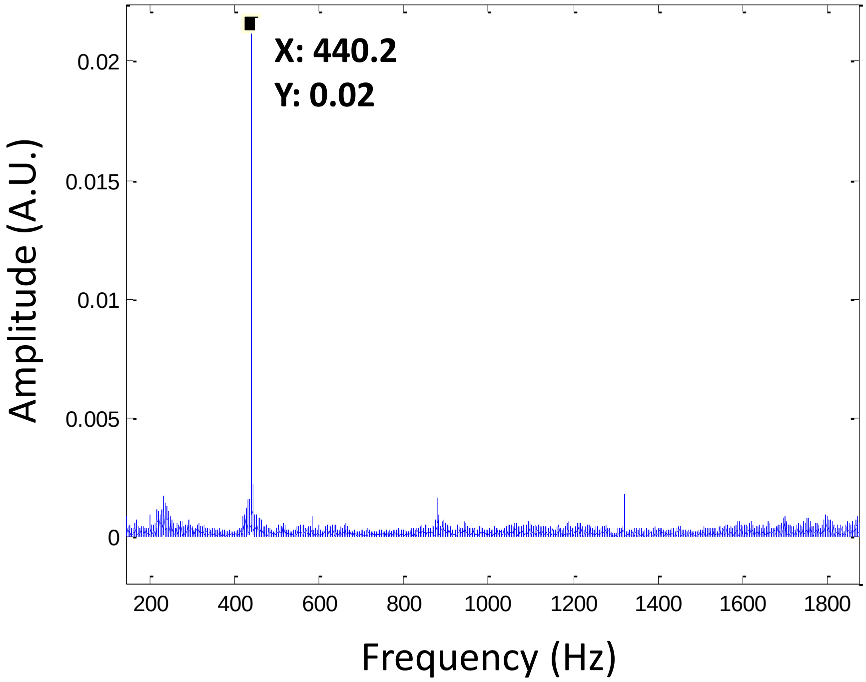


Figure 3.16 FFT output for recording of a tuning fork calibrated for 'A' 440 Hz

A MATLAB script was created (Appendix 2) to engineer both lower and higher frequencies. The sounds were played through amplified speakers (Sony SRS-PC300D, USA) to enable the microphone to record them. All engineered sounds were created with not only certain frequencies, but also corresponding amplitudes with increasing specific increments.

Table 3.5 Frequencies and Amplitudes created in MATLAB for use in Experiment

Frequency (Hz)	Amplitude
100	0.1
200	0.2
300	0.3
400	0.4
1000	0.1
2000	0.2
3000	0.3
4000	0.4

When considering amplitudes, both Figure 3.17 and Figure 3.18 show that the proportional increase of each set of frequencies was not completely recorded by the microphone. However, a general trend is seen, so it was concluded that the microphone is able to distinguish between the extreme of each set of amplitudes, but not to the required accuracy of the original engineered sounds.

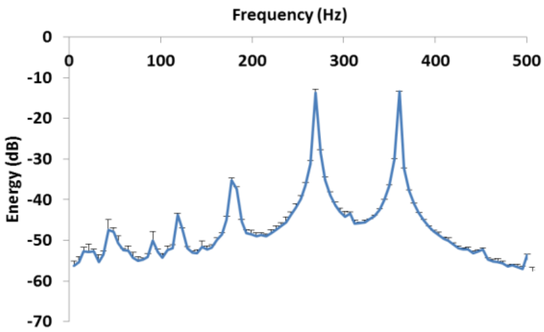


Figure 3.17 Frequency vs. Energy (dB) graphs showing the capability of the microphone of recording low range of frequencies via speakers.

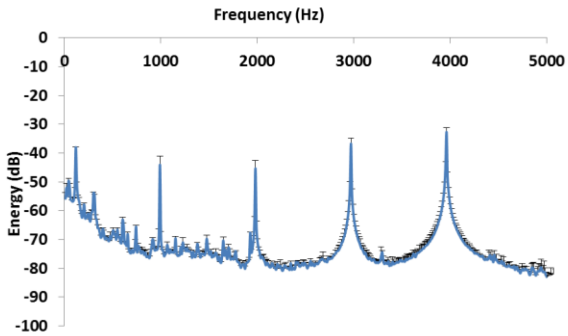


Figure 3.18 Frequency vs. Energy (dB) graphs showing the capability of the microphone of recording high range of frequencies via speakers.

When comparing the high to low frequencies recorded it was apparent that the microphone was capable of accurately detecting the higher range, as seen in Figure 3.18. However, there was a margin of error when recording the lower frequencies (Figure 3.17). The shift in frequencies recorded in the lower range could be attributed to the ability of the speakers to play out exactly the required engineered frequencies, as the ability to measure 440 Hz accurately was previously seen in Figure

3.16. It was important to note when carrying out further analysis of frequencies, either calculated or measured, there was a potential for error (approx. 10%) to enter all final results.

3.3.2.8 Conclusion to friction capture

From the methods previously discussed within this section it was decided that the SRR would run at Speed 3 (184 mm s^{-1}) and with 100 lbs wire. The fabrics would be orientated in the warp direction for both the sled and base samples.

3.3.3 Characterisation of apparel and model fabrics

In order to fully understand the characteristics of the fabrics, in terms of surface roughness and microstructure the following measurement techniques were carried out.

3.3.3.1 Interferometer and gold sputtering

Interferometric measurements of samples were performed using a MicroXAM2 Interferometer (Omniscan, UK); operated whilst using a white light source setting, an objective lens at 10× resolution and a field of view magnifier at 1.0×, which then acquired an 8 by 8 grid array of the fabric sample taking one image at each of the 64 sections. These sections were then 'stitched' together and overlapped at 25% to create one overall image (Figure 3.19 (left)). Scanning Probe Image Processor (SPIP) software (Image Metrology, Denmark) was employed for the analysis of acquired images.

Interferometry requires the use of reflecting light to measure the dimension of each fabric sample. However, it was apparent during scoping experiments that the fabric samples were not able to reflect light without any pre-treatment, and therefore coating the surface with gold enabled this. A SC7640 sputter coater (Polaron, UK) was used to completely cover the fabric with a thin layer of gold using the coating method. Sputtering was carried out over a three minute period to ensure that all surfaces on each fabric sample were covered.

As well as producing an image of the fabric sample the SPIP was designed to record the height of the sample (z) (see Figure 3.2), which was then plotted to show the image as a cross section of the fabric depending on which selection was chosen (indicated by the white line) using the SPIP software (Figure 3.19). The dimensions of the fabric were calculated using the change in light reflected, i.e. where the highest/thickest part of the fabric reflected more light and a dip or an aperture in the weave reduced reflectance. Light reflectance was recorded and converted into a colour chart, dark colours showing areas further away from the microscope and light colours closest.

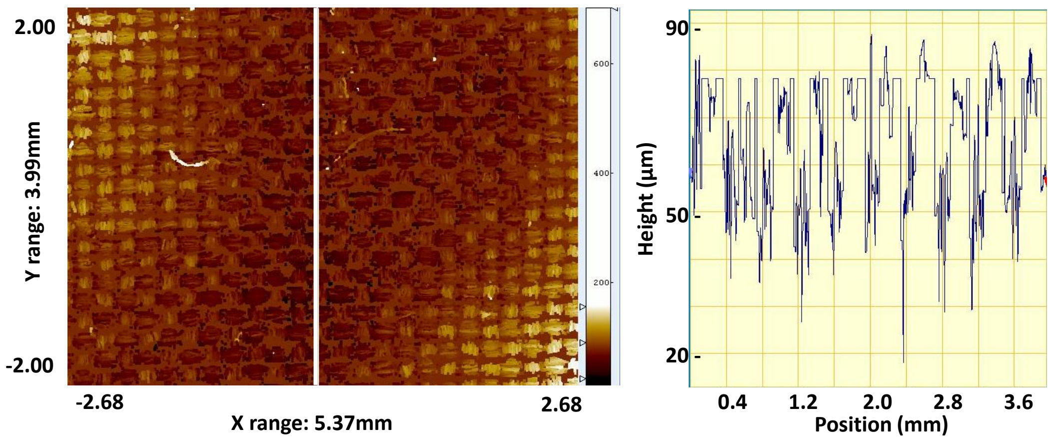


Figure 3.19: An example of an interferometry image of original silk fabric (left) and the corresponding height profile of the white line depicting the change in surface height via shades (right).

3.3.3.2 Microscopy, image capture and analysis

A portable microscope (Veho Discovery$^{\text{VMS-004 Deluxe}}$, UK) was chosen for two purposes: 1) it was able to be transported around easily when recording images between runs of apparel and model fabrics and 2) being able to analyse the samples from two resolutions: individual threads and weave patterns to overall understanding of microstructure of the fabric (Figure 3.1 and Figure 3.3).

The light microscope required calibrating as the resolutions of 20 and 400 were only considered to be labels and not an accurate representation of the scale, therefore a graticule of 1 mm length was used to calibrate the microscope.

3.3.3.3 Method of measuring microstructure

In order to understand the dimensions of each apparel and model fabrics the microstructure was measured using the images produced by the light microscope. Figure 3.20 shows the areas that were measured: the width of individual threads (a), the distance between adjacent (b) and opposing threads (c).

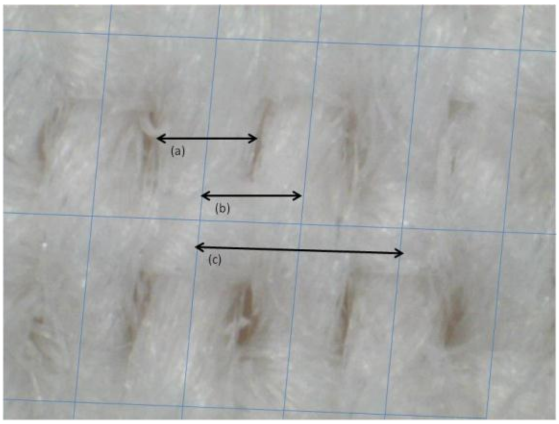


Figure 3.20 An example of the measurements taken to calculate the microstructure of fabric and mesh samples where (a) width of thread diameter, (b) adjacent and (c) opposing threads. Example is cotton.

$$\frac{\text{Average pixels (px)}}{\text{Pixels in 1}\mu\text{m (px)}} = \text{Length of required area } (\mu\text{m})$$

Eq. 3.2

Using Eq. 3.2 and the pixels/μm measured using the calibration technique in Section 3.3.3.2 the length of the required areas were calculated, with five repeats from three separate areas on each fabric sample, and averaged.

As the model fabrics are constructed using a specific desired set of dimensions (information supplied by G.BOPP, UK), measuring them using this technique was also considered to be an accurate way of calibrating the microscope. All measured dimensions of model fabrics were within 0.001 mm, on average, of the quoted dimensions.

3.3.3.4 Microstructural frequency calculations

Frequency is defined as the number of occurrences of an event, and in terms of apparel and model fabrics, the number of threads within either the warp or weft direction of an area which are either adjacent or opposing (Figure 3.20). A theoretical frequency can be calculated: each thread runs over another one which should create a sound, and how often this occurs is the frequency. These theoretical frequencies would be present, based on microstructure, in sound spectra produced from the frictional noise and would stand alone from the main bulk of the random frictional noise.

Eq. 3.3 was used to calculate said frequencies and the space between adjacent threads was measured for both apparel and model fabrics using the calibrated microscope.

$$\boldsymbol{Frequency\ (Hz)} = \frac{\boldsymbol{speed\ (mm\ s^{-1})}}{\boldsymbol{(S.B.A.T)\ (mm)}}$$

Eq. 3.3

All resulting frequencies for both apparel and model fabrics can be seen within Section 4.3.

3.3.4 Frictional noise analysis

In order to correctly analyse the frictional sound produced by both apparel model fabrics, a succession of MATLAB programmes were created and their suitability decided. All data shown has a minimum x-axis of 500 Hz, as opposed to 0 Hz, to show in more detail the change each MATLAB script had on the original data. In summary sound files were subjected to:

1) Original wav. files FFT'd to Frequency vs. Amplitude;
2) Average of raw rata;
3) Smoothed raw data;
4) Average of smoothed raw data;
5) Sorted raw data;
6) Area under a curve of sorted data.

All stages are fully explained within this section and it was found that 'sorting the raw data files successfully represented the original sounds well and taking an Area Under Curve (AUC) calculation of those sorted files enabled averaging and correlation relationships to be investigated and was therefore used throughout all results in Chapter 4 where frictional noise was concerned.

3.3.4.1 Fast Fourier Transformation of original sound file

An FFT script was written in MATLAB (see Appendix 1) to transform all original sound files, in WAV format, from Amplitude vs. Time into Amplitude vs. Frequency. This enabled comparisons of all original sound files before any further analysis. Figure 3.21 shows an example of the transformation of an original sound file and comparing 1, 5 and 10 runs.

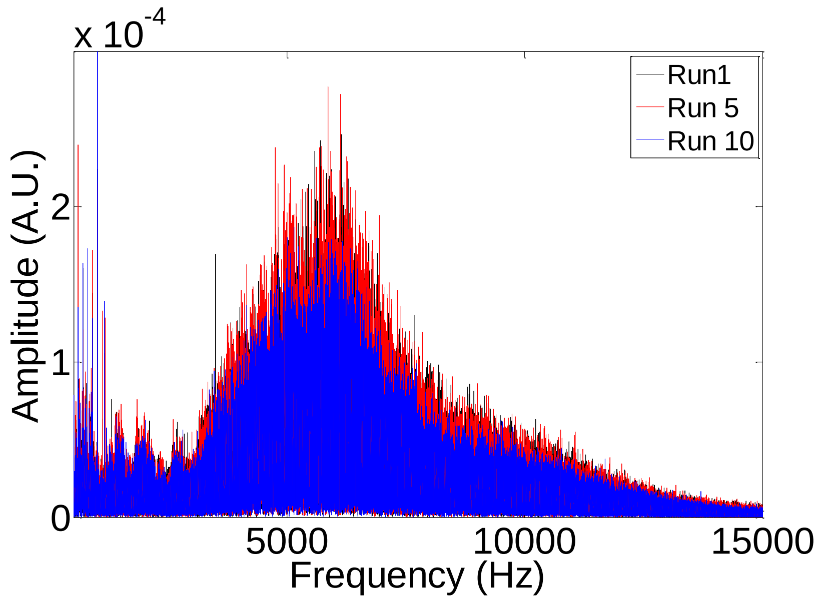


Figure 3.21 An example of frequency vs. amplitude sound spectrum raw data, in original format.

When comparing original sound WAV files it was apparent that there was a great amount of ‘noise’ which prevented one from being able to detect differences between separate variables; as in Figure 3.21, being able to distinguish between Run 1 and 5 was difficult.

As 10 repeats (runs) were originally taken of each fabric sample, an average was calculated to enable further analysis between both repeats and conditioning results using Appendix 3. The script written extracted all frequency and amplitude values for each repeated sound file and stored them; an average of these was then taken and automatically plotted. Figure 3.22 shows the comparison between averaging the 10 runs and original sound files of runs 1, 5 and 10. Although the average calculated by MATLAB was correct, it was not deemed a true representation of the original sound files as the average reduced the sound spectrum, and many individual strong peaks were lost in transformation.

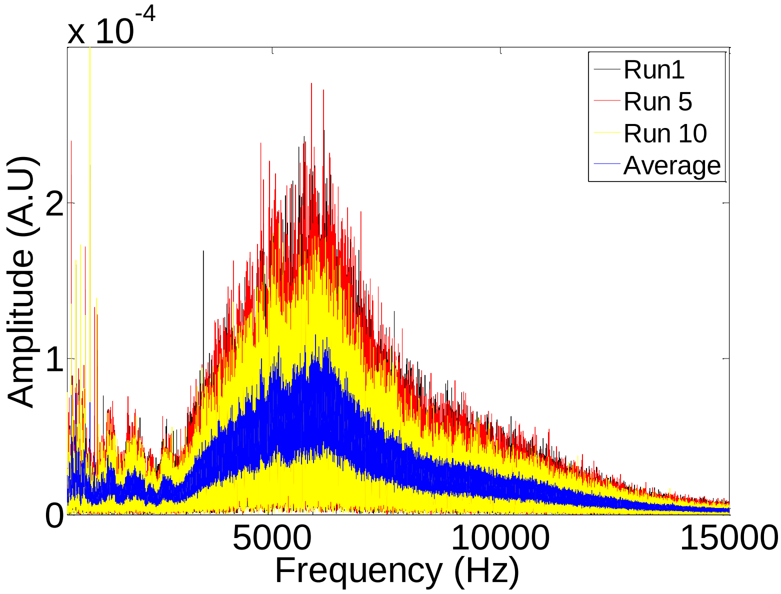


Figure 3.22 An example of frequency vs. amplitude sound spectrum raw data, in original format and the average calculated from all 10 repeats.

In order to try to eliminate the reducing effect of averaging, a further method of analysing in MATLAB was created to be able to smooth the data based on the original sound file by providing a moving average (Appendix 4). The script enabled a moving average of any size, however, for the purpose of this analysis it was taken for every 50 frequency values, and their corresponding amplitude value. For all original sound files the frequency points were 262145, each with an amplitude level available for analysis. The moving average was named 'smoothing' for consistency.

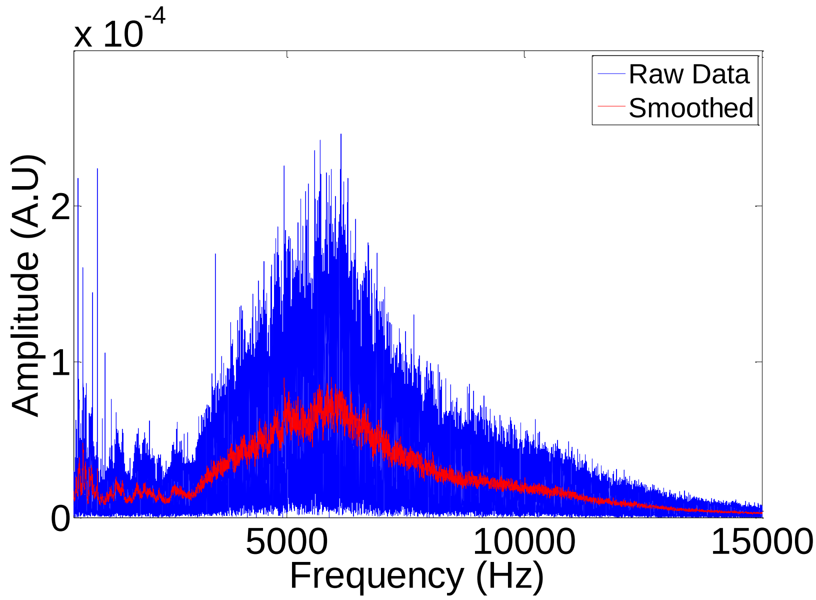


Figure 3.23 An example of frequency vs. amplitude sound spectrum of raw data, in original format, and a smoothed data set.

The moving average analysis enabled comparisons between the original raw data and the new smoothed data (Figure 3.23), in which it was apparent that this method also reduced the data to a level where it no longer represents the original sound file (the red line of smoothed data does not represent the original blue data). When comparing an average of the raw data and the average of the smoothed data it was apparent that the data analysis had taken the original data too far in both averaging techniques and therefore further analysis of the original data was required (Figure 3.24).

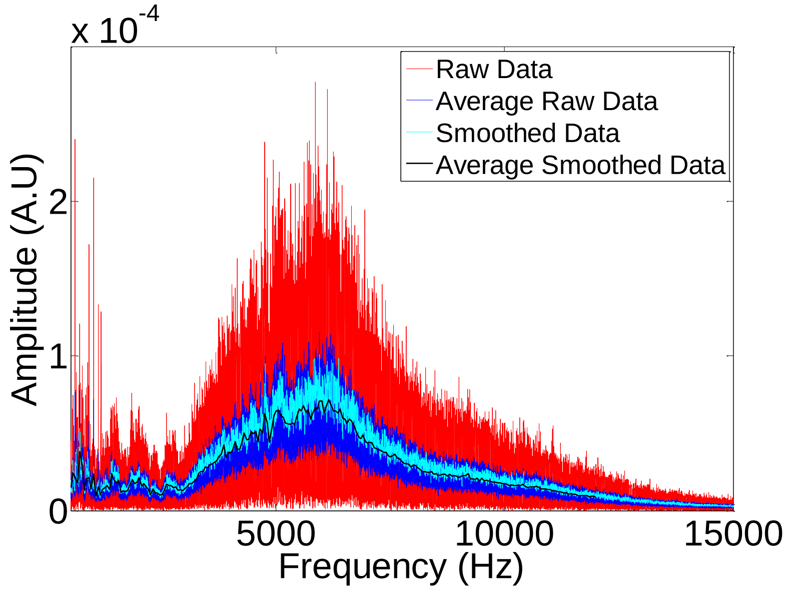


Figure 3.24 An example of frequency vs. amplitude sound spectrum raw data, in original format, averaged raw data, smoothed data and average smoothed data

As the data was continuously being reduced and not representative of the original sound, effort was made to select only the peaks of the data, i.e. taking the highest amplitudes of frequency points and rejecting the lowest as 'noise'. Therefore, a MATLAB script was written to select these points by a sorting method (see Appendix 5). The fundamentals of the script are to analyse a set of three frequency points and compare the amplitude of the centre frequency to its neighbouring frequencies; if a frequency was lower than its neighbours it was rejected and then moved on to the next subsequent three frequencies. The script was written in such a way that the 'sorting' could be repeated automatically by a certain number of 'passes' i.e. how many times the whole set of frequencies was subjected to the script. A frequency vs. amplitude plot was produced to compare the raw data and the data points for each pass. As each pass occurred, the data presented in the workspace of MATLAB was the number of frequency points that were left after elimination of lower peaks i.e. the starting value of frequency points was in excess of 260,000 and would be reduced along the process; from these values the optimum number was selected for plotting against the raw data (this was mainly achieved by trial and error). For example, if too few points were selected (Figure 3.25) it would not, again, be representative, and if too many were chosen the task would be deemed not necessary (Figure 3.26). An example of an optimum number of passes can be seen in Figure 3.27, where only the top level of amplitudes per certain frequencies were selected (generally 7 or 8 passes were chosen to represent the original data).

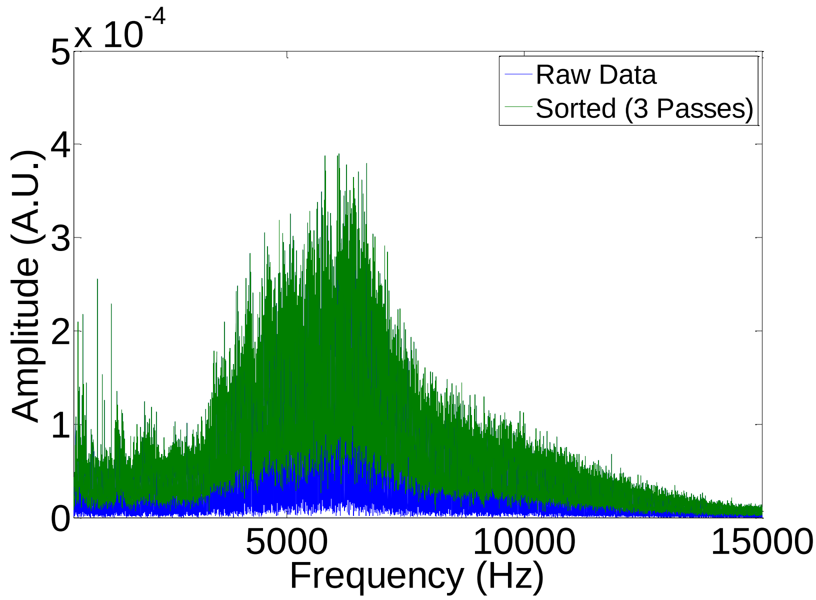


Figure 3.25 An example of frequency vs. amplitude sound spectrum raw data, in original format and sorted data passed 3 times.

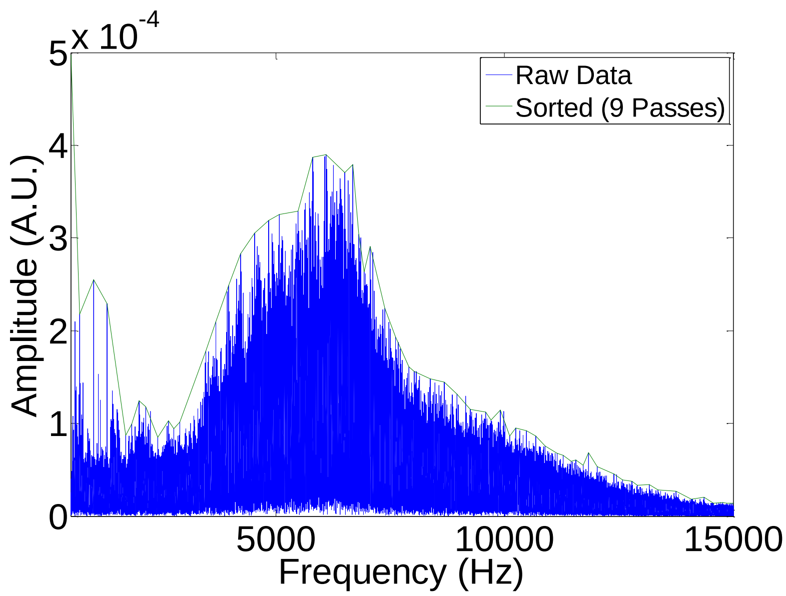


Figure 3.26 An example of frequency vs. amplitude sound spectrum raw data, in original format and sorted data passed 9 times.

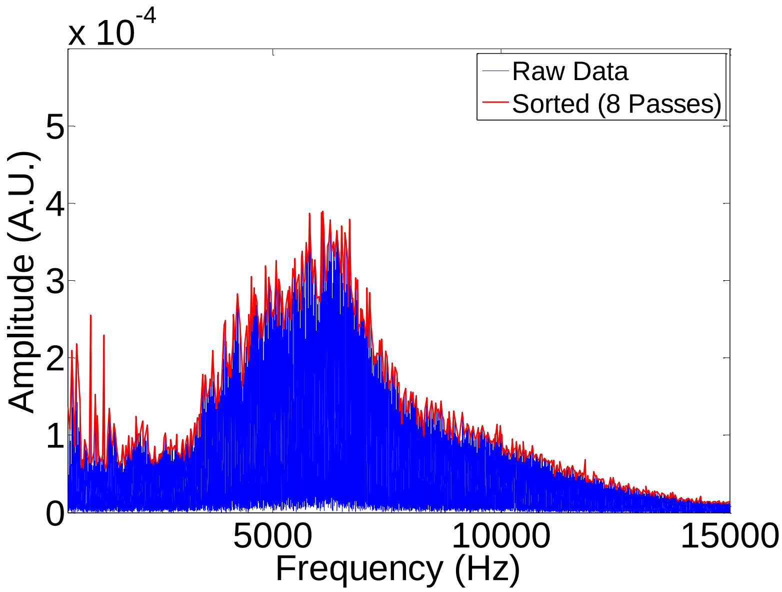


Figure 3.27 An example of frequency vs. amplitude sound spectrum raw data, in original format and sorted data passed 8 times.

When comparing the apparel fabrics frictional noise produced by any one of the analysis methods previously discussed, only subjective measures were available i.e. which amplitude looked louder or greater than another. A method to calculate the AUC was created in MATLAB and used to be able to plot values of the sorted data to give an objective measurement (Appendix 6).

As many aspects of data analysis were experimented with, it was apparent that a method of keeping the original amplitudes of all data sets was essential; however, ensuring that there was a manageable data amount was also crucial. Based on these needs it was decided that sorting the data via Appendix 5 and producing it using a number of passes that was adequate for each data set individually, therefore ensuring that no vital data was missed. Deciding on what constituted an adequate pass number was carried out using trial and error approach.

3.3.5 Washing Methods

3.3.5.1 De-sizing of apparel and model fabrics

As previously described in Chapter 2, when sourcing fabrics from wholesale, and therefore not knowing what products were used to treat the original fabrics by manufacturers, it was essential to start all experiments with a ‘de-sized’ state of fabric samples i.e. the removal of any conditioning (or sizing) at the point of manufacture. In order to achieve this, a de-sizing technique was carried out:

1) A ratio of 100g of washing powder (Dreft, P&G) to 2kg of either silk or cotton materials was added to a washing machine (Beko, Germany);
2) All fabrics were washed at 40 °C for 2 hours and 11 minutes with a spin cycle speed of 1600rpm. This was repeated a second time for denim due to the added coloured dyes to achieve a dark fabric, which could have had potential effects on the washing process;
3) All were then subjected to a 25 minute rinse cycle to remove any residue of sizing or washing powder and a further spin cycle;
4) Fabrics were then line dried for 24 hours in 21 °C for consistent results.

Dreft is a detergent used to de-size within P&G as it contains no fabric softening ingredients or perfume and is considered not to have an influence on any future washing or softening.

The model fabrics were de-sized using an alcohol rinse. They were then hung to line dry in a 21 °C laboratory environment.

3.3.5.2 Washing apparel fabrics

Three methods of washing were analysed; the original fabric was not treated and subsequently had all manufacturers sizing still intact (MS), de-sized fabric only (DS) and an extreme method of conditioning (CFE).

For the CFE condition de-sized fabric samples were treated with a commercially available fabric conditioner using a hand washing method; each de-sized fabric sample was coated in 40g of liquid fabric conditioner and left to line dry in a 21 °C laboratory environment. The hand washing technique was carried out according to manufacturer’s guidelines.

3.3.6 Fluid gel production

This section describes the methods used to created fluid gels by means of sheared gelation; only a pin-stirrer method was used within the research as large quantities were required for further tribology testing. The fluid gels were subjected to mechanical testing and analysis post production, which is detailed towards the end of this chapter.

3.3.6.1 Hydrocolloid solutions

κC gel solutions were prepared by dispersing 2% w/w κC powder in 0.3% w/w KCl solution (with deionised water) and stirring whilst heating to 90 °C until completely dissolved. 2% w/w agar powder was dispersed in deionised water and heated on stirring to 85 °C until dissolved.

3.3.6.2 Gelling temperatures of fluid gels

In order to ensure that all fluid gels were created by gelling under shear and not a quiescently cooled gel then being sheared, gelling profiles of both κC and agar solutions were carried out using a rheometer (Kinexus, Malvern, UK) which then measured the onset of gelation; a temperature at which all FGs solutions must be kept above before sheared gelation can occur. The rheometer sequence was designed to run at 2 °C/min with a shear speed of 200 s^{-1} in order to replicate the mechanism by which the pin-stirrer achieved shear at the highest rotational speed, previously established by Gabriele (2011).

3.3.6.3 Fluid gels

A continuous process was used in the production of the fluid gels consisting of two jacketed units; a holding temperature vessel (with no shear) and a pin stirrer (see Figure 3.28). The pin stirrer consists of two sections; a shaft with 16 pins distributed along the length which is inserted into a chamber also with 16 pins along its inside edge alternating in position to the shaft pins.

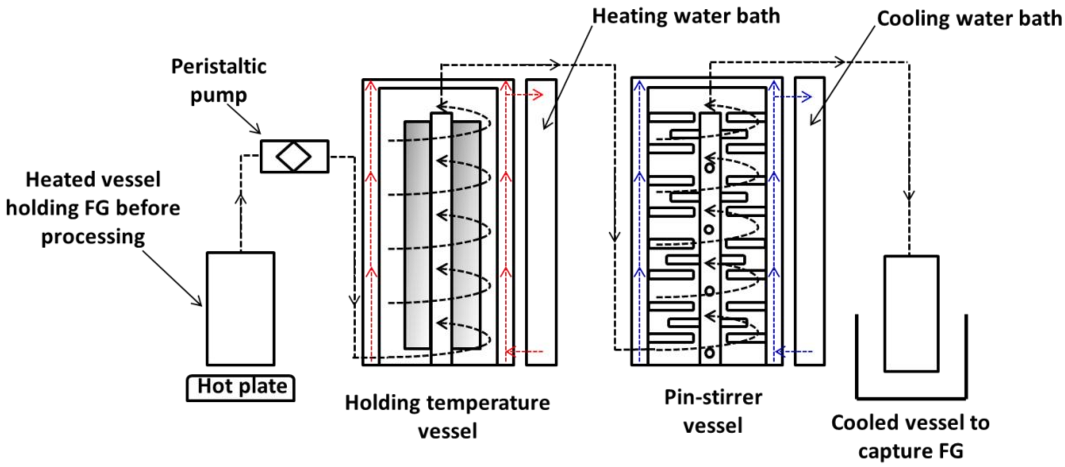


Figure 3.28 A schematic of the fluid gel production within a jacketed pin-stirrer. Schematic is not to scale.

After the initial production of the FGs described within Section 3.3.6.1, the gel solutions were kept at a constant temperature under agitation with the use of a hot plate and fed into the no shear vessel at 10 ml/min with a constant temperature of 70 °C to ensure that minimal heat loss possible occurred before entering the silicone tubes via the peristaltic pump to be sheared. 10 ml/min was chosen due to previous work carried out by Garrec and Norton (2012d), leading to a cooling rate of 2 °C/min, also used within the rheometer, as the internal volume of the pin-stirrer was measured at 150 ml. Initial experiments were carried out to vary the cooling rate, however, it was noticed that at higher speeds of the peristaltic pump lumps were forming; an indication of inadequate shearing taking place. At lower speeds the inlet temperature fell below the minimum allowable onset of gelation temperature allowed and therefore solutions were gelling before entering the pin-stirrer resulting in a quiescently cooled and sheared gel. On exiting the pin stirrer vessel the fluid gel was collected and cooled quiescently within an iced vessel to 5 °C.

3.3.6.4 Processing parameters of the fluid gels

Four different gelling structures were created using different processing parameters which consist of inlet (T_{inlet}) and outlet (T_{exit}) temperatures, and shear speeds for the pin stirrer for all experiments which can be seen within Table 3.6. Specific changes in processing parameters were chosen due to earlier work carried out by Garrec and Norton (2012d) and Gabriele *et al.* (2010), where by, both reported a change in particle size and structure of the FGs when temperatures were changed and shear speeds, respectively.

Table 3.6 Summary of processing parameters chosen on the pin stirrer vessel for all FG tested

Fluid Gel (code)	Concentration (%w/v)	Pin Stirrer Speed (rpm)	T_{inlet} (approx. °C)	T_{exit} (approx. °C)
κC T_{40}	2	1500	69	29
κC T_{56}	2	1500	63	7
Agar RS_{1500}	2	1500	55	7
Agar RS_{300}	2	300	55	7

3.3.7 MTM Tribometer

Within this section, the method used to affix both apparel and model fabrics is described, as well as how the typical tribometer setup has been altered to accommodate the novel surfaces.

3.3.7.1 Tribometer surfaces

As fabrics have not previously been used within MTM tribology, major work was carried out to establish a method that was, not only reproducible, but also feasible and efficient. Speeds which were to be employed within the tribology methods would reach levels that exceed anything which has been tested on fabrics previously and to ensure that fabric samples stayed attached to the base steel surface a number of methods were carried out including gluing samples, pinning samples and finally sticking samples. Gluing material samples with superglue interfered dramatically with the microstructure of the fabrics, whereby, glue was observed to penetrate the surfaces ensuring that individual fibres were permanently attached to one another, which would therefore produce false results and also in terms of model fabrics the glue filled in the macrostructure leaving the effect of surface roughness and apertures redundant (see Figure 3.29). As was reported in Chapter 4, apertures and surface roughness values are essential to friction, in the form of acoustics, and in understanding the surface characteristics of both apparel and model fabrics.

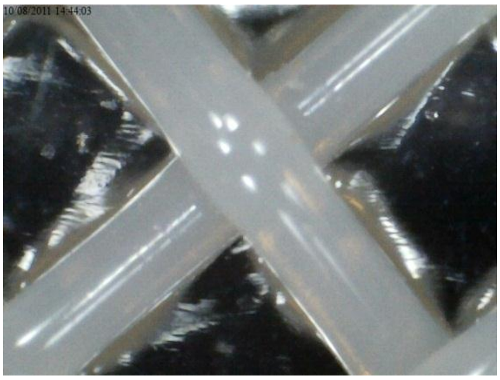


Figure 3.29 A photograph of model fabric super glued to the stainless steel surface indicating the spread of the glue around the threads

The final method chosen, which proved reliable and strong enough to withstand high speeds, affixed fabric samples using double sided tape in the following way:

1) Stainless steel disc was cleaned thoroughly and air dried;
2) Double sided tape was attached to both bottom, top and side of the disc (depicted by red areas);
3) Fabric samples were cut to allow for an even coverage on the underside of the disc and attached when top side of tape is removed, ensuring fabric was not stretched at any point;
4) Samples are left for 24 hours before processing top side up;
5) All handling and attaching was carried out using gloves to avoid any oil transfer or contamination.

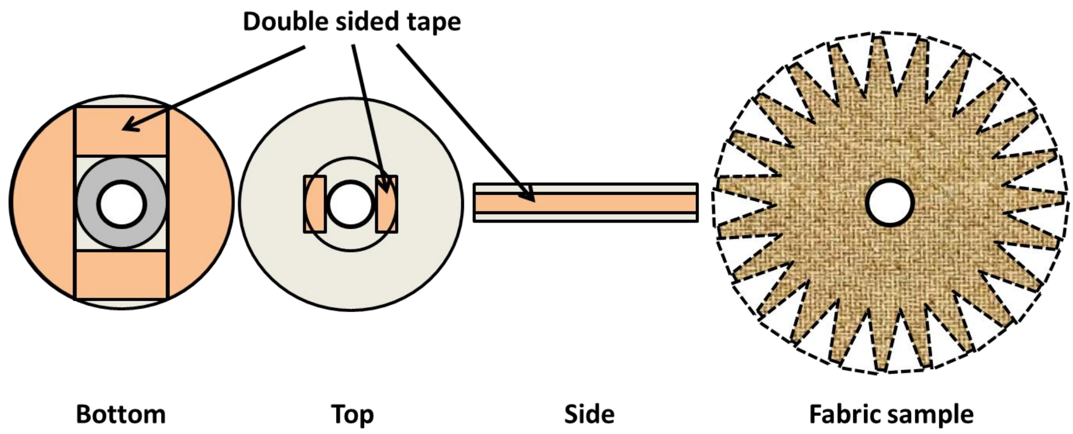


Figure 3.30 Schematic of method to attached fabric samples to the stainless steel disc. Orange areas depict the double sided tape.

3.3.7.2 Construction of silicone balls

The ball surface of the tribometer was prepared using Sylgard, 184 silicone elastomer kit (Dow Corning) which housed two products, 1) a base which was mixed with 2) a curing agent in a ratio of 10:1 using an overhead stirrer for 5 minutes. This mixture was the vacuumed to take away any excess bubbles introduced by the stirring, for around 30 minutes, and then poured into the steel moulds designed to create ¾ inch silicone balls. The PDMS balls were dried in a 20 °C oven with vacuum, to permanently set the silicone to further use. The balls were cleaned via a process of sonication in ethanol for 5 minutes, followed by further sonication in distilled water and air dried ready for tribology use. The silicone balls were only used once for all tribology tests carried out.

3.3.7.3 Method setup

In order to measure the frictional properties of surfaces, both lubricated and unlubricated, a Mini Traction Machine (MTM2) tribometer (PCS Instruments, London, UK) was used. The instrument consists of a ball running across a flat surface mounted on a steel disc, under load, either both disc and ball are free to rotate or only the disc is free to move.

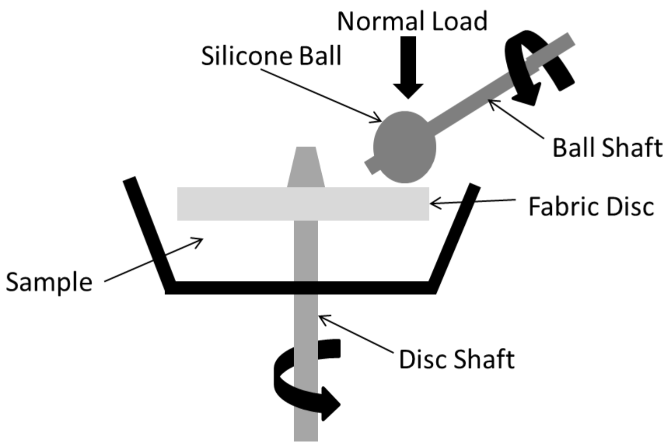


Figure 3.31 Schematic of MTM Tribometer (adapted from Garrec and Norton (2012b)). Zoomed in image: example of fabric on a tribometer stainless steel disc.

The tribometer is run at an entrainment speed, *U*, which is a mean of the ball and disc speeds and the slide roll ratio (SRR) between the rolling speeds of the disc and ball speed; U_{ball} and U_{disc} respectively. Both *U* and *SRR* were chosen specifically for fabrics after initial testing (see Sections 5.2.1 and 5.2.2).

Eq. 3.4

$$SRR = \frac{U_{disc} - U_{ball}}{U}$$

Friction coefficient, μ, is calculated using the frictional force measured by a force transducer, *F*, and the load, *W*, applied using Equation 2.

Eq. 3.5

$$\mu = \frac{F}{W}$$

3.3.7.4 Methods: Stribeck and pin-on-disc

In order to present friction properties data can be represented in a time against friction coefficient (μ) and a Stribeck curve; *U* plotted against μ. μ produced by both apparel and model fabrics were recorded using two settings; pin-on-disc (timed) and Stribeck and all results are seen within Chapter 5.

Stribeck tests are traditionally used within tribology research and the curves they produce are related to the lubrication of a system via three different methods; a boundary regime (most commonly seen initially) whereby no particles or fluid are entrained between the two surfaces (ball and disc) and therefore exhibit high levels of μ and is generally seen to plateau before fluid is partially entrained leading into a mixed regime. Within the mixed regime the surfaces are separated by the fluid leading to a dramatic decrease in μ and is most widely observed regime within food research. When the lubricant is fully entrained between the surfaces, the hydrodynamic regime has been entered and an increase in μ is observed. Within literature the hydrodynamic regime is not very often entered, however, it is essential that very smooth surfaces are used to achieve this regime.

Pin-on-disc measures the μ produced when the ball is stationary and the disc has free motion, resulting in a *SRR* of 100% with regards to the disc. Pin-on-disc was used to understand μ produced by dry fabrics, and when lubricant was added, in terms of hand feel, i.e. when a consumer feels fabric in a real life setting like washing or buying garments. Tests were carried out at 3 mm s^{-1} with 2 N for 10 min (in line with approximate consumer testing speeds).

To understand the effect of surface roughness, material properties and the effect that change in fluid gel processing has on μ; Stribeck tests were carried out with a SRR of 50%. *U* was increased from 1 and 3200 mm s^{-1} followed by the reverse in *U* until 6 runs were completed. This was then repeated three times giving a total of 18 repeat runs, each with new fabric surfaces and the average of μ is plotted with an error of two standard deviations. As with pin-on-disc, the load was 2 N.

3.3.8 Textural Analysis

The structural properties of both κC and agar were measured using a TAXT.plus texture analyser (Stable Micro Systems Ltd, UK) by performing a number of compression tests. Quiescent gels were produced in the same method as preproduction of fluid gels for both κC and agar, cooled and set in cylindrical tubes. The length of gel cylinders were approximately 20 mm and had a diameter of 20 mm and compressed using an aluminium probe of 40 mm in diameter with a compression rate of 0.2 mm s^{-1} to 75% of their original height (Thrimawithana *et al.* 2010). All compression tests were repeated 10 times and an average was taken for all results shown. The force/distance measured to compress the samples was converted into true stress and true strain values using the equations adapted from Moresi and Bruno (2007), Norton *et al.* (2011) and Hermansson *et al.* (1991) and are seen below:

Eq. 3.6

$$\mathcal{E}_E = \frac{(H_o - h)}{H_o}$$

Eq. 3.7

$$\mathcal{E}_H = -\ln(1 - \mathcal{E}_H)$$

Eq. 3.8

$$\sigma_E = \frac{F}{A_o}$$

Eq. 3.9

$$\sigma_T = \sigma_{\mathcal{E}}(1 + \mathcal{E}_E)$$

In order to understand the strength of the hydrocolloid fluid gels, the true stress/ true strain plots were converted into 'work done' i.e. the area under curve up until the point of fracture (the sudden drop of true stress). The work done was calculated using a macro system in Sigma Plot 12, where by each individual repeat was subjected to the macro in which the trapezoid rule was employed and an arbitrary figure represented the area was given as a result and an average of all repeats was recorded.

Both Young's and Bulk Modulus were calculated using the gradient of the curve from the same true stress/true strain plots; Young's modulus, initial linear region, was taken as the gradient below 0.05 strain values and Bulk above 0.1 strain values; the second linear region (for more information on calculating all characteristics readers are referred to Norton, A. B. *et al* (2011)).

3.3.9 Microscopy of disc surfaces

The same method of microscopy was employed for imaging and assessing the effect of friction on both the micro and macro structures of the tribo surfaces, as was used in Chapter 4. A portable microscope (Veho, UK) was used to image before and after tribology experiments were carried out to assess for visible wear and to ensure that, specifically apparel fabrics, were not stretched beyond their original dimensions (refer to Section 3.3.3.2 for more calibration and methodology information).

3.3.10 Goniometry

To understand the hydrophilic nature of the apparel fabric surfaces used in the tribometry tests a Krüss Easy Drop FM40 goniometer was used. A 3-5 μL amount of distilled water was dropped onto the fabric surfaces and with the use of recording the time taken (milliseconds) for the drop to be absorbed within the fabric surface with a camera, the wettability was measured. It was regarded that the longer the time for a drop to be absorbed, the less hydrophilic the surface was deemed to be.

3.3.11 Sensory methods

Two individual studies were carried out: 1) one-to-one in-depth interviews and 2) sound manipulation in real-time. For the interviews participants were recruited via an email advert circulated around Proctor and Gamble (P&G), Newcastle Innovation Centre, Newcastle, UK. No correction for sight or hearing was implemented and no participants were excluded from the study after applying. For the sound manipulation study all participants were recruited from within the

University of Birmingham community via leaflets, posters and emails. Participant's for the sound manipulation study were requested to have normal hearing based on what they, themselves, considered to be normal hearing, meaning that no initial hearing tests were carried out. The design for each study was ethically approved by the University of Birmingham's ethical review panel. For both studies, all participants were given an information sheet to read through before commencing the studies, a consent form to read and sign, and a debriefing form after the studies were completed for the participants to take away. All forms can be found within Appendix 7. The participants who took part in the one-to-one in-depth interviews were given a £20 supermarket voucher to compensate for their time and those who were a part of the sound manipulation study were given a £10 book voucher. All statistical analysis was performed using SPSS Statistics 20.

3.3.11.1 One-to-one interviews

Results of this study are described in Chapter 6.

3.3.11.1.1 Aims and objectives

One-to-one in-depth interviews were carried out with the following overall aims:

1) To understand how consumers assess fabrics during everyday life;
2) To explore which of the five senses (sight, touch, smell, taste and hearing) consumers use when assessing fabrics, and the importance given to each sense when making judgements about fabric attributes;
3) Comprehend the sound sensory vector in order to fully understand the relationship between sound and fabric feel.

With the following, more specific, aims to be gained from the pre-work:

1) To gain an insight into what consumers think about garments and how they describe them;
2) To gain an insight into how consumers evaluate fabrics using their senses via pictorial images and, whether sound is used.

Furthermore, from the interviews:

3) To gain an insight into how consumers think about fabrics and fabric characteristics;
4) To understand if consumers are influenced by having a real garment and:
    a) Are consumers more able to describe fabric attributes?;
    b) Are different, or additional, descriptors given?;
5) To understand the importance of the different senses by producing a hierarchy of senses;
6) To understand if consumers consider sound when describing fabric attributes.

3.3.11.1.2 Participants

Ten participants (3 Male and 7 female) were recruited to take part in one-to-one in-depth interviews. Demographic information asked for (age range and job specification) was provided sporadically and therefore not discussed within the results of the interviews. All participants were employees of P&G, Newcastle Innovation Centre, Newcastle, UK and worked within the Laundry department.

It is important to note that as both sensory studies were carried out with two, separate demographic sets of consumers, they were from specific walks of life i.e. employees of P&G and mostly students from University of Birmingham for the interviews and manipulation study (see Section 3.3.12.1 for more participant information), respectively, and therefore cannot fully represent the general population as a whole.

3.3.11.1.3 Apparatus

In order to successfully capture all that was said within the interviews, a microphone (Marantz, UK) was used with a solid state recording device to audio record. Video recording was not employed for the interviews. All photographs displayed were taken using a phone (Apple, UK). A white board and black non-permanent pen was used to capture participant’s sensorial hierarchy.

3.3.11.1.4 Procedure

3.3.11.1.4.1 Pre-work

All individual interviews were carried out in P&G's consumer interactive kitchen and living area which has a two-way mirror to analyse consumers responses, however, this was not utilised for the interviews. The interviews were planned to last 1 hour; however, two interviews ran for 1 hour 15 min. A script was created and was followed for each participant (Appendix 8) alongside exploratory and spontaneous questions/conversations.

Participants were asked to complete 'pre-work' prior to coming to the interview. Participants were sent the pre-work one week before the live interview. The pre-work consisted of two sections:

1) Thought bubbles using denim jeans, cotton shirt and silk night dress;
2) Images that reflect the participant's thoughts on fabric feel using all senses available.

3.3.11.1.4.2 Thought Bubbles

Photographs were taken of three everyday garments: denim jeans, cotton shirt and silk nightdress, being held up and with them, thought bubbles were attached along with the question:

"What do you think this person is thinking or feeling when considering this item of clothing?"

The thought bubbles given to participants can be seen in Appendix 8.1.

Instructions to participants were as follows:

Please fill out each thought bubble with words and/or pictures that you think the people in the images are thinking about when considering or choosing these fabrics.

3.3.11.1.4.3 Sensorial images

For the second part of the pre-work, participants were given the instructions:

Please bring with you 6-8 pictures/images (which could include family photographs, images cut out of magazines or newspapers, or images searched on the internet) that represent how you assess the feel of a fabric using all your senses.

3.3.11.1.5 Interviews

Firstly, the participants were assured that all discussions that were to occur during the interview were confidential and that were not for the purposes of P&Gs marketing or research for advertising etc. Participants were made aware that they could withdraw at any point during the hour interview and were also free to withdraw their information up until May 2013. All participants were asked if they had any questions before starting the interviews and then were asked to sign a consent form after reading the information sheet provided (see Appendix 7).

The interviews were started with ice breaker questions (see Appendix 8 for more information), firstly about their job roles, followed by questions which then referred more to fabrics and garments to engage the participant and to make them feel more comfortable with the audio recording and to the interviewer.

3.3.11.1.5.1 Pre-work

Participants were asked if they had completed the pre-work and if they would like to show their findings; firstly, the thought bubbles and secondly, the images. Participants were asked to elaborate on their thoughts of each garment to specifically address what the person holding the garment would be thinking if it was not already communicated. Exploratory questions were used based on each participant's responses to each thought bubble.

Participants were asked to show the images they had brought with them and elaborate on which senses were used to select the images.

3.3.11.1.5.2 Main interview

There were 6 sections to the main interview for the participants to work through and were as follows:

1) Grouping fabric swatches exercise

   30 fabric swatches were laid out in front of each participant and they were asked to place the swatches into groups based on any thoughts they had (1st grouping). This was then followed by a 2nd and 3rd grouping exercise, where they were then asked to re-group, again, in any way they would like, but that was different to the 1st grouping.

2) Sensory probe 'If I were an alien…'

   Participants were asked to describe three garments: a grey silk night dress, a 100% cotton white shirt and a blue denim pair of jeans using the five senses (touch, smell, taste, sound and sight) along with an emotion and a colour which represented the garment they were feeling. The participants were asked to imagine that they were describing the garments to an alien, and therefore were not able to use the spoken word to describe their feelings e.g. they were expected to show the alien an object or an image that represented the texture/feel of the garment. Participants were also asked to give the alien opposite opinions i.e. what should the alien not look at to describe the fabric.

3) Senses hierarchy

   Participants were asked to fill out a hierarchy using the five senses (touch, sight, sound, taste and smell) based on how they themselves think when choosing or interacting with fabrics. They were also asked to put a weighting, in terms of percentage, to each sense based on importance, which was required to total to 100%.

4) Descriptors of sounds that would relate to fabrics and garments

   Participants were asked to provide descriptive words that they would use to describe sounds of fabrics.

5) Relating a garment to the extreme descriptors: rough and smooth

   Participants were asked to put two garments to either of the descriptors: rough and smooth.

6) Return to senses hierarchy

   Participants' attention was drawn back to the senses hierarchy having discussed sound and asked whether they would change their hierarchy.

All participants were thanked for their time and contributions and given their compensation, in addition to taking a debriefing sheet away with them.

3.3.11.2 Data analysis

The audio recording of each interview was listened to and transcribed allowing for multiple rereads and thorough analysis. As each interview was individual, and therefore not part of a discussion within a group of participants, all findings were purely based on each participant's opinion, and therefore important themes and main findings were drawn out of the transcripts to allow for comparisons and similarities to be observed.

3.3.12 Sound Manipulation Study

The results of this study are described within Chapter 7.

3.3.12.1 Participants

34 participants were initially recruited from within the University of Birmingham's community to take part in the study. However, 29 participants completed the study and who's data was used in analysis due to: 1 participant's data set being incomplete; 1 participant looked behind the staging at the setup of the study; and 2 participant's guessed that it was the same fabric that they were feeling during the study. Therefore, these participant's data were removed from the whole data set. Out of the 29 participants that were analysed, 22 were females and 7 were males.

3.3.12.2 Apparatus

A schematic of the experimental setup to enable participants to listen to real-time manipulated fabric sounds can be seen in Figure 3.32.

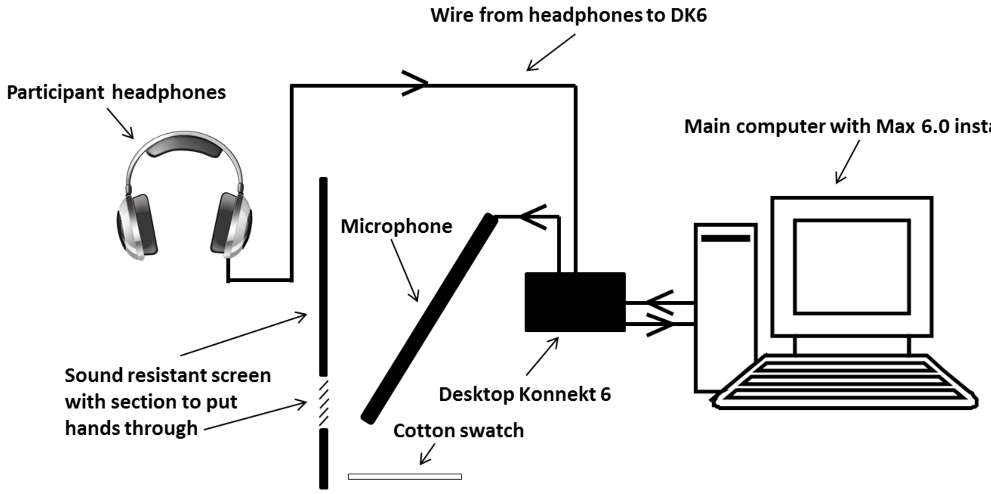


Figure 3.32 A schematic of the sound manipulation setup.

Sound manipulations (see Section 3.3.12.5 for more information) were carried out using sound software (MAX 6.0, Cycling ’74, USA) sound software, created by Jesper Ramsgaard at DELTA SenseLab, Denmark. The ‘face’ of the system can be seen in Figure 3.33. The sounds were played out using a standard desktop computer with a 0.3 second delay in real-time.

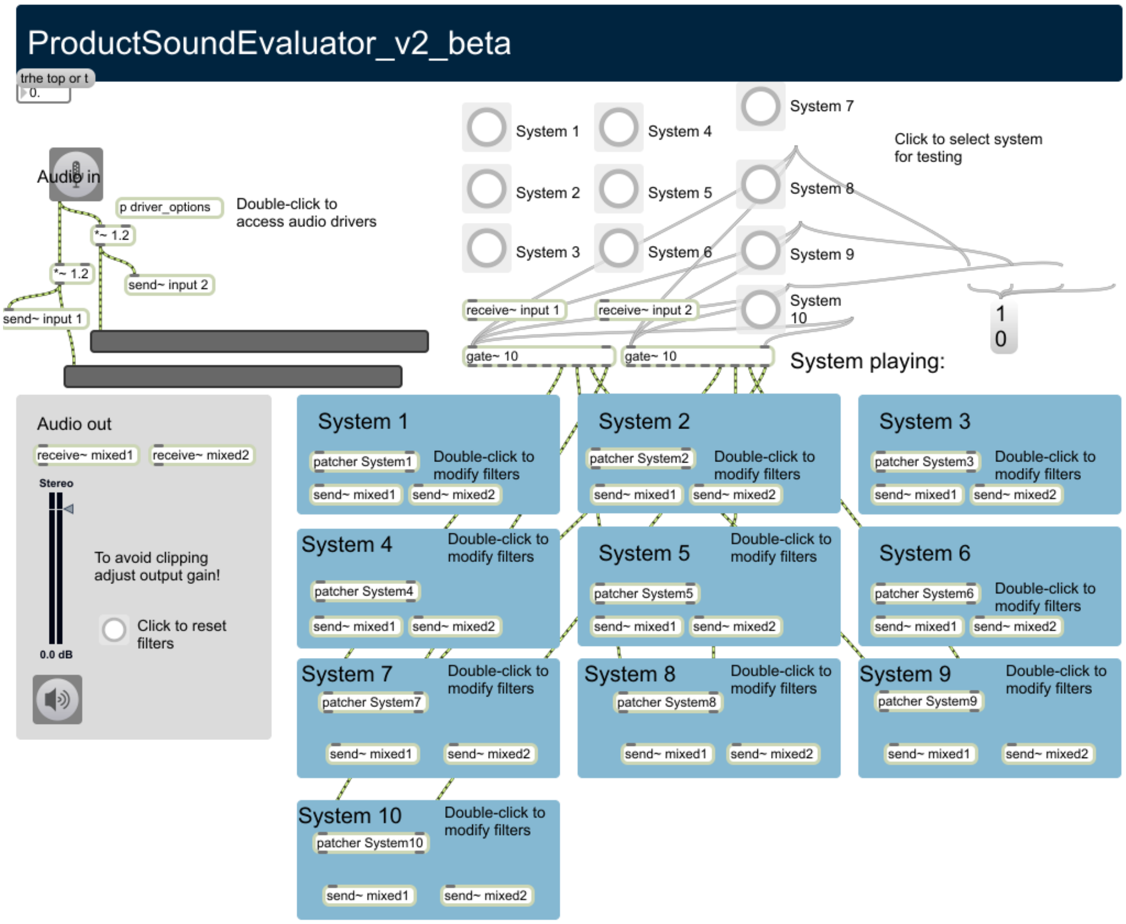


Figure 3.33 The face of MAX 6.0 sound manipulation software. 'System' refers to each sound manipulation.

A Desktop Konnekt 6 Firewire Audio Interface and Monitor Control (TC Electronic, Denmark) was used to, firstly, enable the real-time sound of the fabrics to be transmitted into the MAX 6.0 software, and then secondly, relay the manipulated sound into the headphones worn by the participant. A K6 Microphone (Sennheiser Electronic, GmbH & Co., Germany) was used to capture the fabric sound created by the participants when feeling the cotton fabric swatch and despatched into the MAX 6.0 sound software to be manipulated. Participants sat behind a sound resistant screen (created using wood covered in Acoustilay foam) with an opening for their hands to reach through to feel the fabrics.

3.3.12.3 Procedure

Initially, participants were asked to sit down in front of the sound resistant screen and read the information sheet (see Appendix 7), definitions of attributes (see Section 3.3.12.4) and sign the consent form (see Appendix 7). Participants were asked if they understood the list of attributes and their definitions, and to write all answers with their dominant hand therefore using their non-dominant hand to feel the fabrics.

The method of the study consisted of:

1) Each individual sound manipulation being selected before the sound was created without the participant being aware;
2) Fabric sounds being created by the participants;
3) The sound being captured by the microphone and fed into the computer via the Desktop Konnekt Control to be manipulated;
4) The manipulated sound being fed back into the participants headphones via the Desktop Konnekt Control;
5) Participants being asked to rate the attributes of the fabric feel whilst continuing to feel the fabric.

The participants carried out two practices of the procedure to become familiar with the requirements and also to ask any questions about the method before the main study began.

Participants were asked to wear headphones under the false pretence of needing to have all senses available to them except sight and were told it was fabric feel that was most important for the rating task and they were not to be influenced by sight. Unbeknown to the participants the sounds that were being fed into their ears was a manipulated sound. As the delay was so small, at 0.3 seconds, the participants were unaware of any change in sound.

Participants felt 10 individual cotton swatches that were cut from the same reel of cotton fabric to ensure that the sample was consistent, and no wear occurred in the swatch during the experiment which could potentially affect the original sound produced.

Participants were asked to rate the sensory attributes defined in Section 3.3.12.4 using a Visual Analogue Scale (VAS). Seven 100mm randomised VAS's were presented with a headed question "How [sensory attribute] do you think the fabric is?" and were anchored with opposing statements from left to right e.g. "Not at all [sensory attribute]" (scoring 0) and "Extremely [sensory attribute]" (scoring 100) (an example can be seen in Figure 3.34). Questions were varied slightly so that they were grammatically correct. After the study the lines were measured to determine the scores.

1. How smooth do you think the fabric is?

Not at all smooth | Extremely smooth

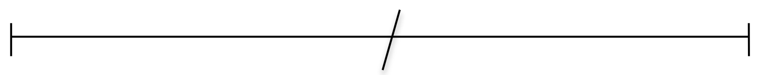


Figure 3.34 An example of a VAS question used to show attributes how the participants should rate.

3.3.12.4 Descriptions of attributes

The participants were given the following definitions to better understand the attributes that they were required to rate:

Liking (verb): Find agreeable, enjoyable or satisfactory.
Synonyms: be fond of, inclination.

Smooth (adjective): Even and regular, free from perceptible projections or indentations
Synonyms: even, sleek, soft, level, flat and fluent.

Rough (adjective): Having an uneven or irregular surface; not smooth or level
Synonyms: coarse, rugged, harsh, uneven, and ragged.

Soft (adjective): Easy to mould cut, compress or fold; not hard or firm to the touch
Synonyms: gentle and smooth.

Textured (verb): rough or raised.

Silky (adjective): of or resembling silk, smooth
Synonyms: silken, soft and silk.

Crisp (adjective): Firm, dry, and brittle.
Synonyms: fresh, crisps and crunchy.

3.3.12.5 Sound Manipulations

One original sound and nine manipulates were used, in a randomised order for each participant, and a summary of which manipulations were executed can be seen in Table 3.7. Where the overall decibel level has been manipulated, it refers to all sounds emitted at all frequency levels. MAX 6.0 software enables a number of manipulations to be carried out at one time to one sound inputted e.g. changing high and low frequencies, in addition to overall level, and specific frequencies. However, only one part of the sound which the participants heard was manipulated; high frequency manipulations were carried out on those frequencies above 1000 Hz, low frequencies were consequently below 2043 Hz and peak frequencies refer to those frequencies around 6500 Hz. All manipulations can be seen in Appendix 9.

Table 3.7 A table showing all sound manipulations. Code refers to what is written throughout the thesis; OL: Overall level (all frequencies), HF: High frequencies (above 2043 Hz), LF: Low frequencies (below 2043 Hz) and PI: Peak increase (frequencies around 6500 Hz)

Sound Manipulations	Code	Overall dB level	High frequency (Hz)	Low frequency (Hz)	Peak frequencies (Hz)
M1	OL +0 dB	0	0	0	0
M2	OL +3 dB	+3	0	0	0
M3	OL +6 dB	+6	0	0	0
M4	OL -3 dB	-3	0	0	0
M5	HF +6 dB	0	+6	0	0
M6	HF +3 dB	0	+3	0	0
M7	LF +3 dB	0	0	+3	0
M8	LF +6 dB	0	0	+6	0
M9	PI +6 dB	0	0	0	+6
M10	PI +3 dB	0	0	0	+3

3.3.12.6 Data Analysis

A number of repeated measures ANOVAs (Analysis of Variance) were performed on the data set to investigate the effect of sound manipulation on ratings of sensory attributes. Where a significant difference was established T-tests were carried out to establish for each sensory attribute which manipulations were significantly different from one another. To understand how true a statistical result is effect sizes, R, were also calculated for ANOVA results. Effect sizes for between-subjects designs are well known; however, as the sound manipulation study was within-subjects the method was modified and calculated using Eq. 3.10. The total sum of squares was calculated using the outputs from the ANOVA results (see Figure 3.35) and Eq. 3.11.

Eq. 3.10

$$\eta^2\ (effect\ size,\ R^2) = \frac{Treatment\ of\ sum\ of\ squares}{Total\ sum\ of\ squares}$$

Eq. 3.11

$$Total\ sum\ of\ squares = (\color{red}{Treatment\ of\ sum\ of\ squares} + \color{blue}{error\ of\ sum\ of\ square} + \color{green}{error\ (between) squares})$$

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
Sound	Sphericity Assumed	5001.917	9	555.769	2.684	.005
	Greenhouse-Geisser	5001.917	6.351	787.634	2.684	.014
	Huynh-Feldt	5001.917	8.414	594.450	2.684	.007
	Lower-bound	5001.917	1.000	5001.917	2.684	.113
Error(Sound)	Sphericity Assumed	52183.683	252	207.078		
	Greenhouse-Geisser	52183.683	177.816	293.471		
	Huynh-Feldt	52183.683	235.602	221.491		
	Lower-bound	52183.683	28.000	1863.703		

Tests of Between-Subjects Effects

Measure: MEASURE_1

Transformed Variable: Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	35721.270	1	35721.270	208.959	.000
Error	4786.570	28	170.949		

Figure 3.35 An example of ANOVA output used to calculate effect sizes. Coloured rings refer to coloured text in Eq. 3.11.

T-tests establish if there is a significant difference between two groups e.g. sound manipulations for a sensory attribute. Bonferroni T-tests were chosen as they are more conservative, and therefore any significant data that is observed is a true reflection of the data set and not by chance. T-test results can only be considered as true data when the variance between each group of variables, i.e. attributes and manipulations, is equal and therefore as a part of the T-test statistical analysis the variances are calculated and when they are equal Sphericity is met; a term used to explain the assumptions made that the relationship between the pairs of variables is similar. When the assumption of Sphericity is violated, the power of the data set is reduced and results are not statistically accurate in term of the F-statistic. This is corrected for by the means of other statistical methods also seen within the T-test output and for the purposes of this research the method chosen is Greenhouse-Geisser as it is more conservative, again, leading to true statistical results. Sphericity is violated when the significance value for Mauchly's Test of Sphericity is significant at $p < 0.05$.

ANOVA, for the purpose of this research, is a statistical procedure to compare, for each attribute, the mean scores of more than two conditions and compares the variance between the different conditions (i.e. 10 sound manipulations) with the variability within each condition (assumed to be due to chance i.e. error). As previously indicated an ANOVA was carried out for each attribute (i.e. 7 ANOVAs were performed). ANOVA results are presented in the form of an *F*-ratio which represents the variance between the conditions, divided by the variance within the conditions; a large *F*-ratio indicates more variability between the conditions, than within the conditions i.e. the difference between the mean scores of each sound manipulation is greater than the variability between the scores given by each participant.

Pearson's correlation, *r*, coefficients were used to gain further understanding of how the sensory attributes within each sound manipulation were related to each other and how significant the relationship was.

Results for the sound manipulation study were considered significant at $p < 0.05$ (i.e. 95% confidence). The results for ANOVA analysis are presented as [F (df_{sound}, df_{error}) = F-value, p = significance value, R = effect size] and the results of the t-test are presented in the following manner: [$\bar{X}$ (mean values, σ (standard deviation), p = significant value]. Correlations are presented in the form of tables with *r* values and significance values and written within the text as follows: [*r* (N (number of participants)-2) = correlation, *p* = significance value]. All data is presented as means with two standard deviations. Correlation results were considered to be significant when $p < 0.05$, and the strength of the relationship is as follows:

- Small: $r = .10$

- Medium: r = .30
- Large: r = .50

These relationships are also true for effect sizes, R, as in essence an effect size is a correlation which includes the strength value and its significance.

4 Investigations into the acoustics of apparel and model fabrics

4.1 Introduction

As described within Chapter 2 previous researchers have investigated the relationship between surface roughness and the total noise emitted from a wide range of materials such as paper (Aguilar *et al.* 2009), deliberately modified surfaces (to create a range of roughness') (Othman & Elkholy 1990; Othman *et al.* 1990; Stoimenov *et al.* 2007; Ben Abdelounis *et al.* 2010) manmade and natural fibre fabrics (Yi & Cho 2000; Yi *et al.* 2002) and non-woven fabrics (Tuscan & Vaughn 2008). However, a comparison between the surface roughness, total noise and specific frequencies emitted (without the use of KES or Zwicker's model) from apparel fabrics, model fabrics or conditioned samples has not been fully investigated.

Efforts have previously been made to understand how specific frequencies, seen within sound spectra produced under human load, change with the increase of deliberately engineered surface roughness (R_a) of metal samples. It was shown that on increasing Ra, the value of five specific frequencies also increased, and corresponded to their previously determined theoretical free vibration values (Stoimenov *et al.* 2007). The intention of this work was to begin to understand the relationship between fabric characteristics (i.e. the microstructure, including surface roughness) and the acoustics of friction (total noise and frequency). As fabrics are inherently complex (having many fibres and threads, and a specific weave), a simplified 'model' fabric (a mesh constructed of single fibre threads, with a uniform structure) can provide valuable understanding of the sound spectra that is produced in simplified systems (Moholkar & Warmoeskerken 2003). For this reason, in this work a 'model' polyester mesh was investigated, in addition to apparel fabrics (specifically denim, cotton and silk).

Further aims of the work presented in this chapter were to understand the characteristics of apparel and model fabrics, i.e. microstructure (thread diameter, aperture size, fibre count/diameter etc.) and surface roughness in addition to the frictional noise they produce. Efforts were made to relate the frictional noise to surface roughness, and consider the effect of surface modifiers e.g. fabric conditioners. As well as understanding total noise within a sound spectra, this work also aimed to relate the fabric microstructure to specific frequencies that would be expected based on the method created in Section 3.3.3.4 that considers the space between adjacent threads.

Apparel fabrics (denim, cotton and silk) and model fabrics were subjected to friction and their resulting frictional noise was recorded within the SRR (described within Section 3.3.2). The frictional noise captured in WAV. format was FFT'd in MATLAB producing Frequency vs. Amplitude sound spectra. The total noise of each sound spectrum was measured using an AUC method. The characteristics of each fabric tested were imaged using two methods: interferometry and microscopy. Microscopy images were used to measure the microstructure of the fabrics which was then used to calculate theoretical frequencies expected to be seen in sound spectra produced. Interferometry was used to establish the surface roughness measurements of each fabric sample.

4.2 Frictional noise of model and apparel fabrics

The frictional noise produced by both model and apparel fabrics can be seen in Figure 4.1 and on observation there were two distinguishing differences between the spectra: specific frequencies below 2000 Hz for model fabrics and a broad peak around 5000 Hz for apparel fabrics. As model fabrics are single fibre structures, the difference between the two spectra is thought to be a combination of reasons, i.e. the lack of fibres presents and also the relationship between apertures and thread diameters in both types of fabrics. The reasons behind the differences are hypothesised extensively below.

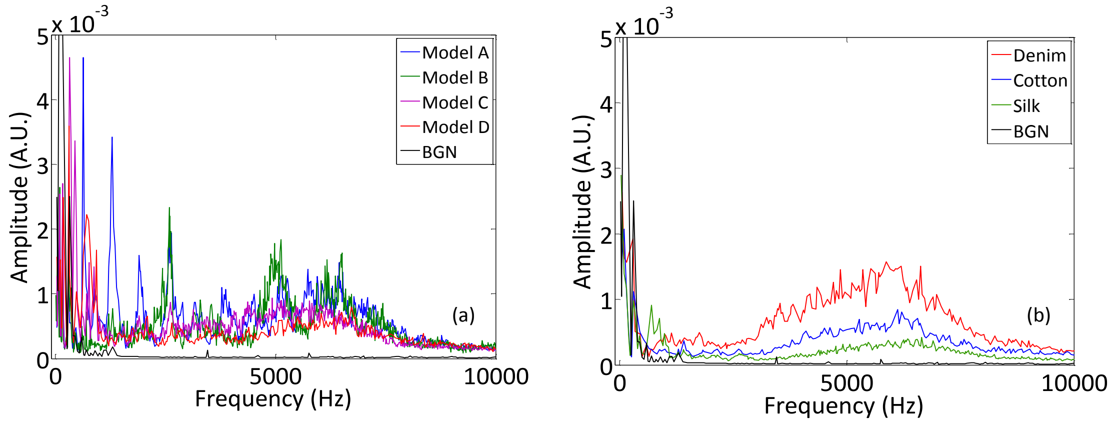


Figure 4.1 Frequency vs. Amplitude spectra (one repeat) for (a) model (A, B, C and D) and (b) apparel fabrics (denim, cotton and silk) produced within the SRR. Background noise (BGN) is also presented. Characteristics (including dimensions) of all the apparel and model fabrics can be seen in Table 3.1.

4.3 Relationship between microstructure and frictional noise

4.3.1 Model fabrics

As was presented in Section 3.3.3.4, it was possible to calculate the predicted frequency based on the microstructure (S.B.A.T (mm)) and the speed in which the SRR was run. For all model fabrics the expected frequencies were calculated and are presented in Table 4.1. These predicted frequencies were also observed within the measured sound spectra. The calculated frequencies were regarded as the fundamental and harmonics of the sound, based on the single calculation of the microstructure.

Table 4.1 Fundamental frequencies both calculated and measured for all Model Fabrics. Characteristics of the model fabrics can be seen in Table 3.1.

	Model A	Model B	Model C	Model D
Calculated (Hz)	2300	1142	585	286
Measured (Hz)	2602 ± 25	1217 ± 16	652 ± 29	309 ± 8

A sound that produces a periodic wave is a combination of harmonics and produces a specific pitch at a certain frequency (a schematic example can be seen in Figure 4.2 (a)). This frequency can be calculated and its resulting pitch should be relatively close to the one produced (when background noise and material properties have been taken into consideration). The model fabrics exhibit a defined and consistent aperture and thread diameter, resulting in a structure that is 'sinusoidal' (periodic wave) (see Figure 3.3 for microstructural images). When considering each fibre individually and when that fibre was made to produce a sound, (either by plucking, vibrations or in the case of the SRR, created by friction between two surfaces), it would be related to the simplest form of that sound, more commonly known as the fundamental harmonic.

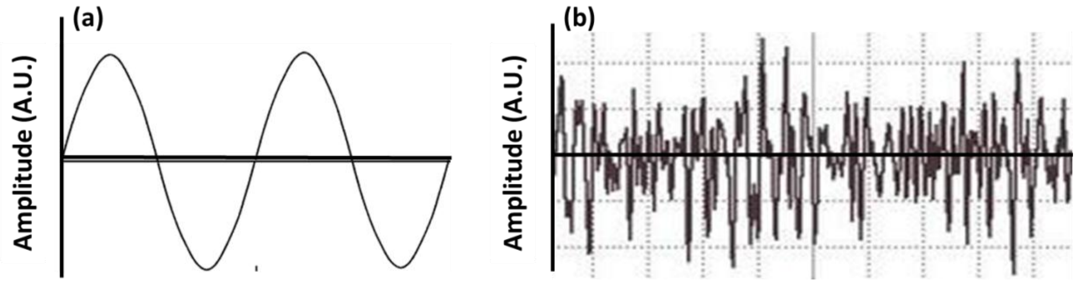


Figure 4.2 A schematic of (a) a periodic sine wave and (b) a non-periodic wave, showing amplitude (A.U.) vs. any variable required i.e. for this research it represents (a) woven thread pattern and (b) fibre arrangement (figure adapted from (Crowell 2011))

As can be seen in Figure 4.3, for the model fabrics, a number of individual frequency peaks were apparent, and those with a black asterisk are representative of the fundamental harmonic. When comparing both the calculated and measured frequencies a perfect correlation was seen (R^2 = 1.00) in Figure 4.4, indicating that it is possible to create a 'fingerprint' of frequency according to microstructure. This fingerprint can be used to accurately predict the fundamental harmonics of an unknown mesh sample and has not been established previously within literature (Cooper *et al.* 2013).

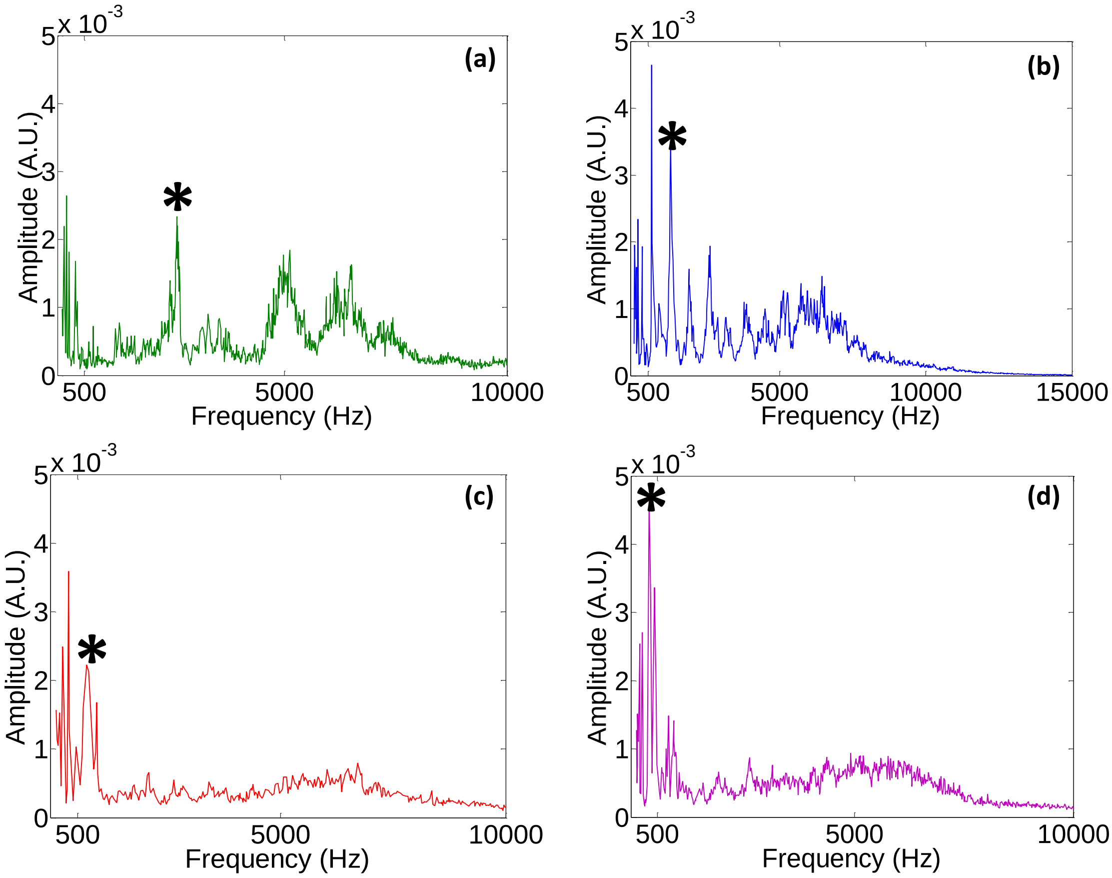


Figure 4.3 Frequency vs. Amplitude (A.U.) sound spectra (one repeat) of Model Fabric (a): Model Fabric A, (b): Model Fabric B, (c): Model Fabric C and (d): Model Fabric D). Black asterisk identifies the measured fundamental frequency corresponding to the fundamental harmonic as calculated using Equation 1. Characteristics of the model fabrics can be seen in Table 3.1.

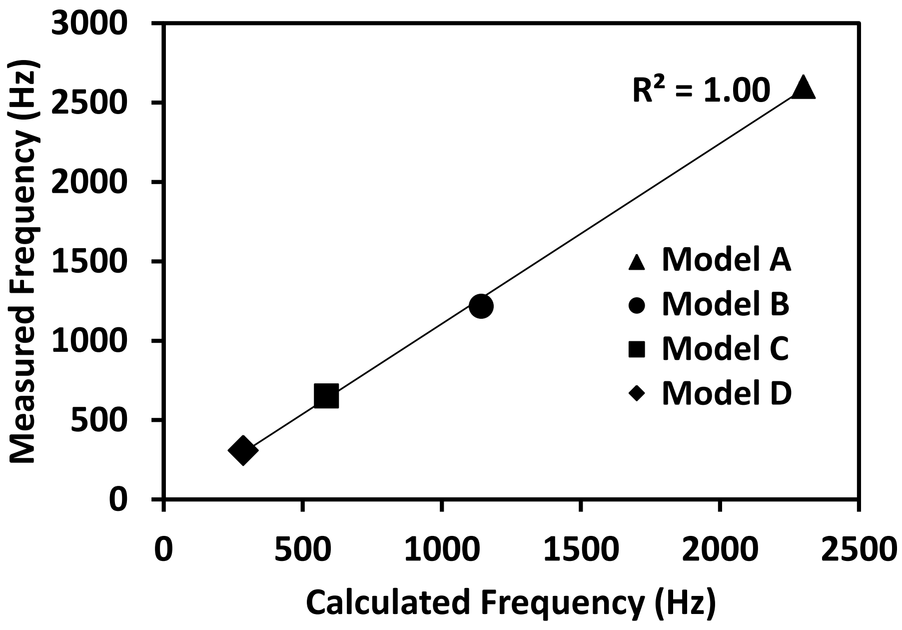


Figure 4.4 Comparing fundamental frequencies of both calculated (using Equation 1) and measured (3 repeats from sound spectra produced) for model fabrics 'A', 'B', 'C' and 'D'. A correlation of R^2 = 1.00 indicates a perfect linear correlation. Characteristics of the model fabrics can be seen in Table 3.1.

As previously discussed, the model fabrics would not only produce a fundamental harmonic, but multiples of this frequency/harmonic to create an overall sound. The multiple strong specific peaks recorded (see Figure 4.3) could be attributed to the multiple harmonics expected. The frequencies were measured and plotted against calculated harmonics i.e. second, third and fourth, and once again showed a strong correlation (R^2 = 0.93) (presented in Figure 4.5).

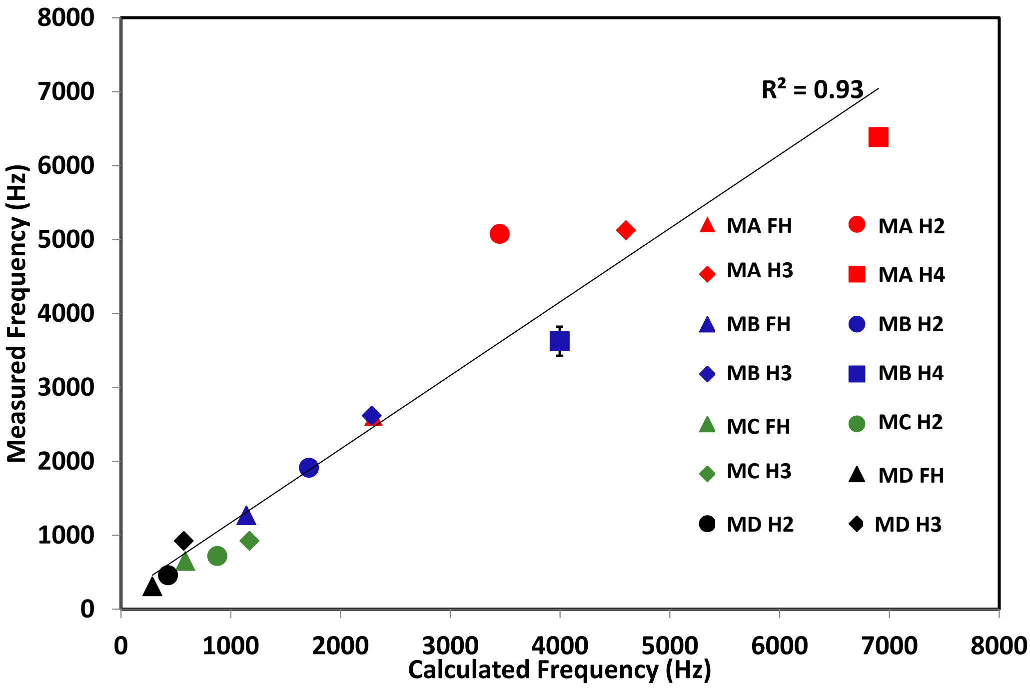


Figure 4.5 Comparing calculated frequencies with those measured from the sound spectra produced in Figure 4.3 in terms of the series of harmonics for each model fabric tested with the SRR. Coding is broken down into: where 'MA' refers to Model A, 'MB refers to Model B etc., and 'FH' refers to fundamental harmonic and 'H2' refers to second harmonic etc. A correlation of R^2 = 0.93 is presented.

4.3.2 Apparel fabrics

The apparel structure can be divided into three layers or scale: firstly, the macro scale: that which can be seen by the eye (potentially a weave pattern if large enough) and is generally the surface structure and could be known as texture; secondly, the macro-micro scale: each individual thread within the main weave; and thirdly, the micro scale: the number of fibres which make up those threads. In this research, macro-micro and micro scales were considered and in particular fibre count.

As with the model fabrics, the theoretical frequencies were also calculated for apparel fabrics to determine whether a fingerprint prediction could also be made for multi-fibre systems. Using the same method, the space between adjacent threads was measured using the portable microscope in both the warp and weft orientations (see Section 3.3.2.6 for methodology) of the fabric to establish an overall understanding of the apparel fabrics characteristic (Table 4.2). The frequencies for all three apparel fabrics tested are one order of magnitude lower than Models A and B; however, they sit relatively close to Model C and D, indicating that the space between adjacent threads is similar and therefore could be used as a direct comparison between single and multi-fibre systems. When analysing the sound spectra produced by the three apparel fabrics it was clear that there were no distinguishing or stand-alone frequency peaks which, from calculations in Table 4.2 (Figure 4.6), represent the fundamental harmonic.

Table 4.2 Calculated fundamental frequencies of all apparel fabrics and the space between adjacent threads (S.B.A.T) (mm) as measured using a Veho Light Microscope and Image J. Average of 6 measurements.

	Silk		**Denim**		**Cotton**	
	Warp	**Weft**	**Warp**	**Weft**	**Warp**	**Weft**
S.B.A.T (mm)	0.228 (±0.005)	0.350 (±0.005)	0.531 (±0.0006)	1.670 (±0.009)	0.211 (±0.012)	0.367 (±0.025)
Frequency (Hz)	807	534	347	114	872	501

When considering the difference between the model and apparel fabrics, aside from being made from different raw materials, the lack of frequencies present are attributed to the single and multi-fibre structures respectively, particularly as all models, cotton and silk are all created with the same plain weave. There are between tens and hundreds of times more fibres within a single thread of an apparel fabric, than the single fibre model thread, as can be seen in Figure 3.1. In the previous section it was discussed that harmonics are responsible for producing a periodic sound wave (see Figure 4.2 (a)), and that, that schematic sound wave was mimicked by the structure of the model fabric. However, when we consider a plainly woven cotton or silk, which we could assume to be periodic in macro-micro structure, the number and nature of the fibres within a thread must also be considered and are deemed to be non-periodic in characteristic.

A non-periodic sound, unlike a sinusoidal wave, would not produce specific frequencies with certain pitches and would result in a wave spectrum similar to Figure 4.2 (b): that represents the fibre structure. The fibres present are thought to affect the frictional noise in two ways: 1) that they absorb any harmonics produced and 2) that a non-periodic wave would not produce different harmonics sought.

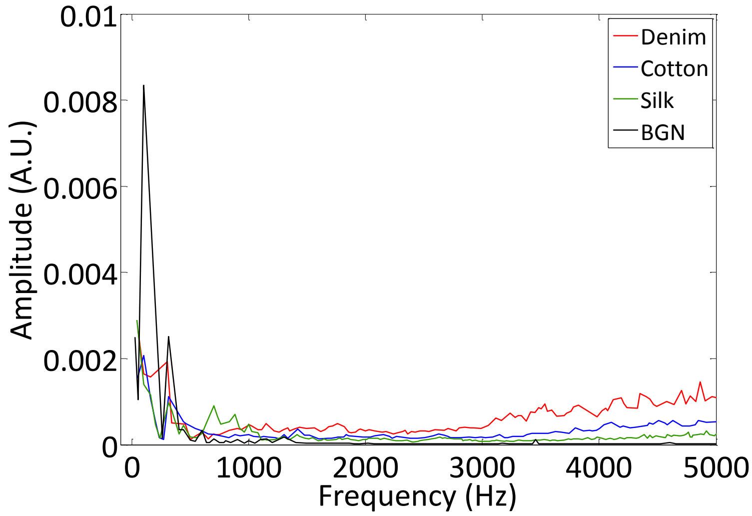


Figure 4.6 Frequency vs. Amplitude sound spectra showing the lack of frequency peaks below 5000 Hz for all three apparel fabrics and back ground noise (BGN)

As described within Section 2.6, a common use for fabrics is the absorbance of unwanted noise, i.e. the material lining a sound proof room, car interiors and soft furnishings within a home. A wide range of materials/fabrics have been developed with such a requirement in mind and generally are very densely packed with multiple fibres in order to increase the potential for the fabric to absorb the background noises. A method of engineering such fabrics is to create hollow fibres that are better able to absorb louder noises; Mahmoud *et al.* (2011) found that the more hollow the fibre, the more effective the sound absorbance was. This understanding can be used to further explain the lack of fundamental frequencies seen for apparel fabrics when compared to model fabrics, as the sheer number of fibres and the spaces; 'hollow areas', between those fibres could be responsible for absorbing harmonic frequencies, produced by the macro-micro scale. It is thought that the noise that was produced from each thread (calculated frequencies) is acoustic energy and vibrational energy from the elastic and plastic deformation of the fibres themselves (discussed in Section 4.4) and was theoretically dissipated into the bulk, (i.e. within the fibres). Whereas, the model fabrics were designed by the manufacturers to be rigid and not easily deformed due to the pressure being inflicted upon them during screen printing and therefore, do not elastically or plastically deform and consequently the acoustic energy is emitted as microstructural frequencies.

4.4 Establishing surface roughness of apparel and model fabrics and the relationship with total noise

4.4.1 Apparel fabrics

All apparel fabrics were imaged using Interferometry (see Figure 4.7) which enabled an overall surface roughness (R_a) value to be determined: denim R_a = 68 μm, cotton R_a = 24 μm and silk R_a = 11 μm. However, on further reflection this method used initially was deemed not representative for a number of reasons. As previously described within Section 3.3.3.1, R_a is calculated using the average change in colour over the whole area imaged and therefore, particularly with silk, the aperture between threads was also taken into account (apertures do not directly influence the surface of the fabric). As the aperture of the fabric was seen to reflect little light, and therefore produced the darkest areas, it would influence the value of R_a calculated, and did not represent the fabric as a whole. 'Tilt', which is affected by the angle at which the sample lay on the measuring stand, was also deemed a limitation of the method (as can be seen in Figure 4.7 (b)); where the colour which represented the tops of threads changed over the area tested, and therefore what was actually a high point of the sample, because it reflected poorly, was understood by the software (SPIP) as a low value and these issues affected the R_a value. As such, it was decided that an overall roughness measurement (R_a) could not be relied upon for all apparel fabric surfaces.

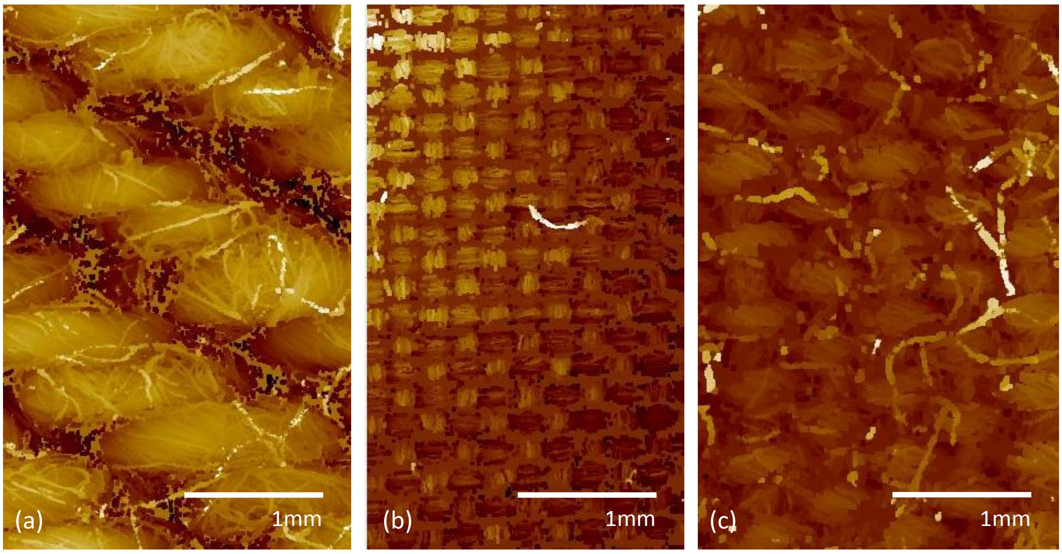


Figure 4.7 Interferometry microstructural images of 'de-sized' wardrobe fabrics: (a) denim, (b) silk and (c) cotton.

Figure 4.8, Figure 4.9 and Figure 4.10 show the progression of establishing the surface roughness values for each apparel fabric: denim, silk and cotton, respectively. It was established that in order to reduce the effect of aperture reflectance on roughness measurement, the change in height over an individual thread was deemed to be more representative. All (a) and (b) sections of each interferometry figures below depict the images and change in height (μm) of a section of the apparel weave (shown by the white line). From this, the roughness measurement was calculated using a single thread height and can be seen in sections (c) and (d) of the figures.

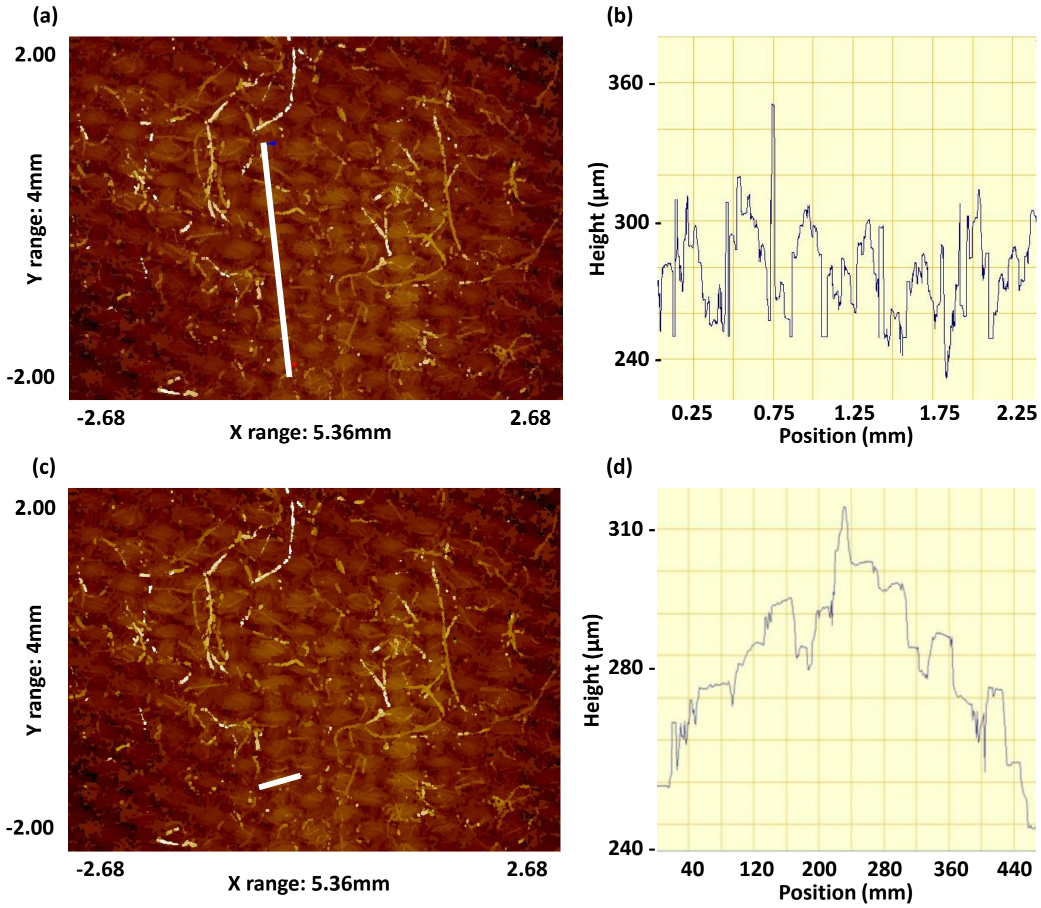


Figure 4.8 Interferometry images and plots for cotton. An overall image of an area of fabric (4 mm x 5.36 mm) seen on the right of the figure (a,c) with the cross sectional height change plot over the weave of the fabric (µm) (b,d). Each image shows a white line to depict where the plot has been taken from; (b) is an overall understanding of the weave pattern and (d) is the change in height over one thread. The height is calculated using the SPIP.

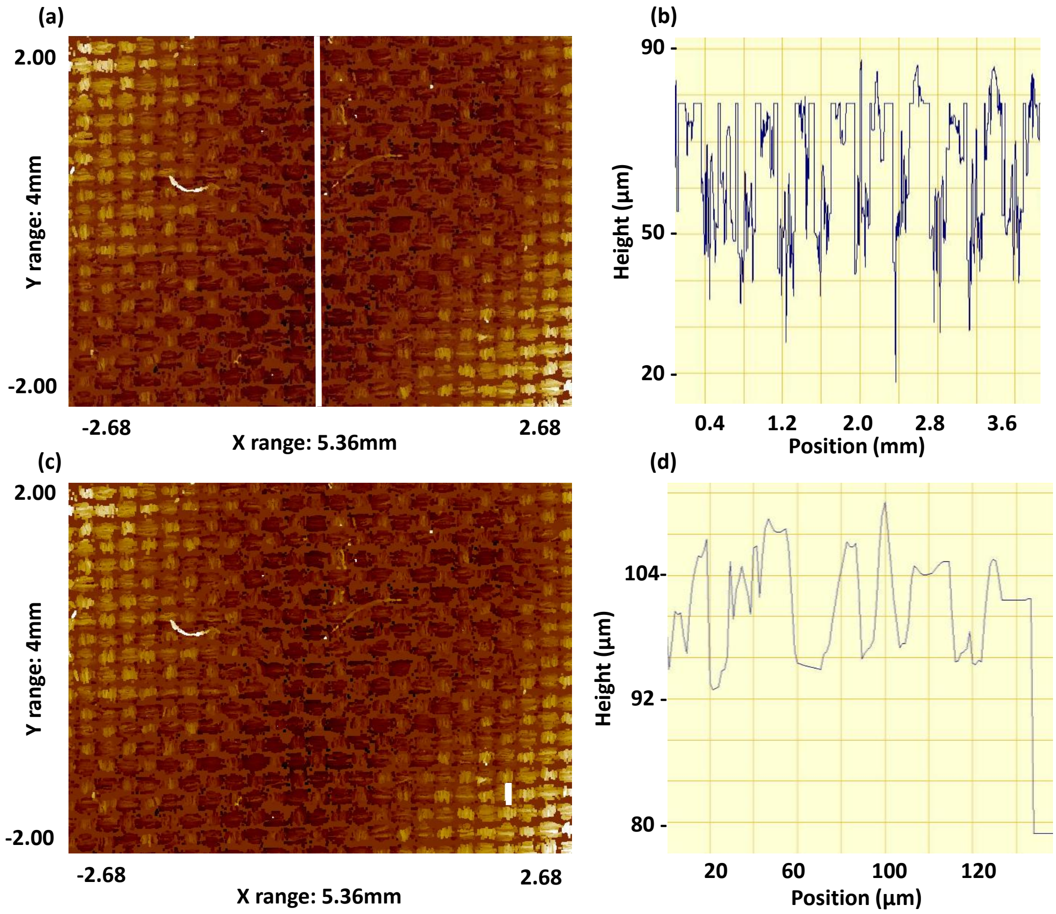


Figure 4.9 Interferometry images and plots for silk. An overall image of an area of fabric (4 mm x 5.36 mm) seen on the right of the figure (a,c) with the cross sectional height change plot over the weave of the fabric (μm) (b,d). Each image shows a white line to depict where the plot has been taken from; (b) is an overall understanding of the weave pattern and (d) is the change in height over one thread. The height is calculated using the SPIP.

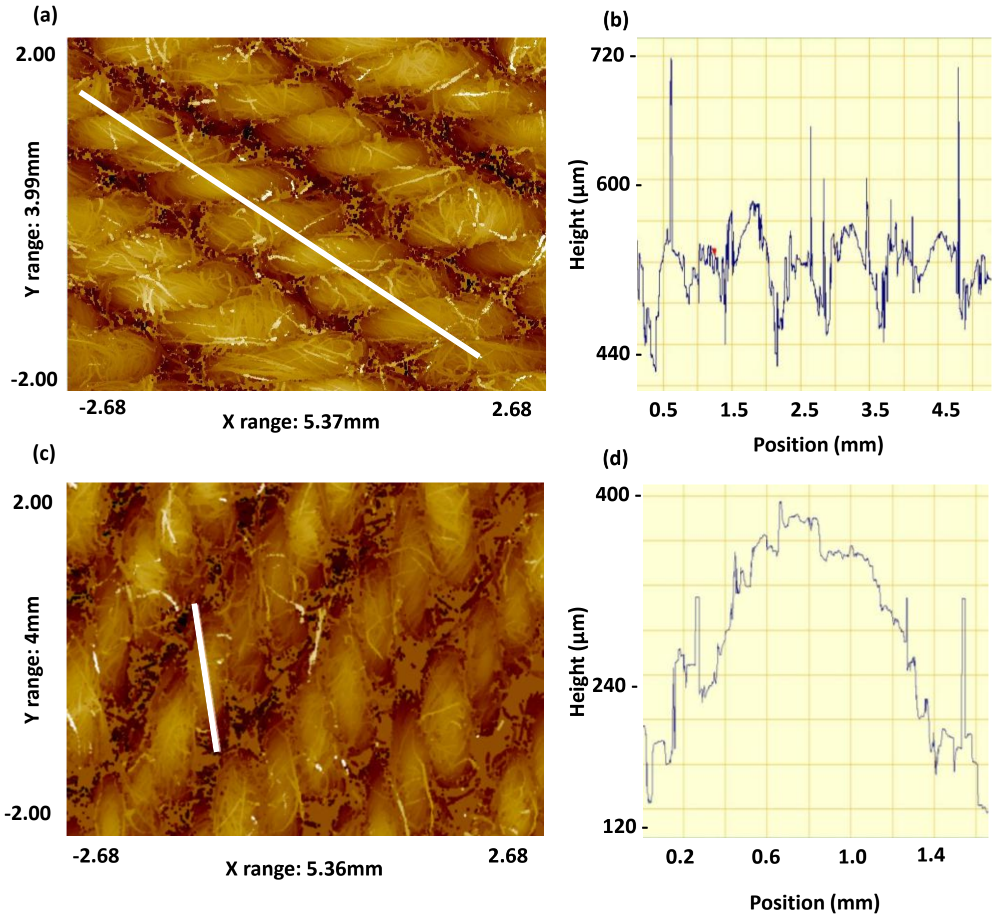


Figure 4.10 Interferometry images and plots for denim fabric. An overall image of an area of fabric (4 mm x 5.36 mm) seen on the right of the figure (a,c) with the cross sectional height change plot over the weave of the fabric (μm) (b,d). Each image shows a white line to depict where the plot has been taken from; (b) is an overall understanding of the weave pattern and (d) is the change in height over one thread. The height is calculated using the SPIP.

4.4.1.1 Effect of surface roughness on total noise

To establish if, like previous surfaces mentioned within Section 2.4.1 (Othman & Elkholy 1990; Othman *et al.* 1990; Akay 2002; Ben Abdelounis *et al.* 2010; Akay *et al.* 2012), there was a relationship between the measured R_a values for the apparel fabrics' total noise produced, all sound spectra were compared to interferometry data (see Figure 4.11). As can be seen there was a noticeable difference between the sound spectra of the three de-sized apparel fabrics (Figure 4.1 (b)) and when related to total noise (AUC) which is plotted in Figure 4.11. A strong correlation was observed between the two variables (R^2 = 0.97), whereby, the higher the surface roughness the louder the frictional noise produced. As previously discussed this relationship was formerly well investigated for a range of materials (Othman & Elkholy 1990; Othman *et al.* 1990; Cho *et al.* 2001b; Stoimenov *et al.* 2007; Ben Abdelounis *et al.* 2010), both manmade and natural, however, for fabrics it is less so. Theories have been presented within literature to explain the relationship between surface roughness and the noise created; Das *et al.* (2005) suggests that when surfaces with a certain degree of roughness, when under light load, slide over one another, it is their asperities that impact and 'jump' causing energy to be dissipated in the form of acoustic energy. Therefore, as the number of asperities is increased, which increases surface roughness, there will be a higher level of dissipated energy, and in turn increased acoustic energy. This relationship was also seen within Othman's (1990) research on metal surfaces, however, a comprehensive explanation was not given.

In this research, asperities were considered to be the fibres and, the friction created by one sample of apparel fabric running over the same fabric. It is thought that fibre number and density are related to the friction noise, as described within Section 4.3, and it is those fibres which could be attributed to the increase in total noise. As one fibre moves towards the next available fibre it results in an interactive force, albeit a weak one (Das *et al.* 2005). In simple terms, both fibres will 'lock' to one another, either on the top or side of the surfaces of each for a short time (i.e. milliseconds) and the energy required to 'pull' the fibres apart results in the force being dissipated in the form of frictional noise. If each fibre creates its own frictional force to enable it to be released, an increase in the number of fibres results in a greater increase in overall frictional force and would, then, go some way to explain the increase in total noise with surface roughness.

As fibre number was discussed earlier, alongside this understanding the effect of the original fibre type on fibre count was imperative. As can be seen in Figure 3.1, the construction of each thread for silk and cotton is very different: silk fibres are aligned in parallel and are generally the length of the thread itself, however, cotton and in particular denim, are short, coarse and are bunched together in a less uniform pattern. The latter arrangement results in a 'hairiness' of the macro surface (Arshi *et al.* 2012): a greater number of fibres being freely able to move away from the main structure, and therefore more available for the interlocking forces to occur. If cotton is considered to be hairier than silk it would result in a greater total noise being produced, which was observed in Figure 4.11. The proportional increase between materials in terms of weave can be further explained that when silk and cotton are compared they are both examples of plain weave. The hairiness difference between cotton and denim could be explained by the change from plain to twill weave which was also observed by Bueno *et al.* (1996) whereby the friction coefficient was higher for twill woven cotton compared with plain weave.

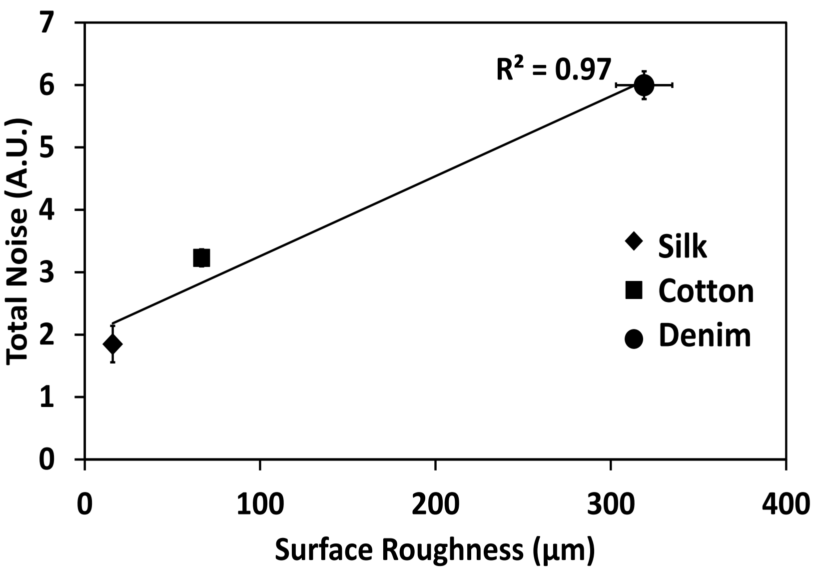


Figure 4.11 Surface Roughness (µm) (measured using Interferometry) vs. Total Noise (A.U.) (area under curve) for all apparel fabrics. An R^2 value of 0.97 is also shown.

As only three woven fabrics were tested, it would be beneficial to both enhance and verify the strong correlation seen in Figure 4.11 by increasing the number of fabric types, which in particular would have surface roughness' that were below silk and above denim, and potentially have different weave patterns. As with model fabrics, it would be a good opportunity to try to create another 'fingerprint' theory based on fibre count, fibre type and thread diameter etc. with the apparel microstructures given and that an unknown sample could be mapped to a predicted total noise. An example of such theory was created by Aguilar *et al.* (2009) in which they produced an algorithm with parameters including roughness measurements, frequencies and total noise and was tested with known tissue paper samples. In order to verify the algorithm they then measured 51 new tissue paper samples and showed confidence in 90.2% of the results. Based on the sound parameters they suggest that their algorithm is capable of predicting the surface roughness of paper samples.

To summarise it was thought that fibres within apparel fabrics are responsible for two actions: the bulk of the frictional noise (AUC) and also absorbing the fundamental harmonics.

4.4.2 Model fabrics

It was not possible to measure the surface roughness of the model fabrics using Interferometry as they were too reflective; the arc of the cylinder was too great for light reflectance which resulted in obscure and not reproducible values. Using the theoretical understanding that the change in height over the thread is related to surface roughness, the surface roughness of the model fabrics was predicted using the model in Figure 4.12 and Eq. 4.1 and is presented in Table 4.3.

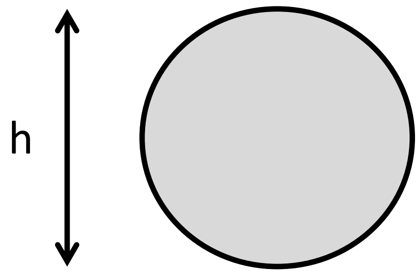


Figure 4.12 Schematic of the cross sectional area of a model fabric used to theorise the surface roughness

Eq. 4.1

$$\mathbf{Surface\ roughness} \cong \frac{\mathbf{h}}{\mathbf{2}}$$

Table 4.3 Surface roughness measurements for model fabrics

	Model A	Model B	Model C	Model D
Surface Roughness (mm)	0.017	0.032	0.056	0.1055

4.4.2.1 Effect of surface roughness on total noise

When the surface roughness was compared to the total noise produced within the SRR (see Figure 4.13), it was observed that there was no relationship between the two variables. This would suggest that the increase in both aperture and thread diameter of each model fabric did not affect the total noise produced. As model fabrics are single fibre structures the fibre interlocking force theory cannot be used to explain the total noise produced here, however, the surface roughness was theoretical and therefore cannot be confidently relied upon to dismiss a lack of relationship as a true result.

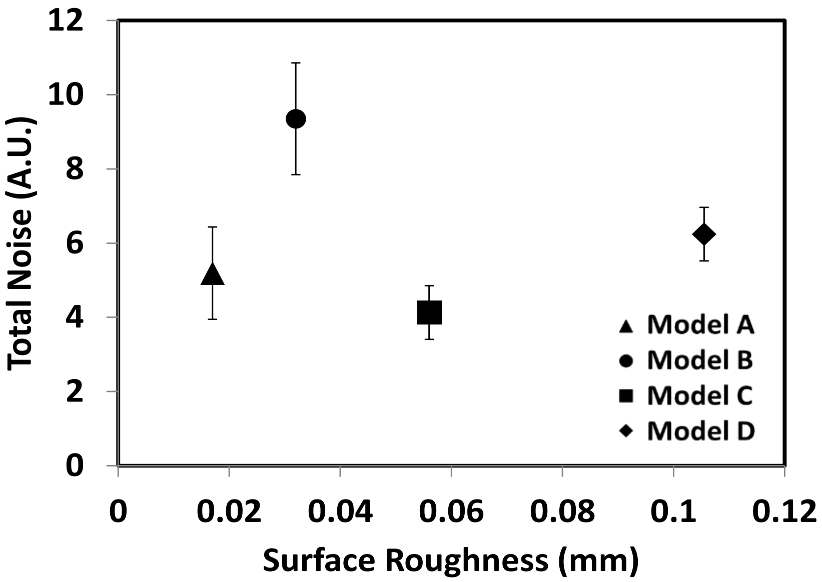


Figure 4.13 A plot showing the relationship between surface roughness and total noise of all model fabrics

However, if the lack of relationship is to be regarded as a true result (regardless of theoretical roughness values) the action of how the single fibres interact and consequently how this then impacted on frictional noise produced was understood. The microstructure of the model fabrics, under the process of producing frictional noise, was investigated in terms of ratio between aperture size and thread diameter where: Model A = 0.71; Model B = 0.75; Model C = 0.45 and Model D = 0.51. With a higher ratio level the aperture size is not too dissimilar to the thread diameter (a ratio of 1:1 would be as a result of an aperture and thread diameter with the same measurement) and therefore as the fibre of the sled surface is entering the aperture of the base surface it could be thought to be exiting almost exactly at the same time and impacting on the next fibre producing lower levels acoustic energy (see Figure 4.14 (a)). However, when the ratio is small, and in the case of Model C and D, the size difference between the aperture and thread diameter becomes insignificant when increasing both variables of the microstructure. As model D is almost double the dimensions of Model C they will behave in a similar manner, and therefore a difference in total noise would not be expected between either. In terms of the total noise produced, it was thought that the impact between one fibre and another is larger within smaller ratios as there is not a rolling action from the previous fibre to reduce the acoustical energy emitted, resulting in larger peaks at lower frequencies.

The schematic in Figure 4.14 shows the relationship between the size of the aperture and the resulting impact of one fibre against the next: the larger the aperture, the larger the impact and hence a larger acoustical energy. As was already described within Section 4.3.1, frequencies for the model fabrics with larger dimensions (i.e. aperture and thread diameter) were produced at much lower levels and were seen to have larger amplitude heights. This was thought to be due to the aperture size and that the rolling fibre would have to travel further to impact upon the base thread and therefore would happen less frequently and on the contrary those with smaller apertures, e.g. Model A were seen to produce much higher frequencies (Figure 4.3).

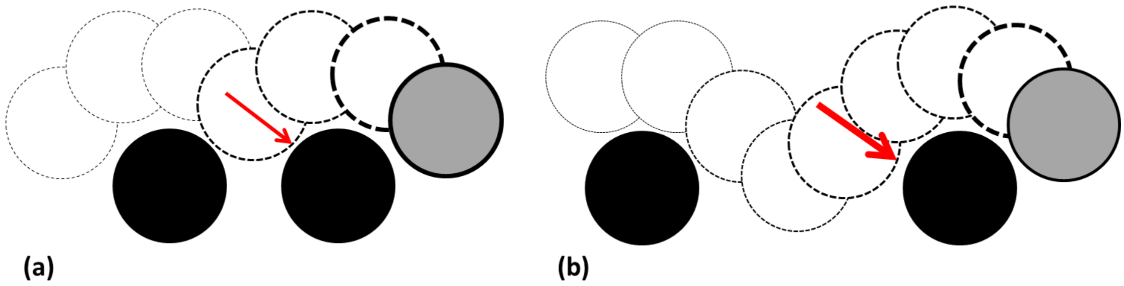


Figure 4.14 A schematic depicting the momentum of one model fabric (grey threads) running over a base model fabric (black threads) of (a) small aperture and (b) large aperture size, with respect to one individual fibre. The red arrows indicated the impact factor of one fibre interacting with the adjacent fibre; a larger impact is achieved by a larger aperture.

It is also difficult to compare apparel and model fabric roughness' in terms of total noise due to the nature of the construction of the specific model fabrics used where the warp and weft threads are welded together as opposed to only being woven (this method gives the model fabrics their strong characteristic when being pulled) which could give a different behaviour. This is something to consider for future work: to investigate the effect of welding on model fabrics when compared with non-welded fabrics in more detail.

4.5 Effect of washing on total noise

Apparel fabrics were subjected to surface modifications by means of fabric conditioners (CFE), as described in Section 3.3.5.2, in addition to being left with the manufacturer's sizing (MS) intact to understand the effect of original conditioning. This was then compared to the data already presented for de-sized fabrics (Figure 4.1 (b)). The surface modified apparel fabrics were run within the SRR and the resulting sound spectra are presented within Figure 4.15. As can be seen, there was not a noticeable difference between surface modifications, surface roughness or total noise (see Figure 4.16). However, previous research shows that when a fabric is treated with an enhancer or conditioner it, both objectively and subjectively, changes the surface roughness of said fabric (Hasani 2010; Zia *et al.* 2011). Figure 4.16 shows that when all 9 variables (three surface modifications per three apparel fabrics) were plotted in terms of surface roughness against total noise, a positive correlation ($R^2 = 0.86$), albeit not as strong as for de-sized fabrics ($R^2 = 0.97$), was seen. It is not to say, however, that a change in surface roughness did not occur when the apparel fabrics were modified, only that it was not determined by the interferometry method used. As has already been stated, surface roughness was measured as a change in height over one individual thread and it was thought that the mechanism of a fabric conditioner is not to swell a fibre/thread but to fill in the available spaces between said fibres and threads, and therefore would not be measured in any significant detail by the interferometer.

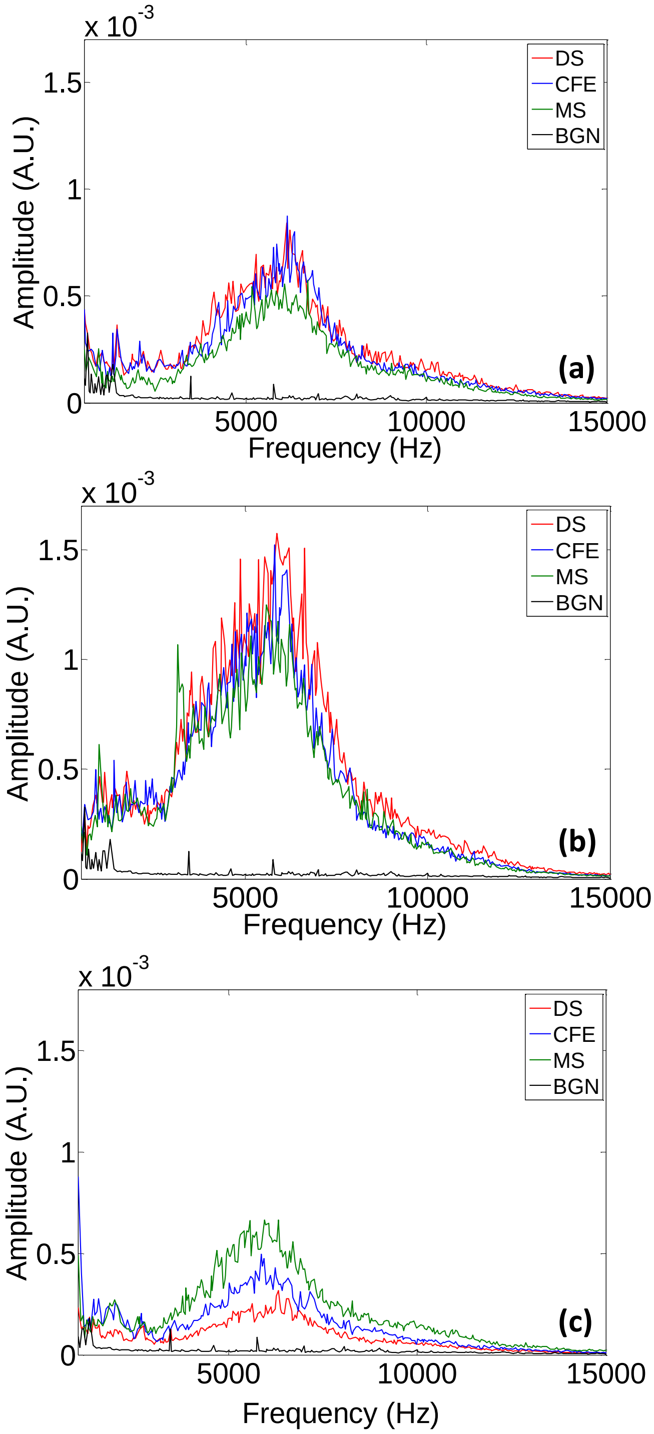


Figure 4.15 Frequency vs. Amplitude sound spectra showing the effects of the different conditioning treatments (DS – de-sized, CFE – concentrated fabric enhancer, MS – Manufactures sizing and BGN – background noise) on the noise produced in the SRR of the three apparel fabrics: (a) cotton, (b) denim and (c) silk.

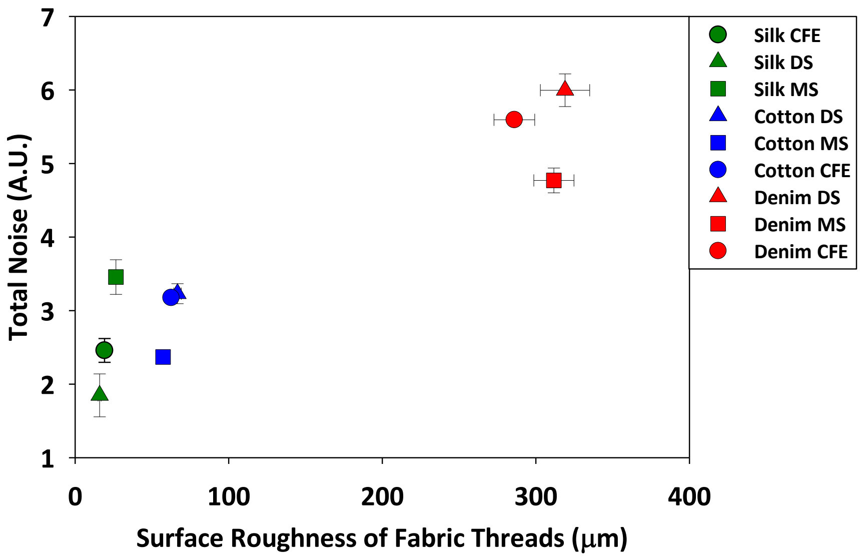


Figure 4.16 Relationship between Total Noise (A.U), calculated using area under curve from sound spectra captured within the closed SRR, and Surface Roughness (μm), measured using Interferometry, of all de-sized (DS), manufacturer's sizing (MS) and treated with fabric enhancer (CFE) apparel fabrics. Overall R^2= 0.86. Error bars are for three repeats.

4.6 Areal density

Although there seems to be a relationship between sound (particularly total noise) and surface roughness, the effect of areal density was also considered. The areal density of each de-sized and modified fabric type of both model and apparel fabrics was measured in kilograms per unit area to investigate if there was relationship between total noise and/or surface roughness. The data is presented in Figure 4.17 showing a significant correlation (R^2 = 0.99 for both comparisons) for de-sized apparel fabrics where by the heavier the fabric the greater total noise and higher surface roughness. It is important to note that areal density of fabric is not independent and is a function of many factors, including weave pattern, thread and fibre count, thread and fibre diameter which may in turn affect surface roughness.

There was no observed relationship between areal density and total noise for model fabrics, however, as would be expected there was a strong correlation (R^2 = 0.96) between areal density and surface roughness; as the thread diameter increases, used to theoretically measure surface roughness, it would be assumed that the weight of the fabric also increased (see Figure 4.18).

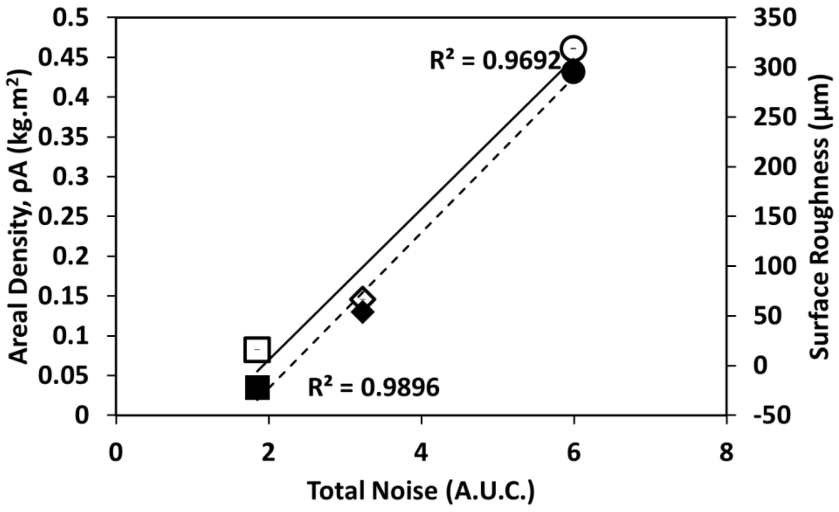


Figure 4.17 Comparing apparel fabrics Total Noise (A.U.) and Surface Roughness (μm) (measured using Interferometry) (open symbols) and Areal Density (kg.m^2) and Total Noise (A.U.C.) (closed symbols) as captured from within the SRR.

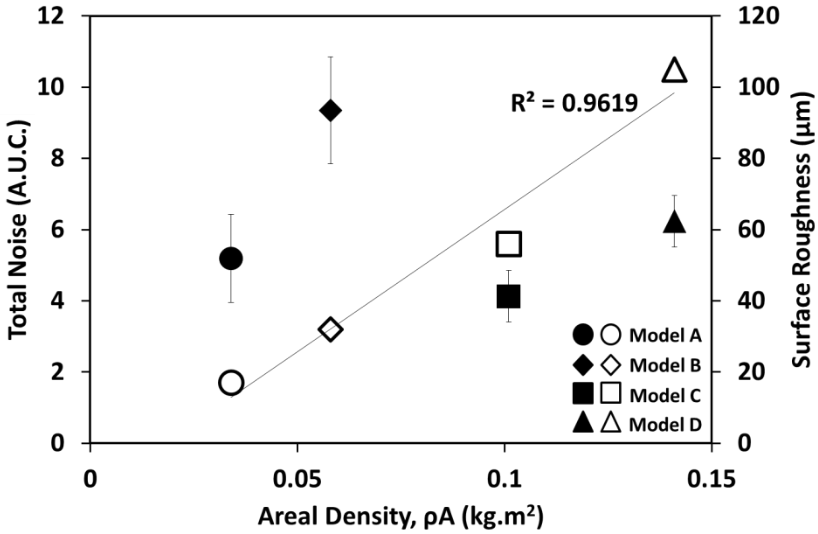


Figure 4.18 Comparing model fabrics Total Noise (A.U.) and Surface Roughness (μm) (measured using Interferometry) (open symbols) and Areal Density (kg.m^2) and Total Noise (A.U.C.) (closed symbols) as captured from within the SRR.

4.7 Summaries

Using the SRR to produce frictional noise from both apparel and model fabrics was successful and resulting frequency vs. amplitude sound spectra were produced.

A difference was observed between the sound spectra produced by the apparel and model fabrics; whereby, apparel fabric was seen to have a large, broad peak between 4000 and 5000 Hz and minimal low range frequency peaks and in contrast model fabrics that had many distinguishable frequencies below 3000 Hz, yet did produce small levels of high frequency outputs, i.e. for Model A fabric.

The difference seen was thought to be as a result of a number of factors: the influence of single fibre structures (model fabrics) when compared with multi-fibre structures (apparel fabrics); acoustical energy dissipation and ratio between aperture and thread diameter.

The multi-fibre structure within apparel fabrics was thought to have two different forms of frictional noise: firstly fibre-fibre noise and the energy needed to overcome the interlocking force between those fibres which is responsible for the large broad peak around 5000 Hz, and; the frequencies that would have been expected (below 2000 Hz): representative of the influence of microstructure on frictional noise.

A strong relationship (R^2 = 0.97) between apparel surface roughness and total noise was seen which was in agreement with literature described in Section 2.4.1, where rougher surfaces produced louder frictional noises. This was explained, as previously discussed within this section, a fibre on fibre noise as opposed to macro scale frictional noise i.e. individual threads, and as the fibre count increased (seen in Figure 3.1) the surface roughness also increased along with total noise.

To further understand the difference between both model and apparel sound spectra produced in terms of specific frequency peaks below 3000 Hz, and the theory that they could be a result of microstructure, frequencies were calculated and correlated with those frequencies measured in the sound spectra. A perfect correlation (R^2 = 1.00) was seen when comparing two sets of frequencies which enables a ‘fingerprint’ theory for unknown fabric microstructures to be developed. In contrast, however, these microstructural frequencies were not correlated with apparel fabrics as has previously been explained within this section as energy dissipation.

The change in microstructure of model fabrics on frictional noise produced was investigated and was seen to not have a noticeable effect on total noise and was understood to be due to two reasons: that AUC was not an accurate method of measuring narrow peaks as opposed to large broad peaks and also when considering the ratios of aperture to thread diameter it was thought that a significant difference should not have been expected.

When considering the effect of surface modification on apparel fabrics and both, surface roughness and total noise produced, a correlation was not seen, however, this has been explained due to the equipment available and the technique used to asses surface roughness.

5 Investigations into the frictional characteristics of apparel and model fabrics by the means of tribology

5.1 Introduction

Friction occurs when fabric is in contact with surfaces such as human and animal skin and other fabrics. Chapter 2 (section 2.3.2) discusses, at length, fabric friction in terms of when it occurs, how it is measured i.e. methods used to measure varying friction values (coefficients, force, resistance etc.), the effect that changing speed and load/pressure have on friction values and the influence of fibre type on resulting friction characteristics. The Kawabata Evaluation System for Fabrics (KES-FB) is a used method of calculating many mechanical properties of fabrics including bending, compression, tensile strength and friction (Kawabata 1980); however, due to the expense of the equipment a new method of establishing fabric friction in-house was desired and therefore tribology was investigated. Tribology is the study of friction and wear and is used more commonly within the automobile, and most recently, food industries. In the context of food, silicone surfaces have been shown to mimic mouthfeel, and friction levels have been related to sensory perception of foods. Garrec and Norton (2013) suggested that the surface roughness (R_a) of a silicone surface can be adapted by filling the gaps with food hydrocolloid particles with a size of ~1 μm (see Section 2.8 for more information), so that the system then acts as a smoother surface, reducing friction levels. Using this theory and the knowledge that Howell (1959) presented within Section 2.3.2, whereby, filling in asperities of a fabric surface (fibres and threads) would reduce fabric friction; the aim of this chapter is to advance the knowledge of in-*situ* fabric conditioning (using the control system of hydrocolloid particles to imitate conditioners). It was decided that the use of hydrocolloids to reduce surface roughness would be employed, as opposed to the conventional method of altering the surface chemistry of apparel fabrics due to the novelty of employing a change in roughness by filling in asperities. Conventional methods of changing surface chemistry have been known to swell individual fibres as well as effectively gluing free fibres to the main threads as described within Chapter 2, section 2.8. As hydrocolloid technology has been used, as previously described, to alter mouth feel and was readily available within this research project, it was the aim of this chapter to utilise the technology for fabric purposes.

To that end, the aims of this Chapter were to gain further understanding of the behaviour of fabric friction using specific multi-fibre apparel (denim, cotton and silk) and single-fibre model fabrics (polyester screen printing material with a specific engineered aperture size, thread diameter and weave structure). In order to measure the friction caused by the sliding of a surface over a fabric, a MTM tribometer; a well-known and calibrated measurement technique of friction, was used. Fabric samples were employed as novel surfaces within the tribometer and tested using different processing parameters. Firstly, initial mechanical parameters of the MTM tribometer were investigated and their effect on fabric friction was established i.e. speed and load. Once a final working method was achieved, fabric friction was evaluated in wet and dry conditions (i.e. with and without the addition of water, respectively) and the influence of lubricants at low speeds was investigated. In order to establish the influence of R_a of fabrics on friction values produced, Stribeck tests were carried out to gain an insight into the effect of extremely high speeds on friction. Using the knowledge, discussed in Section 2.8.1.3.1, that R_a can be altered using specifically engineered viscous liquids with varying particle sizes, hydrocolloids were engineered to gain an insight into the ability to achieve a reduction in friction due to a reduction in R_a.

5.2 MTM Tribometer methodology: set up and parameters

Within this section of Chapter 5, results are discussed from preliminary studies carried out as a result of the varying parameters available to users of the MTM Tribometer: speed and load, and how these have influenced a final working method. The full methodology used is described in Section 3.3.7.

5.2.1 Effect of changing load on friction coefficients

As described in Section 2.3.2, fabric friction previously investigated within literature deviates from Amonton's law: '*friction coefficient is independent of load*', and therefore experiments were carried out on dry cotton fabric samples, using pin-on-disc methodology (described within Section 3.3.7.4), to investigate, if indeed, this deviation is true for an MTM system with fabric surfaces.

In order to establish an understanding of the MTM system at 0 N, cotton samples were measured and analysed. In theory, running a system with zero load would initiate no forced or real contact between the ball and disc, and therefore would produce 'noise' that was as a direct result of the behaviour of the arm movement holding the ball. As can be seen from Figure 5.1, a substantial amount of noise was observed for 0 N, indicating that a minimum load is required for all testing on fabric systems to be able to achieve a true result. From this result, two further loads were investigated: 2 N and 4 N, results of which can be seen in Figure 5.1. The greatest level of μ resulted from 2 N load, with a steady value over time of approximately 0.5. For 4 N the value was between 0.3 and 0.4. It can be deduced that fabrics tested on the MTM do indeed deviate from Amonton's law, in that μ is not independent of load. This finding is in agreement with the worked carried out by Carr *et al.* (1988) in which frictional coefficients (both dynamic and static) decreased with an increase of pressure on the fabric surface.

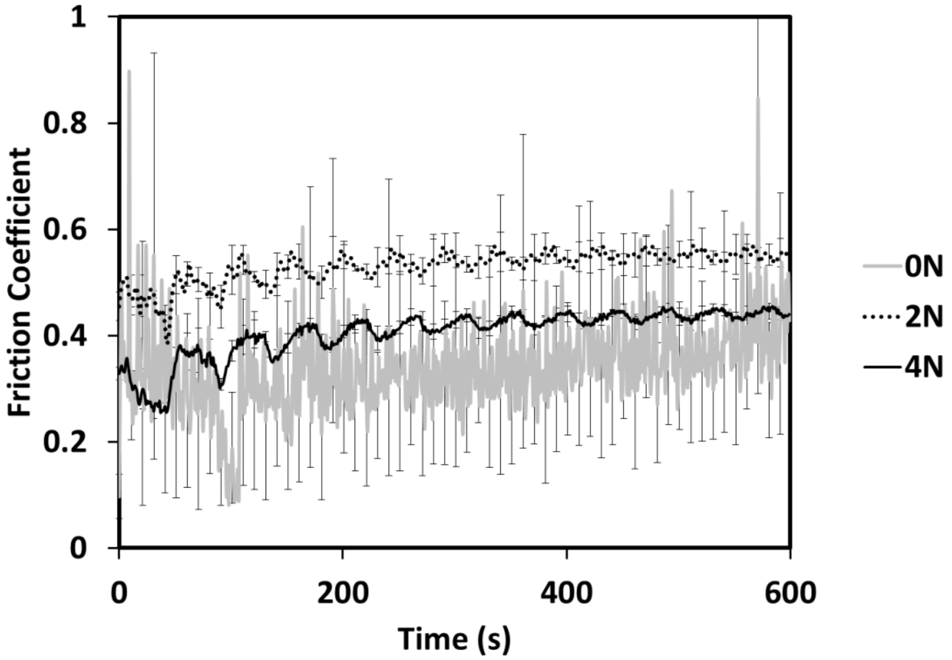


Figure 5.1 Time (s) vs. friction coefficient produced by dry cotton fabric sample using pin-on-disc methodology at varying loads: 0 N, 2 N and 4 N. Mean of three repeats is plotted; error bars represent two standard deviations.

5.2.2 Effect of changing speed within pin-on-disc tribology on friction coefficients

As with load, Coulomb's third law of friction *'kinetic friction is independent of sliding velocity'* was investigated with respect to fabrics. The influence of changing speed on pin-on-disc friction coefficients of cotton fabric samples were measured and can be seen in Figure 5.2. Two speeds were initially chosen: 3 mms^{-1} and 184 mms^{-1}, due to the lowest being closer to consumer testing of fabric speeds and the faster, due to it being the same speed used to establish fabric frictional sound within Chapter 4, therefore enabling further relationships and conclusions to be drawn between the friction and sound levels produced by the apparel fabrics. Over a two fold increase in friction coefficient was observed when speeds increased between 3 and 184 mms^{-1}, with means of 0.5 and 1.1, respectively. As velocity is defined as speed with a direction, and a constant velocity is one which exhibits a constant speed in a constant direction, and as sliding velocity is defined as kinetic or moving speed with a direction, it is apparent that friction of fabrics exhibited using an MTM tribometer also deviate from Coulomb's law. This finding is in agreement with the research carried out by Ramkumar *et al.* (2004b) and Hermann *et al.* (2004), whereby friction increased with increasing sliding velocity.

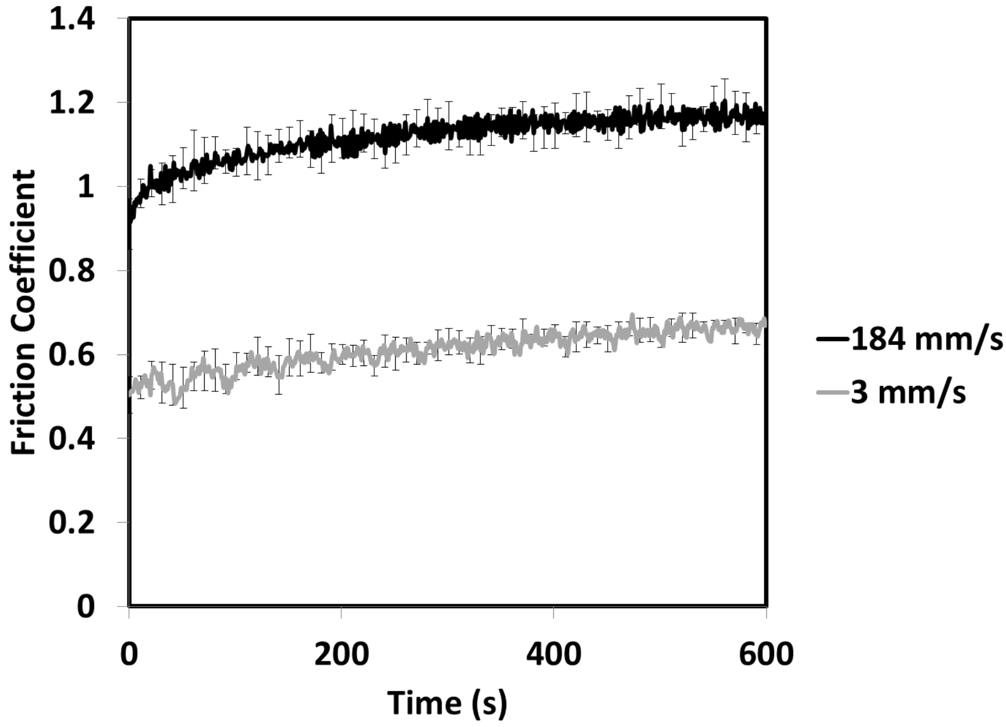


Figure 5.2 Time (s) vs. friction coefficient produced by dry cotton fabrics using pin-on-disc methodology at varying speeds: 3 mms^{-1}, 184 mms^{-1}. Mean of three repeats is plotted; error bars represent two standard deviations.

In order to further understand the relationship between friction coefficient and speed, and to establish if the deviation from Coulomb's law is as a result of apparel fabrics (i.e. multi-fibre) or all woven fabrics (i.e. single fibre), both model fabrics (Model A and B) were subjected to a wide range of intervals between 3 and 184 mms^{-1}. Figure 5.3 shows the results of increasing speed (mms^{-1}) on friction coefficient and it was observed that, as with cotton fabric, μ also increases in order of increasing speed levels.

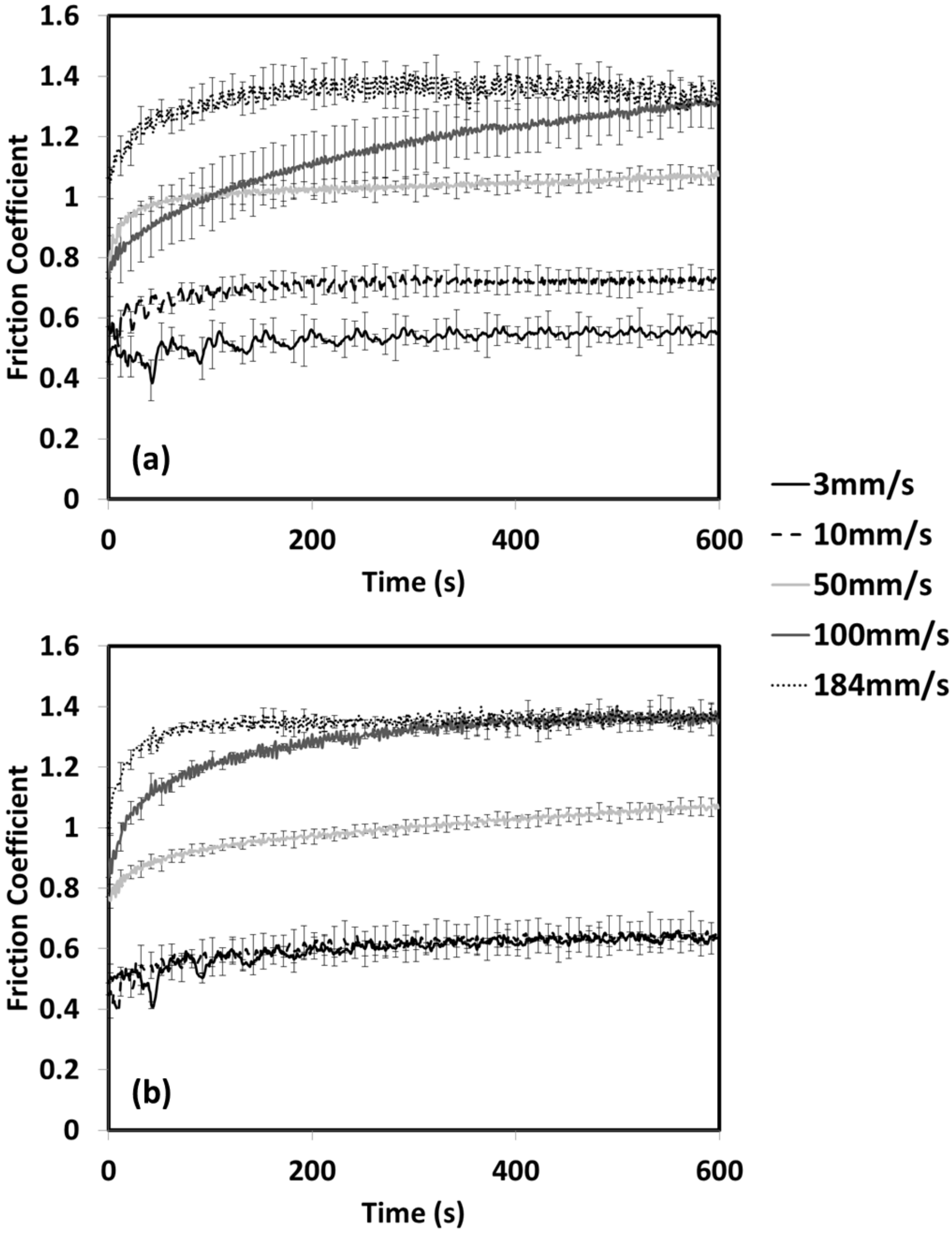


Figure 5.3 Time vs. Friction Coefficient produced by dry (a) Model A and (b) Model B fabrics using pin-on-disc methodology at varying speeds: 3 mms^{-1}, 10 mms^{-1}, 50 mms^{-1}, 100 mms^{-1} and 184 mms^{-1}. Means of three repeats is plotted; error bars represent two standard deviations.

5.2.3 Conclusions to MTM tribometer setup

Preliminary tests were carried out on fabric samples to establish a working method for all future tribology work and it was concluded that 3 mms^{-1} would be chosen for the speed (for pin-on-disc) due to its relationship with consumer speed testing (see Section 2.7). Although 184mms^{-1} is used within Chapter 4, it was observed that, particularly with silk, an amount of wear occurred which then resulted in some fabric samples tearing and therefore 3 mms^{-1} was also more reproducible and non-destructive. A load of 2 N was chosen as it represents the weight of the TAS used within Chapter 4 to capture friction noise of apparel and model fabrics and therefore able to draw future conclusions between the two Chapters. It must be noted that, although it was desirable to relate both speed and load of friction measurements and frictional noise, a different speed was chosen and therefore care must be taken.

5.3 Frictional characteristics of apparel and model fabrics

Within this section the friction coefficients produced by dry and wet (lubricated with water) apparel and model fabrics are presented and discussed.

5.3.1 Dry and wet friction of apparel fabrics

Friction coefficients were measured using the pin-on-disc method described in Section 5.2.3, produced by the three apparel fabrics (denim, cotton and silk), (see Figure 5.4). When considering the apparel fabric friction coefficients measured, it was observed that denim produced a greater value than both silk and cotton, respectively. As was concluded within Chapter 4, R_a plays a vital role in the level of frictional noise produced by apparel fabrics. As friction is expelled as energy in terms of heat, wear and noise, this relationship may also have an influence on friction coefficients observed, in which surface roughness increases frictional levels. In terms of R_a values (see Table 3.1 for apparel characteristics), it would be expected that, particularly in dry conditions, denim would result in the highest level of μ. The 'hairy' characteristics of fabrics, which were deemed responsible for the level of friction noise produced in Chapter 4, can also be attributed to the friction coefficients produced by apparel fabrics within the MTM system (Das *et al.* 2005). Due to the large twill weave of denim, there are a vast number of hairy fibres available to interact with the silicone ball (in a similar fashion to fibre-on-fibre interactions described within Section 4.4.1.1), which can be seen in Figure 5.5 and therefore, the number of interlocking areas increases, due to a higher surface area, which consequently increases the force needed to push the ball along the surface. If surface roughness is to be the single parameter affecting friction coefficients produced by the MTM system, cotton's friction coefficient would then appear below denim due to it having a lower R_a (and greater than silk). However, as can be seen from Figure 5.4 (a), dry silk exhibited the second greatest level of μ, and therefore the influence of fibre type on friction is considered.

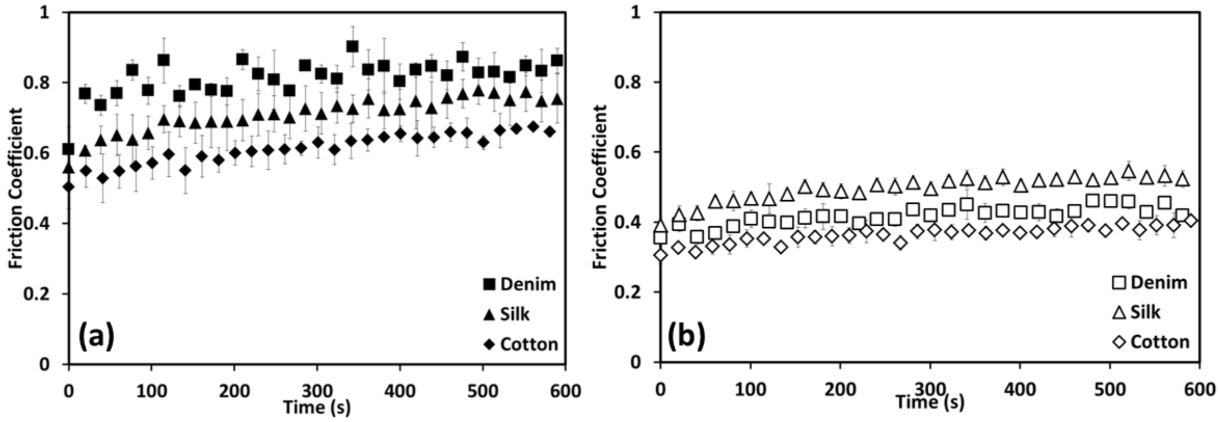


Figure 5.4 Time (s) vs. μ produced by (a) dry and (b) wet apparel fabrics (denim (□), cotton (◊) and silk (Δ)) using an MTM tribometer (pin-on-disc run at 3 mms^{-1}). Means of three repeats is plotted; error bars represent two standard deviations.

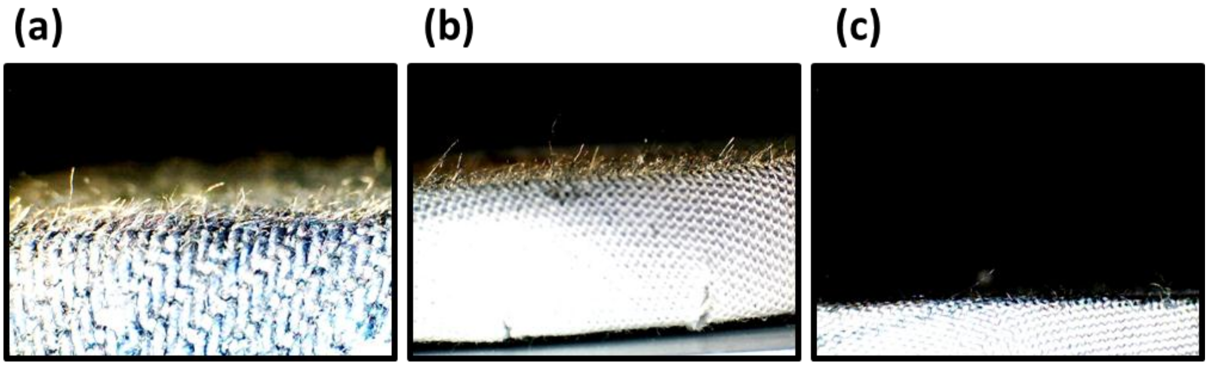


Figure 5.5 Side view images of (a) denim, (b) cotton and (c) silk fabrics, fixed to the tribometer discs, depicting the 'hairy' nature of the different fibre types. Images have been taken using a Veho microscope (see Section 3.3.3.2 for more information).

The hygroscopic nature of the fabric samples was considered to be an influence on resulting friction coefficient from dry fabrics, due to the laboratory's relative humidity levels in which the experiments were carried out. This theory is based on literature discussed within Chapter 2, Sections 2.3.2.3.2 and 2.3.2, whereby a significant difference in friction levels as a function of hydration was observed (Gerhardt *et al.* 2008). Both silk and cotton are hydrophilic according to their chemical structure;

however, in order to further establish the hydrophilic nature of the apparel fabrics a goniometer was used to measure the time taken for a drop of distilled water to fully soak into the surfaces. The theory of absorption of the drop of water is that the more hydrophilic the fabric surface, the quicker the drop of water will be absorbed into the surface. Results showed that the drop of water soaked into the silk surface 3.4 times slower than cotton and 14.3 times slower than denim (see Table 5.1). An example of the images collected using the goniometer can be seen in Figure 5.6, where, at 0.6 seconds, it is apparent that silk has the greatest amount of water on the surface (i.e. that has not been absorbed), followed by cotton and denim, respectively. These results show that the silk used within this research was less hydrophilic than both the cotton and denim, although all are hydrophilic as the water droplet did not sit or stay on the surface of the apparel fabrics without being drawn in to the microstructure i.e. the droplet would sit on the surface for an extended period of time if the fabrics were hydrophobic. This result differs from literature discussed within Section 2.1.1, whereby, silk has been reported to uptake, on average, 5% more water in humid environments than cotton. Although literature would suggest that silk is more hydrophilic than cotton, the nature of treatment of both fabric samples within the manufacturing and distribution of original fabric reels is unknown and therefore results and discussions for this section of work are based on the measurements taken from the goniometry experiments. As literature is concerned with the chemical structure, in that silk has more OH groups for absorption and bonding to water, it can only be assumed that the silk used within this research have had their polar groups hindered by treatment. Efforts were made to de-size original fabrics; however, the methodology will not always rid all fabric samples of all residual treatment.

Figure 5.6 Images of a drop of water soaking into the surfaces of (a) cotton, (b) denim and (c) silk, produced by a goniometer. Frame is taken from a video at 0.6 seconds.

Table 5.1 Time taken in milliseconds for a 3-5 μL drop of distilled water to fully soak into the surfaces of silk, cotton and denim. Results are a mean of ten repeats; two standard deviations is also given.

	Silk	Cotton	Denim
Time (ms)	13893	4093	973
Standard deviation (ms)	5336	2069	61

How the strength of the hydrophilic nature of the fabric samples affects the friction levels can be partly explained using previous results gained from MTM tribology in food research (Garrec & Norton 2012a). In contrast to the methods used to create the hydrophobic PDMS ball used within this thesis (see Section 3.3.7.2), Garrec and Norton rendered the PDMS ball and PDMS disc surfaces hydrophilic by the addition of siloxane surfactant (verified using Goniometry (see Section 3.3.10 for similar information/method)). The authors carried out Stribeck tests using both the original hydrophobic, and new hydrophilic tribopairs (ball and disc), and found that the hydrophobic pair resulted in higher friction coefficients than the hydrophilic pair. They report that a decrease in μ observed by the hydrophilic pair was explained by the increased ability of the pair to be fully wetted, as a result of increasing polar group numbers, which enables more efficient entrainment of, in their research, corn syrup, leading to an increased ability to lubricate. This research can be used to relate the less hydrophilic nature of silk to an increased level of μ as, even with small levels of relative humidity, it is less able to be wetted and therefore is as a consequence, not as lubricating as cotton. It must be noted that the tribopairs used within this research do not have the same hydrophilic tendency i.e. the silicone ball is hydrophobic and silk is hydrophilic, however, it is the lesser hydrophilic nature of the silk when compared to cotton that is likened to the hydrophobic nature of the ball. When relating this theory back to fabrics, both Kenins (1994) and Ramalho (2013) also concluded that silk's reduced hydrophilic nature was responsible for an increase in friction when compared to cotton fabric, due to a inhibited ability to be wetted which was therefore responsible for lower levels of lubrication.

In summary, in dry conditions it appears that both the hairiness of the fabric and its hydrophilic nature affect the levels of friction produced.

As opposed to the 'dry' condition, whereby, uptake of water was minimal, but still effective and would have been as a result of relative humidity, the fabric samples used within the 'wet' condition were flooded with water. Figure 5.4 (b) shows the friction coefficients produced by apparel fabrics within the wet condition and, as expected, a decrease was observed due to two mechanisms which have previously been presented by Arshi *et al.* (2012): 1) 'ploughing' in which the surface roughness is the main consequence and 2) adhesion, where the polar groups of hydrophilic fibres are able to uptake water in greater amounts, therefore increasing the hydrophilic nature of the fabric, which in turn increases adhesion (i.e. attachment).

When considering the first theory, 'ploughing', the water within the system is acting as a lubricant by reducing the number of 'hairy' fibres of all apparel fabrics. This is achieved by wetting, and therefore reducing R_a, and in turn creating a smoother surface, allowing the silicon ball to pass over the fibres within the samples with less force required. The greatest change in levels of μ was seen between the dry and wet denim samples with a decrease of around 0.5. This result is in agreement with the ability for denim to uptake water more quickly than cotton and silk, discussed previously, and therefore an increase in water uptake leads to an increase in lubricating ability and that denim has more hairy fibres initially which enable higher uptake of water. The lubrication observed is as a direct result of the apparel fabrics ability to uptake water, and after saturation levels are reached within the fibres and threads themselves, all excess water is employed to create a thin film on the fabric surface (Arshi *et al.* 2012), and therefore it is cotton and in particular denim, that is able to take in more water, producing a thin film more quickly, resulting in a greater level of lubrication.

This result is in agreement with results seen by Arvanitaki *et al.* (1995) in which a sharp decrease in μ was observed when elastomers were lubricated in comparison to dry systems. However, when comparing this to literature of human skin being rubbed on dry and wet fabrics, the opposite was seen. As the silicone ball is designed to mimic human skin within this experimental set up, comparing results found to those who have used real human skin, whether in-*vivo* or in-*vitro* is necessary. Gerhardt *et al.* (2008) reported a two fold increase of μ produced when hospital cotton-polyester materials were wetted and tested. In contrast to the experiments carried out within this research, Gerhardt *et al.*'s (2008) materials were 'soaked' in 0.9% w/v sodium chloride solution and therefore minimal free water was available for further lubrication or even boundary lubrication, as opposed to the vast amount of free water within the tribometer cell enabling increased lubrication. Kenins *et al.* (1994) also studied the effect of dry and wet human skin on fabrics and reported an increase in the friction force measured; however, the fabric samples were not at any time fully wetted and were only subjected to a change in relative humidity (RH) (from 10% RH to 90% RH) in order to alter moisture levels. Both Kenins *et al.* (1994) and Gerhardt *et al.* (2008) reported an increase in frictional parameters (force and coefficients, respectively) when the skin was wetted, due to the changes in the skin itself e.g. swelling, therefore producing two highly hydrophilic surfaces, in which adhesion forces may be responsible.

Arshi *et al.* (2012) carried out experiments using a fabric-to-fabric friction method and investigated the effect of increasing relative humidity and observed that an increase in friction occurred as a result of increasing relative humidity. They conclude that an increase in RH leads to an increased number of water molecules within each fabric surface causing a swelling of fibres with as a consequence increases the true contact area. When the newly swollen fabric surfaces come into contact with each other an increase in attraction of hydrogen bonding would occur. In order to move the fabrics over one another, the force is consequently increased by the shear need to break the adhesive forces between the two surfaces and bonds. This result can be used to directly explain the increase in friction previously mentioned between wetted skin and wetted fabric samples, that the attraction between the two surfaces is greater than in dry conditions. However, as the silicone ball within this research is hydrophobic is it not able to be easily wetted, or take in moisture/water from the system and therefore does not create additional adhesive forces.

In summary of the two theories explored, that of 'ploughing' and adhesion, both play a vital role in friction produced by fabric-to-fabric and fabric-to-skin, however, in contrast it is believed that a swollen fibre does indeed increase the total contact area, but it is thought that they then create a smoother surface, which therefore reduces friction. Thus is it not as a result of adhesion.

5.3.2 Dry and wet friction of model fabrics

As with the methodology used within Chapter 4, it was essential to understand the effect that a multi-fibre system (apparel fabrics) has on friction by comparing results with a single-fibre control system with defined thread and aperture sizes. Therefore Model fabrics A and B were tested with the same pin-on-disc method used for apparel fabrics (see Table 3.1 for model characteristics). Unlike with Chapter 4, only two models were used within this Chapter's research due to the challenge of attaching model fabrics with larger apertures and thread diameters to the stainless steel disc; reproducible results were not possible as the fabrics would not hold for a sufficient amount of time and separated during testing.

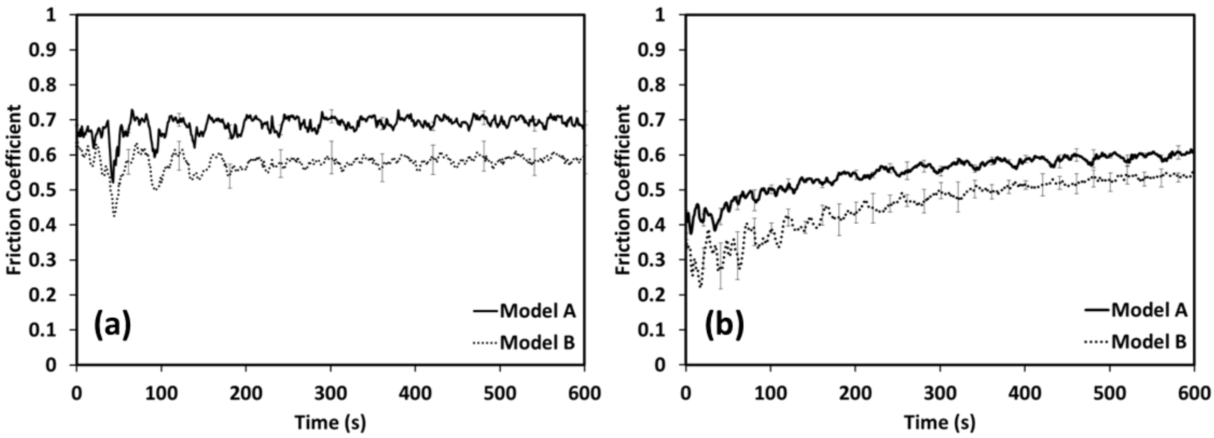


Figure 5.7 Time (s) vs. μ produced by (a) dry and (b) wet model fabrics (Model A and model B) using an MTM tribometer set to pin-on-disc and run at 3 mms^{-1}. Means of three repeats is plotted; error bars represent two standard deviations.

When looking at the model fabrics (see Figure 5.7), the same relationship was established: that friction coefficient decreases with the addition of water, however, not as great a reduction was seen within apparel fabrics. The difference between the lubrication of model fabrics and apparel fabrics is due to the lack of fibres within the model fabrics and as a consequence the ability to uptake water is at a very low level, if not zero uptake, due to their hydrophobic nature. However, an inclusion of water within the tribometer cell will still lubricate the system producing a slight decrease in μ due to the fact that the force needed to rub two dry surfaces against each other will always be higher than when lubricated.

As can be seen from Figure 5.7, Model A produced higher levels of friction than Model B and this is thought to be due to the contact points between the polyester fabric and silicone ball. The thread count of Model A is double that of Model B, resulting in twice the amount of contacting points, which can be likened to the hairs of apparel fabrics, whereby, the force needed to push the silicone ball along Model A's multiple contact points is higher than for Model B.

5.4 Understanding Stribeck behaviour of apparel and model fabrics

As pin-on-disc runs at relatively low speeds, and significantly lower speeds than are usually considered in tribology, full entrainment of the lubricant was not achieved (i.e. only boundary lubrication was observed), and therefore the influence of higher speeds on both apparel and model fabrics were investigated using Stribeck tests (see Section 3.3.7.4 for methodology). Stribeck results are presented with speeds between 6 and 3200 mms^{-1} as speeds lower than 6 mms^{-1} within Stribeck curves present significantly noisy data (Mills 2011).

A consistent positive relationship between speed and friction coefficients was observed for all disc surfaces (see Figure 5.8): as speed increases friction also increased and at higher speeds a maximum friction coefficient was seen at 600 mms^{-1}, for all fabrics apart from silk. When comparing Stribeck results to those gathered using pin-on-disc, it was apparent the that friction coefficient produced was greater for Stribeck which is in agreement with researched carried out by Hermann *et al.* (2004) and Ramkumar *et al.* (2004b), who report that friction of fabrics increases with speed (also seen in preliminary studies in Figure 5.2).

In order to compare the effect of fibre type and R_a on friction coefficients, a stainless steel disc was also tested with water (see Figure 5.8 (b)) to act as a control surface. The stainless steel disc produced a typical Stribeck curve; a plateau which can be related to the boundary regime, followed by a sharp decrease in μ representing the mixed regime. For both apparel and model fabrics, a decrease in friction coefficients to their original value is not observed (even at the highest speeds), indicating that the mixed regime is not fully entered and in turn suggests that the force produced by the surfaces and lubricant combined do not separate the ball and disc fully. Cassin *et al.* (2001) reported that an increase of R_a from 0.2 to 1.50 μm shifted the mixed regime to be entered at higher speeds for the higher R_a. This is in agreement with friction coefficients presented: in this thesis the minimum possible roughness measurements of the stainless steel surface when compared with the high surface roughness' of apparel and model fabrics. The authors also showed that on increasing R_a there was a loss in boundary lubrication, which can also be seen in Figure 5.8 (a) as there is a lack of plateauing area within lower speeds.

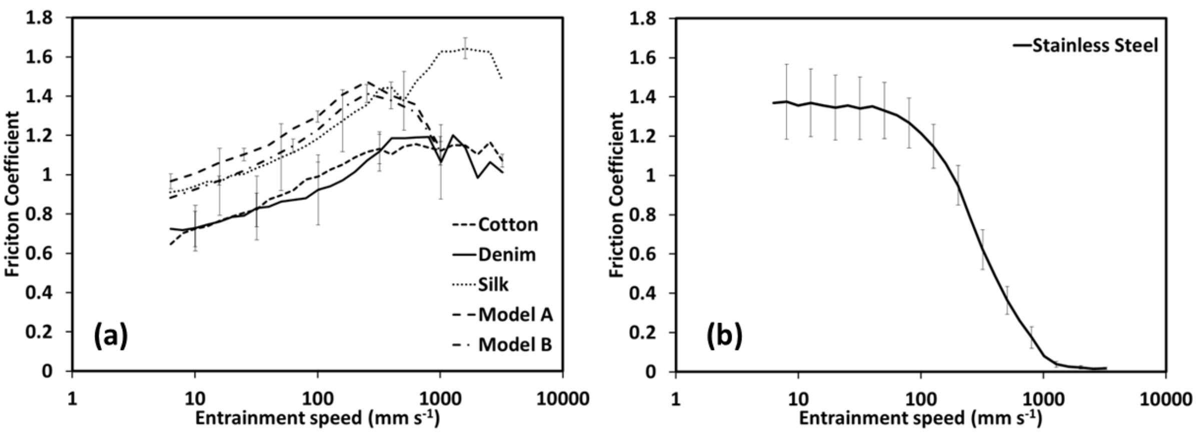


Figure 5.8 Friction coefficient (μ) vs. entrainment speed (mms^{-1}) (Stribeck curves) plots produced by (a) all apparel and model fabrics and (b) stainless steel using deionised water as lubricant. Mean of 3 repeats (of 6 runs) and error bars represent two standard deviations of the mean.

The hydrodynamic region was not entered within Cassin *et al.*'s research considering the effect of guar gum on μ and was believed to be due to the high surface roughness values tested. A lack of hydrodynamic regime and a minimal mixed regime suggests that complete entrainment of a lubricant is not achieved. As such, further understanding of the requirements to achieve hydrodynamic lubrication is needed. This can be further substantiated, in terms of surface roughness, by referring to Figure 5.8 (b), whereby, stainless steel created a typical Stribeck curve as it has an R_a value of 0.01 μm (data taken from PCS Instruments, UK).

When considering apparel and model fabric friction coefficients produced and presented in Figure 5.8 (a), it was observed that friction levels between the cotton fabrics and polyester and silk fabrics were different, where μ was approximately 0.2 higher in the latter fabrics. As described in the previous pin-on-disc results section, both cotton and denim are more hydrophilic than silk and the hydrophobic nature of polyester and this difference in hydrophilic nature is responsible for the observed difference in μ. The same relationship is seen, in terms of ordering of friction coefficient according to original fibre type, as pin-on-disc measurements: silk has a higher level of friction than cotton and denim. Here the effect of the nature of Garrec and Norton's hydrophilic/phobic surfaces are seen: the hydrophobic model fabric coupled with the hydrophobic silicone ball results in a higher friction coefficient and can be explained due to the adhesion theory previously discussed.

Although the surface roughness of the fabrics, on the whole, when compared to stainless steel surface was imperative in order to understand the change in Stribeck behaviour observed; however, when the R_a values of the apparel and model fabrics are considered for their individual differences (i.e. comparing silk to denim, to cotton etc.) the values on friction becomes less significant. The nature of the method used to achieve Stribeck behaviour is such that all areas of the fabric surfaces are subjected to friction multiple times and therefore wear of the surface will occur, changing the R_a values (see Figure 5.9). The percentage of wear was calculated, based on its original height (μm), for each apparel fabric. A 25% reduction in denim, 50% for silk and 79% for cotton, it was therefore appropriate to assume that as wear occurs in such high levels that the effect of surface roughness for wet Stribeck tests were insignificant.

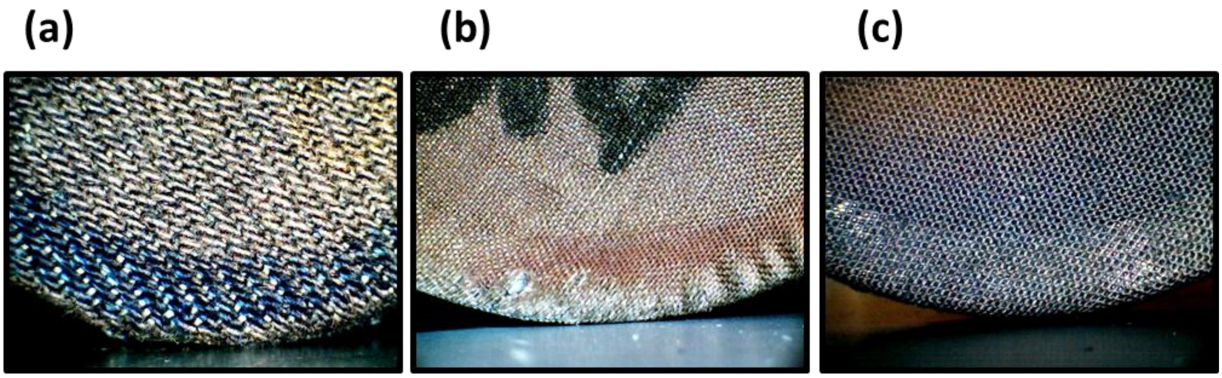


Figure 5.9 Areal view images of (a) denim, (b) silk and (c) cotton fabrics, fixed to the tribometer discs, depicting the wear of the different fibre types. Images have been taken using a Veho microscope (see Section 3.3.3.2 for more information).

5.5 Fluid gel properties

As was described within Section 2.8, the use of hydrocolloid fluid gels has been known to reduce friction coefficients via the mechanism of reducing R_a values of the surfaces tested. This section provides the characteristics of the fluid gels produced using a jacketed pin-stirrer method (described in Section 3.3.6), their mechanical properties, followed by the influence of said fluid gels on the friction produced by apparel and model fabrics (see Section 5.6).

5.5.1 Gelling profiles

In order to ensure that the optimum amount of gelling occurred under shear (as opposed to quiescent gels (QG) being passed through the sheared unit and chopped up, resulting in a hard non spherical gel) the inlet temperature of the hydrocolloid solution had to be kept above the onset of gelling temperature. Figure 5.10 shows the gelling profiles of both hydrocolloids used and as can be seen, the onset of gelation (red arrows) was approximately 55 °C for κC and 38 °C for Agar. When referring back to Table 3.6, T_{inlet} was kept above both gelling temperatures successfully, therefore by knowing that the hydrocolloids had not gelled outside of the system (jacketed pin stirrer) it was assumed that the majority of gelation had taken place within the unit.

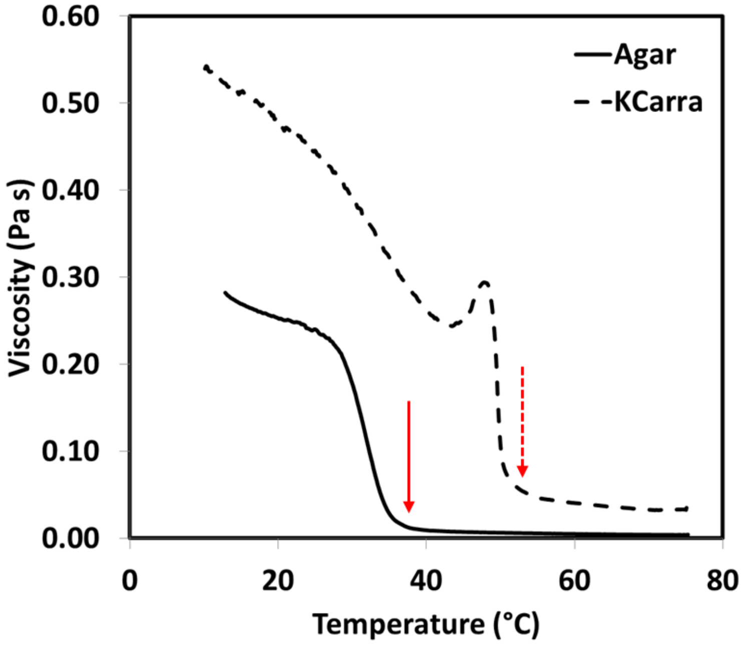


Figure 5.10 Viscosity (Pa s) vs. temperature (°C) produced by 2% w/w and 0.3% w/w KCl Kappa Carrageenan and 2% w/w Agar. The red arrows depict the onset of gelling temperatures (dashed line for kappa carrageenan and solid line for agar). Viscosity profiles are obtained using a Kinexus Rheometer.

The process of gelation of hydrocolloid gels within a jacketed pin stirrer is heavily dependent on a number of factors: the concentration of the gelling polymer, shear rate, gelation rate etc. Shear rate is the main contributing factor to fluid gel particle size in which small spherical particles are produced on high shear, however, on reduction of shear the main distribution of particle size increases; this also occurs on the increase of rate of gelation via the increase of concentration of the gelling polymer. The shape of the gelled particles remains constant i.e. spherical up until a point when gelation occurs faster than disruption due to shear and particles are much bigger and irregular in size resembling gelled fragments (Gabriele *et al* 2010, 2011).

5.5.2 Textural analysis

The hardness properties of the QGs (used to give an understanding into the properties of the FGs) were tested using a TAXT.plus textural analyser and the resulting true stress vs. true strain profile can be seen in Figure 5.11, and resulting properties can be seen within Table 5.2. It was observed that κC resulted in much higher values of true stress and strain up the point of fracture, and consequently greater amount of work was required to break the gel (calculated using methodology in Section 3.3.8). In contrast to κC, the effort required to break the QG of agar was considerably lower therefore resulting in a softer more pliable gel, which is often described a 'weak' gel.

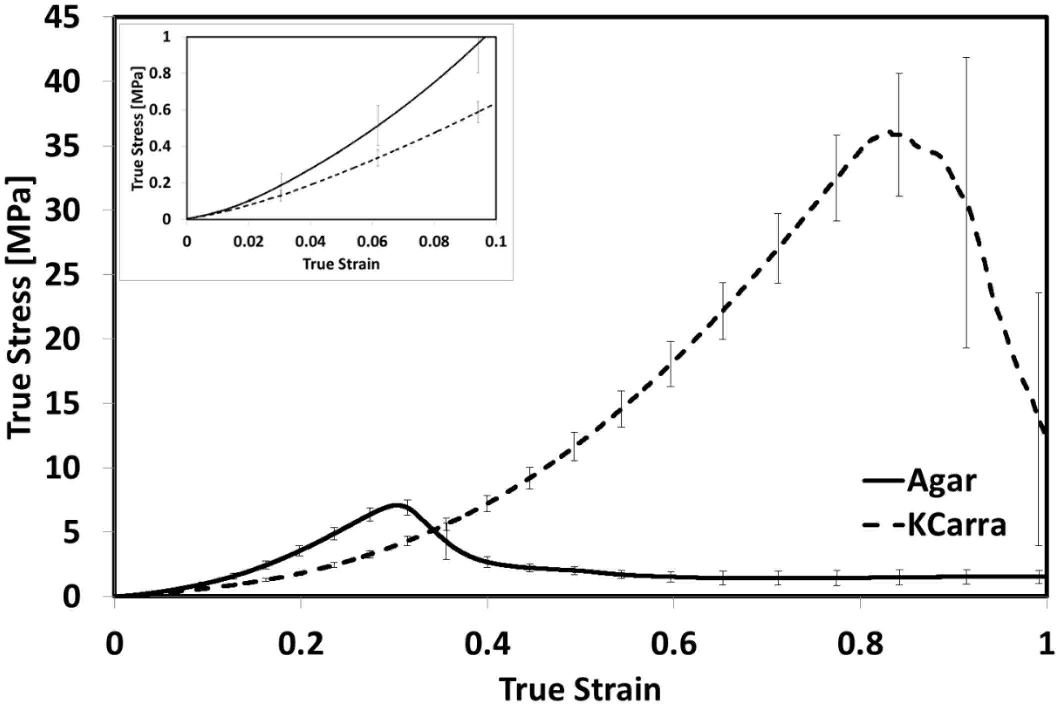


Figure 5.11 True stress vs. true strain curves for 2% Kappa Carrageenan and 2% Agar measured using TAXT.plus texture analyser. Whole graph shows the effort needed to break the quiescent gels and the after effect of breakage. Young's Modulus can be seen within the inset graph (top left).

When comparing the elastic/plastic nature of the two FGs produced, the Young's modulus for agar was higher than κC, meaning that the ability of the agar QG to return to its original state under preliminary strain values was greater than that of κC.

Table 5.2 Material properties for FG tested measured using a TAXT.plus texture analyser

Fluid Gel	Work Done	Bulk Modulus (MPa)	Young's Modulus (MPa)
Agar	3.692	37.54	6.16
κC	25.52	80.81	6.15

5.5.3 Friction coefficients of fluid gels

In order to understand the overall lubrication behaviour in a controlled system, the FGs, agar and κC, were tested using the stainless steel disc and the resulting Stribeck curves can be seen in Figure 5.12. When comparing with water (see Figure 5.8 (b)) the resulting friction coefficient is lower for all FG systems: water (1.4), κCT_{56} (1.0), κCT_{40} (0.6), agar RS_{300} (0.5) and agar RS_{1500} (0.1). A lack of boundary regime was also observed for all fluid gels when compared to water. However, all enter a mixed regime; therefore indicating that entrainment of the fluid gel particles and systems is achieved.

The aim of this section of research was to understand how processing parameters affected lubrication, therefore when comparing the two different FGs it was apparent that agar produces lower friction coefficients than κC, particularly for agar RS_{1500} (agar produced with a rotational speed of 1500 rpm) which produced the lowest level of friction. Understanding of the mechanical properties of the FGs can be used to explain the differences observed (see Section 5.5.2). Agar required a significantly lower amount of work to deform the QG cylinder than κC, and therefore can be considered to be more deformable under loads or stresses. Garrec (2013) reported that κC individual particles observed to be oddly shaped 'hairy' particles and therefore produce a harder QG/FG, which on entrainment exhibit behaviour similar to that of hard spheres. With that in mind, it is reported that the weaker the gel particles the more easily the FG is entrained during tribology (Garrec 2013). Although the QG's mechanical properties are not an exact representation of the strength of each particle within a FG, it is assumed that the difference between each FG is representative.

Altering the rotational speed of the pin stirrer has been reported to change the particle size of the FG. Gabriele *et al.* (2010) created a number of FGs with varying shear speeds, and those specific to this research were approximately: 1400 rpm and 300 rpm, and produced particle sizes of 83 μm and 106 μm, respectively. The general trend in particle size was reported to be that the faster rotational speed the more lubricated the system was, due to smaller particles being more easily entrained.

Gabriele *et al.* used a load of 4.5 N, whereas the load within this research was 2 N; however, within MTM tribology of FGs, load did not affect the friction coefficients (2010).

The temperature drop for κC FG between T_{inlet} and T_{exit} was varied, controlled using the jacketing vessel surrounding the pin stirrer, and was controlled at T_{40} = 40 °C and T_{56} = 56 °C. $κCT_{40}$ is shown to exhibit a lower level of friction than that of $κCT_{56}$ when tested against the stainless surface (see Figure 5.12). This is thought to be due to the production of an FG with a smaller particle size, which is achieved by a slower cooling rate (°C/min) via a smaller temperature drop and therefore exhibits a greater lubricating ability (Garrec & Norton 2012d).

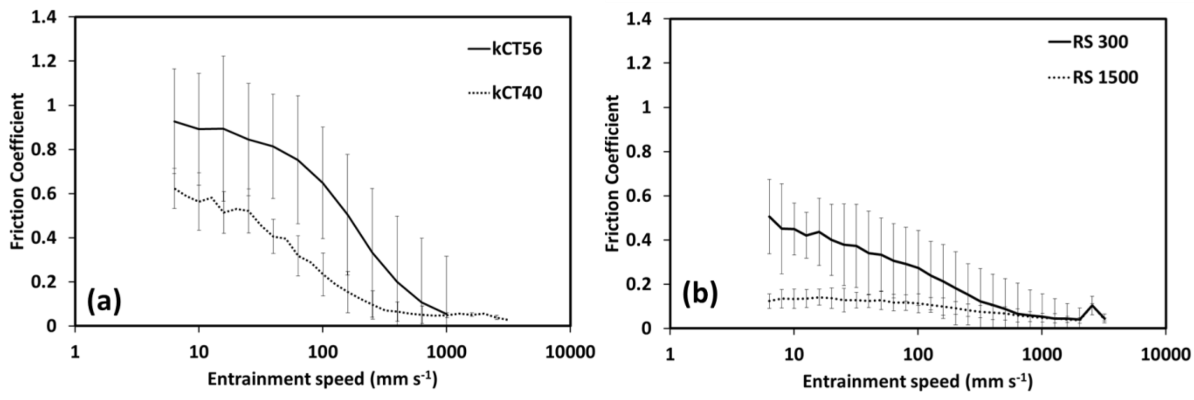


Figure 5.12 Friction coefficient vs. entrainment speed plots (Stribeck curves) of (a) κ-carrageenan and (b) agar. Means are of 3 repeats (6 runs in each repeat); error bars represent two standard deviations. Codes are $κCT_{56}$: temperature drop of 56 °C, $κCT_{40}$: temperature drop of 40 °C and agar RS_{1500}: rotational speed of 1500 rpm and RS_{300}: rotational speed of 300 rpm (see Table 3.6 for more information).

5.6 Influence of fluid gels as a lubricant on the friction of apparel and model fabrics

As the aim of this research was to investigate the influence of hydrocolloid particle size on altering the R_a of apparel and model fabrics, it was essential that both fluid gel systems were introduced to the tribometer and the resulting friction coefficients explored.

When either apparel or model fabrics become the base surface and are measured with the FGs produced within the MTM2 tribometer the opposite result is seen to that observed when the stainless steel disc is used (see Figure 5.12). κC has a greater lubricating effect than agar when the results are considered as overall trends in friction coefficient. This behaviour can be explained by the theory enhanced by Garrec and Norton (2013) (initially written by Coulomb in 1788) where the asperities within a PDMS disc were filled with fluid gel particles (made from 2% κC with 0.3% KCl). Their results showed that the PDMS disc had a R_a of approximately 1-3 μm and therefore that the resulting particle size of the κC FG (~1 μm) fitted within the asperities creating a smoother surface, resulting in a lower friction coefficient. This theory was presented in early literature by Coulomb, specifically for fabrics, whereby the asperities (micro scale: fibres; and macro scale: threads) are filled by lubricants, creating a layer on fibres and threads that is smoother, which reduces friction by acting as a lubricating thin film (Howell *et al.* 1959). Lowering the roughness at the nanoscale has also been shown to result in a lower friction coefficient.

In terms of fabric surfaces, which have considerably higher R_a than a PDMS or stainless steel disc, it was thought that FG particles are able to fit and fill the apertures of both apparel and model surfaces in a number of ways:

1) FG with a significantly small particle size will fill an aperture/recess with a great number of particles;
2) FG with a specifically engineered particle size will fit exactly within an aperture/fibre recess;
3) FG with a too large particle size will be excluded from the aperture/recess resulting in no lubrication;
4) FG with a range of particle sizes will behave in such a way that the small particles will fill the asperities creating a smoother surface and the large particles, at significantly high speeds, will be entrained, therefore reducing friction.

Based on the strength of the QG previously discussed, a change in friction between κC and agar can be attributed to the mechanical properties of the particles. As the work required to deform a κC particle is significantly greater than to deform an agar particle, and when entering the apertures and asperities, it would therefore create a significantly stronger, semi-permanent, if not permanent, smoother surface as it is less likely to be deformed or removed from the gaps. The silicone ball is able to run across the new smoother surface and therefore increases the ability to lubricate the system. If an agar particle is being entrained into an aperture, with a much lower strength, it is more likely to be deformed out of the recess within the macrostructure of the surface (i.e. an asperity) and therefore leaving the same original rough surface of the fabric and consequently resulting in a higher friction coefficient.

In contrast to a stainless steel surface, the influence of processing on each type of FG is negligible for all fabric surfaces, as can be seen in Figure 5.13; the friction coefficient for each individual FG particle size is somewhat similar regardless of processing. As the roughness of the surfaces was dramatically increased from 0.01 μm for steel to ~390 μm for denim it was considered that the magnitude of the roughness when compared to the particle size is the overriding parameter.

Model fabrics reach mixed regime at much higher speeds than apparel fabrics and exhibit a sharp decline in friction coefficients to initial levels; however, this is not observed for apparel fabrics. The friction curve produced by model fabrics is more similar to stainless steel than those produced by apparel fabrics, particularly for agar FG lubrication. This may be due to the lack of fibres with the model fabrics and therefore the silicone ball is able to run more smoothly over the surface.

Denim results in a consistently lower friction coefficient compared to cotton, silk and model fabrics as there are no apertures to speak of therefore all available space between fibres and threads (based on surface roughness, this space would be vast) are easily filled by each FG, creating an extremely smooth surface, therefore resulting in high levels of lubrication. As the hydrocolloids used within this research are created using distilled water, any free water from within the FG system is likely to be soaked up by the fabrics causing swelling of the fibres, as was discussed previously, and as denim exhibits the most hydrophilic nature, this also explains the dramatic reduction in friction. When the percentage of wear was again looked at for the denim surface, it was noted that a 36% reduction in height (μm) was achieved by the addition of κCT_{40}, 46% with κCT_{56}, 19% agar RS_{1500} and a 60% reduction for agar RS_{300}, therefore indicating that the surface roughness of denim was altered.

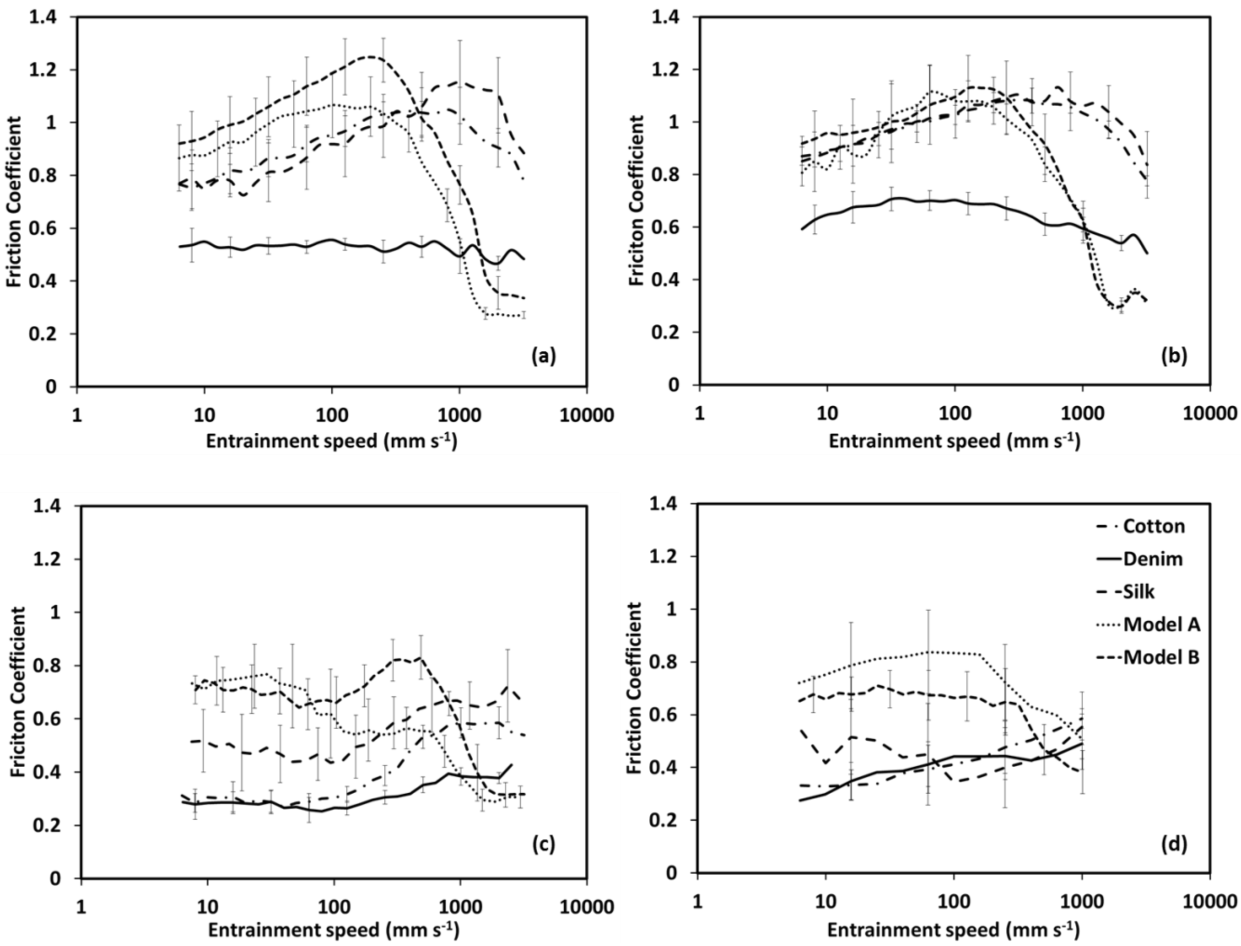


Figure 5.13 Friction coefficient vs. entrainment speed (mms^{-1}) plots (Stribeck curve) for all apparel and model fabrics tested with FG (a) agar RS_{1500}, (b) agar RS_{300}, (c) κCT_{40} and (d) κCT_{56}.

5.7 Summaries

Advancement in tribology, specifically measured using an MTM tribometer, was successfully achieved by the introduction of a fabric disc surface, which has not previously been reported. The friction coefficients were established using two methods: pin-on-disc and Stribeck, of both apparel and model fabrics also used within Chapter 4.

When considering apparel fabrics tested within dry conditions at low speeds, it was shown that denim exhibited the highest friction coefficients, which was expected due to it having such high surface roughness values; however, the influence of fibre type was imperative when understanding resulting friction coefficients of cotton and silk. In contrast to the surface roughness theory, silk exhibited a higher level of friction than cotton, although it has a lower R_a. The hydrophilic nature of the two fibre types was considered to be responsible for the difference, in which cotton's ability to uptake water was considerable higher than silk and therefore more easily wetted which in turn increasing lubrication.

All apparel and model fabrics friction, when subjected to a wetted environment, decreased in friction coefficients, and it was the ability of the most hydrophilic fabric to uptake water which resulted in the highest lubricating ability: denim. When comparing apparel and model fabrics lubricating ability, it was apparent that apparel fabrics were more effective due their fibrous nature having an increased ability to uptake water, swell, and create a smoother surface.

The ability to subject fabric surfaces to high frictional speeds (up to 3200 mms^{-1}) was achieved by the introduction of fabric discs to Stribeck tests with water as the lubricant. The same relationship between the hygroscopic nature of the apparel and model fabrics and friction coefficients was observed, and it was the extreme surface roughness values which inhibited the system entering mixed or hydrodynamic regimes. In order to establish these regimes, hydrocolloid fluid gels were engineered to achieve higher lubrication levels by fully entraining particles into the system.

Fluid gels made from the hydrocolloids agar and kappa carrageenan were subjected to varying processing parameters to achieve varying particle sizes and were seen to exhibit different lubricating behaviour on stainless steel discs. It was the hard, less deformable nature of the κC FG that was considered to hinder the lubrication between the silicone ball and steel disc due to a less efficient thin film layer being produced on such a smooth surface as steel (0.01 μm), when compared to agar. The processing parameters produced FGs with two groups of particle sizes, established using research taken from literature by Gabriele (2011) for agar and Garrec (2013) for κC, which are consistent with the results observed for this research where by:

- The faster the rotational speed creating agar FG, the smaller the particle size and the more well entrained the particles are, resulting in the lowest level of friction coefficient;

- The slower the cooling rate of the production of κC, the smaller the particle size and higher lubricating ability.

The introduction of the same FGs to the apparel and model disc surfaces resulted in κC exhibiting a greater lubricating ability than agar. This difference in relationship has been attributed to the theory that asperities of the fabric surface are filled by κC particles which are less likely to be deformed out of said asperities and therefore result in a semi-permanent smoother surface. The influence of particle size was deemed insignificant in contrast to the surface roughness values of the apparel and model fabrics and therefore it is the mechanical properties: hardness and elastic/plastic nature, which were considered to be of the highest importance.

6 Understanding consumers' thoughts on apparel fabrics and how they are influenced by different senses and in particular, sound.

6.1 Introduction

The aims of the study were to gain an insight into how consumers interact with fabrics and garments and which senses are primarily used to assess them, via one-to-one in depth interviews. Along with these aims, understanding how consumers regard sound in terms of fabric feel was essential to this Chapter's research in two scenarios: 1) without having introduced sound as an individual sense and 2) whether this opinion changes, and if so how, after having discussed sound at length. Where sound was concerned, the interviews were both subtle: pre-work, grouping, sensory probe and initial senses hierarchy or direct: sound descriptors, rough and smooth garments and return to senses hierarchy.

6.2 Pre-work

All except one participant completed the full set of pre-work. Participant 8 did not bring sensory images with them to the interview, and therefore results do not reflect a full data set. The following section describes those answers provided by participants of their thoughts on fabric feel via thought bubbles and images, and subsequent discussions during the interviews.

6.2.1 Thought bubbles

When exploring what participants thought of the denim jeans, based on what a person would be thinking about when wearing them, the feel and look of them were the most important aspects recorded. Participants were most often concerned with the iron ability of the jeans, reiterating on occasions that it indicated that they felt rough.

"…it would feel rough...the wrinkles, I would associate this with the roughness…they would feel uncomfortable."

"…I think they'd feel quite rough and you have to sort of bend and try and get them on. They don't look like soft jeans. I like the soft, stretchy jeans. These look stiff and rough on your skin."

Participants were generally indifferent to the white cotton shirt, neither placing its perceived softness with the softness of the silk night dress, or with and extreme roughness that the denim jeans were perceived to be. The cotton shirt thought to be soft and a staple item of clothing, mostly worn for work and not as a fashionable item.

Responses to the silk night dress were more animated and intriguing and participants found it the easiest garment to describe without it being in front of them.

"…Oh, absolutely amazing. I can tell from the picture it would feel very soft, luxurious and almost comforting, very nice."

"…soft silk, smooth, bright colour and nice to wear. The type of fabric is very silky, nylon, polyester; it would be nice on the skin. The colour is bright and shiny. And light."

As per the aim of this section of the interviews, it was understood that participants were able to judge garments without being to hand, with only the sense of sight, however, many could reflect upon the feel of the garments well too. It was apparent that only sight and touch were used to assess the garments presented and not sound, taste or smell. It was suspected that sound may not have been thought as being an important sense and therefore allowed for further sound probing to occur throughout the main interviews.

All participants' thoughts are written in the thought bubbles and can be seen in Appendix 10.

6.2.2 Sensory images

Participants were asked to bring with them to the main interview images (to see all images refer to Appendix 10) which they felt reflected how they feel about fabrics and garments using all senses available to them. By asking participants to engage with all senses it provided an insight into whether sound plays an important role in their judgements of fabrics. Overall, participants used the senses (including total numbers): touch (38), sight (31), smell (17) and sound (6) to either choose images or when asked to put a sense to the image however, it must be noted that some images carried with them more than once sense.

Some examples of the images chosen for touch were: a cat sat on a fur blanket, a made bed, a rose, a hug of a jumper, fur fabrics, babies in towelling and being kissed, plenty of garments being worn, towelling, skin being touched etc. Many of the same examples were chosen for sight, as previously described, many of the participants used both touch and sight together, however, only sight examples were: scarves, colours, trousers which would look comfortable, etc.

As can be seen touch and sight were most often used when assessing images, followed by smell. From this one can infer that participants seldom use sound (three out of ten participants mentioned sound) and do not use taste at all. When participants were asked to relate all senses to the images a number of spontaneous responses were given for sound in particular:

> *"…P: No, I don't think there is any missing… I: because we have 5 senses … P: Yes, but these are the ones I use as a consumer to assess fabrics. These are the ones I use with laundry, smell is around 60/70% of a judgment of product, another important thing is the appearance of the fabrics, the way the colours are still bright, I would say is around 20% absolutely, I really take care of the colours. In Italy we love colours, we don't like dark colours and the other 20% is about the touch. Everything else (senses) are not important, for me as a consumer."*

"…so sound, about wearing that sort of fabric, I find that quite hard to think about to be honest."

When sound was mentioned by one participant it was in relation to having sound as a desired sense.

"…no, I don't think you'd want a sound, if there is it means there is friction. I don't think you can have a taste of clothes."

Participant 4 tended to be more methodical about approaching the task, whereby, they placed images to each sense, as opposed to all other 8 participants finding images they liked and then related senses to them in turn. Silence for participant 4 was desired (as previously quoted above) and the images which related to this can be seen in Figure 6.1.

Figure 6.1 Participant 4's responses to sound in relation to fabrics in image format

6.3 Grouping exercise

In order to gain further understanding of what senses are important to consumers when assessing fabrics and garments, participants were asked to take part in a grouping exercise of 30 swatches of varying types of fabrics. Participants were asked to group the fabrics in any way they desired and were asked to explain which senses they had used to achieve the groups. The grouping exercise was carried out three times to pull out all aspects of sensory understanding and thoughts of the participants (all images of groups for each participant can be seen in Appendix 11).

Results for all participants can be seen in Table 6.1 and are presented with the primary and secondary sense used within one group and specifically which part of each sense was important. It was apparent that participants chose groups using more than one sense (10 groupings were executed with two senses), and the order they used varied. When looking at participant's ability to group the swatches for a second time, one individual sense was used in 9 out of 10 responses; whereas for the first grouping 7 out of the 10 groups were achieved using two senses.

Participants most commonly used sight for all groups which was expanded upon to include colours i.e. tone, shades and aesthetically pleasing aspects along with matching swatches, the look of fabric in terms of texture and type i.e. synthetic or natural and finally which were generally appealing.

> *"… I am already starting to group these according to colours, even though I know there is a difference in texture (feels fabric swatch). The first way I would do it is the colour or the tone…I would say first of all the colour, they must all be the same colour however, when you look at it they are not perfectly the same colour but the tonality is similar. And in second place I would group in terms of the quality of the fabric but then first thing that is driving me is the colour."*

Touch was the sense used, after sight, to group throughout the exercise, either as the primary or secondary sense, and was described by participants as most commonly reflecting texture, followed by those swatches which aesthetically and texturally fit together, fabric type i.e. natural or synthetic and then according to preference.

> *"…the feel of them. They feel like they should be in a group. The texture feels the same. That's silky but not the same as those one[s]. They feel rougher. Even though that's velvet, velour, the texture feels the same."*

Grouping the fabric swatches for a third time proved to be a more difficult with participants taking a longer time to decide upon which direction to take as well as exactly which sense they had used.

"…I: Did you find it difficult to group for a 3rd time?

P: Yes, I did. To me, touching fabric it's either look for feel. They are the two main ones when you think about fabric."

"…This is very tricky and awful to think of a third way."

By asking the participants to regroup for a third time, it was hoped that they would be forced to think 'outside of the box' and possibly engage in the idea that more than just two of the five senses could be used to group. As well as deciphering which senses were chosen, the grouping exercise was considered to provide an insight into whether sound was thought of. However, as previously mentioned participants did not independently discuss sound in any part of this exercise.

Table 6.1 Participants responses to the 'Grouping Exercise' for each grouping of the 30 swatches presented; Group 1, 2 and 3 showing which sense they used to group, both Primary (1st) and Secondary (2nd) sense used within these groups. The more specific reasons for choosing each group are also shown i.e. description of sense.

Participant		Group 1		Group 2		Group 3	
		1st	2nd	1st	2nd	1st	2nd
1	Sense	Sight		Sight		Touch	
	Description of group	Colours and Tone		Colour and Shades		Texture	
2	Sense	Touch	Sight	Sight		Sight	Touch
	Description of group			Colours		Look of texture	Texture
3	Sense	Touch	Sight	Sight		Touch	
	Description of group		Colours	Colours liked, go together		Texture	
4	Sense	Sight		Touch		Touch	Sight
	Description of group	Colour				Texture	Look of texture
5	Sense	Sight	Touch	Sight		Touch	
	Description of group	Materials that go together		Colours that go together			
6	Sense	Touch	Sight	Sight		Touch	
	Description of group	Swatches that go together		Colours		Synthetic and Natural	
7	Sense	Sight	Touch	Sight		Touch	
	Description of group			Colours			
8	Sense	Touch		Sight		Touch	Sight
	Description of group			Colours - light and dark		Richness	
9	Sense	Sight		Sight	Touch	Sight	
	Description of group	Colours				Synthetic and Natural	
10	Sense	Sight	Touch	Sight		Feel	
	Description of group	Knowledge of fabric types		Colours		Preferences – likes and dislikes	

6.4 Sensory Probe – 'If I was an alien…'

Within the third section of the interviews, participants were asked to carry out a sensory probe task in which they were asked to imagine that the interviewer was an alien, who could not understand the spoken word and only had their senses plus emotion and colour. Although colour is sensed by sight, it was decided that colour should be introduced separately, as it could reflect one' thoughts in a different way. The task was designed to pull out all levels of sensorial aspects of fabric feel by getting the alien to look at colours, textures, smell, listen to, feel an emotion towards and taste what the participant believed to best represent the garment they were holding. As In addition to asking the participants to answer what they thought epitomised the fabric, they were also asked to counteract these answers with what did not or would not reflect the garment.

It must be noted that for some participants, data is missing for 'what is not' and is represented by a dashed line. All data can be seen in Appendix 12.

The senses explored were touch, sight, smell, sound and taste along with, colour reflection of feel and emotion. The order in which each participant was asked to describe each garment was alternated to allow for learned behaviour and ordering influences.

When asked to describe the first garment, participants on the whole struggled with the concept of how to describe the first sense. However, when asked to describe *"how would they not"* describe the garment the participants were more receptive and more able to answer the *"what is…"* part.

When considering each sense in turn, participants were more able to identify what they would want the alien to feel and have an emotion to when compared to the remaining senses. For the denim jeans, touch varied between participants, whereby participant 3 related the feel of jeans as *"…skin of a peach"* and when asked how not to describe the touch it was likened to *"…the skin of a honeydew melon, with a rough texture"* and in contrasting opinion participant 5 reflected that jeans felt like touching *"…a hard, rough surface on a table"* and not *"…soft, fur fabric"*.

Those participants that described jeans, within the interviews, as having a smoother touch, in contrast, when talking about the jeans within the pre-work generally had a negative opinion on wearing and feeling them. This contrast reflects how important touch is when assessing fabrics, alongside sight which goes someway to explain why a number of senses were used for the grouping exercise; sight goes hand-in-hand with touch.

A consensus in opinion was apparent for what participants would want the alien to touch that would represent the feel of the silk night dress: words such as smooth, soft and silky were often used coupled with a vast contrast in what the alien would not feel: rough, hard, prickly and spiky were noted. Participants generally found it easier to describe silk and were more engaging and interactive with the garment.

When considering what the alien should touch to represent the cotton shirt, paper and other furnishings and garments made from cotton were chosen more than twice and the general thought around cotton was of indifference; neither exciting nor extremely negative. Participants equally chose smooth and rough items to not touch: soft towels coupled with sand paper and soft suede shoes with pineapple skin.

Participants were asked to describe an emotion around the garments. Silk was consensually described as having positive connotations, adjectives such as seductive, calm, sexy and pleasurable and five out of the ten participants described the night dress as relaxing. The emotion behind cotton was more intermediate and average in terms of descriptors: gentle, relaxed, functional, smart were words used to portray the shirt. In contrast, participants who had previously described the jeans with negative touch adjectives, it was then perceived as having a comfortable emotion.

As previously described in Section 3.3.11.1.1, one of the aims of the interviews was to tap into what participants thoughts and feelings around using sound as a primary sense when considering fabric feel and in order to ensure that the whole interview was not biased towards sound, it was essential to initially mask the interest in sound to allow for natural and true responses to be recorded.

Tables 6.2 to 6.4 show the participants responses to how they would describe the garment they were feeling in terms of sound; what would the alien listen to? When considering which categories of sounds were chosen it was apparent that music and songs were most popular, along with sounds in nature.

For those sounds in nature, participants described moving sounds: a flowing river, running water, rustling leaves, wind blowing through trees to name but a few. The adjectives used to describe the action of moving nature sounds were related to which garment was being described: silk adjectives were generally slow and smooth, whereas denim was fast and energetic.

"…constant, slow bubbling water."

"…like a river, a smooth river…it's flowing but in a gentle way."

"…a train; dirty, smoky…fast and loud."

Musical and song based adjectives were commonly representative of the garment to hand in a similar way to those sounds in nature, whereby, for the silk garment songs represented a relaxing environment: cotton: jazz, rhythm and blues, soft music. However, for denim it was thought to be denoted by upbeat cheerful, soothing and easy listening.

The sounds, particularly in terms of music and songs, could be related to the environment in which the garments are commonly worn, as opposed to the sounds that the fabrics make i.e. friction created when rubbing the fabrics together in the hand, indicating that the concept of sounds of fabrics was still not thought about or was difficult to understand.

Table 6.2 Participant responses to Sensory probe 'If I was an alien…' for what silk sounds like and what silk does not sound like.

What SILK is	What SILK is not
A gently flowing river Edith Piaf (classical) Sound of a hug	-
Squirrels running on grass - delicately	-
Bird song, little chirpy birds, butterflies Sensuous	Screeching cat
Water running, bubbling slowly	Heavy metal Thunder
Soothing music - Strauss (calming)	Heavy metal music
Soft, relaxing music. Water, waves, slow	Loud dance music
Relaxing, instrumental arrangement with pianos and violins	Rap music
Radio static	Marvin Gaye
Whisper, gentle	Train going through a tunnel, slow heavy goods train
Classical music, opera, smooth	Rap music

Table 6.3 Participant responses to Sensory probe 'If I was an alien…' for what cotton sounds like and what cotton does not sound like.

What COTTON is	**What COTTON is not**
Drop of water Georgia (R&B, blues - gentle voices) Turning page of a high quality magazine - rhythmic, smooth	-
Friction Wind blowing Ruffling Driving on a road	-
Soft music Indian pipes	Heavy rock
Wardrobe door closing Rustling leaves	Very soft rain
Silence (quiet)	Loud music
Washing up, cooking with utensils	Train - dirty, smoky, steam train, fast moving
Light wind blowing through a forest - not fast moving	Thunderstorm, heavy and loud
Wind chimes, airiness, breeze blowing	Industrial noise (no freedom or space)
Jazz music, enjoyable	Aircraft engine, bold, noisy
Sound of electric car rolling slowly at speed limit	Bullet train

Table 6.4 Participant responses to Sensory probe 'If I was an alien…' for what denim sounds like and what denim does not sound like.

What DENIM is	What DENIM is not
Hand brushing on the table Children screaming, kids in the park (noisy, having fun) Metallic sound - tinny	-
Steam (running reasonably fast)	-
Cheerful pop song, easy listening	Opera, doesn't go with jeans
Metallic wrapping paper	Silence
Bright, upbeat music	Calm music, not one to get up and dance to
Opening crisps, rustling	Bird song - (cheerful, happy)
Pop song, romantic, easy to listen to, familiar	Heavy metal music
Town/city sounds including traffic	Waves breaking on the beach, any size of waves
Classic FM, soothing music	Traffic on motorway - noisy, erratic
Country music, workers music, strong, full of beat	Classical musical

6.5 Senses Hierarchy

In order to investigate objectively which senses are used when considering fabrics and garments, participants were asked to create a senses hierarchy, an example of which can be seen in Figure 6.2. Participants were asked to fill out the hierarchy in order of importance they believed each sense has when considering fabrics and assign a percentage to each of the five senses. Participants were able to fill out the hierarchy in any way they chose on the white board provided. A summary of the participant's weightings (in percentage) can be seen in Table 6.5 and all photographs of the hierarchies produced can be found in Appendix 13.

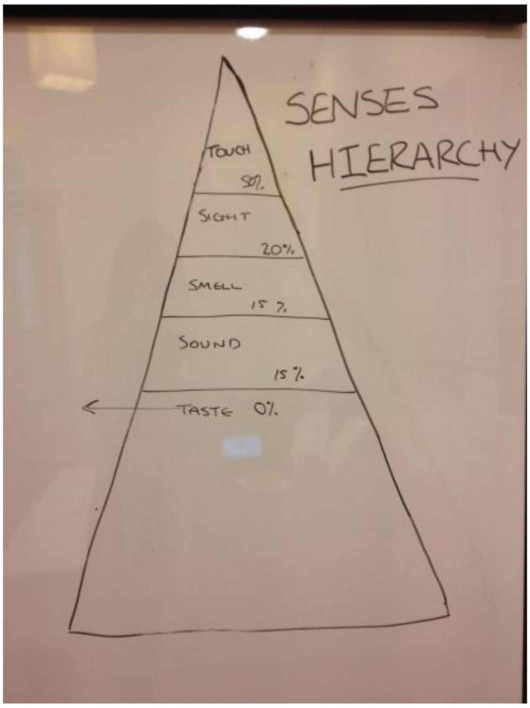


Figure 6.2 An example of participant's senses hierarchy.

Corresponding with the results previously seen with the grouping exercise, touch and sight were imperative when considering fabrics and garments, whereby 7 out 10 participants reported that feel is the most important sense with an average of 51%, leaving 3 out of the 10 participants rating sight with the highest weighting with an average of 34%. 7 out of 10 participants rated sound with an importance on the hierarchy, but no higher than 25%. 3 out of 10 participants thought that taste was an important sense (one participant thought it was equally as important as sound, one more and one less important).

When participants who did not rate sound as an important sense were asked in more detail about their decision, responses were:

"… P: Then in terms of the sound, not really, that's why during the previous exercise I was struggling to identify the sound. With fabrics, it's definitely hard to relate a sound… I: Would you put sound on the hierarchy at all? … P: no, definitely not… I: Would you put it outside the hierarchy? … P: yes"

"…the two important things for me are sight and touch when thinking about it. Everything else isn't that important to me."

"… I: Have you ever considered sound? … P: No… I: Do you ever think clothes have a particular sound? … P: no I've only thought about sight and feel, sound wouldn't come into it."

The hierarchies were returned to after exploring sound (see Section 3.3.11.1.5.2 for more details) to understand if, having talked at length about sound, participants would have changed their opinion or rating of the importance of sound. 3 of the 10 participants did not change their opinion of sound as an important sense when considering fabrics, and out of the 7 who did change their opinion, participant 4 lowered the percentage weighting and participant 6 changed the priority of importance from smell then sound to sound then smell.

"…I'd move sound up to 20%, taste out entirely and going to take smell down to 10%. Feel, sight, sound, smell and not taste"

Table 6.5 Ratings of each sense within the senses hierarchy. The results show their initial weighting for each participant and how they changed or did not change their responses after talking in depth about sound as a sense.

Participant		Touch	Sight	Smell	Sound	Taste
1	Initial	60	35	5	0	0
	Changed	No change in hierarchy scores				
2	Initial	50	50	20	25	0
	Changed				30	
3	Initial	40	60	0	0	0
	Changed	No change in hierarchy scores				
4	Initial	50	40	5	5	0
	Changed			7	3	0
5	Initial	30	60	5	0	5
	Changed			0	5	0
6	Initial	50	20	15 (1st)	15 (2nd)	0
	Changed			15 (2nd)	15 (1st)	
7	Initial	45	25	20	10	0
	Changed	No change in hierarchy scores				
8	Initial	50	20	20	5	5
	Changed			10	20	0
9	Initial	80	15	4	1	0
	Changed	75		5	5	
10	Initial	50	15	20	10	5
	Changed				15	0
Average		**51**	**34**	**12**	**6**	**2**

It is important to note that, having mentioned sound extensively throughout the last section of the interviews along with having sound within the sensory probe, whether participants may have been biased or influenced by highlighting sound, when reassessing their hierarchy scores, as other senses were not singled out within the last section. It is difficult to assess, without asking participants, whether their change in opinion was true or encouraged, however, if fabric care and measurement techniques of fabric feel were to move forward into using sound, it would be prudent to raise the awareness of fabric sound and the ability to lower it.

6.6 Sound as a sense

The final section of the interviews was to explore how sound was not only thought of, but also how it can be used to describe fabrics and garments. Participants were either placed into one of two categories: those who had thought of sound a sense at all and those who had not. For the majority, these categories were based on the interviewer's objective perception (i.e. whether participants had mentioned or talked in length about sound) and occasionally subjectively (i.e. gauging a participant's opinion of sound). Participants were asked whether they agreed with the perception of their thoughts of sound and then interview was either changed or carried on with to understand further thoughts on sound.

Participants were asked to give descriptive words for how they would describe fabric sounds and a summary of each participant's descriptors can be seen in Table 6.6. 5 out of the 10 participants gave adjectives and two participants gave silence as a descriptor for sound of fabrics and deemed it to be an important, if not essential, part of a fabric's overall quality. The desire for silence was noted throughout the interviews for all garments:

"…pure silence, as I move can I hear my cotton shirt. Unobtrusive, not interrupting. Background noise. Not at the fore front…"

"…I think positive sounds would be no sound, or a flowing sound, doesn't make a sound at all. A very low sound of a fabric would be good…"

"…It shouldn't have a sound. I went through the five senses and thought there shouldn't be a sound, no rustling…"

As well as trying to engage the participants into thinking of sound descriptors, it was deemed useful for the basis of future sensory work (see Section 3.3.12) to understand what descriptive attributes had common themes. It must be noted that although participants gave an insight into what descriptors are used, not all were used within the sensory attributes chosen in Chapter 7.

Table 6.6 Participant responses when having been asked to give words that describe fabric sounds.

Participant	Descriptors
1	When fabrics are being pulled out of a washing machine, the sound is heavy
2	Crisp, silky, smooth, lubricated, slippy, rough
3	Loud - in terms of patter. None for actual sound produced
4	Pure silence, background noise, not crinkle or rustle
5	Loud pattern. Rustling. Quiet
6	Rustle, scraping
7	Light, heavy, loud or quiet, sound of running, sport, sleeping in a bed
8	-
9	Rustling, crunchy, stiff, no sound
10	Ripping, stiff

When considering the extreme descriptors, participants were asked to name a garment which they would relate to the attributes "smooth" and "rough", therefore allowing an insight into which, albeit broadly, apparel fabrics are considered to be either. Participant responses (see Table 6.7) were similar between the set interviewed, whereby, a silk garment, in particular a night dress, was chosen as the smoothest and in contrast jeans were often chosen as the roughest apparel garments. A silk night dress and jeans were also used throughout the interview (for the pre-work thought bubbles and the sensory probe) and therefore could have influenced the participants' responses (being at the forefront of their minds when considering any garment of any descriptor).

Table 6.7 Participant responses to being asked to put a garment to the extreme descriptors 'rough' and 'smooth'

Smoothest	Roughest
Silk nightie for a woman An expensive Italian cotton shirt	Jeans when walking in them
Night dresses, silky dresses	Jeans - I accept the sounds
Silky nightie	Corduroy
Silk nightie, wear a slip undresses for quietness	Jeans
Jersey/cotton dress or top	Taffeta dress
Silk night dress	Synthetic, outdoor coat, waterproof coating
Nightie	Jeans
Evening dress, feminine	Outdoor wear, waterproof jacket
Silk garment	Taffeta dress
Fleecy PJs, super soft towels	Rain coat, over dried towels and jeans

6.7 Summaries

One-to-one in depth interviews were carried out with 10 participants with the aim of gaining an insight into consumer thoughts around fabric feel and which senses are more important than others. The interviews consisted of two parts: 1) pre-work, which participants were asked to complete before arriving to the interview and 2) the main interview in which a script was followed. The overall aim was to establish if consumers used or have previously thought about sound when choosing or interacting with garments, without the interviewer biasing the participants towards thinking about sound as an individual sense at least for the first 4 sections of the interview.

Discussions based around the participant's pre-work showed how, when asked to describe their thoughts on fabrics using all senses available to them, touch and sight were most commonly thought of initially as would be in agreement with fabric literature which mainly focuses on the feel of a garment or how it is made to look, closely followed by smell i.e. the influence of fabric conditioners. Two participants referred to sound being a sense that was relevant, but was not an important factor when considering fabrics, and one in particular raised the awareness that if there were to be a sound it should be 'silence'.

When participants were asked to group the 30 fabric swatches the same two most common senses were used as within the pre-work: touch and sight. Participants within the first two rounds of groupings tended towards using two senses, interchangeably or with one being the primary sense and one a secondary sense. No participants used sound, smell or taste when grouping the swatches. Participants in general found grouping for a third time more difficult than the previous two groupings.

When participants were moved into relaying what they believed three garments (cotton shirt, silk night dress and denim jeans) felt like when trying to make an alien understand without using spoken words, it was here where participants struggled to come to terms with the concept. When descriptors were chosen it was noticed that the senses most easily given were for touch and emotions, whereas, all other senses (colour, sight, smell sound and taste) were not so easily thought of. When concentrating on descriptors given for sound, it was enlightening to observe that all were either part of two categories: music or songs. For songs it was established that these may well be a reflection of where the participant could see themselves wearing the garment, as opposed to the friction noise created whilst rubbing the garments together.

For the senses hierarchy, in the first instance 7 out of 10 participants rated sound with an importance on the hierarchy, but no higher than 25% and after having spoken about sound extensively 3 of the 10 participants did not change their opinion of sound as an important sense when considering fabrics and out of the 7 who did change their opinion; participant 4 lowered the percentage weighting and participant 6 changed the priority of importance from smell then sound to sound then smell.

In summary, interviews were most insightful when requiring understanding into consumer responses to sound of fabrics and related sound to fabric feel, reflecting previous thoughts that sound is generally un-thought of and not important when it was thought of.

7 Exploring the influence of manipulating real-time fabric sounds on consumer perception on fabric feel

7.1 Introduction

The investigations into the sensory perceptions of fabric sounds are imperative when relating the importance of reducing frictional noise of apparel fabrics, for the purpose of consumer desires. However, as discussed within Chapter 2, research into the understanding of consumer and sensory perceptions of fabric sounds has solely been investigated using pre-recorded fabric sounds captured from within a laboratory. The gap in knowledge based on the understanding the effect of real-time fabric sounds on sensory perception is vast as, to the author's knowledge, has not yet been fully explored.

Where a pre-recorded fabric sound has been manipulated, and the investigators aims were to understand the effect of increasing overall sound levels on both psychological and physiological responses in terms of perception, a relationship has been found where negativity to the sounds has increased with the noise level (Yi & Cho 1999; Cho *et al.* 2001b; Sukigara & Ishibashi 2001; Cho *et al.* 2005; Cho *et al.* 2006).

Although, real-time manipulation of fabric sounds has not been explored within the literature, for other products such as food (Zampini & Spence 2004; 2010) and toothbrushes (Zampini *et al.* 2003), along with frictional noise of skin (Jousmäki & Hari 1998; Guest *et al.* 2002), has been investigated. Manipulations of varying sound characteristics found within a sound spectrum have been achieved using the first three-block design created by Jousmäki and Hari (1998) whereby both high and low frequencies were attenuated and amplified, along with overall sound level being attenuated and amplified whilst also comparing the effect of all characteristics together. This design was further enhanced by the research group lead by Charles Spence, in which the manipulation of sounds produced when eating crisps and apples was seen to influence the sensory perceptions in terms of attributes (rough, smooth, stale and fresh) (Zampini & Spence 2004). As sounds were attenuated in both the high frequencies and overall sound levels, participants rated the crisps they tasted as more stale, consequently less fresh and rougher. A similar relationship was observed for the manipulation of electric toothbrushes, in which a louder sound (high and low frequencies and overall sound levels were amplified) was perceived as more unpleasant and rough.

Using an adapted version of Jousmäki and Hari's three-block design and in order to advance literature in terms of fabrics, the aims of this study were to investigate whether manipulating real-time fabric sounds created by participants affected their perceptions on fabric they were feeling. Participants were asked to rate a number of attributes, (liking, softness, smoothness, crispness, textured, silkiness and roughness), on a visual analogue scale (VAS) based on their perceptions of the fabric they were feeling, whilst not being privy to the information that the fabric sounds were the only variable being changed.

7.2 Results

To understand the effect of sound manipulation on ratings of sensory attributes, all data captured were analysed using ANOVA. A significant effect (i.e. $p < 0.05$) was observed for the sensory attribute textured [$F_{(9,252)} = 2.864$, $p = .005$, $r = .28$], however significant effects were not seen for liking [$F_{(9,252)} = 0.988$, $p = .450$], smoothness [$F_{(9,252)} = .869$, $p = .553$], roughness [$F_{(9,252)} = 1.118$, $p = .350$], softness [$F_{(9,252)} = 0.234$, $p = .989$], silkiness [$F_{(6,169)} = 1.132$, $p = .346$] or crispness [$F_{(9,252)} = 1.152$, $p = .327$] (means and two standard deviations for data can be seen in Figure 7.2. It must be noted that Mauchly's test indicated that the assumption of sphericity had been violated for silkiness (χ^2 (44) = 65.524, $p < .022$) and therefore the F-ratio was read from Greenhouse-Geisser (with different degrees of freedom and error) as opposed to Sphericity Assumed within the ANOVA output (refer to Section 3.3.12.6 for the explanation of sphericity).

As a significant effect of manipulation on ratings of 'textured' was observed, individual T-tests were carried out to establish which manipulations were significantly different from one another. Results from the T-test for textured showed a significant difference between Manipulations 7 [$\bar{X}$ = 41.86, $\sigma = 17.76$] and 8 [$\bar{X}$ = 28.1, $\sigma = 14.32$, p = .019] whereby, participants rated the material as more textured when the sound was manipulated using manipulation 7 than by 8. A significant difference was also observed between Manipulation 2 [$\bar{X}$ = 40.4, $\sigma = 17.7$] and Manipulation 8 [$\bar{X}$ = 28.1, $\sigma = 14.32$, p = .015], whereby participants rated the material as more textured when the sound was manipulated using manipulation 2 than by 8 (see Figure 7.2 (g)). Significant results were not seen for other manipulations for the attribute 'textured':

- Manipulation 1 [$\bar{X}$ = 34.52, $\sigma = 20.34$] and M2 [$\bar{X}$ = 40.4, $\sigma = 17.7$, p = 1.00], M3 [$\bar{X}$ = 39.14, $\sigma = 22.75$, p = 1.00, p = 1.00], M4 [$\bar{X}$ = 32.52, $\sigma = 18.98$, p = 1.00], M5 [$\bar{X}$ = 34.93, $\sigma = 20.93$, p = 1.00], M6 [$\bar{X}$ = 34.10, $\sigma = 17.06$, p = 1.00], M7 [$\bar{X}$ = 41.86, $\sigma = 18.60$, p = 1.00], M8 [$\bar{X}$ = 28.1, $\sigma = 14.32$, p = 1.00], M9 [$\bar{X}$ = 31.24, $\sigma = 20.94$, p = 1.00] and M10 [$\bar{X}$ = 33.34, $\sigma = 15.28$, p = 1.00];
- Manipulation 2 [$\bar{X}$ = 41.14, $\sigma = 18.1$] and M3 [$\bar{X}$ = 39.14, $\sigma = 22.75$, p = 1.00], M4 [$\bar{X}$ = 32.52, $\sigma = 18.98$, p = .831], M5 [$\bar{X}$ = 34.93, $\sigma = 20.93$, p = 1.00], M6 [$\bar{X}$ = 34.10, $\sigma = 17.06$, p = 1.00], M7 [$\bar{X}$ = 41.86, $\sigma = 18.60$, p = 1.00], M9 [$\bar{X}$ = 31.24, $\sigma = 20.94$, p = 1.00] and M10 [$\bar{X}$ = 33.34, $\sigma = 15.28$, p = .615];
- Manipulation 3 [$\bar{X}$ = 39.14, $\sigma = 22.75$] and M4 [$\bar{X}$ = 32.52, $\sigma = 18.98$, p = 0.831], M5 [$\bar{X}$ = 34.93, $\sigma = 20.93$, p = 1.00], M6 [$\bar{X}$ = 34.10, $\sigma = 17.06$, p = 1.00], M7 [$\bar{X}$ = 41.86, $\sigma = 18.60$, p = 1.00], M8 [$\bar{X}$ = 28.1, $\sigma = 14.32$, p = .172], M9 [$\bar{X}$ = 31.24, $\sigma = 20.94$, p = 1.00] and M10 [$\bar{X}$ = 33.34, $\sigma = 20.94$, p = .615];
- Manipulation 4 [$\bar{X}$ = 32.52, $\sigma = 18.98$] and M5 [$\bar{X}$ = 34.93, $\sigma = 20.93$, p = 1.00], M6 [$\bar{X}$ = 34.10, $\sigma = 17.06$, p = 1.00], M7 [$\bar{X}$ = 41.86, $\sigma = 18.60$, p = 1.00], M8 [$\bar{X}$ = 28.1, $\sigma = 14.32$, p = 0.172], M9 [$\bar{X}$ = 31.24, $\sigma = 20.94$, p = 1.00] and M10 [$\bar{X}$ = 33.34, $\sigma = 15.28$, p = .615];

- Manipulation 5 [$\bar{X}$ = 34.93, $\sigma = 20.93$] and M6 [$\bar{X}$ = 34.10, $\sigma = 17.06$, *p* = 1.00], M7 [$\bar{X}$ = 41.86, $\sigma = 18.60$, *p* = 1.00], M8 [$\bar{X}$ = 28.1, $\sigma = 14.32$, *p* = 1.00], M9 [$\bar{X}$ = 31.24, $\sigma = 20.94$, *p* = 1.00] and M10 [$\bar{X}$ = 33.34, $\sigma = 15.28$, *p* = 1.00];
- Manipulation 6 [$\bar{X}$ = 34.10, $\sigma = 17.06$] and M7 [$\bar{X}$ = 41.86, $\sigma = 18.60$, *p* = 1.00], M8 [$\bar{X}$ = 28.1, $\sigma = 14.32$, *p* = 1.00], M9 [$\bar{X}$ = 31.24, $\sigma = 20.94$, *p* = 1.00] and M10 [$\bar{X}$ = 33.34, $\sigma = 15.28$, *p* = 1.00];
- Manipulation 7 [$\bar{X}$ = 20.94, $\sigma = 18.60$] and M8 [$\bar{X}$ = 28.10, $\sigma = 14.32$, *p* = 1.00], M9 [$\bar{X}$ = 31.24, $\sigma = 20.94$, *p* = .759] and M10 [$\bar{X}$ = 33.34, $\sigma = 15.28$, *p* = .814];
- Manipulation 8 [$\bar{X}$ = 28.10, $\sigma = 14.32$] and M9 [$\bar{X}$ = 31.24, $\sigma = 20.94$, *p* = 1.00] and M10 [$\bar{X}$ = 33.34, $\sigma =15.28$, *p* = 1.00]
- Manipulation 9 [$\bar{X}$ = 31.24, $\sigma = 20.94$] and M10 [$\bar{X}$ = 33.34, $\sigma = 15.28$, *p* = 1.00].

As a significant difference was observed between manipulations 2 and 8, and 7 and 8 it was important to understand the effect of the specific manipulation on the attribute textured. As,

- M2 is an increase in overall dB level by +3 dB (no change in high or low freq)
- M7 is an increase in low frequencies by +3 dB (no change in overall level)
- M8 is an increase in low frequencies by +6 dB (no change in overall level)

When referring back to the definitions of attributes that were given to the participants to read, textured was defined as rough and raised. This could indicate a higher surface roughness value, which from Chapter 4 is correlated to total noise; thus, if the total noise is greater it would be expected that it would be perceived as rougher. Manipulation 7 (an increase of low frequencies by +3 dB) was perceived to be significantly more textured than manipulation 2 where there was an increase overall in +3 dB, however, surprisingly neither manipulations were significantly different from the original sound; the mean differences (M.D) were for manipulation 1 and 7 [M.D = 7.345 ± 4.058, *p* = 1.00] and manipulation 1 and 2 [M.D = 4.327 ± 4.327, *p* = 1.00], respectively.

Literature that has investigated the effect of real-time sound manipulation on perception of varying attributes for different products (crisps, apples and other food products as well as toothbrushes and sandpaper), have seen differing effects of the specific manipulations of the sound e.g. low vs. high frequency changes. Zampini and Spence (2004), when investigating the manipulation of real-time sounds when eating crisps, showed that when the overall sound and the high frequencies within the sound (2-20 kHz) were increased, by 12 dB, participants perceived the crisps to be more crisp and fresh, when rating using scales of soft to crisp and stale to fresh. When toothbrushes were investigated by Zampini (2003) and sound was manipulated in real-time, participants significantly rated the devices as being more unpleasant (rating on a scale of unpleasant to pleasant) when both the high frequencies (2-20 kHz) were lowered by 12 dB and the overall level was decreased to -40 dB. When participants were asked to rate the toothbrushes from rough to smooth, there was a significant effect of manipulation, with the toothbrushes being rated as more rough with an increase in high frequencies (than without manipulation, or an attenuation of the sound). As these products are primarily either consumed or used within the mouth and within Zampini's research, the effect of perception of the product cannot easily be related to the change in real-time fabric sounds being investigated within this chapter, due to the extra influence of bone conduction within the jaw explained within the literature review (see Section 2.7.3). The added influence of bone-jaw conduction causing extra vibrations between the jaw and the ear could affect perception and therefore cannot be completely translated to touch. However, Guest *et al.* (2002) investigated the effect of sound manipulation on perception of roughness of sand paper using the same manipulation method. Participants were given a pair of samples of sand paper and asked to choose which one was the rough or smooth sample within the pair whilst always feeling the same grade of sand paper. In contrast to when participants within Zampini and Spence (2004; 2010) and Zampini *et al.*'s (2003) experiments were asked to rate on a VAS scale, participants within Guest *et al.* (2002) research were asked to make a choice, therefore analysis was carried out on reaction times and errors of choices. Results showed that participant error was highest when choosing rough rather than smooth, particularly when the sounds were manipulated in comparison to the original sound. However, there was no significant effect of sound manipulations on reaction times. Guest *et al.* (2002) progressed within their research to investigate the effect of sound manipulation on the perception of wet-dryness and smooth-roughness of participants hands being rubbed together. Although they observed a significant effect of the manipulation when the real-time sounds were increased in both in overall level of total noise and high frequencies, a major flaw in their research, and one which they themselves acknowledge, is that participants are more than aware that their hands are not physically changing during the experiment and therefore why a significant difference is found is unknown. An explanation for why a significant effect was observed is that of demand characteristics, whereby, participants were aware that an outcome was desired by the researcher and therefore were more than willing to oblige with a result. In order to reduce the effect of researcher's expectations on results, it is imperative that participants are not aware of the any information surrounding the study e.g. hypothesis/es, equipment, materials, motives etc. Whilst these experiments reported in literature are centred on touch, they do not investigate the effect of sound manipulation on ratings of attributes of materials or surfaces, as was investigated in this chapter.

The manipulation method used within Zampini and Spence (2004; 2010) and Guest *et al.*'s (2002) research altered both the overall level of the sound and a selection of high frequencies (between 2 and 20 kHz). Their overall sound level was attenuated (reduced) by 0 dB, 20 dB or 40 dB, and within these the high frequencies were attenuated by 12 dB, not changed or amplified by 12 dB. When comparing these levels of manipulation (in terms of decibels) to the research carried out within this chapter, they are a lot larger and therefore could explain why the only one significant difference was observed. Changing the dB levels within this research by 3 dB and a maximum of 6 dB is more subtle and in contrast to sounds made within the mouth, or those produced from sandpaper, fabric sounds created by touch are extremely quiet and therefore any increase beyond 6 dB would be detected as being too obscure and not real which may have led to the participants guessing that the sounds were being manipulated. A basic pilot study was carried out with students from within Chemical

Engineering, University of Birmingham, by changing the real-time fabrics using the same method created by Zampini and Spence (2004; 2010), however, when participants were asked for feedback on sounds the general consensus was that of the sounds were 'fake' and therefore unlike fabric sounds. As such, a much lower amplification or attenuation was selected. It would be interesting to determine whether Zampini and Spence (2004; 2010), Zampini *et al.* (2003) and Guest *et al.* (2002) experienced the same issue, however, this unfortunately was not discussed within their work.

It comes into question here whether the manipulation of fabric sounds is not as influential as the change in eating or mechanical sounds, due to the lack of significant difference observed. As was discovered during Chapter 6, sounds of fabrics are not generally thought of, and certainly not when compared to touch and sight. As with this research, in order to eliminate the participants' knowledge of the manipulating method and if hearing is disregarded, the only available sense was touch, which can potentially have been heightened as it was singled out, and therefore sound becomes even less significant. It could also be thought that sounds produced from within the mouth whilst eating are more influential and recognisable.

Based on results reported within Chapter 4, fabric-on-fabric friction sounds were recorded around 6000 Hz (see Figure 7.1), and therefore this frequency range was included as a specific 'peak increase' within the manipulations, to investigate whether any significant effect was observed on attribute perception. No significant difference was reported between the original sounds (manipulation 1) and PI +3 dB or PI +6 dB for any attributes. However, this may have been expected as the fabric sounds were being achieved by skin-fabric contact which may reside in a separate frequency range.

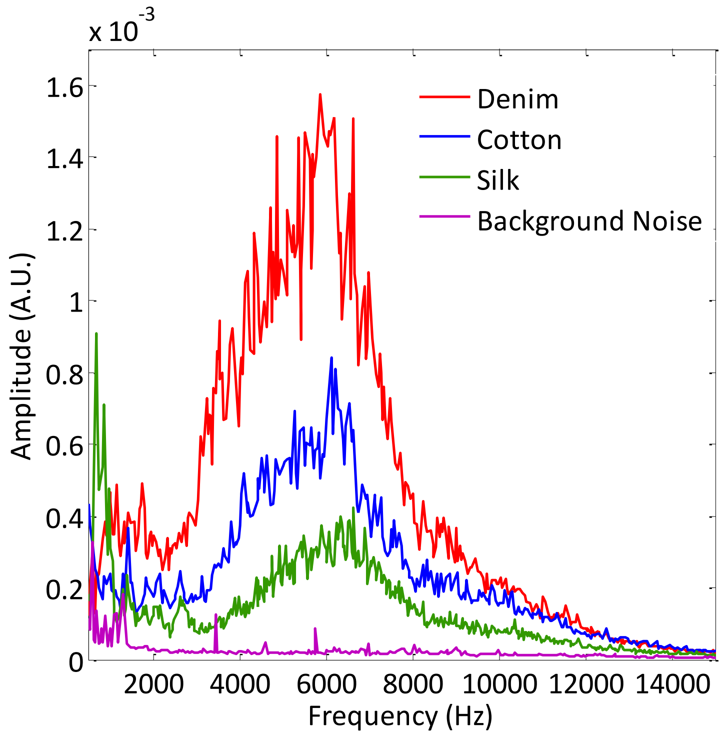
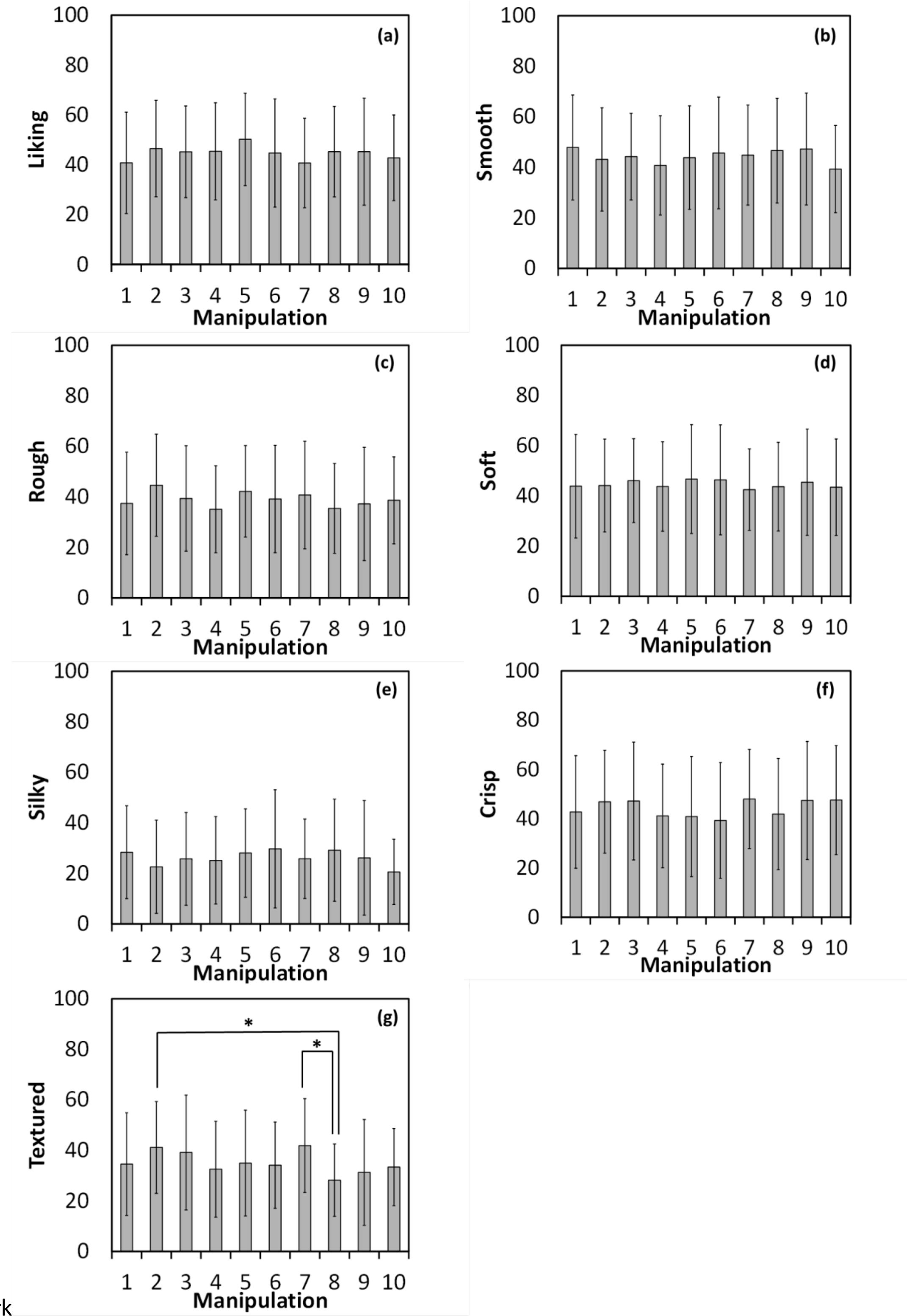


Figure 7.1 Frequency vs. Amplitude spectra (one repeat) for apparel fabrics (denim, cotton and silk) produced within the SRR (method explained in Section 3.3). Background noise (BGN) is also presented. Characteristics (including dimensions) of all the apparel and model fabrics can be seen in Table 3.1.

Results observed within this chapter were further understood using literature which investigated participant responses to fabric sounds, albeit not real-time. Cho and Cho (2007), used a MAFN, described within Section 2.5.1, to capture frictional noise created by fabrics, and investigated the effect of original fibre i.e. silk, cotton, wool etc. on those frictional sounds produced. Eight carefully selected fabric sounds, from a selection of 60 fabrics sounds, were played to the participants at either 40 dB, 50 dB or 60 dB sound pressure level (SPL) whilst they rated certain sensory attributes on a seven point semantic differential scale (SDS) which included “hard vs. soft”, “quiet vs. loud”, “dull vs. sharp”, “obscure vs. clear”, “smooth vs. rough”, “low vs. high” and “unpleasant vs. pleasant”. Cho and Cho (2007) observed that on increasing the SPL, sounds were perceived as being harder, louder, sharper, more obscure, rougher, higher and less pleasant. This relationship was first observed within Chapter 4 (Section 4.4.1.1), whereby, the rougher the surface on an apparel fabric, the louder the total noise emitted. They reported favourable perceptions of fabrics such as Cotton

Pique and with higher ratings of attributes such as soft, quiet, dull, smooth, low and pleasant. In terms of loudness vs. quietness, higher SPL levels were reported as feeling louder and all fabrics at 40 dB were perceived to be. This is what would be expected based on the findings that a rougher, more unpleasant fabric produces a louder sound. As described earlier, this difference between the original fabric sound (manipulation 1) and manipulations 2, 3 and 4 was not significant, however, in line with Zampini and Spence (2003; 2004) and Guest *et al.* (2002), the increase in SPL within Cho and Cho's (2007) experiments was both 10 dB and 20 dB, greater than 3 dB and 6 dBs used within this research's manipulations.

Using the MAFN fabric recordings, manipulating to levels of 50 dB, and 60 dB from 40 dB in SPL and presenting them to participants has been used widely within literature for a range of fabrics and aims of the research, all of which have similar results: the louder the fabric sound the more unpleasant it is perceived to be (Cho *et al.* 2001a; Cho *et al.* 2001b; Yi *et al.* 2002; Cho *et al.* 2006).



PRework

Figure 7.2 Mean values for all manipulations for each of the sensory attributes investigated. * refers to where results were significantly different at a p < 0.05 level. Error bars represent two standard deviations of the mean. Codes for the manipulations used within the Chapter are: M1 (OL +0 dB), M2 (OL +3 dB), M3 (OL +6 dB), M4 (OL -3 dB), M5 (HF +6 dB), M6 (HF +3 dB), M7 (LF +3 dB), M8 (LF +6 dB), M9 (PI +6 dB) and M10 (PI +3 dB) where OL: overall level, HF: high frequencies, LF: low frequencies and PI: peak increase (refer to Section 3.3.12.5 for more details).

7.3 Pearson's correlations between sound manipulations and sensory attributes

The following section describes at length about significant and relevant relationships between attributes, however, it must be noted that it is not an exhaustive list and an explanation is not given for all correlations, the readers are referred to Table 7.1 to Table 7.5 for more information.

The relationship between the sensory responses for each manipulation was analysed using Pearson's correlation coefficient and carried out by SPSS. All correlations can be seen in Table 7.1 and Table 7.5. Correlations with significance of $p < 0.01$ (i.e. 99% confidence) are colour coded in green and those with $p < 0.05$ (i.e. 95% confidence) are coded in red.

As can be seen from all tables of correlations, more relationships between sensory attributes were significant at $p < 0.05$ than were not significant, therefore this infers it was more conscious; that the sensory attributes were closely related and understanding of why is extensively described below.

Firstly, as has been previously described, a significant difference between the attribute 'textured' was observed for manipulations 2 [$\bar{X}$ = 41.14, $\sigma = 18.17$], 7 [$\bar{X}$ = 41.86, $\sigma = 18.60$] and 8 [$\bar{X}$ = 28.17, $\sigma = 14.32$]. When correlating textured with other attributes it was apparent that a multitude of significant relationships existed. A correlation between rough and textured was observed for 8 out of the 10 manipulations (manipulations 7 and 10 did not produce a significant relationship) with a consistent positive relationship at $p < 0.05$, and in 6 out of the 8 relationships at a $p < 0.01$ level, indicating a significant relationship between these two attributes. It is important to refer back to the list of definitions of attributes (see Section 3.3.12.4) in which textured was defined as being rough, in addition to raised, and therefore this may have influenced the participant's ratings. In an expected contrast, textured was consistently correlated negatively with smoothness in all manipulations, however, a significant relationship was observed in 5 out of the 10 manipulations and only one manipulation at a $p < 0.01$ level. This is also an indication that a stronger relationship was observed for rough and textured than smooth and textured. As textured has been observed to be strongly related to roughness, its relationship with liking was also explored showing a significant, medium, negative correlation [*r* (27) = -.415, *p* = .025] for manipulation 9 but no other manipulations, indicating that the attribute textured is not significantly related to liking.

Although the VAS used was anchored from not at all to extremely, in contrast to literature (i.e. Zampini and Spence (2004) anchoring their scales smooth to rough and stale to fresh) for 8 out of the 10 manipulations there was a consistent negative correlation between smoothness and roughness (the strength of the relationship is also reported) (M1: [*r* (27) = -.345, *p* = .060] (medium), M2: [*r* (27) = .469, *p* = .010] (medium), M3: [*r* (27) = -.498, *p* = .010] (medium), M4: [*r* (27) = -.480, *p* = .008] (medium), M5: [*r* (27) = -.537, *p* = .003] (strong), M6: [*r* (27) = -.327, *p* = .047] (medium), M7: [*r* (27) = -.533, *p* = .003] (strong), M8: [*r* (27) = -.527, *p* = .003] (strong), M7: [*r* (27) = -.593, *p* = .001] (strong), M9: [*r* (27) = -.593, *p* = .001] (strong) and M10: [*r* (27) = -.185, *p* = .336] (small)). These results are encouraging when considering the relationship between sound of fabrics and consumer perceptions; that participants consistently rated the sound as being smoother than rough and vice versa. To confirm these thoughts on the relationship seen between roughness and smoothness, the correlations between liking and both attributes were considered.

A significant negative relationship ($p < 0.05$) was observed between liking and roughness for 6 out of the 10 manipulations, and in contrast the relationship between smoothness and liking was significantly positively correlated ($p < 0.05$) for 9 out of the 10 manipulations. The strongest correlation value for liking and smoothness was observed for Manipulation 2; a change in the overall sound by +3 dB [*r* (27) =.838, *p* = .000], followed by Manipulation 6; a change in the high frequencies of the sound by +3 dB [*r* (27) = .677, *p* = .000]. These correlations indicate that, although slightly unexpected, the increase in sound levels gave way to a strong affinity between liking and smoothness.

Many of the attributes rated by the participants could be assumed to fall into groups. Smoothness, silkiness and softness, when considering fabric feel would promote liking (‘soft’ group); it was observed within Chapter 6's interview results that softness is a desired attribute and in contrast a 'rough' group was also apparent which encompasses the relationship between rough, crisp and textured as well as understanding how they are related to liking. It was Manipulation 2 which produced the strongest correlations between the attributes in the soft group with 4 out of the 6 relationships producing *r* values > .600: liking vs. smoothness [*r* (27) = .838, *p* = .000], liking vs. softness [*r* (27) = .818, *p* = .000], liking vs. silkiness [*r* (27) = .424, *p* = .022], softness vs. silkiness [*r* (27) = .483, *p* = .008], soft vs. smoothness [*r* (27) = .822, *p* = .000] and silkiness vs. smoothness [*r* (27) = .605, *p* = .001]. As previously described, Manipulation 2 involved increasing the overall level of the sound by +3 dB and therefore again, an unlikely and unpredicted relationship has been observed between a louder sound and softness. When looking specifically at the mean scores for each attribute (liking $\bar{x} = 46.80$, $\sigma = 19.31$, smoothness $\bar{x} = 43.10$, $\sigma = 20.45$, softness $\bar{x} = 44.07$, $\sigma = 18.51$ and silkiness $\bar{x} = 22.59$, $\sigma = 18.46$) to understand this relationship observed, it is apparent that liking, smoothness or softness are not particularly rated as high scores; all gave means under the half-way point on the VAS scale and therefore, although a significant relationship is observed it is not wise to assume that participants strongly liked nor felt that the fabric was smooth, soft or silky. When looking at the opposite possible group of attributes i.e. a 'rough' group and the relationship between those attributes within the group, it was apparent that there were less significant relationships present: liking vs. rough [r (27) = .550, *p* = 0.002] and rough vs. textured [r (27) = 0.618, *p* = 0.000], when compared to 'soft', however, unlike 'soft' they were expected relationships and reflect the effect of changing the real-time sound by +6 dB. Again, to further understand the relationship the mean scores were taken into account: (liking $\bar{x} = 46.80$, $\sigma = 19.31$, roughness $\bar{x} = 44.59$, $\sigma = 20.23$ and textured $\bar{x} = 41.14$, $\sigma = 18.17$), however, the means show how either relationships are not extreme along this VAS scale and therefore are only an indication.

With manipulation 7, the 'soft' and 'rough' groups were also analysed to further understand what effect a change in low frequencies by +3 dB exerted on the participants' ratings. Within the soft group the following significant correlations were observed: liking vs. smoothness [*r* (27) = .566, *p* = .001], soft vs. smoothness [*r* (27) = .471, *p* = .010] and silkiness vs. smoothness [*r* (27) = .403, *p* = .030]. When exploring the 'rough' group, the same opposite expected result was seen; the number of correlations was higher for manipulation 7 than 2: liking vs. rough [*r* (27) = -.450, *p* = .014], rough vs. crisp [*r* (27) = .495, *p* = .003], textured vs. crisp [*r* (27) = .371, *p* = .047] therefore indicating that a change in low frequencies was perceived as being more 'rough' than the same change in all frequencies. To further understand this, in terms of a reality i.e. is the change in roughness perception due to low frequencies, the 'rough' group was also looked at in further detail for manipulation 8; LF +6 dB. As can be observed from the following correlations: liking vs. roughness [*r* (27) = .471, *p* = .010], rough vs. textured [*r* (27) = .561, *p* = .002], relationships within the group were less in numbers and therefore thoughts centred on whether a manipulation limit can be reached for the human ear and to what value it exists. In terms of the correlations observed within the 'soft' group for manipulation 8 the resulting correlations were observed: liking vs. smoothness [*r* (27) = .494, *p* = .006], liking vs. softness [*r* (27) = .479, *p* = .009], liking vs. silkiness [*r* (27) = .520, *p* = .004], smoothness vs. softness [*r* (27) = .525, *p* = .003], smoothness vs. silkiness [*r* (27) = .597, *p* = .001] and softness vs. silkiness [*r* (27) = .483, *p* = .008].

The previous manipulations, 2, 7 and 8, were an increase in decibel levels and were contrastingly observed to be more influential on softness as opposed to roughness, and therefore the following section looks in depth at the significant relationships established for a reduction in decibel levels; manipulation 4, which based on literature: a reduction in sound for touch, eating and other personal care products resulted in a more pleasant, smoother, staler response (Guest *et al.* 2002; Zampini *et al.* 2003; Zampini & Spence 2004; 2010). Significant correlations were observed for manipulation 4 within the soft group: liking vs. smoothness [*r* (27) = .625, *p* = .000], liking vs. softness [*r* (27) = .513, *p* = .004], silkiness vs. smoothness [*r* (27) = .466, *p* = .011] and smoothness vs. softness [*r* (27) = .739, *p* = .000] and those within the rough group were: liking vs. roughness [*r* (27) = -.550, *p* = .002], roughness vs. textured [*r* (27) = .618, *p* = .000]. If the relationship between quietness and softness is true for real-time fabric sounds, the results described above would not have been predicted, whereby, stronger and more significant correlations would have been observed within the 'soft' group. In particular, when comparing with number of relationships and their strength with those seen in manipulations 2 (an increase of all frequencies by +3 dB) only 4 out of the 6 possible attribute combinations within the soft group were present in manipulation 4 and of those 4, all gave a correlation strength less than those in manipulation 2. This may be a direct result of the subtlety of the manipulation change; that a decrease in all frequencies by 3 dB was not great detectable enough by the participants, however, an extreme change, as in Zampini and Spence (2003), was not possible due to the quietness of fabrics and that unlike their research the original fabric sound was not amplified as a starting point for participants to hear.

In terms of all attribute correlations for Manipulation 10, it was observed that the levels of significance were at their lowest, whereby, only 4 pairs of relationships were significantly correlated and were observed to be medium correlations and not strong: liking vs. smooth [r (27) = .506, p = .005], rough vs. soft [r (27) = -.410, p = .027], crisp vs. rough [r (27) = .391, p = .036] and textured vs. smooth [r (27) = -.375, p = .045]. All significant relationships observed were considered to be in line with what would have been expected i.e. where textured is negatively correlated to smoothness and in contrast liking is positively correlated to smoothness, however, it is unknown why, when compared to other manipulations, so few relationships were observed. Manipulation 10 resulted in a change in the peak frequency with an increase in +6 dB. However, this could also be explained by the reasoning behind the nature of the high frequencies within touch on fabric sound; that they are not recognised at an influential level by the human ear and is only a product of the fibre-fibre interaction previously discussed in Chapter 4.

Table 7.1 Pearson's correlation coefficients, *r*, for manipulations 1 and 2, and attributes. All correlations are shown and where results are in green it relates to a significance at $p < 0.01$ (2 tailed) and those in red are $p < 0.05$ (2 tailed)

	Manipulation 1				**Manipulation 2**		
	Attribute	***r* value**	***p* value**		**Attribute**	***r* value**	***p* value**
Like	Like	1.000		Like	Like	1.000	
	Smooth	0.350	0.063		Smooth	0.838	0.000
	Rough	-0.285	0.134		Rough	-0.554	0.002
	Soft	0.448	0.015		Soft	0.818	0.000
	Silky	0.115	0.554		Silky	0.424	0.022
	Crisp	-0.151	0.435		Crisp	-0.084	0.664
	Textured	0.830	0.669		Textured	-0.370	0.105
Smooth	Like	0.350	0.063	Smooth	Like	0.838	0.000
	Smooth	1.000			Smooth	1.000	
	Rough	-0.354	0.060		Rough	-0.469	0.010
	Soft	0.390	0.037		Soft	0.822	0.000
	Silky	0.425	0.021		Silky	0.605	0.001
	Crisp	-0.175	0.365		Crisp	-0.157	0.416
	Textured	-0.405	0.029		Textured	-0.219	0.253
Rough	Like	-0.285	0.134	Rough	Like	-0.554	0.002
	Smooth	-0.354	0.060		Smooth	-0.469	0.010
	Rough	1.000			Rough	1.000	
	Soft	-0.145	0.454		Soft	-0.521	0.004
	Silky	-0.335	0.076		Silky	-0.348	0.640
	Crisp	0.524	0.004		Crisp	0.570	0.001
	Textured	0.449	0.015		Textured	0.532	0.003
Soft	Like	0.448	0.015	Soft	Like	0.818	0.000
	Smooth	0.390	0.037		Smooth	0.822	0.000
	Rough	-0.145	0.454		Rough	-0.521	0.004
	Soft	1.000			Soft	1.000	
	Silky	0.116	0.116		Silky	0.483	0.008
	Crisp	0.275	0.275		Crisp	-0.183	0.342
	Textured	0.235	0.235		Textured	-0.293	0.123
Silky	Like	0.115	0.554	Silky	Like	0.424	0.022
	Smooth	0.425	0.021		Smooth	0.605	0.001
	Rough	-0.335	0.076		Rough	-0.348	0.064
	Soft	0.298	0.116		Soft	0.483	0.008
	Silky	1.000			Silky	1.000	
	Crisp	-0.044	0.819		Crisp	-0.399	0.720
	Textured	-0.102	0.598		Textured	-0.322	0.089
Crisp	Like	-0.151	0.435	Crisp	Like	-0.840	0.664
	Smooth	-0.175	0.365		Smooth	-0.157	0.416
	Rough	0.524	0.004		Rough	0.570	0.001
	Soft	0.210	0.275		Soft	-0.183	0.342
	Silky	-0.044	0.819		Silky	-0.339	0.720
	Crisp	1.000			Crisp	1.000	
	Textured	0.416	0.025		Textured	0.366	0.510
Textured	Like	0.083	0.669	Textured	Like	-0.307	0.105
	Smooth	-0.405	0.029		Smooth	-0.219	0.253
	Rough	0.449	0.015		Rough	0.532	0.003
	Soft	-0.228	0.235		Soft	-0.293	0.123
	Silky	-0.102	0.598		Silky	-0.322	0.890
	Crisp	0.416	0.025		Crisp	0.366	0.051
	Textured	1.000			Textured	1.000	

Table 7.2 Pearson's correlation coefficients, *r*, for manipulations 3 and 4, and attributes. All correlations are shown and where results are in green it relates to a significance at $p < 0.01$ (2 tailed) and those in red are $p < 0.05$ (2 tailed).

Manipulation 3				Manipulation 4			
	Attribute	***r* value**	***p* value**		**Attribute**	***r* value**	***p* value**
	Like	1.000			Like	1.000	
	Smooth	0.404	0.030		Smooth	0.625	0.000
	Rough	-0.193	0.316		Rough	-0.550	0.002
Like	Soft	0.219	0.254	Like	Soft	0.513	0.004
	Silky	-0.014	0.941		Silky	0.224	0.242
	Crisp	0.125	0.519		Crisp	-0.184	0.340
	Textured	0.060	0.759		Textured	-0.195	0.311
	Like	0.404	0.030		Like	0.625	0.000
	Smooth	1.000			Smooth	1.000	
	Rough	-0.498	0.006		Rough	-0.480	0.008
Smooth	Soft	0.610	0.000	Smooth	Soft	0.739	0.000
	Silky	0.452	0.014		Silky	0.466	0.011
	Crisp	-0.363	0.053		Crisp	-0.084	0.665
	Textured	-0.342	0.086		Textured	-0.385	0.039
	Like	-0.193	0.316		Like	-0.550	0.002
	Smooth	-0.498	0.006		Smooth	-0.480	0.008
	Rough	1.000			Rough	1.000	
Rough	Soft	-0.384	0.039	Rough	Soft	-0.431	0.020
	Silky	-0.358	0.057		Silky	-0.022	0.910
	Crisp	0.486	0.008		Crisp	0.145	0.452
	Textured	0.691	0.000		Textured	0.618	0.000
	Like	0.219	-0.140		Like	0.513	0.004
	Smooth	0.610	0.000		Smooth	0.739	0.000
	Rough	-0.384	0.039		Rough	-0.431	0.020
Soft	Soft	1.000		Soft	Soft	1.000	
	Silky	0.484	0.008		Silky	0.251	0.190
	Crisp	-0.280	0.142		Crisp	-0.222	0.247
	Textured	-0.103	0.593		Textured	-0.416	0.025
	Like	-0.014	0.941		Like	0.224	0.242
	Smooth	0.452	0.014		Smooth	0.466	0.110
	Rough	-0.358	0.057		Rough	-0.022	0.910
Silky	Soft	0.484	0.008	Silky	Soft	0.251	0.190
	Silky	1.000			Silky	1.000	
	Crisp	-0.532	0.003		Crisp	-0.184	0.339
	Textured	-0.338	0.730		Textured	-0.141	0.467
	Like	0.125	0.519		Like	-0.184	0.340
	Smooth	-0.363	0.530		Smooth	-0.084	0.665
	Rough	0.486	0.008		Rough	0.145	0.452
Crisp	Soft	-0.280	0.142	Crisp	Soft	-0.222	0.247
	Silky	-0.532	0.003		Silky	-0.184	0.339
	Crisp	1.000			Crisp	1.000	
	Textured	0.550	0.002		Textured	0.154	0.424
	Like	0.060	0.759		Like	-0.195	0.311
	Smooth	-0.324	0.086		Smooth	-0.385	0.039
	Rough	0.691	0.000		Rough	0.618	0.000
Textured	Soft	-0.103	0.593	Textured	Soft	-0.416	0.025
	Silky	-0.338	0.073		Silky	-0.141	0.467
	Crisp	0.550	0.002		Crisp	0.154	0.424
	Textured	1.000			Textured	1.000	

Table 7.3 Pearson's correlation coefficients, *r*, for manipulations 5 and 6, and attributes. All correlations are shown and where results are in green it relates to a significance at $p < 0.01$ (2 tailed) and those in red are $p < 0.05$ (2 tailed).

	Manipulation 5			Manipulation 6		
	Attribute	***r* value**	***p* value**	**Attribute**	***r* value**	***p* value**
Like	Like	1.000		Like	1.000	
	Smooth	0.593	0.001	Smooth	0.677	0.000
	Rough	-0.278	0.144	Rough	-0.579	0.001
	Soft	0.473	0.009	Soft	0.607	0.000
	Silky	0.255	0.182	Silky	0.718	0.000
	Crisp	-0.202	0.293	Crisp	-0.431	0.020
	Textured	-0.318	0.093	Textured	-0.290	0.127
Smooth	Like	0.593	0.001	Like	0.677	0.000
	Smooth	1.000		Smooth	1.000	
	Rough	-0.537	0.003	Rough	-0.372	0.047
	Soft	0.724	0.000	Soft	0.587	0.001
	Silky	0.690	0.000	Silky	0.757	0.000
	Crisp	-0.377	0.044	Crisp	-0.425	0.021
	Textured	-0.438	0.018	Textured	-0.115	0.553
Rough	Like	-0.278	0.144	Like	-0.579	0.001
	Smooth	-0.537	0.003	Smooth	-0.372	0.047
	Rough	1.000		Rough	1.000	
	Soft	-0.340	0.071	Soft	-0.360	0.055
	Silky	-0.403	0.030	Silky	-0.348	0.065
	Crisp	0.480	0.008	Crisp	0.476	0.009
	Textured	0.517	0.004	Textured	0.423	0.022
Soft	Like	0.473	0.009	Like	0.607	0.000
	Smooth	0.724	0.000	Smooth	0.587	0.001
	Rough	-0.340	0.071	Rough	-0.360	0.055
	Soft	1.000		Soft	1.000	
	Silky	0.438	0.018	Silky	0.498	0.006
	Crisp	-0.292	0.124	Crisp	-0.251	0.190
	Textured	-0.439	0.017	Textured	-0.317	0.094
Silky	Like	0.255	0.182	Like	0.718	0.000
	Smooth	0.690	0.000	Smooth	0.757	0.000
	Rough	-0.403	0.030	Rough	-0.348	0.065
	Soft	0.438	0.018	Soft	0.498	0.006
	Silky	1.000		Silky	1.000	
	Crisp	-0.356	0.580	Crisp	-0.397	0.033
	Textured	-0.480	0.008	Textured	-0.284	0.136
Crisp	Like	-0.202	0.293	Like	-0.431	0.020
	Smooth	-0.377	0.044	Smooth	-0.425	0.021
	Rough	0.480	0.008	Rough	0.476	0.009
	Soft	-0.292	0.124	Soft	-0.251	0.190
	Silky	-0.356	0.058	Silky	-0.397	0.033
	Crisp	1.000		Crisp	1.000	
	Textured	0.554	0.002	Textured	0.431	0.020
Textured	Like	-0.318	0.093	Like	-0.290	0.127
	Smooth	-0.438	0.018	Smooth	-0.115	0.553
	Rough	0.517	0.004	Rough	0.423	0.022
	Soft	-0.439	0.017	Soft	-0.317	0.094
	Silky	-0.480	0.008	Silky	-0.284	0.136
	Crisp	0.554	0.002	Crisp	0.431	0.020
	Textured	1.000		Textured	1.000	

Table 7.4 Pearson's correlation coefficients, *r*, for manipulations 7 and 8, and attributes. All correlations are shown and where results are in green it relates to a significance at $p < 0.01$ (2 tailed) and those in red are $p < 0.05$ (2 tailed).

	Manipulation 7				Manipulation 8		
	Attribute	***r* value**	***p* value**		**Attribute**	***r* value**	***p* value**
Like	Like	1.000		Like	Like	1.000	
	Smooth	0.566	0.001		Smooth	0.494	0.006
	Rough	-0.450	0.014		Rough	-0.575	0.001
	Soft	0.332	0.078		Soft	0.479	0.009
	Silky	0.225	0.241		Silky	0.520	0.004
	Crisp	0.101	0.604		Crisp	-0.228	0.235
	Textured	0.022	0.910		Textured	-0.208	0.279
Smooth	Like	0.566	0.001	Smooth	Like	0.494	0.006
	Smooth	1.000			Smooth	1.000	
	Rough	-0.533	0.003		Rough	-0.527	0.003
	Soft	0.471	0.010		Soft	0.525	0.003
	Silky	0.403	0.030		Silky	0.597	0.001
	Crisp	-0.149	0.440		Crisp	-0.188	0.330
	Textured	-0.240	0.209		Textured	-0.328	0.083
Rough	Like	-0.450	0.014	Rough	Like	-0.575	0.001
	Smooth	-0.533	0.003		Smooth	-0.527	0.003
	Rough	1.000			Rough	1.000	
	Soft	-0.230	0.230		Soft	-0.401	0.031
	Silky	-0.146	0.450		Silky	-0.361	0.055
	Crisp	0.495	0.006		Crisp	0.254	0.183
	Textured	0.350	0.062		Textured	0.561	0.002
Soft	Like	0.332	0.078	Soft	Like	0.479	0.009
	Smooth	0.471	0.010		Smooth	0.525	0.003
	Rough	-0.230	0.230		Rough	-0.401	0.031
	Soft	1.000			Soft	1.000	
	Silky	0.163	0.399		Silky	0.483	0.008
	Crisp	0.021	0.915		Crisp	0.236	0.219
	Textured	-0.360	0.055		Textured	-0.154	0.425
Silky	Like	0.225	0.241	Silky	Like	0.520	0.004
	Smooth	0.403	0.030		Smooth	0.597	0.001
	Rough	-0.146	0.450		Rough	-0.361	0.055
	Soft	0.163	0.399		Soft	0.483	0.008
	Silky	1.000			Silky	1.000	
	Crisp	-0.136	0.481		Crisp	-0.582	0.001
	Textured	0.149	0.441		Textured	-0.112	0.563
Crisp	Like	0.101	0.604	Crisp	Like	-0.228	0.235
	Smooth	-0.149	0.440		Smooth	-0.188	0.330
	Rough	0.495	0.006		Rough	0.254	0.183
	Soft	0.021	0.915		Soft	-0.236	0.219
	Silky	-0.136	0.481		Silky	-0.582	0.001
	Crisp	1.000			Crisp	1.000	
	Textured	0.371	0.047		Textured	0.267	0.162
Textured	Like	0.022	0.910	Textured	Like	-0.208	0.279
	Smooth	-0.240	0.209		Smooth	-0.328	0.083
	Rough	0.350	0.062		Rough	0.561	0.002
	Soft	-0.360	0.055		Soft	-0.154	0.425
	Silky	0.149	0.441		Silky	-0.112	0.563
	Crisp	0.371	0.047		Crisp	0.267	0.162
	Textured	1.000			Textured	1.000	

Table 7.5 Pearson's correlation coefficients, *r*, for manipulations 9 and 10, and attributes. All correlations are shown and where results are in green it relates to a significance at *p* < 0.01 (2 tailed) and those in red are *p* < 0.05 (2 tailed).

	Manipulation 9				Manipulation 10		
	Attribute	*r* value	*p* value		Attribute	*r* value	*p* value
Like	Like	1.000		Like	Like	1.000	
	Smooth	0.635	0.000		Smooth	0.506	0.005
	Rough	-0.516	0.004		Rough	-0.212	0.271
	Soft	0.652	0.000		Soft	0.240	0.210
	Silky	0.401	0.031		Silky	0.062	0.751
	Crisp	-0.095	0.625		Crisp	-0.029	0.882
	Textured	-0.415	0.025		Textured	-0.239	0.211
Smooth	Like	0.635	0.000	Smooth	Like	0.506	0.005
	Smooth	1.000			Smooth	1.000	
	Rough	-0.593	0.001		Rough	-0.185	0.336
	Soft	0.487	0.007		Soft	0.359	0.056
	Silky	0.470	0.010		Silky	0.230	0.231
	Crisp	-0.292	0.124		Crisp	0.117	0.544
	Textured	-0.478	0.009		Textured	-0.375	0.045
Rough	Like	-0.516	0.004	Rough	Like	-0.212	0.271
	Smooth	-0.593	0.001		Smooth	-0.185	0.336
	Rough	1.000			Rough	1.000	
	Soft	-0.335	0.076		Soft	-0.410	0.027
	Silky	-0.259	0.175		Silky	0.050	0.795
	Crisp	0.466	0.011		Crisp	0.391	0.036
	Textured	0.629	0.000		Textured	0.264	0.166
Soft	Like	0.652	0.000	Soft	Like	0.240	0.210
	Smooth	0.487	0.007		Smooth	0.359	0.056
	Rough	-0.335	0.076		Rough	-0.410	0.027
	Soft	1.000			Soft	1.000	
	Silky	0.326	0.085		Silky	0.264	0.166
	Crisp	-0.089	0.646		Crisp	-0.347	0.065
	Textured	-0.405	0.029		Textured	-0.260	0.172
Silky	Like	0.401	0.031	Silky	Like	0.062	0.751
	Smooth	0.470	0.010		Smooth	0.230	0.231
	Rough	-0.259	0.175		Rough	0.050	0.795
	Soft	0.326	0.085		Soft	0.264	0.166
	Silky	1.000			Silky	1.000	
	Crisp	-0.161	0.403		Crisp	-0.040	0.837
	Textured	-0.516	0.004		Textured	-0.084	0.664
Crisp	Like	-0.950	0.625	Crisp	Like	-0.029	0.882
	Smooth	-0.292	0.124		Smooth	0.117	0.544
	Rough	0.466	0.011		Rough	0.391	0.036
	Soft	-0.089	0.646		Soft	-0.347	0.065
	Silky	-0.161	0.403		Silky	-0.040	0.837
	Crisp	1.000			Crisp	1.000	
	Textured	0.346	0.066		Textured	0.227	0.237
Textured	Like	-0.415	0.025	Textured	Like	-0.239	0.211
	Smooth	-0.478	0.009		Smooth	-0.375	0.045
	Rough	0.629	0.000		Rough	0.264	0.166
	Soft	-0.405	0.029		Soft	-0.260	0.172
	Silky	-0.516	0.004		Silky	-0.084	0.664
	Crisp	0.346	0.066		Crisp	0.227	0.237
	Textured	1.000			Textured	1.000	

7.4 Summaries

A sound manipulation study was designed in order to manipulate/alter the real-time fabric sounds created by a participant. Manipulations altered the overall sound level, specific high and low frequencies and those frequencies residing close to 6.5 kHz. 29 participants were recruited from the University of Birmingham and were asked to rate seven sensory attributes: liking, smoothness, silkiness, softness, crispness, textured and roughness.

Participant responses were analysed using a repeated measured ANOVA which resulted in a significant difference between the sensory attributes and sound manipulations at a $p < 0.015$ level. Bonferroni t-tests were employed to establish where the overall significance lay between manipulations for each sensory attribute. It was observed that within the sensory attribute textured, three sound manipulations were significantly different: manipulation 2 was rated as significantly more 'textured' than manipulation 8, and manipulation 7 was rated as significantly more textured than manipulation 8. In terms of other manipulations and sensory attributes, no other significant differences were observed.

To further understand the relationships between all manipulations and sensory attributes Pearson's correlations were carried out which produced a vast number of strong correlations at both $p < 0.05$ and $p < 0.01$. Expected relationships were observed, where perceptions of fabrics were concerned, between opposing attributes such as smoothness and roughness, liking and smoothness and liking and roughness. A consistent negative correlation was observed between smooth and rough.

As was previously mentioned, the lack of significant differences observed within the ANOVA analysis could be attributed to thoughts that fabric sounds are extremely subjective and individual and may not be as influential as eating, mechanical sounds (e.g. toothbrush) or skin friction sounds.

8 Conclusions

Investigations into the methods used to capture fabric frictional sounds and their relationships with mechanical properties of said fabrics have been documented within the literature. Influences on frictional noise include, but are not limited to, surface roughness, fibre type, fibre count and microstructure (Yi & Cho 1999; Eunjou & Cho 2000; Yi *et al.* 2002; Moholkar & Warmoeskerken 2003; Cho *et al.* 2009; Cooper *et al.* 2013). Understanding the specific effect of a multi-fibre fabric on both total noise and specific frequencies has not been established and the use of a model system to control for both original fibre material and microstructure has not been investigated. The sensory perception of fabrics, in terms of fabric sounds, has not been presented within literature for in-*situ* real-time situations and an understanding of the true effect of fabric sounds would be most beneficial.

To that end, the aims of this study were to:

- Investigate the frictional noise of everyday apparel fabrics in terms of total noise and specific frequency analysis, and relate the microstructure of the fabrics to frictional noise using a single fibre model system i.e. to enable the comparison between single and multi-fibre systems;
- Investigate the frictional properties of everyday apparel fabrics, in terms of frictional coefficients and wear, and how the friction can be altered via lubrication of specifically engineered hydrocolloid particulate systems. The effect that the microstructure of the fabrics has on friction is explored by comparing multi-fibre and single-fibre systems;
- Explore consumers' thoughts on the senses (sight, touch, smell, taste and sound) used to assess apparel fabrics and to gain an understanding of the importance of sound;
- Investigate whether manipulating real-time fabric sounds (to attenuate or enhance the whole spectra or specific frequencies) affects consumer ratings of sensory attributes.

Understanding the mechanical properties of fabrics, and aiming to adapt friction and sound by producing a more appealing fabric, which would hypothetically have a quieter sound, smoother surface and lower friction coefficient, without understanding consumer needs and be considered to be premature and costly. Thus, using knowledge and experience from both aspects of the science behind fabrics: engineering and psychology, it is essential to form an effective and well-rounded study into frictional noise and sound perception of fabrics.

In an engineering capacity the following conclusions were drawn around the subjects of frictional noise, friction and modification of mechanical properties.

A sound resistant rig (SRR) was successfully designed, constructed and calibrated in order to achieve fabric friction sound capture without the interruption of background noise. Based on extensive method development to ensure the most efficient and effective sound capture, a method was instilled for all capture of apparel and model fabrics.

Given that apparel fabric treatments (i.e. sizing and conditioning), is unknown and all de-sizing processes cannot be 100% relied upon, despite best efforts, and that all micro and macrostructure dimensions are not always exactly reproducible, a control system was invaluable. Model fabrics made from polyester were chosen to be able to understand the influence of the number of fibres within the fabric (i.e. a multi-fibre vs. single-fibre structure) has on the frictional noise produced. Model fabrics were constructed with uniform dimensions and due to these characteristics specific frequencies within resulting sound spectra could be sought in terms of fundamental, and subsequent, harmonics. A perfect correlation between the calculated and measured harmonics was observed for fundamental harmonics (R^2 = 1.00) and a R^2 value of 0.93 for multiple harmonics. It was established that a 'finger print' theory can be used to further predict the sound spectra produced by unknown model fabrics. To the author's knowledge this is the first time within literature that a model system has been employed and verified. This theory was designed using polyester fibre material and therefore material type has a large influence on resulting harmonics i.e. a model fabric constructed using a natural fabric such as silk or cotton could potentially result in a different measured frequencies.

Apparel fabrics, with the original fibres cotton and silk, were chosen due to the world consumption of cotton and a contrasting luxury fabric, respectively. Three apparel fabrics were chosen: two cottons: 'denim' with a twill weave and 'cotton' with a plain weave; one 'silk' woven into plain weave. The surface roughness of all apparel fabrics was determined and was shown to strongly correlate with the total frictional noise captured from within the SRR (R^2 = 0.96). The roughness of an apparel fabric is attributed to the 'hairy' fibres of the microstructure i.e. the individual fibres which are spun into a thread, the more hairy fibres present, the higher the surface roughness. In terms of total noise produced it is thought that the interactions between the greater numbers of hairy fibres, results in a higher level of friction which is emitted as noise.

Methods were carried out to investigate the theory that a smoother surface should exhibit a quieter noise by reducing the hairy nature of the fibres via washing and conditioning the apparel fabrics with commercially available fabric conditioners. A relationship was not observed between total noise and surface roughness for treated fabrics and this was thought to be due to the challenge of measuring the surface roughness with the use of interferometry, as the mechanism of a fabric conditioner is to swell the fibres resulting in a smoother surface as opposed to 'sticking' the fibres down (i.e. reducing the hairiness).

As was established, friction caused by the sliding of one surface over another is emitted as noise, wear and energy in the form of heat, and it was therefore crucial to understand friction coefficients of all apparel fabrics investigated within Chapter 4 and again to employ the control model fabrics in order to gain further understanding of the influence of the number of fibres on friction. Chapter 5 presented the frictional results achieved using an MTM tribometer to measure friction coefficients by employing the apparel and model fabrics as model disc surfaces not seen before within literature. It was established that under dry and fully wetted/lubricated, slow friction conditions (3 mms^{-1}) the influence of surface roughness and fibre type had the greatest impact on the results produced. Denim, with the highest surface roughness, exhibited the largest dry friction coefficient, but also the greatest lubricating ability seen with the largest reduction in friction of all apparel fabrics. It was the hygroscopic nature of the fabrics (i.e. their ability to uptake water, measured using goniometry), which was observed to be imperative. Cotton's ability to uptake water, due to its greater hydrophilic nature, resulted in being more easily wetted which enabled swelling of the fibres, producing a smoother surface and therefore a lower friction coefficient. Initial experiments using pin-on-disc methods within tribology resulted in boundary lubrication being observed: not full entrainment of the lubricant was achieved and based on knowledge of surfaces with high surface roughnesses, mixed regime (partial entrainment) is not entered until higher rotational speeds are reached, and therefore Stribeck tests were carried out to investigate the effects of surface roughness and speeds.

When compared to smooth stainless surfaces (which exhibited typical Stribeck behaviour), the rough surfaces of both apparel and model fabrics produced opposing behaviour, with water as the lubricant: boundary lubrication was achieved, however, was a gradually increased with increasing speed (boundary lubrication is generally observed to be a constant plateau), mixed regime was not fully entered, hydrodynamic regime was not entered at all and a decrease in friction coefficients to original values was not attained. Apparel fabrics, denim and cotton, were observed to produce considerably lower friction coefficients than silk and the polyester model fabrics and it was the hydrophilic nature which again was accountable for the friction coefficient observed. Gaining results with the use of fabrics as novel disc surfaces has instilled confidence in the development of a method to adapt the MTM tribometer, and can be used for future work on establishing friction coefficients of new, different and challenging surfaces in all areas of tribology research.

As was the aim with Chapter 4 (reducing the frictional noise by conditioning fabrics), Chapter 5 showed how, with the use of specifically designed hydrocolloid particulate systems to replicate a control fabric conditioner, the friction coefficients of apparel and model fabrics were reduced.

Knowledge gained from literature within the food industry demonstrated that lubrication of surfaces was increased by filling in the asperities within the surface with particles of specific sizes; this knowledge can be transferred into the fabric industry. As such, fibres and threads of apparel fabrics and apertures within the model systems were thought to be filled with the fluid gel particles, creating smoother surfaces and therefore reducing friction coefficients. Two hydrocolloid fluid gels (kappa carrageenan and agar) were successfully designed to possess different particle sizes and exhibit different mechanical properties in terms of hardness of the particles. They were observed to have opposing behaviour when comparing friction coefficients produced on smooth steel and fabric surfaces. Both agar fluid gels were more lubricating than kappa carrageenan, due to their softer characteristics. They were more pliable and more easily entrained between the ball and disc surfaces resulting in reduced friction coefficients. However, agar was not as lubricating when apparel and model fabrics were the disc surfaces. Here, the soft nature of the agar was responsible for not permanently creating a smoother surface for the ball to run along, unlike the hard particles of kappa carrageenan which were believed to fill in the asperities of the fabrics without being easily deformed and therefore reduced the roughness. It was considered that the processing parameters effect on the particle size of the fluid gels was insignificant when compared to the roughness of the apparel and model fabrics, which is attributed to a lack of difference observed between the two sizes of each type of fluid gel investigated. Particle sizes of fluid gels were taken from literature due to challenges in characterising the system i.e. fluid gels were not able to be visualised in order to physically measure individual particles on a micron scale. Being able to accurately, reproducibly and efficiently measure the fluid gels to understand if indeed the difference observed in friction coefficients was as a result of differences in particle sizes, and also for verification of literature used would beneficial in the future.

As all previous methods were established in-house and in-*situ*, it was important to understand the relevance of fabric sounds to consumers in terms of thoughts and perceptions, therefore both

Chapter 6 and 7 results were established using an un-trained panel of consumers, to establish the importance and essentiality of past and future engineering research.

One-to-one in depth interviews were carried out to explore consumers' thoughts of fabrics, focussing on the senses used to assess feel, desirability and interactions with everyday garments. General consensus was such that touch and sight were the most commonly used senses to assess fabrics, followed by smell. It was established that although a low number of participants regarded sound as being a sense they would use when interacting with fabrics, it was imperative that the fabric itself did not exhibit any sound, but was silent. It must be noted that as the senses hierarchy started after 'If I were an alien...' task, in which consumers were asked to describe a fabric feel as objects, emotions, music and places within the world etc., it could have been considered to have an influence. Participants may not have been thinking about fabric sounds before the alien task, yet being asked to describe a fabric feel using noises in nature, songs and voices to name but a few, could have influenced the perceptions. On reflection, it would have been prudent to alter the order in which the hierarchy was initiated to ensure that minimal bias, if not any bias was instilled. The use of an interview based qualitative method was valuable to gain an insight into consumer perceptions, particularly when comparing potential thoughts gained from a focus groups where influence could have been caused by other participants. Within a one-to-one interview participants can be fully understood, explored and discussed giving a deep insight into their thoughts. Based on these findings, and that Chapter 4 showed how everyday apparel fabrics do indeed exhibit noise (in the form of friction), it was decided that understanding the influence manipulating real-time fabric sounds produced by participants in further sensory tests was essential to completing the interaction between mechanical and sensory properties of apparel fabrics.

A method was developed to enable the manipulation of real-time fabric sounds produced by participants without their knowledge in terms of decibel levels for varying aspects of the fabric sounds: high and low frequencies, specific frequencies and total noise. Participants were asked to rate sensory attributes (liking, roughness, smoothness, silkiness, crispness, softness and texture) of the fabric they were feeling; whilst the fabric sounds being relayed to them was being altered. A significant difference in ratings was observed for the attribute ‘textured’ for three individual manipulations (M): M2: an increase in overall dB level by +3 dB (no change in high or low frequencies); M7: an increase in low frequencies by +3 dB (no change in overall level) and M8: an increase in low frequencies by +6 dB (no change in overall level).

Manipulations of fabric sounds were carried out in ‘sections’ of the characteristics found within sound spectra (e.g. particular frequencies and total noise were separated); however, combining these different ‘sections’ to further understand the interaction with sensory perception, could be carried out within future experiments (e.g. an increase of both high and low frequencies together, or low frequencies with overall level). As this methodology was also employed within Zampini and Spence’s (2002; 2003; 2004) research, from where the inspiration for this study came from, results can be further compared and the influence on fabrics as opposed to food products, toothbrushes, textiles etc. can be investigated.

On initial analysis of ANOVA results, it was observed that a significant difference existed between female’s and male’s sensory ratings of ‘roughness’, however, due to an insufficient number of participants in each gender, this result could not be relied upon.

As quantitative analysis has not been determined between all the variables researched within the thesis, it is left to qualitative analysis to explain the major conclusions. Although mechanically, apparel fabrics have been shown to exhibit frictional noise, which has been correlated to surface roughness, which in turn was correlated to friction coefficients, the measurements have been established from in-situ experiments and were not, therefore, produced by human contact on fabrics. Establishing if the same level of correlation would exist between human participants and sound captured or friction coefficients measured would be most beneficial. However, it still leads on to the question of whether consumers would detect a change in sound via a reduction in surface roughness and friction or whether they would use this sensory information when selecting or considering a garment, or when judging a conditioning treatment. As was concluded in Chapter 6, fabric sound was not generally thought of as important by participants, and this coupled with the lack of significant differences between manipulated sounds for the sensory attributes give an insight into the importance of altering fabric frictional noise to potentially influence and reduce friction of garments when worn. It is believed that overall, sound of fabrics is not of great importance to consumers, particularly when compared to influence of sound in foods and electrical items, and therefore in order to input experimental methods into industry, the awareness of fabric sounds must first be established by marketing and understanding of the general population. Without the need from consumers to alter the frictional noise produced by garments, instilling extensive laboratory methods may seem premature, however, all future work suggested may go some way in achieving this.

9 Future Work

Surface Roughness and Total Noise

The model relationship between surface roughness and total noise was designed using polyester fibre material and therefore material type has a large influence on resulting harmonics i.e. a model fabric constructed using a natural fabric such as silk or cotton could potentially result in a different measured frequencies. It would be prudent to test the theory with other materials in future work. When considering this latter explanation and thinking forward to future work it would be interesting to understand the frictional noise produced from model fabrics with extreme ratios i.e. $Model_{n1}$ = 0.10 and $Model_{n2}$ = 1.00.

In order to further strengthen the relationship between surface roughness and total noise, it would be prudent to investigate a wider variety of apparel fabrics with varying aperture sizes, thread counts, fibre counts, roughness' and fibre types. It can be predicted from the work discussed within Chapter 4 that the rougher a fabric the louder the frictional noise produced, and therefore additional apparel fabrics would not only improve the hypothesis but also to serve as verification for the fabrics investigated thus far. Although, a strong relationship was observed, to ensure that the relationship is true for all apparel fabrics, a wider variety of surface roughness should be tested.

Further method development on establishing the change in surface roughness based on measuring the swelling of fibres; establish/quantify hairiness and possibly uptake of treatment on the total noise produced would be wise to expand the research presented.

Friction of apparel and model fabrics

It would be extremely beneficial to find another technique, besides interferometry, that would be capable of measuring the surface roughness change in modified and unmodified surfaces. AFM was considered initially for this research; however, as the area to be measured was in the order of millimetres as opposed to micro or nanometres it was discarded. Although, as has been established, the surface modification acts on individual fibres it could be a considered as a future measurement technique as the scale of fibres is much lower.

As the overall difference seen between the apparel and model fabrics has been attributed to a multi-fibre system versus a single fibre system and the difference between natural and manmade fibres, it would be beneficial to explore manmade fabrics which are multi-fibre woven structures to further assess the relationship between fibre type and frictional noise produced i.e. suit linings are generally synthetic and woven with a tightly controlled structure, however, have the feeling of silk when touched. An insight into whether these types of fabrics would produce a different sound spectra, shape, and overall level and specific frequency fingerprint would be most valuable.

As the fluid gels were created as a model system for fabric conditioners, a further step for this work would be to introduce commercially available conditioners and assess their lubrication and friction properties. Using this information, coupled with the model system, future conditioners can be formulated and engineered to exhibit specific characteristics in order to successfully reduce the friction of fabrics and can be related to consumer use. The work has highlighted the potential for hydrocolloid fluid gel systems to be used in this context.

As this thesis is concerned with the investigation of fabric sounds, it would be prudent to understand if capturing the friction sound produced by the fabrics directly within a tribometer in order to more accurately relate friction coefficients to frictional noise. However, care would be needed to account for the noise created by the mechanical noise created by the MTM.

As the theory of hydrophilic and hydrophobic surfaces was used to explain these findings, in order to complete a comprehensive experiment, the ball surface would need to be altered to be both hydrophilic in nature and also, the most insightful test, creating a corresponding fabric ball.

As reasoning was achieved from the literature, an experiment to measure the individual fabrics uptake of water with varying relative humidity percentages to accurately establish the differences between fibre type should be considered in the future. These results would then further enhance the relationship established within this research and would be in more close agreement with research discussed within Section 2.3.

As particle sizes were not able to be measured for the FGs produced due to challenges within the measurement methods used in previous research, it would be prudent to create a sound experiment to measure particle sizes and also to be able to visualise the FGs themselves e.g. with microscopy. Being able to achieve this would further verify the results observed. Also, as the FGs created were used to achieve a particle size control system for commercially available fabric conditioners, imperative further work would be to combine the tribometer system designed and further investigate the effect of changing particle size within more complex systems.

Consumer understanding of apparel fabric noise

On initial analysis of ANOVA results, it was observed that a significant difference existed between female’s and male’s sensory ratings of ‘roughness’, however, due to an insufficient number of participants in each gender, this result could not be relied upon. Therefore, repeating this research with a greater number of males and females could be fruitful when considering whether either gender is more affected to changes in fabric sounds.

Due to the uneven number of males and females that were recruited, gender was not able to be included as a variable within the statistical analysis, and therefore repeating the study with an even number of each gender would be beneficial.

Although the sound software MAX 6.0 was engineered to carry out certain sound manipulations, being able to record the fabric sounds that were being played to the participants would a very insightful way of understanding exactly what the difference being heard was and also the variation between participants, which may be the cause of such variability in results leading to a lack of significant results observed within the t-tests.

In order to improve upon the interviews carried out, the influence of which garments were selected for the sensory probe analysis needed to be kept to a minimum, particularly when considering participant responses to which garments they believed would be most related to rough and smooth descriptors. As well as which garments were chosen, it would have been more prudent to have eliminated sight from the sensory probe analysis as it was observed that participants were more influence by the look of the garment, particularly when assessing colour and sight of the fabric feel, and therefore all results are understood with caution.

To ensure that participants were not biased towards sound in terms of the hierarchy of senses future interviews could be carried out in a different order, whereby the hierarchy would be first to be established and introducing sound to the participants may potentially need to be more subtle.

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Appendices

1 Original FFT Script

```
function [f,amp]=fftsignal_v2(filename)
[y, Fs, nbits]=wavread(filename);
L=length(y);
NFFT = 2^nextpow2(L); % Next power of 2 from length of y
Y = fft(y,NFFT)/L;
f = Fs/2*linspace(0,1,NFFT/2+1);
% Plot single-sided amplitude spectrum.
amp=2*abs(Y(1:NFFT/2+1));
%plot(f,amp,'b')
%title('Single-Sided Amplitude Spectrum of y(t)')
%xlabel('Frequency (Hz)')
%ylabel('Amplitude (A.U.)')
```

2 Engineered Sound Frequencies

```
Fs = 10000
Ts = 1/Fs;
L = 100*Fs;
t = (0:L-1)*Ts;
s = signalsine(t,100,0.1) + signalsine(t,200,0.2) + signalsine(t,300,0.3)+ signalsine(t,400,0.4);
subplot(1,2,1)
plot(Fs*t,s)
L=length(s);
NFFT = 2^nextpow2(L);
S = fft(s,NFFT)/L;
f = Fs/2*linspace(0,1,NFFT/2+1);
subplot(1,2,2)
plot(f,2*abs(S(1:NFFT/2+1)))
xlabel('Frequency (Hz)')
wavwrite(s,Fs,'lowerfrequencytest.wav');
```

3 Averaging

```
fname1='BDEWE101M.wav';
fname2='BDEWE102M.wav';
fname3='BDEWE103M.wav';
fname4='BDEWE104M.wav';
fname5='BDEWE105M.wav';
fname6='BDEWE106M.wav';
fname7='BDEWE107M.wav';
fname8='BDEWE108M.wav';
fname9='BDEWE109M.wav';
fname10='BDEWE110M.wav';


[f1,amp1]=fftsignal_v2(fname1);
[f2,amp2]=fftsignal_v2(fname2);
[f3,amp3]=fftsignal_v2(fname3);
[f4,amp4]=fftsignal_v2(fname4);
[f5,amp5]=fftsignal_v2(fname5);
[f6,amp6]=fftsignal_v2(fname6);
[f7,amp7]=fftsignal_v2(fname7);
[f8,amp8]=fftsignal_v2(fname8);
[f9,amp9]=fftsignal_v2(fname9);
[f10,amp10]=fftsignal_v2(fname10);


meanamp=mean([amp1;amp2;amp3;amp4;amp5;amp6;amp7;amp8;amp9;amp10]); %averaging 10 runs
plot(f1,meanamp)

figure; plot(f1,amp1,'k')
```

4 Smoothing

```
clear; close all; format short g
clc

fname1='BDEWE101M.wav';
fname2='BDEWE102M.wav';
fname3='BDEWE103M.wav';
fname4='BDEWE104M.wav';
fname5='BDEWE105M.wav';
fname6='BDEWE106M.wav';
fname7='BDEWE107M.wav';
fname8='BDEWE108M.wav';
fname9='BDEWE109M.wav';


[f1,amp1]=fftsignal_v2(fname1);
[f2,amp2]=fftsignal_v2(fname2);
[f3,amp3]=fftsignal_v2(fname3);
[f4,amp4]=fftsignal_v2(fname4);
[f5,amp5]=fftsignal_v2(fname5);
[f6,amp6]=fftsignal_v2(fname6);
[f7,amp7]=fftsignal_v2(fname7);
[f8,amp8]=fftsignal_v2(fname8);
[f9,amp9]=fftsignal_v2(fname9);

%averaging 9 runs
meanamp=mean([amp1;amp2;amp3;amp4;amp5;amp6;amp7;amp8;amp9]);
plot(f1,meanamp)

figure; plot(f1,amp1,'k')

%smoothing
s_pnts=input('enter number of smoothing points (default 10): '); %number of points to do the running average over
if isempty(s_pnts)==1
   s_pnts=10;
end

Lf1=length(f1); Lf2=length(f2); Lf3=length(f3); Lf4=length(f4); Lf5=length(f5); Lf6=length(f6); Lf7=length(f7); Lf8=length(f8); Lf9=length(f9);

amp_s1=zeros(Lf1-s_pnts,1);
amp_s2=zeros(Lf2-s_pnts,1);
amp_s3=zeros(Lf3-s_pnts,1);
amp_s4=zeros(Lf4-s_pnts,1);
amp_s5=zeros(Lf5-s_pnts,1);
amp_s6=zeros(Lf6-s_pnts,1);
amp_s7=zeros(Lf7-s_pnts,1);
amp_s8=zeros(Lf8-s_pnts,1);
amp_s9=zeros(Lf9-s_pnts,1);
```

```
f_s1=f1(s_pnts+1:end);
f_s2=f2(s_pnts+1:end);
f_s3=f3(s_pnts+1:end);
f_s4=f4(s_pnts+1:end);
f_s5=f5(s_pnts+1:end);
f_s6=f6(s_pnts+1:end);
f_s7=f7(s_pnts+1:end);
f_s8=f8(s_pnts+1:end);
f_s9=f9(s_pnts+1:end);

%smooth set 1

for i=1:Lf1-s_pnts
   amp_s1(i)=mean(amp1(i:i+s_pnts));
end

%smooth set 2

for i=1:Lf2-s_pnts
   amp_s2(i)=mean(amp2(i:i+s_pnts));
end

%smooth set 3

for i=1:Lf3-s_pnts
   amp_s3(i)=mean(amp3(i:i+s_pnts));
end

%smooth set 4

for i=1:Lf4-s_pnts
   amp_s4(i)=mean(amp4(i:i+s_pnts));
end

%smooth set 5

for i=1:Lf5-s_pnts
   amp_s5(i)=mean(amp5(i:i+s_pnts));
end

%smooth set 6

for i=1:Lf6-s_pnts
   amp_s6(i)=mean(amp6(i:i+s_pnts));
end

%smooth set 7

for i=1:Lf7-s_pnts
   amp_s7(i)=mean(amp7(i:i+s_pnts));
end

%smooth set 8

for i=1:Lf8-s_pnts
   amp_s8(i)=mean(amp8(i:i+s_pnts));
end
```

```
%smooth set 9

for i=1:Lf9-s_pnts
   amp_s9(i)=mean(amp9(i:i+s_pnts));
end


%interp on smoothed data
freq=500:100:12000;

ampn1=interp1(f_s1,amp_s1,freq);
ampn2=interp1(f_s2,amp_s2,freq);
ampn3=interp1(f_s3,amp_s3,freq);
ampn4=interp1(f_s4,amp_s4,freq);
ampn5=interp1(f_s5,amp_s5,freq);
ampn6=interp1(f_s6,amp_s6,freq);
ampn7=interp1(f_s7,amp_s7,freq);
ampn8=interp1(f_s8,amp_s8,freq);
ampn9=interp1(f_s9,amp_s9,freq);


amp_BDEWE1=[ampn1; ampn2; ampn3; ampn4; ampn5; ampn6; ampn7;
ampn8; ampn9];

av_amp_BDEWE1=mean(amp_BDEWE1);
std_amp_BDEWE1=std(amp_BDEWE1);

data_BDEWE1=[freq' av_amp_BDEWE1' std_amp_BDEWE1']

figure; plot(f1,amp1,'g', f_s1,amp_s1,'c', freq, av_amp_BDEWE1,'r')

ymin=0;
ymax=max(av_amp_BDEWE1);
xmin=freq(1);
xmax=freq(end);

axis([xmin xmax ymin ymax])

disp('------------------')
disp('enter a filename in the form "*.xls" to save data in'); %gets filename to
save exported data in
disp(' ')
savefile=input('enter the name of the file to save data in to read in excel:
','s');
disp(' ')
disp('------------------')
%gives the correct headings to columns in sheet given name of exported data
%file
xlswrite(savefile, {'Frequency', 'Mean Amp', 'Stdev'}, 'sheet','A2')
%writes the data to same worksheet in excel
xlswrite(savefile,data_BDEWE1,'sheet','A3')

save data_BDEWE1_all

figure; plot(f_s1,amp_s1, 'k', f_s5,amp_s5, 'c', f_s9,amp_s9, 'g', freq,
av_amp_BDEWE1,'r+')
ymax=1e-3;
axis([xmin xmax ymin ymax])
```

5 Sorting

```
clear all
[f,amp]=fftsignal_v2('B&LSAWA105M.wav');

amp1(2,:)=amp;
amp1(1,:)=f;

smooth=input('Passes ');
 for m=1:smooth
Lt=length(amp1);
amp2=zeros(2,Lt);
for i=2:Lt-1
   if (amp1(2,(i-1))<amp1(2,i)) && (amp1(2,(i+1))<amp1(2,i))
      amp2(2,i)=amp1(2,i);
   else
      amp2(2,i)=0;
   end

end
amp2(1,:)=amp1(1,:);

[r,c]=find(amp2==0);
amp2(:,c)=[];

eval(['amp' num2str(m+2) '=amp2;'])
amp1=amp2;
 end
clear amp1
amp1(2,:)=amp;
amp1(1,:)=f;

%this needs changing if you dont want to visualise the data or if it
%requires different number of passes

%needs rearranging for multiple files

plot(amp1(1,:),amp1(2,:),amp7(1,:),amp7(2,:))
AXIS([0 25000 0 0.00015])
legend('original data', 'smoothed')
```

6 Area Under Curve

```
trapz(OSIWA301M_488_7(1,:),OSIWA301M_488_7(2,:)); % calculate area under curve for all values in row 1 and all values in row 2
```

7 Ethical Forms

7.1 One-to-one in depth interviews

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Information Sheet

You have been asked to take part in one-to-one interview which is centred on consumer responses to fabrics when using all senses. The interview will be auditory recorded with Cerise Cooper taking notes also.

The interview will not take longer than 1 hour and you will be compensated for your time. The interview will start with some ice breaking question.

You have been asked to complete prework/homework before attending the interview and to bring this with you. The interview questions will commence with your thoughts about your homework.

There will be a number of engaging conversations about your thoughts around fabrics and also two activities.

The interview will be closed by Cerise Cooper by asking for any further questions or input and filling out a short questionnaire that will help to enhance the recorded data collected.

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Consent Form

This is to certify that I,……………….., hereby agree to participate as a volunteer in a scientific experiment as an authorised part of the research undertakings within the School of Chemical Engineering at the University of Birmingham conducted by Cerise Cooper, under the supervision of Professor Ian Norton.

My part in the interview has been fully explained to me by Cerise Cooper and I understand her explanation. The procedures of this interview and their risks have been answered to my satisfaction. I understand that I will be video and audio recorded. I understand that all data will remain confidential with regard to my identity.

I understand that I am free to withdraw my consent and terminate my participation at any time and without penalty. I understand that I can withdraw my data even after the experiment is complete, and up to the point of publication (January 2013).

My responsibility as a participant is to participate actively and willingly and if I choose not to do so, I will exercise my right to withdraw without penalty. If I choose not to withdraw, I understand that I am expected to participate actively.

I understand that I may request a summary of the results of the study after January 2013. Any complaints concerning the conduct of the research should be addressed to Professor Ian Norton, School of Chemical Engineering, University of Birmingham.

……………………………………………………………………………

Participant's Signature Date

I, the undersigned, have fully explained the investigation to the above individual.

…………………………………………………………………………….

Investigator's Signature Date

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Demographic Information

The following information will be used to compile average data for the group. Your responses will be kept anonymous, and will not be used on an individual basis.

Please complete the following section by ticking the relevant response.

Age:

16-20 ☐

21-30 ☐

31-40 ☐

41-50 ☐

51-60 ☐

61+ ☐

Gender:

Male ☐

Female ☐

Occupation / area of study:

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Debriefing

Thank you for taking part in the 1:1 interview. The purpose of the discussion was to investigate how consumers assess fabrics when thinking about all senses and if sound is an important sense either before or after the interviews.

You were asked to complete a short questionnaire demographic questionnaire and this information will be used in conjunction with the opinions given during the discussion session and will be used to compile average data for the group.

As already mentioned, your data will remain confidential with regards to you identity. If you wish to do so you can withdraw your data even after the experiment is complete, and up to the point of publication, you may request to do so by contacting Cerise Cooper or Professor Ian Norton, up until January 2013.

You may request a summary of the results of the study by contacting Cerise Cooper from January 2013.

Any complaints will need to be made to Professor Ian Norton, School of Chemical Engineering, University of Birmingham.

You may take this debrief sheet with you when you have completed the study

Contact Details:

Cerise Cooper

School of Chemical Engineering

University of Birmingham

B152TT

Professor Ian Norton

School of Chemical Engineering

University of Birmingham

B152TT

7.2 Sound manipulation study

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VOLUNTEERS WANTED!

Volunteers needed to participate in a study investigating fabric sound.

I am looking for participants with normal hearing to take part in a 20-30 minute study between 18th-21st March.

You will be compensated for your time with a £10 Waterstone's voucher.

If you are interested contact Cerise Cooper on

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This session will last approximately 20 minutes.

You are required to touch 10 different fabric samples in succession and rate how much you like the fabric, and rate them according to a number of sensory attributes. You will be required to put your hand through the enclosure (i.e. you won't be able to see the fabric) and touch the sample.

You will be given a questionnaire, and will be required to use line scales to rate how much you like it, and also according to a number of attributes (i.e. smoothness, roughness, silkiness, textured, softness and crispness) on the answer sheet. Rating the attribute will be performed by marking with a vertical line on the horizontal line provided at the point that you consider to represent the fabric you are touching. In all cases the lines are anchored from 'not at all' to 'extremely'. See the example below.

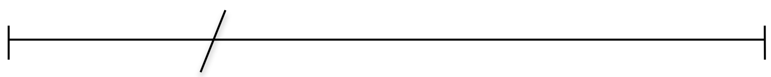
For example:

Feel Fabric

Rate the Fabric Feel According to the Attribute

1. How smooth do you think the fabric is?

Not at all smooth | Extremely smooth



You will be asked to wear ear phones so that you are better able to hear instructions and consider not only the fabric feel but also the sound it produces when you touch it, as without the ear phones you will not be able to hear the fabrics with the enclosure present. The researcher will also be audio recording the session for further analysis of the sounds which are produced by the fabrics when you are touching them.

You will be able to feel the fabric for as long as you need to be able to rate the attributes. There will be 2 practice fabrics in order to get used to the format of the study with regards to what is expected and timings.

Please leave all papers behind when you have finished for the researcher to collect.

The data from this experiment will be kept anonymous and only persons allowed to access the data will be the researcher and their supervisor (contact details below). The data will be kept for a minimum of 10 years after the study has been completed. You are able to access the data at any point between the end of the study and May 2013. Throughout this process you are able to withdraw at any point by contacting either the researcher or their supervisor and you are able to remove your data from the study up until May 2013. All data collected will be used within the researcher’s PhD and if possible a publication.

Contact Details:

Cerise Cooper
School of Chemical Engineering
University of Birmingham
B152TT

Professor Ian Norton
School of Chemical Engineering
University of Birmingham
B152TT

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Consent Form – Sound Describing Study

I have read the Information Sheet for this study and have had the details of the study explained to me. My questions about the study have been answered to my satisfaction, and I understand that I may ask further questions at any time. My responsibility as a participant is to participate actively and willingly and if I choose not to do so, I will exercise my right to withdraw without penalty. If I choose not to withdraw, I understand that I am expected to participate actively.

I also understand that I am free to withdraw from the study at any time that I can decline to answer any particular questions in the study, and can decline to complete any task requested of me. I agree to provide information to the researchers on the understanding that it is completely confidential. I understand that the information will be stored in manual and electronic files. I acknowledge that the information provided is being used by the University.

I confirm that I wish to participate in this study under the conditions set out here and in the Information Sheet.

I understand that I have participated in a pilot study for the purposes of participant number analysis.

Signed: ____

Name: ____

Date: ____

Researcher: ____

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Debriefing – Sound Description Study

Thank you for taking part in this sensory study. The purpose of this study was to find out if changing the level of sounds of real-time fabric sounds changes the way consumers perceive attributes such as roughness.

As previously mentioned, your identity will be kept confidential and all data given will be coded and therefore will not be personal. Demographic questions (age, gender) were asked to enable finding trends after the study has been carried out. If you wish to withdraw you may do so throughout the study and afterwards up until the point of publication.

You may request a summary of the results of the study by contacting Cerise Cooper from January 2013. Any complaints will need to be made to Professor Ian Norton, School of Chemical Engineering, University of Birmingham.

If you would like to withdraw at any point, before, during or after the study has been completed, you may request to do so by contacting Cerise Cooper or Professor Ian Norton, up until January 2013.

Contact Details:

Cerise Cooper
School of Chemical Engineering
University of Birmingham
B152TT

Professor Ian Norton
School of Chemical Engineering
University of Birmingham
B152TT

You may take this debrief sheet with you when you have completed the study

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Practice Answer Sheet – Sound Describing Study

Participant Code:

1. How smooth do you think the fabric is?

Not at all smooth | Extremely smooth

2. How rough do you think the fabric is?

Not at all rough | Extremely rough

3. How silky do you think the fabric is?

Not at all silky | Extremely silky

4. How textured do you think the fabric is?

Not at all textured | Extremely textured

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Answer Sheet – Sound Describing Study

Participant Code:

1. How smooth do you think the fabric is?

Not at all smooth Extremely smooth

2. How rough do you think the fabric is?

Not at all rough Extremely rough

3. How silky do you think the fabric is?

Not at all silky Extremely silky

4. How textured do you think the fabric is?

Not at all textured Extremely textured

8 Script for interviews

"Hello my name is Cerise Cooper, I'm a PhD Student from the University of Birmingham and I'd like to talk to you today about your thoughts about fabrics.

Thank you for taking the time to talk with me today. There are right or wrong answers so please tell me what you are thinking. This interview is being recorded, as I am conducting many interviews and will never remember anything – this information will remain confidential and you will not be on an advert or anything like.

Would you like a drink, cup of tea or coffee?

Ice breaker potential questions

1) Have you attended an interview before?
2) Can you tell me a little bit about yourself, your family, what you like to do?....
3) If you were to be a garment what would you be? Why?
4) Do you have a favourite piece of clothing? Why is it so important above any other one in your wardrobe? (Make sure you can tie back to sensory aspect of the fabrics)

Questions

1) I wonder if you have completed the homework.
a. If we can get it out and lay it onto the surface here and have a conversation about what you have written and brought with you.
b. We'll start with the thought bubbles. Can you take me through thought bubble one and tell me why you have chosen those descriptors? Repeat for 3 thought bubbles
c. How easy did you find it to describe what you were seeing without having the garment in front of you?
d. Would you add anything else to each of your thought bubbles?
e. Shall we have look at the pictures/images that you have brought in with you?
f. Can you tell me why you have brought in these images to show me?
g. What sense/s have you used when thinking about these images?

2) Grouping Fabrics
a. Get out 30 fabric swatches of varying degrees of roughness, smoothness, weight, feel, visual attributes, but all similar pastel colours
b. I would like you to put these into groups. There can be as many groups and as many fabric swatches in each group as you would like.
c. Now you have grouped them please can you tell me why you decided on those groups?
d. Please can you regroup these fabrics in a different way?
e. Why did you choose this grouping method?
f. Please can you regroup these for a third time?
g. Why did you choose this grouping method?

h. Did you think about any particular senses when you were grouping the swatches?

3) Garment Descriptors

a. Remove all swatches and bring out test fabrics, denim, cotton and silk, in garment form and use sensing probe to describe the items in turn.

b. Either if I were an alien how would you describe these fabrics to me using your senses – what would you get the alien to smell, touch, see, hear, what emotion would you show and what colour would you show.

Give consumers a swatch and watch how they interact/struggle with questions.... is this fabric soft...

4) Creating a Senses Hierarchy

a. Remove garments

b. Move A4 flip chart into the area with drawn on hierarchy

c. If we were to create a hierarchy of senses that we use to describe/think about fabrics where would you put the following senses in relation to one another

d. Produce either magnetic or laminated cards with typed words (the senses) to place onto hierarchy.

e. Depending on how well the participant is doing maybe add in some suggestions on previous choices within the interview i.e. grouping or describing garments

f. Just the participant – write around each sense on why it's at that level, what are particularly important descriptors of each sense and why each sense is important and subsequently more important than other senses

5) Sound as a Sense

a. On the proviso that they have either mentioned sound in grouping or garment parts or written/placed sound on the hierarchy:

b. You have mentioned that sound is an important sense when describing or thinking about fabrics so could you tell me any descriptive words that you would associate with sound

i. I.e. looking for crunchy, crispy, swoosh, swish, crackly, squeaky etc.

c. Can you tell me about some fabrics that you would consider to be very rough/the most rough you have felt and the smoothest?

d. When thinking about a rough/smooth fabric what sound descriptors would you use to describe them?

6) Sound as a Sense

a. If they have not mentioned sound as a sense or do not consider it to be on the sense hierarchy:

b. Have you ever thought about sound when thinking about your clothing?

c. If you thought about sound as an important sense when describing or thinking about fabrics so could you tell me any descriptive words that you would associate with sound

i. I.e. looking for crunchy, crispy, swoosh, swish, crackly, squeaky etc.

d. If you do not think sound is an important sense when considering fabrics, why not?

e. Can you tell me about some fabrics that you would consider to be very rough/the most rough you have felt and the smoothest?

f. When thinking about a rough/smooth fabric what sound descriptors would you use to describe them?

7) Now that we have discussed sound as a possible sense to describing fabrics would you change your hierarchy in any way?

<u>Close of Interview</u>

Thank you for taking part in the interview. I was trying to understand consumer's thoughts on fabric characteristics and how these impact choice and in particular which senses are used and with what importance.

I am investigating sound of fabrics in my PhD and was very interested to establish if consumers think of sound when choosing fabrics and also if they would use it in the future after having talked about it during the interviews."

8.1 Pre Work Thought Bubbles

"What do you think this person is thinking or feeling when considering this item of clothing?"

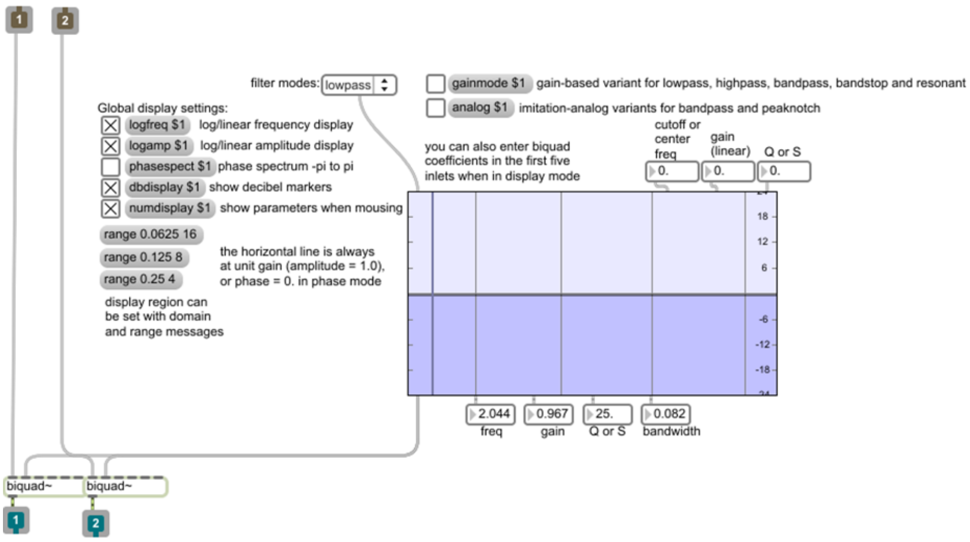
Part 2: Collecting Images

Please bring with you 6-8 pictures/images (which could include family photographs, images cut out of magazines or newspapers, or images searched on the internet) that represent how you assess the feel of a fabric using all your senses?

9 Sound Manipulations

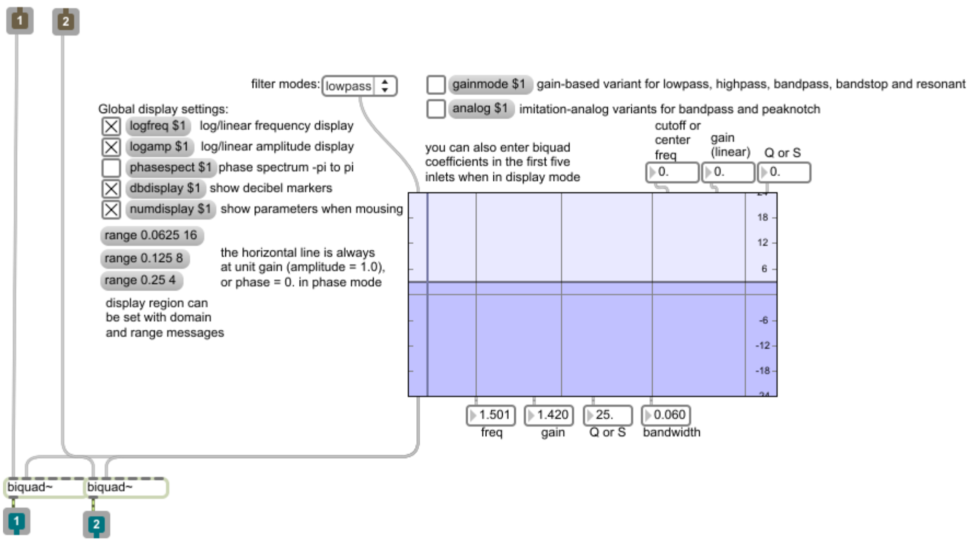
Sound Manipulation 1

- Overall level = 0 dB, High Frequency change = 0 dB



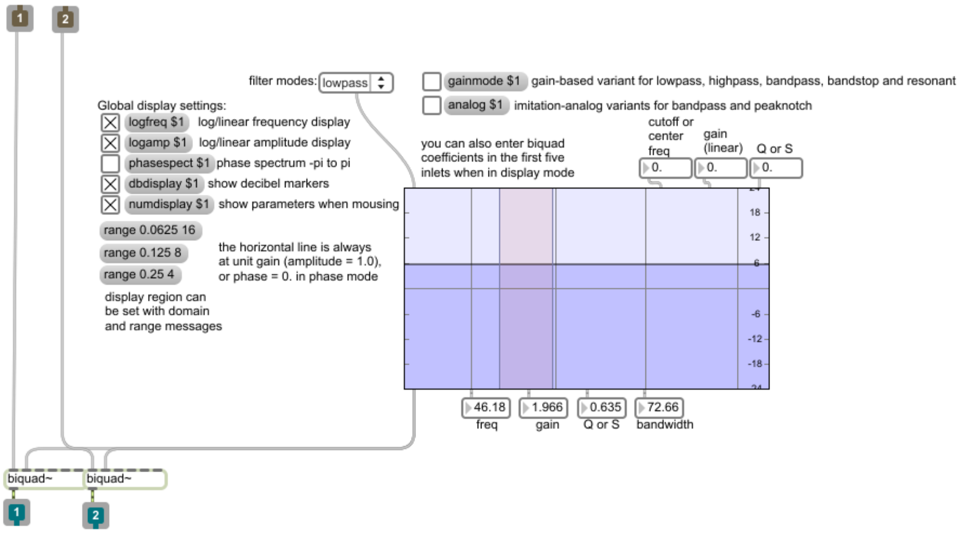
Sound Manipulation 2

- Overall level change = +3 dB, High Frequency change = 0 dB



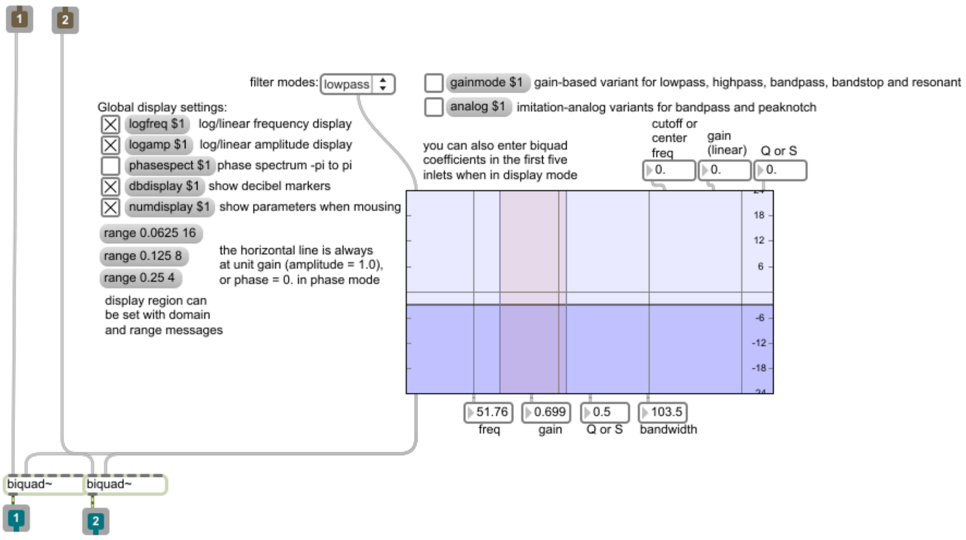
Sound Manipulation 3

- Overall level change = +6 dB, High frequency change = 0 dB



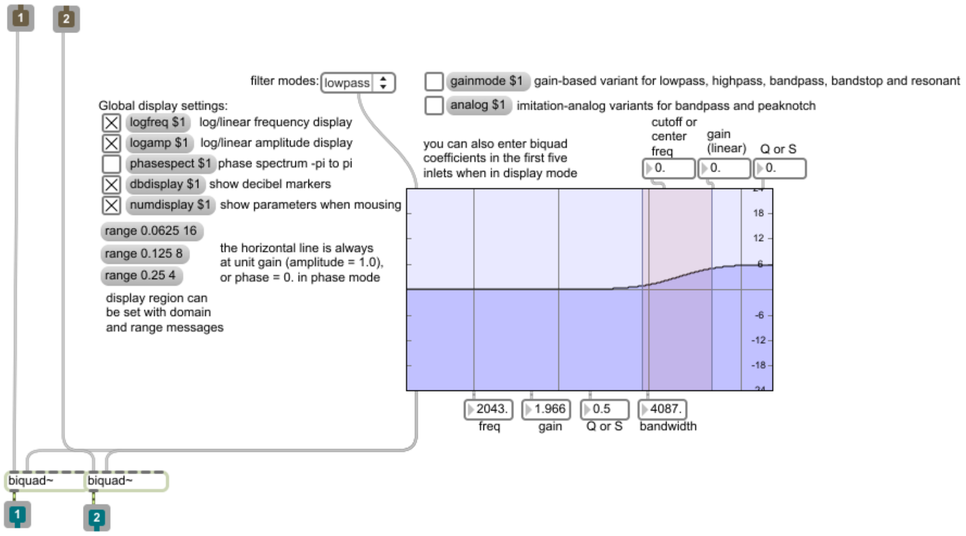
Sound Manipulation 4

- Overall level change = -3 dB, High Frequency change = 0 dB



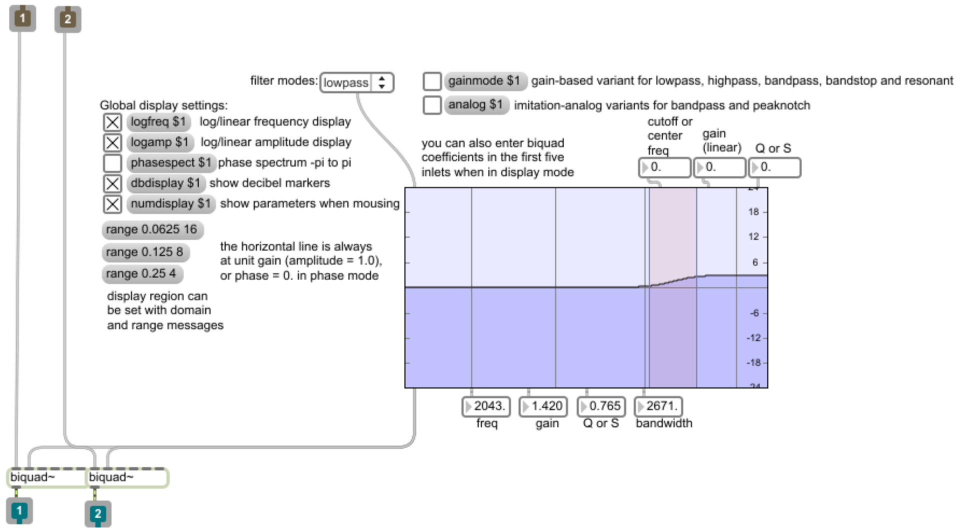
Sound Manipulation 5

- Overall level change = 0dB, High Frequency changes = +6dB



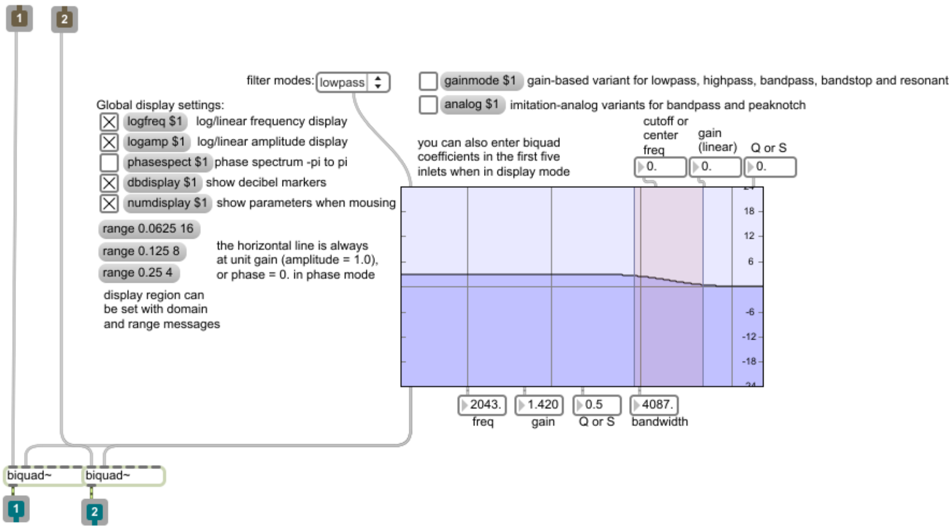
Sound Manipulation 6

- Overall level change = 0dB, High Frequency change = +3dB



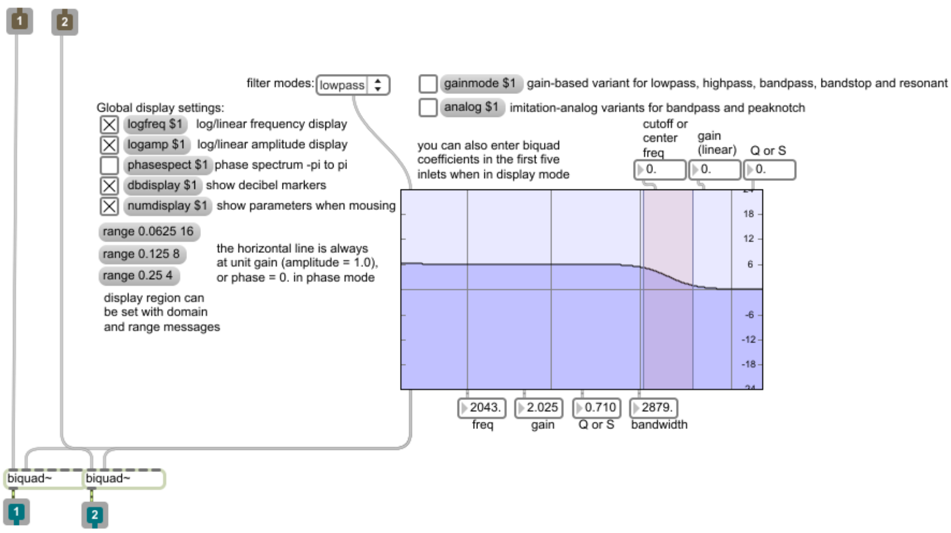
Sound Manipulation 7

- Overall level change = 0dB, Low Frequency change = +3dB



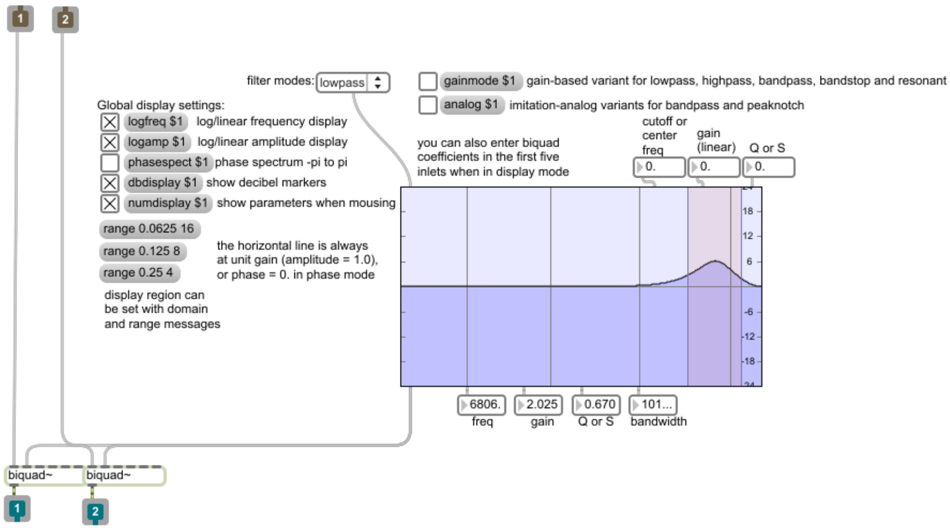
Sound Manipulation 8

- Overall level change = 0dB, Low Frequency change = +6dB



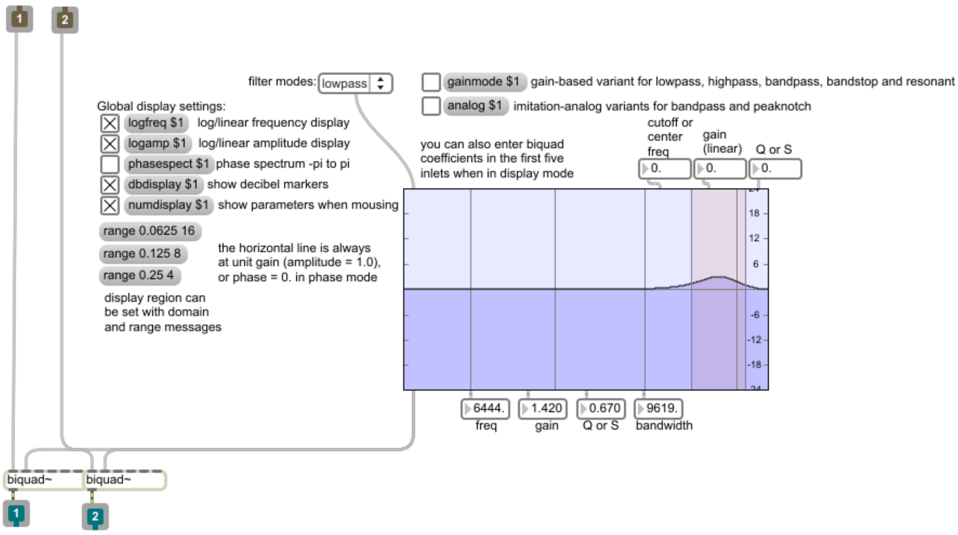
Sound Manipulation 9

- Overall level change = 0dB, Peak Frequency (@6kHz) change = +6dB



Sound Manipulation 10

- Overall level change = 0dB, Peak Frequency (@6kHz) change = +3dB

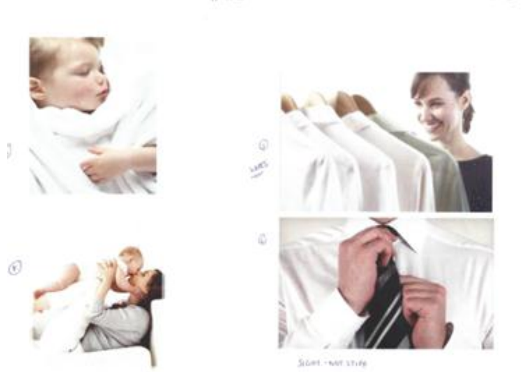


10 Participants Pre-Work

Participant 1

INT I

Participant 2



CLEANING FIRST → SOFTNESS.

Participant 3

Thinking – looking faded

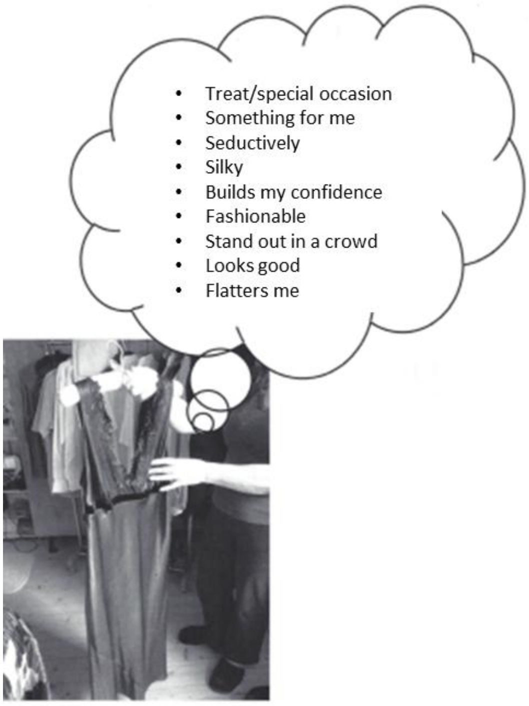
Feeling – rough to the touch

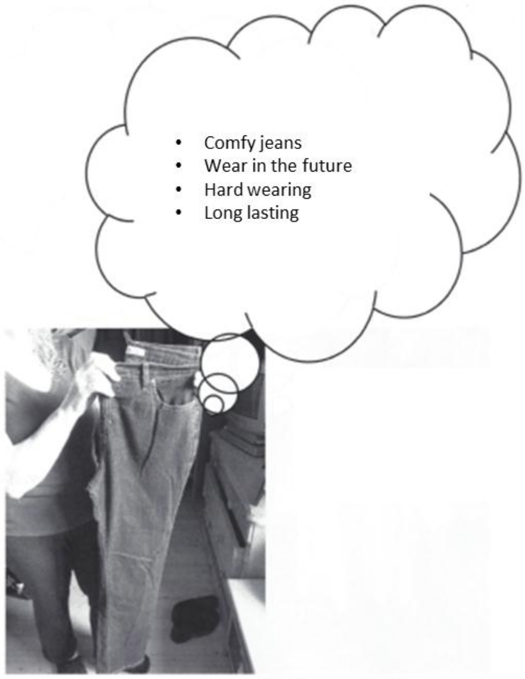
Thinking – soft and silky on the skin

Feeling – nice to touch

Thinking – nice and white, cool to wear

Participant 4





assumed is cream shirt

Eyes: Colours Touch: FEEL TACTILE SMOOTH SOFT

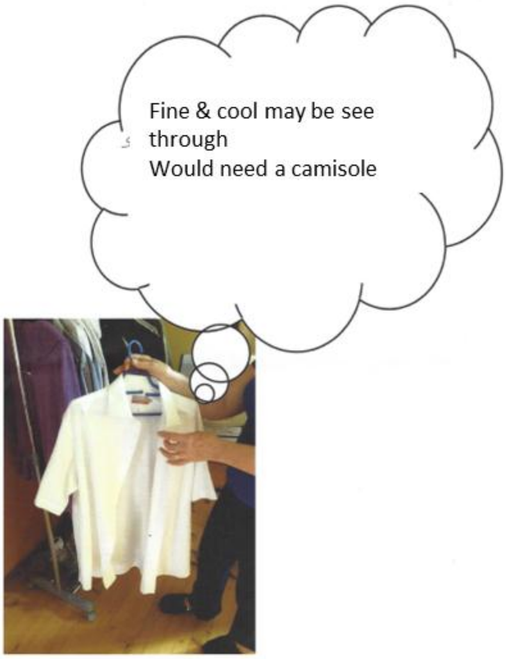




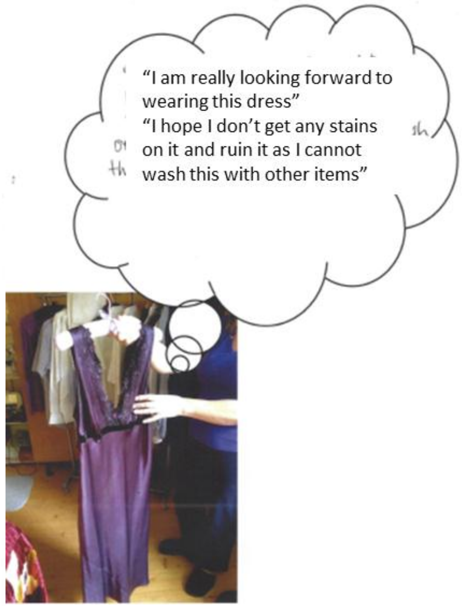


HEAR: no sound/silence as touch clothes i.e. no static sound or rustle, TASTE: no taste, SMELL: freshness i.e. clean sheets

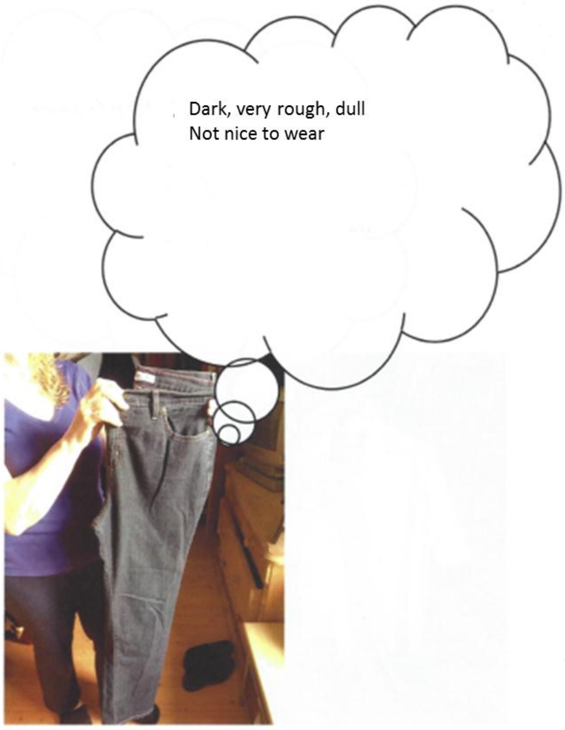
Participant 5



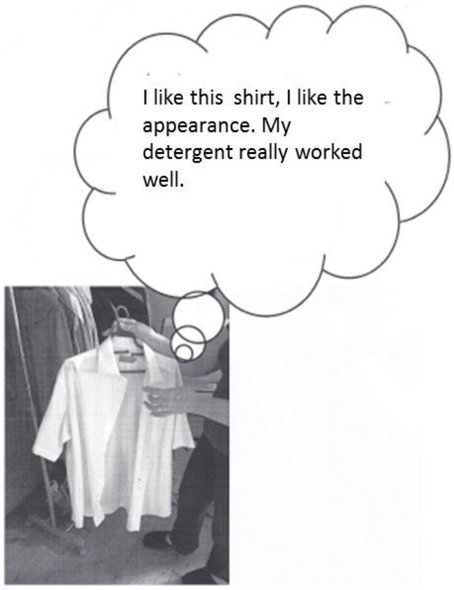
Participant 6

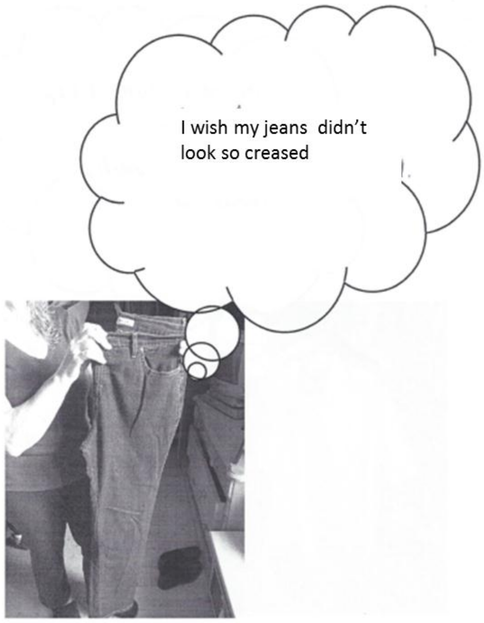


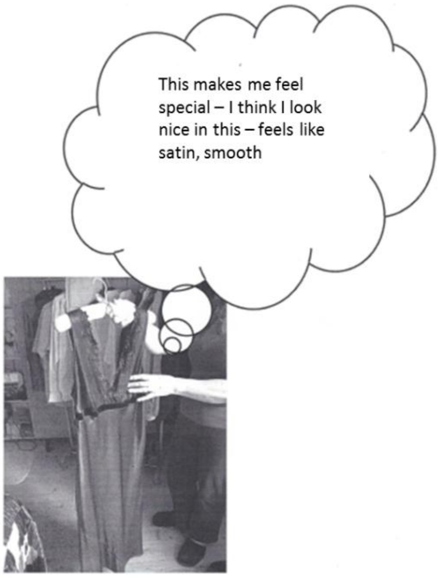
Participant 7



Participant 8







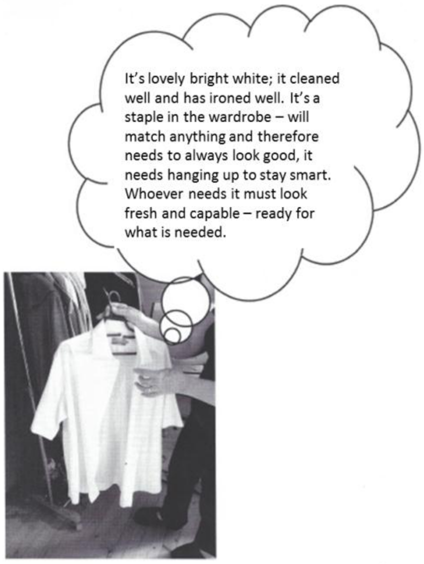
Participant 9

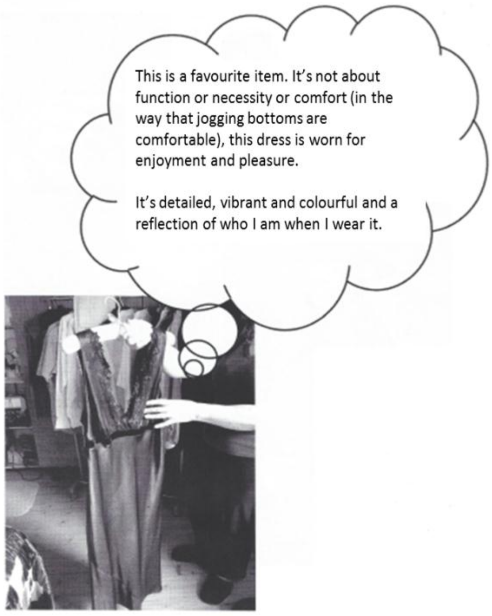
Do they fit to give a flattering look? Are they long in the leg? Can I wear them with boots over or underneath, or wear with heels?
Is the fabric heavy duty or think and therefore cheap in appearance?

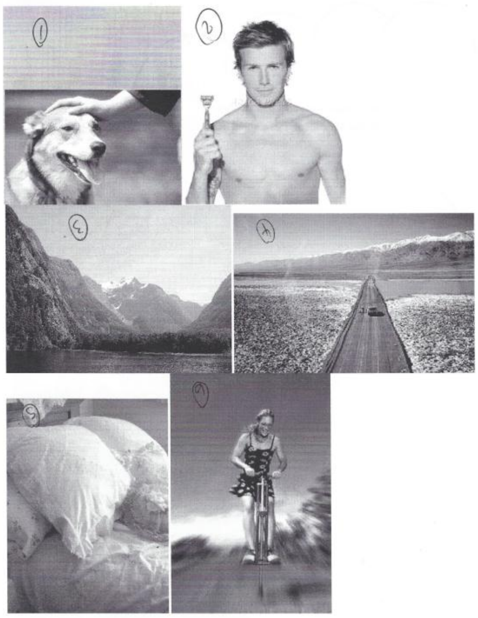
Can I wear this with trousers/jeans I already have or under a tunic for smart wear?
How easy will it be to wash? Does it need ironing?

What underwear do I need to go with this? Is the fabric so thin/shear that it will show lumps and bumps?
Is the length suitable? Will the fabric generate static?

Participant 10







11 Photos of grouping exercise

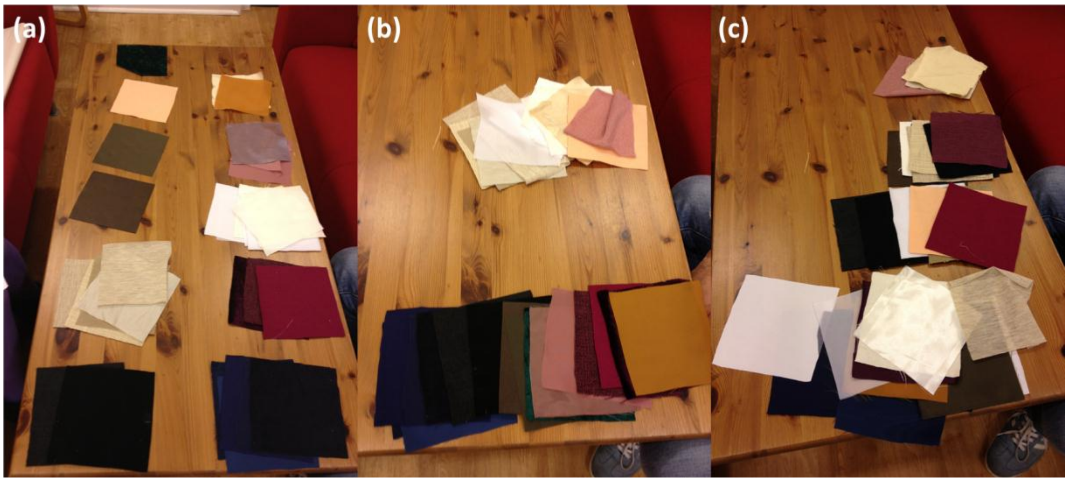


Figure 11.1 Participant 1's response to 'Grouping Exercise' (a) 1st grouping, (b) 2nd grouping and (c) 3rd grouping.

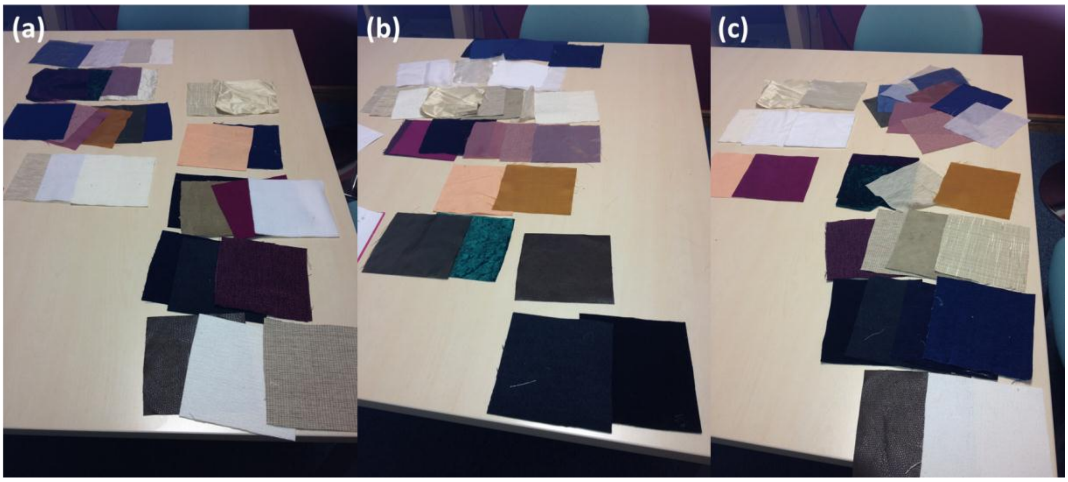


Figure 11.2 Participant 2's response to 'Grouping Exercise' (a) 1st grouping, (b) 2nd grouping and (c) 3rd grouping.

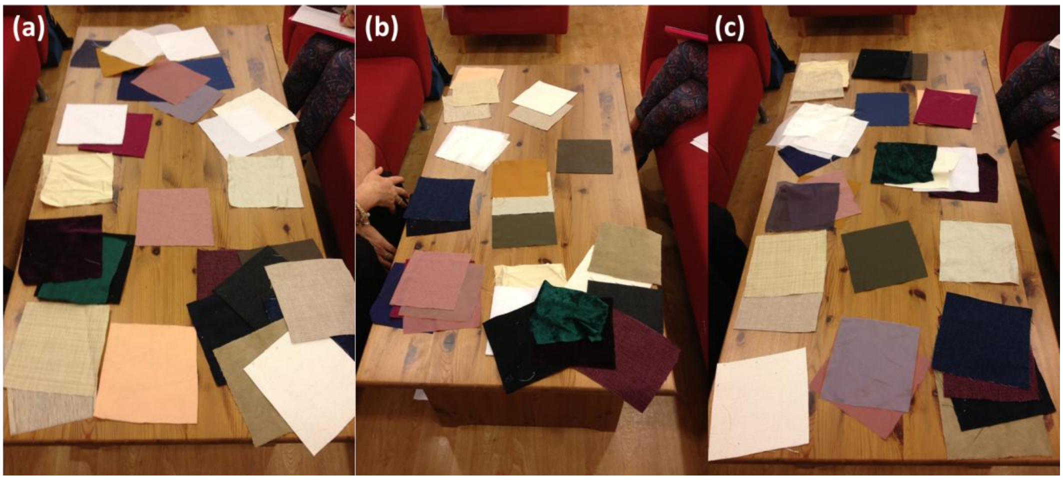


Figure 11.3 Participant 3's response to 'Grouping Exercise' (a) 1st grouping, (b) 2nd grouping and (c) 3rd grouping.

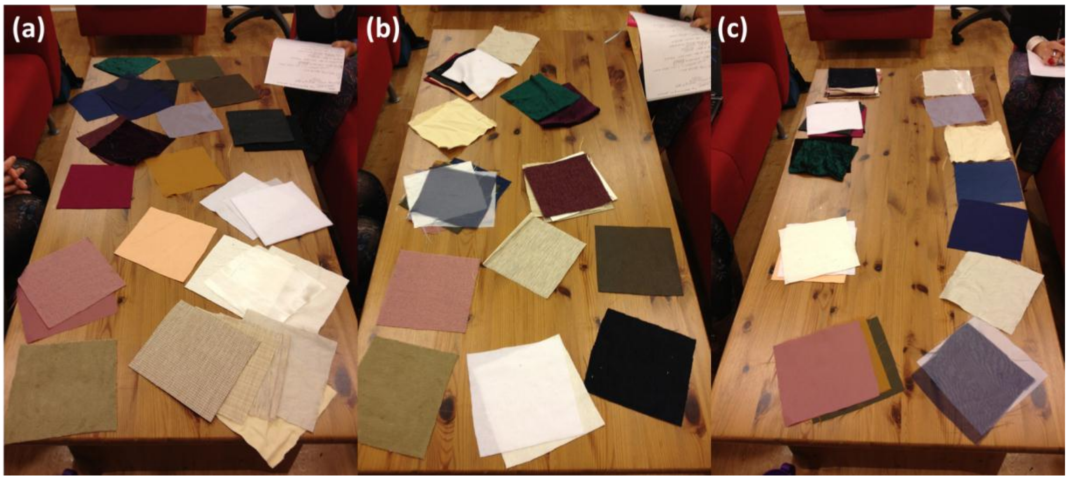


Figure 11.4 Participant 4's response to 'Grouping Exercise' (a) 1st grouping, (b) 2nd grouping and (c) 3rd grouping.

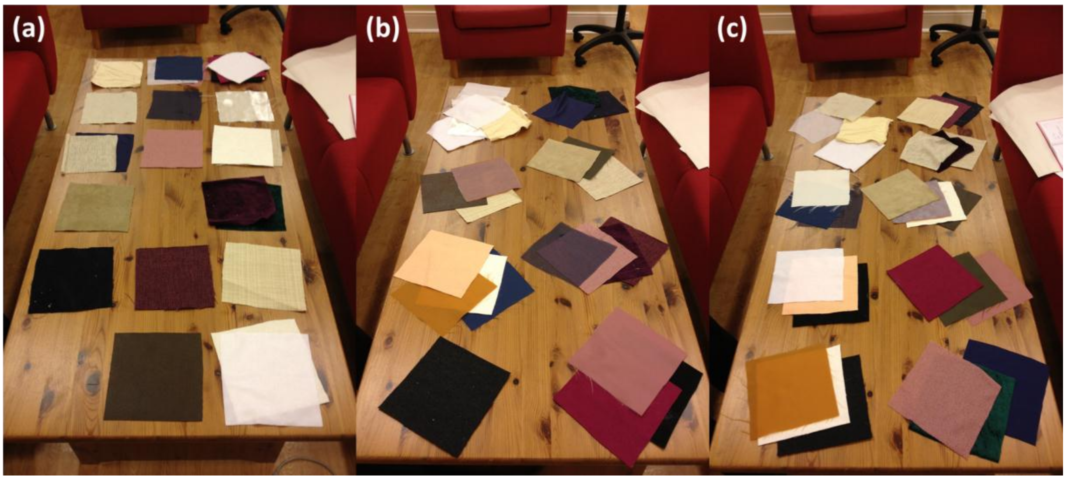


Figure 11.5 Participant 5's response to 'Grouping Exercise' (a) 1st grouping, (b) 2nd grouping and (c) 3rd grouping.

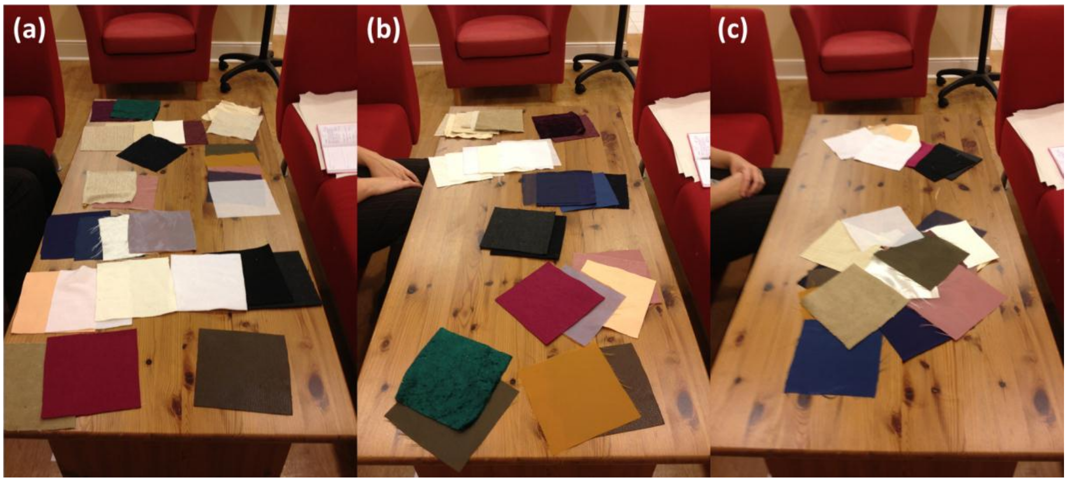


Figure 11.6 Participant 6's response to 'Grouping Exercise' (a) 1st grouping, (b) 2nd grouping and (c) 3rd grouping.

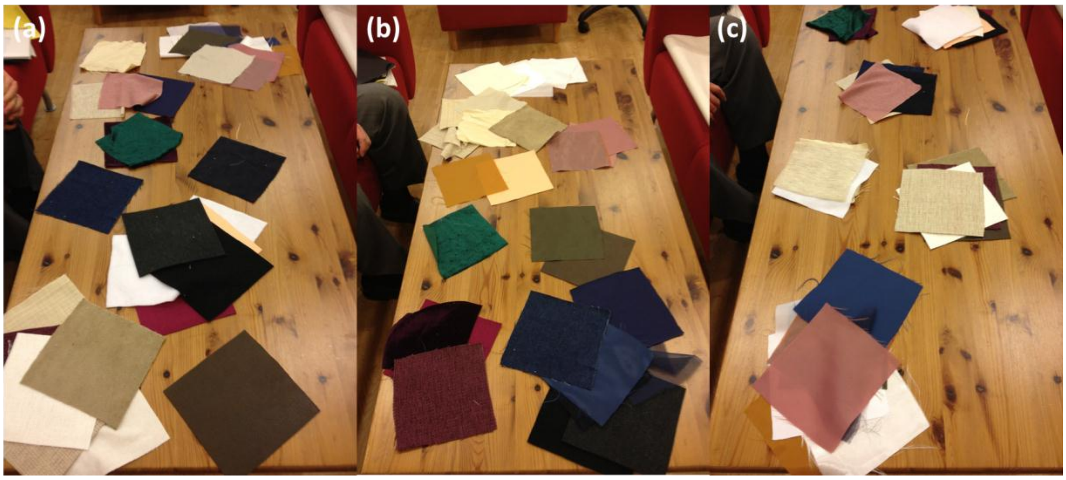


Figure 11.7 Participant 7's response to 'Grouping Exercise' (a) 1st grouping, (b) 2nd grouping and (c) 3rd grouping.

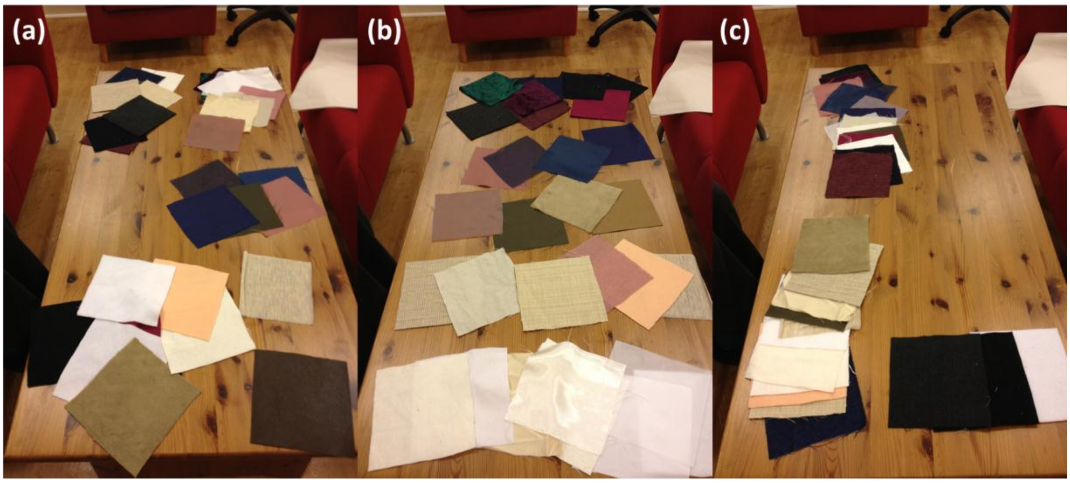


Figure 11.8 Participant 8's response to 'Grouping Exercise' (a) 1st grouping, (b) 2nd grouping and (c) 3rd grouping.

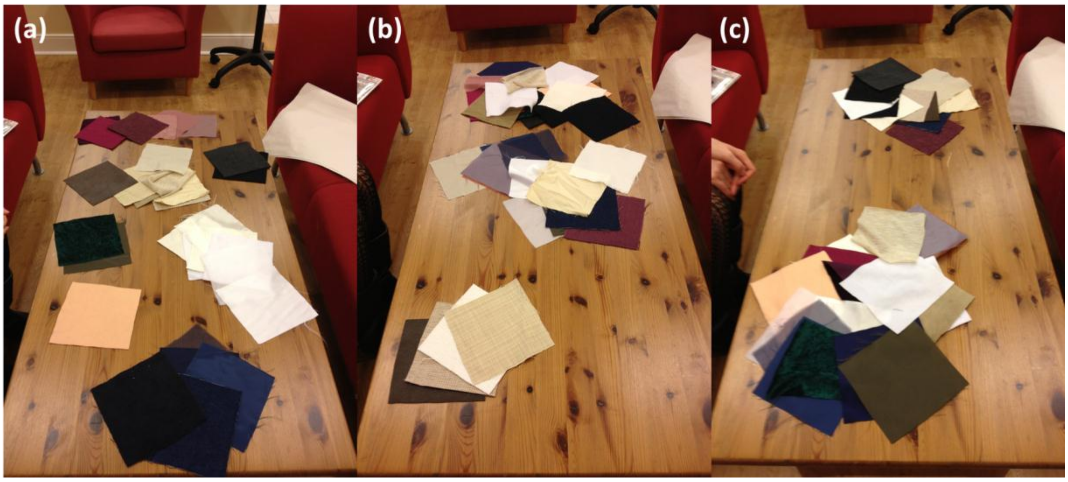


Figure 11.9 Participant 9's response to 'Grouping Exercise' (a) 1st grouping, (b) 2nd grouping and (c) 3rd grouping.

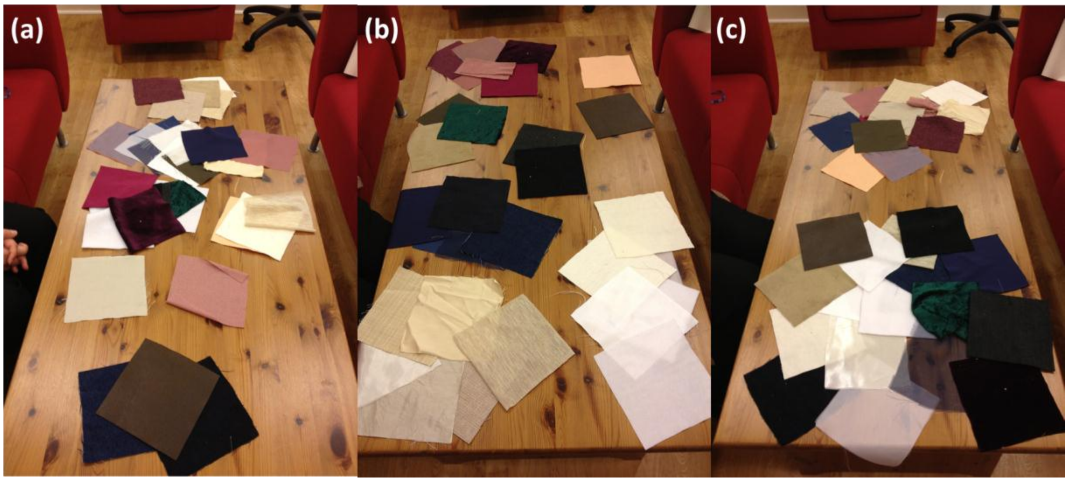


Figure 11.10 Participant 10's response to 'Grouping Exercise' (a) 1st grouping, (b) 2nd grouping and (c) 3rd grouping.

12 Sensory probe results

12.1 Sound

Table 12.1 Participant responses to the sensory probe and the question 'What is SILK' and 'What SILK is not' in terms of sound.

What SILK is	What SILK is not
A gently flowing river Edith Piaf (classical) Sound of a hug	-
Squirrels running on grass - delicately	-
Bird song, little chirpy birds, butterflies	Screeching cat
Sensuous	
Water running, bubbling slowly	Heavy metal Thunder
Soothing music - Strauss (calming)	Heavy metal music
Soft, relaxing music.	Loud dance music
Water, waves, slow	
Relaxing, instrumental arrangement with pianos and violins	Rap music
Radio static	Marvin Gaye
Whisper, gentle	Train going through a tunnel, slow heavy goods train
Classical music, opera, smooth	Rap music

Table 12.2 Participant responses to the sensory probe and the question 'What is COTTON' and 'What COTTON is not' in terms of sound

What COTTON is	What COTTON is not
Drop of water Georgia (R&B, blues - gentle voices) Turning page of a high quality magazine - rhythmic, smooth	-
Friction Wind blowing Ruffling Driving on a road	-
Soft music	Heavy rock
Indian pipes	
Wardrobe door closing	Very soft rain
Rustling leaves	
Silence (quiet)	Loud music
Washing up, cooking with utensils	Train - dirty, smokey, steam train, fast moving
Light wind blowing through a forest - not fast moving	Thunderstorm, heavy and loud
Wind chimes, airiness, breeze blowing	Industrial noise (no freedom or space)
Jazz music, enjoyable	Aircraft engine, bold, noisy
Sound of electric car rolling slowly at speed limit	Bullet train

Table 12.3 Participant responses to the sensory probe and the question 'What is DENIM' and 'What DENIM is not' in terms of sound

What DENIM is	What DENIM is not
Hand brushing on the table Children screaming, kids in the park (noisy, having fun)	-
Metallic sound - tinny Steam (running reasonably fast)	-
Cheerful pop song, easy listening	Opera, doesn't go with jeans
Metallic wrapping paper	Silence
Bright, upbeat music	Calm music, not one to get up and dance to
Opening crisps, rustling	Bird song - (cheerful, happy)
Pop song, romantic, easy to listen to, familiar	Heavy metal music
Town/city sounds including traffic	Waves breaking on the beach, any size of waves
Classic FM, soothing music	Traffic on motorway - noisy, erratic
Country music, workers music, strong, full of beat	Classical musical

12.2 Smell

Table 12.4 Participant responses to the sensory probe and the question 'What is SILK' and 'What SILK is not' in terms of smell

What SILK is	What SILK is not
Chanel No 5	-
Cherry blossom (pretty)	-
Lavender, soothing relaxing smell	-
-	-
Vanilla perfume - fresh and subtle	Heavy going out perfume - Poison, Estee Lauder
Perfume, lace flowers, flowery, smooth	Chocolate, creamy
Perfume, light, blue fabric softener	Citrus/pine cleaning smell (too strong)
Chemical, created, synthetic	Flowers, fresh scene in nature
Nice perfume, musky, ambience	Curry, strong and distinctive
Rosemary, softness	Bad odour, bin

Table 12.5 Participant responses to the sensory probe and the question 'What is COTTON' and 'What COTTON is not' in terms of smell

What COTTON is	What COTTON is not
Neutral odour	-
No smell, clean snow	-
Cucumber, cool and fresh	Onions, not nice to smell
Lemon - functional	Roses - expensive
Water, no smell	Flowers, perfume - overpowering
Clean smell, neutral, no perfume	Coffee, strong and dark
Rose, pink, comforting	Petrol, chemical, not pleasant
Fresh laundry. Sea, gentle	Harsh, spicy, too distinct
Hand soap, hard bar, clean scents	Tuna, smelly, dirty
Cheap perfume - Charlie, Lace, not complex or extravagant	Mango, exotic, exciting

Table 12.6 Participant responses to the sensory probe and the question 'What is DENIM' and 'What DENIM is not' in terms of smell

What DENIM is	What DENIM is not
Plastic - chemical and not natural	-
Cotton, clean towel - no fragrance	-
Lilac	Geranium, unpleasant smell
Thistle, blue purple cornflowers	White roses
Pizzeria, going out for dinner	Atmosphere of an afternoon tea and contents
Ocean, sea - crisp	Sweet, soft ice cream smell
Shower gel, outdoors, woods	Stale, room not aired, B.O.
City, industrial, town	Seaside, light, odour
Seaside, British	Curry, strong
Mud, tough grass	Sweets, fun flavours

12.3 Sight

Table 12.7 Participant responses to the sensory probe and the question 'What is SILK' and 'What SILK is not' in terms of sight

What SILK is	What SILK is not
Sky	-
Sunrise at the start of the day Soft birds	-
A bed made with silky sheets and fluffy pillows	A kitchen, not relaxing, busy
Metallic car	Fridge door - matt, dull
Cosy atmosphere, people sitting and listening to music	People rushing to work
Horse hair, smooth and shiny coat	Run about car, everyday
Bright and smooth sunrise, very colourful	Dark, misty cellar
Manmade seat covering	Natural garment Spiders web with dew
Brightness, young and clear	Stony beach, jagged, bottom of a cliff
The Sage, smooth, wavy	Bed bugs - itchy!!

Table 12.8 Participant responses to the sensory probe and the question 'What is COTTON' and 'What COTTON is not' in terms of sight

What COTTON is	What COTTON is not
White, fluffy cloud	-
Paper	-
Trees blowing in the wind Clothes hanging on the line outside Not a fast breeze	Rain - dull, dark, miserable drizzle
Cotton summer dress	Silk night dress
Light	Table - hard and solid
Clean kitchen, white walls and benches, restaurant	Garden, grass and trees
Sheets, smooth, light, airy, not heavy	Woollen jacket, heavy, thick
Light reflecting off the moon. Sheet on bed, airy, not enveloping	Mud, wet, hard rain. Solid, labour
Flower, daisy, white fresh, natural	Donkey, dark colour and feel/stroke
Group of tired workers, functional	Circus fun

Table 12.9 Participant responses to the sensory probe and the question 'What is DENIM' and 'What DENIM is not' in terms of sight

What DENIM is	What DENIM is not
A bumpy rock	-
Tree - rough, sturdy	-
Field of bluebells or flowers - soft, inviting	Forest, dark
Deep sea - dark	Sky - light blue
Hard, rough material, canvas bag	Fur fabric
Rough sheep fur	Soft cat fur
Sea, bright day. Good contrast between sea and sky	Voile curtains
Dark sky, hard, impenetrable	Sunrise, nature, bright colours
Skin, palm of hands, tough, hard wearing	Table, hard, not moving
Sofa, hardwearing	Bunny rabbits, soft

12.4 Touch

Table 12.10 Participant responses to the sensory probe and the question 'What is SILK' and 'What SILK is not' in terms of touch

What SILK is	What SILK is not
Human skin - an intense caress	-
Feathers - soft, small, inside wings	-
Soft peach, nectarine. Fur around a peach, soft and completely smooth nectarine	Pineapple, something rough
Rose petal	Thorn - spiky
Lily - soft	Thistle - prickly, not comfortable
Stroking a smooth horse	Towels, soft and fluffy
Skin - smooth and silky	Bark of a tree, rough
Space suit, something very prepared	Silk
Smooth forearm	Folder, cardboard, sticky out hard edges
Very smooth, not cut grass - no friction	Plaster ripping off - painful!

Table 12.11 Participant responses to the sensory probe and the question 'What is COTTON' and 'What COTTON is not' in terms of touch

What COTTON is	What COTTON is not
Magazine paper - shiny, high quality like Vogue	-
Paper - not stiff	-
A cotton sheet, smooth and cool	Corduroy bed spread, rough and bobbly
Cotton dress	Wet dog fur - harsher
White handkerchief	Rough bag
Lab/chef coat, clean	Soft towels
Vegetable leaf, spinach - smooth not thick	Pineapple, rough
Paper - lightness, covering, crispness not brittleness	Metallic
	Damp grass
Clean, long hair, soft and silky	Fine sandpaper, scratchy
Rain Mac - plastic not pleasant to the touch	Suede shoes, soft

Table 12.12 Participant responses to the sensory probe and the question 'What is DENIM' and 'What DENIM is not' in terms of touch

What DENIM is	What DENIM is not
Sofa fabric - rough not smooth	-
Dry, crisp leaves	-
Cut up hay	
Skin of a peach	Melon, rough texture
A sofa, not leather - hardwearing	Cat - soft
Dry cut grass	
Rough surface - hard table	Soft, fur fabric
Sheep	Cat
Shoes, slippers, relaxed	Light, glass, break easy, paper
Ground, baked mud	Not candy floss, light movement
Soft cheek, peach	Coarse sand paper
Sofa, upholstery	Bunny rabbits - soft fur

12.5 Taste

Table 12.13 Participant responses to the sensory probe and the question 'What is SILK' and 'What SILK is not' in terms of taste

What SILK is	What SILK is not
Pannacotta	-
Dark chocolate - luxurious	-
Dark, red grapes	Gooseberry - sour
Galaxy chocolate	Dry Weetabix
Dark chocolate	Fizzy drinks - rushing around, not calming
Champagne - special occasion	Orange juice - bitter and refreshing
Dessert - chocolate cake, pleasant	Bitter medicine
Downmarket ice cream - fake magnum	Delicious meal
Chocolate, smooth choc ice	Cereal - grape nuts (small granola)
Galaxy chocolate	Pomegranate seeds

Table 12.14 Participant responses to the sensory probe and the question 'What is COTTON' and 'What COTTON is not' in terms of taste

What COTTON is	What COTTON is not
Glass of water - no taste	-
Water, white, no taste	-
Strawberries and cream, pleasant and fresh	Kiwis - rough
Mince and tatties	Strawberries - decadent and a treat
Water	Jam - sweet and colourful
Water, cold and clean	Chicken dinner, not pure, too many foods on one plate
Lemonade - fresh, light, refreshing	Milk chocolate - heavy
Toothpaste (potentially for colour)	Soup - viscous liquid, ketchup
Ice lolly - orange, crisp fabric	Lasagne - filling
Mash potato - little bit rough and bland	Strawberries - functional

Table 12.15 Participant responses to the sensory probe and the question 'What is DENIM' and 'What DENIM is not' in terms of taste

What DENIM is	What DENIM is not
Larger	-
Rice, pasta - starchy	-
Juicy peach - feel on the outside	An apple - boring taste
Blue berries	White sugar
Pizza - casual	Afternoon tea
Cup of tea - day to day	Champagne - special occasion
Rice, potatoes. Not unusual, always compliment other foods	Sharp, spicy, hot curry
Subway sandwich	Lovely glass of wine, white crispness, openness
Cup of tea - comforting	Bag of crisps - crunchy
Pear - smooth, but gritty	Oysters - slimy

12.6 Colour

Table 12.16 Participant responses to the sensory probe and the question 'What is SILK' and 'What SILK is not' in terms of colour

What SILK is	What SILK is not
Bright white	-
-	-
-	-
Maroon, dark, sensuous	Dark brown, dingy
White - soft	Black - harsh
Dark with night lights	White - cotton wool
Creamy white, pureness	Bright red - too bright
Inside of a tropical fruit	Raw meat, red - not pleasant
Purple	White, light colour
Blue, light blue, sea - flowing, trickling, calm	Green, khaki green. Military.
Olive green, muted, soft	Hot pink - harsh, direct in face

Table 12.17 Participant responses to the sensory probe and the question 'What is COTTON' and 'What COTTON is not' in terms of colour

What COTTON is	What COTTON is not
White	-
-	-
White, fresh	Black
White clouds - for the feel	Blue waterfall - has a smoother feel
White paper	Red
Clouds on a nice day - white	Banana in skins, dry, yellow, dirty
Snow, white	Dark eggplant
Silver	Dark, rich, effervescent
White	Brown - dirty
Grey	Turquoise - bright, fun colour

Table 12.18 Participant responses to the sensory probe and the question 'What is DENIM' and 'What DENIM is not' in terms of colour

What DENIM is	What DENIM is not
Blue - like the ocean	-
-	-
Dark, warm blue	Baby blue
Deep blue sea	White
Black - shoes	White
Blue - medium to dark	Pink
Stones, minerals, pebbles, dark	Yellow - banana
Denim blue/purple	Light, white, pales/pastels
Black, unassuming	Lime green, obscure
Browns, reds - earthy, rough	Blue - pale, sky blue

12.7 Emotion

Table 12.19 Participant responses to the sensory probe and the question 'What is SILK' and 'What SILK is not' in terms of emotion

What SILK is	What SILK is not
Relaxing hug	-
Wellbeing, happy, upbeat - cheers you up	-
Relaxing, lounging around, totally chilled	Stressed
Enveloped, seductive	Not insular or introverted
Calm, relaxing, end of the day	Rushing to go out when late
Relaxed, special	Energetic, gym
Relaxed, sexy	Sad
Disappointed	Not luxurious
Pleasurable	Annoyed, wouldn't want to wear the fabric
Comfortable, peaceful	Angry

Table 12.20 Participant responses to the sensory probe and the question 'What is COTTON' and 'What COTTON is not' in terms of emotion

What COTTON is	What COTTON is not
Relaxed	-
Gentle, caring	-
Happy	Sad
Functional	Not sensual
Work, business, professional	Not fun
Smart, clean cut	Not casual or relaxed
Relaxed	Stressed
Positive, freedom.	Angry, irritated
Contentment	Not jealous, not angry
Bored, flat	Stressful

Table 12.21 Participant responses to the sensory probe and the question 'What is DENIM' and 'What DENIM is not' in terms of emotion

What DENIM is	What DENIM is not
Aggressive	-
Functional	-
Fun, skipping through fields	Sadness
Comfort	Sadness
Outdoor happiness, casual dress	A special emotion
Necessity, day to day routine	Glamorous
Comfortable	Formal, party
Comfortable, practical, positive	Enhanced, indulged
Happiness, comfort	Angry
Abrupt	Exhilarated, not new

13 Sensory Hierarchy results

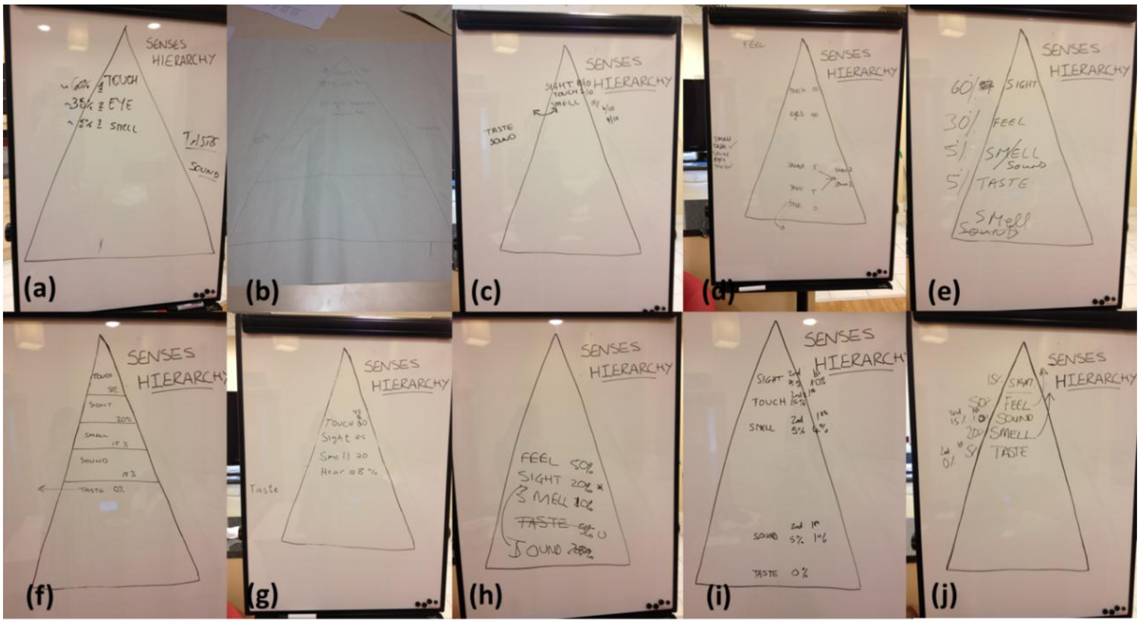


Figure 13.1 Participant responses to their opinions on senses hierarchy