EVALUATION OF PHYSICAL AND VIRTUAL FABRIC DRAPE CREATED FROM OBJECTIVE FABRIC PROPERTIES

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SCHOOL OF MATERIALS

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Abstract

This research aims to obtain more insight into the perception of fabric drape and how this relates to virtual fabric drape created based on objective fabric properties using commercial software applications, as well as the suitability of the currently used objective fabric measurement technologies for this purpose, and subsequently how this insight can contribute to comprehensible assessment of fabrics in a virtual or digital environment.
The fashion and clothing industry can speed up work processes, increase accuracy and reduce material consumption by implementing 3D virtual technology in fit, design and sales. Although the interest in 3D technology increases, the implementation on a large scale is slow. Key for a successful implementation is an accurate, reliable and seamless interaction between virtual humans, 2D patterns and virtual fabrics.
Subjective and objective data were acquired. With established instruments the measurements were taken from a range of 12 selected fabrics; the drape coefficient with the Cusick drape tester, the fabrics physical and mechanical properties with the Kawabata Evaluation System for Fabrics (KES) and Fabric Assurance by Simple Testing (FAST). The data of KES and FAST were used to simulate the virtual cloth, from which a virtual drape coefficient was derived. Drape images were created from two different viewpoints and videos from one view point, both on two different supports. The input of an expert textile panel to define the fabric drape based on these drape images was used to categorise the fabric drape and to retrieve identifying key-words. An expert user panel validated the drape categories and key-words. They also defined the stiffness and amount of drape, as well as the drape similarity of both the physical and virtual cloth. Additionally, they gave their preference for the support and view to obtain information about the fabric drape.
The relationships between drape coefficient and physical and mechanical properties were statistically investigated, as well as the relationships between the physical and virtual fabric drape coefficient. These objective measurements were correlated with the subjective data. For the correlations Pearson’s correlation coefficient was used and the significance values were obtained.
The agreement of the user panel with the drape categories defined and evaluated by the textile panel was high. Further, the agreement of the user panel was above 78% for the majority of the identifying key words. The information obtained from the abstracted drape profile was valuable and the sphere support and the 3D videos of the drape were most preferred.
High correlations were found between the drape coefficients, of the real and virtual drape, and of the subjective assessment of stiffness and the amount of drape. Positive significant correlations were found between the drape coefficients and bending and shear properties measured with KES and FAST, as well as with the fabrics’ weights.
The panels were able to classify fabrics in categories based on the way they drape and the identifying key-words are useful to distinguish between fabrics with a similar drape. The KES and FAST data simulated in a particle mesh with commercial software represent the drape of a fabric in a sufficient way. Moreover, different perspectives on the drape contributed to more insight into the drape of the fabric.

Key-words: Fabric drape category, Drape variation, Drape similarity, Commercial cloth simulation, KES, FAST, Particle mesh, Physical drape coefficient, Virtual drape coefficient, Drape supports.

Declaration

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1 Introduction

1.1 Research background

‘*A piece of fabric may be supported in some parts and not supported in other parts. Such a fabric will be subjected to forces from the supports and to forces from the gravity. The description of the fabric deformation produced by these forces may be called the drape of the fabric*’ (Cusick, 1962, p. 1).

With dedicated software three-dimensional (3D) garments can be simulated in a virtual environment. This is highly interesting for the fashion industry, who have incorporated computer aided design (CAD) successfully into their way of working (Hardaker and Fozzard, 1998). The development of CAD was driven by the developments in the computer aided manufacturing (CAM) by Hughes in the 1960’s who first developed a laser cutter, followed by software for size grading and lay planning. Ten years later the system was acquired by Gerber, also two new companies, Lectra and Camsco Company, entered the market. Yet two-dimensional (2D) pattern drawing solutions, CAD, were developed and introduced at the beginning of the 1980’s. Initially the implementation in the industry emerged slowly until the mid-1980’s when the market emerged. Attracted by this growth, more players made their market introduction (Taylor, 1990, pp. 23-24). The interest in the use of CAD/CAM was prompted by the reduction of development and preproduction time, as well as the reduction of material use and benefits of the numerical data (Collier & Collier, 1990). Today, commercial 2D CAD applications have further extended to facilitate such as 2D pattern drawing, tools for technical drawing, prints, knit and weave designs.

Research and development in 3D simulation of garments started in the 1990’s. This technology enabled the fitting of virtual garments on a parametric Avatar to facilitate the industry, or on a body scan to ease bespoke tailoring (Hardaker and Fozzard, 1998). The technology can be either a 2D to 3D approach were a 3D garment is generated from a 2D pattern (Collier & Collier, 1990) or a 3D to 2D approach where from a 3D design a pattern is flattened. In contrast to the former, the latter is not yet offered in commercial applications for elaborating garments with ease (Sayem, 2016). The 2D to 3D method simulates the 2D patterns around the virtual human based on objective fabric properties (Sayem, Kennon and Clarke, 2010).

‘The textile and apparel industry needs models which are physically justified and directly linked to a 2D CAD software’, (Luible and Bär, 2016). Today, providers of 2D CAD solutions, for pattern making, grading and marker making for the fashion industry offer 3D solutions interacting seamlessly between 2D and 3D. Available options are: Vidya (Human-solutions, Assyst, 2016); Modaris (Lectra, 2016); Accumark 3D (Gerber, 2016); 3D Runway (Optitex, 2016) and Tuka3D (Tukatech, 2016). An exception is Vstitcher (Browzwear, 2014) with only a 3D application, since 2015 Browzwear has teamed up with Grafis (2016) who offer 2D CAD software, a plug-in connects with the 3D Vstitcher software.

The fashion industry can make a headway by implementing 3D virtual technology, virtually simulated garments can contribute to work more accurately and to reduce time and costs during the development and sales (Luible, 2008; Volino and Magnenat-Thalmann, 2000; Pandurangan et al. 2008; Kuijpers and Gong, 2014). Moreover, costume design (Portland, 2015) and customised tailoring (Tao and Bruniaux, 2013) could benefit from this technology. Nevertheless, implementation is slow. (Volino and Magnenat-Thalmann, 2005; Hardaker and Fozzard, 1998).

'*Only an accurate virtual prototype could replace the real thing and provide sufficient information*', (Luible, 2008, p. 5). The virtual garment is an entity composed of the 2D pattern construction, material properties and the human body. The research of Lim (2009) who compared those three entities in two different CAD programs makes clear the complexity of this area where all entities needs to coalesce as in reality. For a successful implementation a seamless highly accurate and reliable interaction between virtual bodies, fabrics and patterns is required (Kuijpers and Gong, 2014), this is illustrated in Figure 1.1. 'Precise material properties play a very important role, since only they can guarantee the technical and aesthetical "feasibility" of a new garment' (Luible, 2008, p. 5).

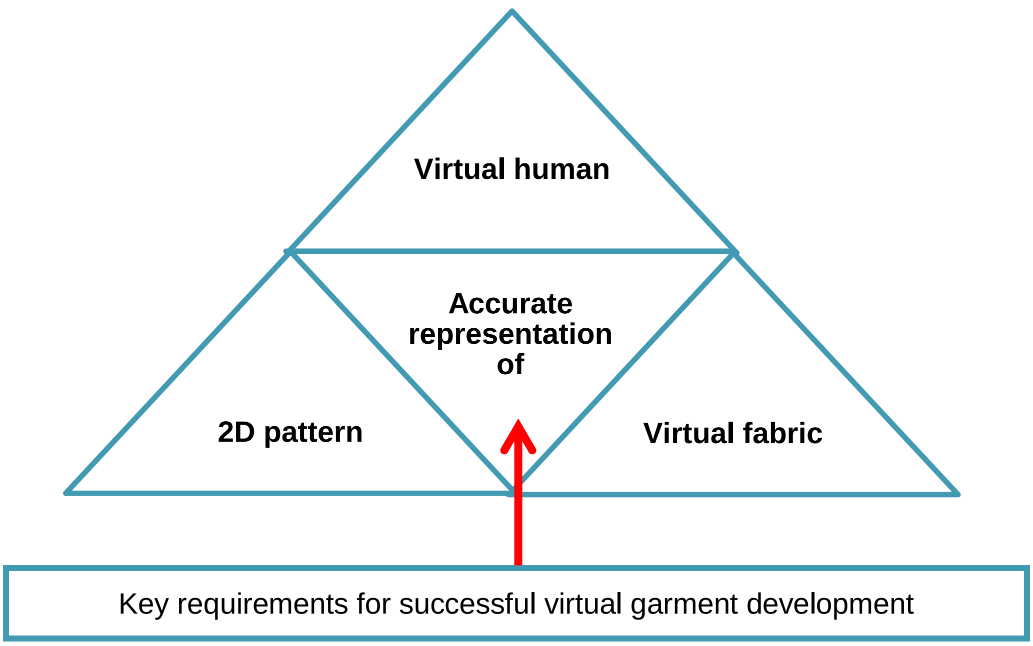


Figure 1.1: Accurate and seamless interaction between key elements for virtual garment development, source Kuijpers and Gong (2014).

The highly anisotropic fabric (Pierce, 1930), a construction held by friction and compression at the intersections between warp and weft yarns (Breen, House and Wozny, 1994), drapes around the body or stands from it based on material properties and weight (Cusick, 1962, p 1), the drape variety within the same fabric (Jeong, 1998) makes this a challenging material to simulate.

In reality fabric drape is judged by combining senses, the eyes register lustre, shape and drape, the hands the haptic experience and weight of the material, whilst the brain associates and connects these senses. Fabric drape has an important role for the fit and appearance of a garment. Within the current emerging applications for virtual garment simulation fabric drape still has a significant part in assessing the simulated garment.

Figure 1.2 illustrates a traditional fit with the final physical samples and a virtual fit, they are both irreplaceable. However, the latter requires new designer skills. Those new skills are illustrated by designer Sarah Bruylant, who experiments with fabric mechanical and physical properties to create volume in her virtual designs.


a

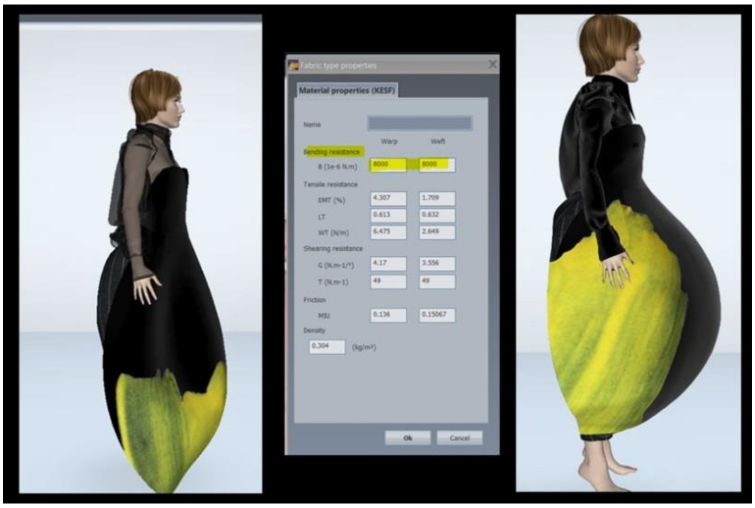

b

Figure 1.2: Physical and virtual fit: (a) iNDiViDUALS fit prior to AFW (Groenhuijzen, A.M., 2013), (b) Hypercraft experimenting with material properties (Bruylant, S., 2016).

Over the past ten years, research in the suitability of fabric properties applied in simulated garments emerged with the work of Luible (2008), Lim and Istook (2011), Kim and LaBat (2013), Power (2013) and Ancutiene, Strazdiene and Lekeckas (2014). This research, focussing on the drape of fabric and how the physical drape is represented in a virtual environment, is closely related with the research of the above mentioned authors.

1.2 Research aims and objectives

This research aims to obtain more insight into the perception of fabric drape and how this relates to virtual fabric drape created based on objective fabric properties using commercial software applications, as well as the suitability of the currently used objective fabric measurement technologies for this purpose, and subsequently how this insight can contribute to comprehensible assessment of fabrics in a virtual or digital environment.

1.2.1 Research questions

1. How virtual fabrics are currently created?
2. What fabric measurement technologies are available and are they suitable for providing input for creating virtual fabric drape?
3. How can fabric drape be categorised?
4. How is fabric drape represented in a virtual environment?

1.2.2 Objectives and approach

The objectives of this research are to obtain insight into:

- Fabric drape, cloth measurement, cloth simulation and the suitability of fabric objective parameters applied in virtual cloth and garments, through literature review.
- Perception of fabric drape through analyses of subjective assessment of drape images by expert panels who:
    - define drape categories and identifying key-words;
    - indicate stiffness and amount of fabric drape;
    - indicate preferred support and view to assess fabric drape.
- Relationships between fabric drape, fabric mechanical and physical properties and subjective assessment of stiffness and amount of drape, through statistical analysis.
- Relationships between physical and virtual fabric drape based on fabric mechanical and physical properties, through statistical analysis of correlations between:
    - physical and virtual drape coefficients;
    - subjective assessment of stiffness and amount of physical and virtual drape;
    - subjective assessment of similarity between physical and virtual drape.

1.3 Contribution of the research

This research will demonstrate whether fabrics can be classified into categories based on their drape. Fabric selection from databases in a virtual or digital environment is mostly done based on composition, weight, weave or visuals of the fabric to name a few. Additional options for selection based on drape category will refine the selection process. With the identifying keywords, introduced in this research, the identification of the fabric can be further increased. Furthermore, the different perspectives on the drape, through the supports and views, presented in this investigation will contribute to the insight in the drape of the digital or virtual material.

Moreover, this research contributes to insight into the suitability of fabric mechanical and physical properties measured with commercial equipment for the representation of virtual fabric drape simulated with a commercial 3D CAD application. It also offers an independent solution to compare real and virtual fabric drape, which can be effortlessly applied in real and virtual environments.

This research will help the understanding of fabric drape in a virtual environment as well as the relationship between the fabric drape and the fabric mechanical and physical properties, further improving the ease and accuracy of the fabric selection process for users of 3D garment simulation software. Additionally, parts of the research could be used by web shops who sell fabrics to provide more insight into the drape of the material they sell.

1.4 Thesis layout

1. Introduction

The research background, the aims, research questions and objectives for the research as well as the contribution are explained in this chapter.

2. Cloth measurement, simulation and suitability

This chapter presents the literature review and theoretical frame work of studied literature regarding the textile area dealing with objective measurement of fabric properties and drape, as well as the relationships between them. It further covers how the engineering and Computer Aided Design fields implements the fabric mechanical and physical properties in virtual cloth, and the suitability and accuracy of these properties for the static simulation of cloth.

3. Materials and methods

The used and developed materials and instruments required for this research as well as the methodology will be explained:

- Fabric selection.
- Development of the supports and procedure for the drape images.
- Objective measurements with KES and FAST.
- Measurement of physical and virtual drape coefficient.

- Subjective data collection.
- Data analysis.

4. Subjective assessment of fabric drape

This chapter presents the results of the subjective assessment of drape. Their definition of fabric drape by means of the categories and fabric identifying key words. The judgement of stiffness and amount of drape, as well as the preferred support will be presented. The analyses of the coherence between the assessed topics are included in the chapter.

5. Relationships between subjective drape assessment and measured fabric properties

The drape measurements and how they relate to the fabrics mechanical and physical measurements will be presented in this chapter, as well as how these objective measurements relates to the subjective assessment of drape presented in the previous chapter.

6. Relationships between real and virtual drape

The drape measurements of the fabrics simulated based on the objective measurements and their correlation with the real drape coefficients will be presented, as well as the subjective assessment of drape of the virtual fabrics and how this relates with the assessment of the real fabrics. Furthermore, the assessed drape similarity between the real and virtual fabrics is discussed.

7. Conclusions, limitations and future work

The results of the research are summarised and the limitations of the research as well as future investigation in this area are outlined.

2 Cloth measurement, simulation, and suitability
Literature review and theoretical frame work

2.1 Introduction

This research aims to study the physically based virtual cloth modelling area, how virtual cloth is created and what properties are required for simulation, as well as the textile area dealing with the objective measurements of fabric properties. Additionally, the suitability and reliability of these measured physical fabric characteristics for creating virtual fabric are also examined. Figure 2.1 gives an outline of the framework of the literature review.

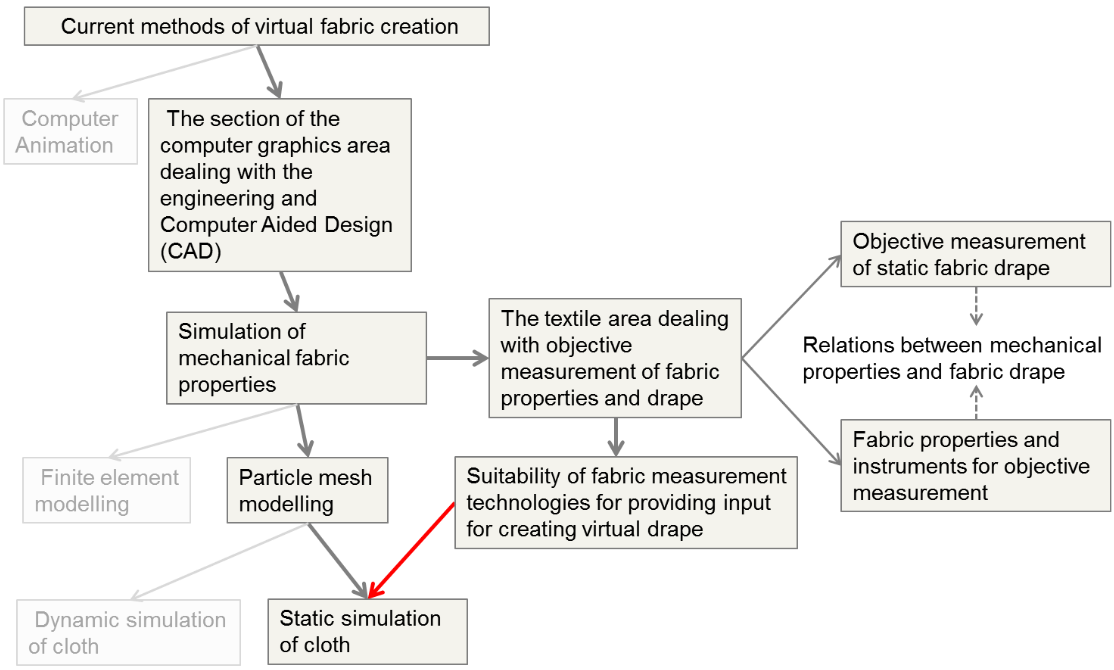


Figure 2.1: Framework literature review.

2.2 Cloth simulation

The research area dealing with the simulation of cloth can be split into two areas. On one side there is computer animation, where the purpose is to have a visually realistic result. This result is based on the visual behaviour of the physical material. On the other side is the engineering and Computer Aided Design (CAD) area. In this area, exact representation is required to make fit and design decisions based on the virtual garment, thus reducing prototypes and samples. Therefore, the virtual garment needs to be a trustworthy copy of the physical one. In the CAD area the mechanical properties and behaviour of physical materials are respected in the simulation to allow accurate virtual fittings (Breen, House and Wozny, 1994; Rizzi, Fontana and Cugini, 2004; Luible, 2008 p. 35), as shown in Figure 2.2.

Figure 2.2: Virtual prototyping of men suits visualizing numerical fitting data (Miralab-University of Geneva), source: Luible 2008.

Luible (2008, pp. 35-36) discussed the differences between the programmes used in both areas. The computer animation area uses programmes such as Syflex, HavokCloth and Autodesk's MayaCloth and ClothFX. The modelling of cloth is done based on estimation. Some of them have basic functions for the 2D pattern generation and seaming. From Maya with Mayacloth and 3D Studio Max with ClothFX, Luible (2008, pp. 67-68) investigated the fabric settings. Yet those programmes have no option for inserting objective fabric parameters, neither was comparison with real fabric properties possible as the units are not displayed. In contrast, 'the garment engineering society focuses on garment draping on virtual mannequins, and accurate mechanical reproduction for visualisation (virtual try on) and prototyping purposes (virtual prototyping)' (Luible 2008, p. 36). This CAD area uses purpose-built programmes for joining patterns into a virtual garment by implementing mechanical properties for the precise draping of material, such as Lectra, Gerber, Assyst and Optitex (Luible 2008, p. 36)

The mechanical properties are obtained with instruments for fabric objective measurement. Currently KES, Kawabata Evolution System (Kawabata, 1980), and FAST, Fabric Analysis by Simple Testing (De Boos and Tester, 1994) are the main systems for this purpose. In section 2.3.2 fabric properties and instruments for objective measurement will be discussed.

Luible and Magnenat-Thalmann (2007) stress the realism of the simulated fabric behaviour depends on both the accuracy of the computational models and the appropriateness of the inserted fabric objective properties. Pandurangan et al. (2008) point out the importance of accurate virtual 3D fabric drape for the fashion and textile industry, and consequently the contribution this will have to various processes in that industry. Al-Gaadi, Göktepe, and Haláz

(2012) stress the complexity of cloth simulation, partly due to the effects that fibre, yarn and weave construction have on the performance of fabric.

2.2.1 Current methods of virtual fabric creation

Particle mesh and finite element modelling are two systems currently used in the textile area to simulate cloth. Although simulations with finite element methods are very precise, they are less suitable for simulating large sheets of cloth; the extensive computation time and the handling of collisions, mismatches with the complex buckling and wrinkling of fabrics. In the research area mainly circular or rectangular fabric sheets are used for finite element simulations. Particle mesh methods are more suitable for the simulation of textile material (Breen, House and Wozny, 1994; Eberhardt, Weber and Strasser, 1996; Volino and Magnenat-Thalmann, 2000, pp. 50-51; Rizzi, Fontana and Cugini, 2004).

2.2.2 Particle mesh modelling based on mechanical fabric properties

In 1994 Breen, House and Wozny delivered a significant contribution to cloth simulation for the CAD area by applying objective fabric measurements into a particle grid (mesh). The authors stress the complexity of textile materials, which are a compound of fibres with their own characteristics and intricate connection: ‘Significantly, all of these components are held together, not by molecular bonds or welds, but simply by friction’. Their model consists of a particle spring system, where the particles represent the intersection points of the warp and weft yarns, as illustrated in Figure 2.3. The particles are discrete points connected by the springs.

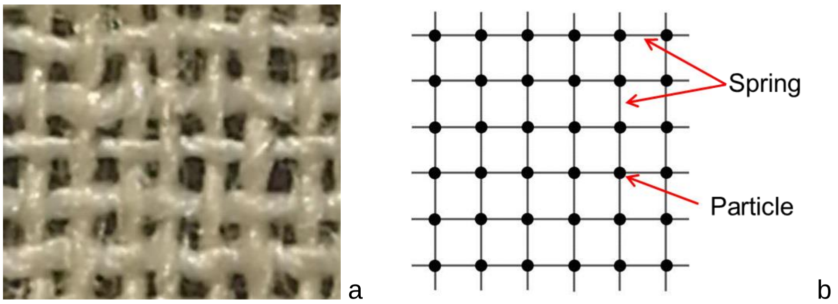


Figure 2.3: Particle mesh principle; (a) plain weave, (b) particle-spring mesh, the particles represent the yarn intersections. The Figure of the particle mesh is adapted by the author from Source: Breen, House and Wozny, 1994.

Eberhardt, Weber and Strasser (1996) improved the model of Breen, House and Wozny with faster computation time and more precise and facile implementation of the fabric’s objective measurements. Eberhardt, Weber and Strasser (1996) stress a significant part, which considers the handling of collisions; how the material interacts with and penetrates itself or the support. Volino, Courchesne, and Magnenat-Thalmann (1995) investigated pleating, buckling, creasing, and came up with improvements for more realistic results and formulae for solving collisions in the cloth itself. Moreover, they approached collision handling by distinguishing between garment and body in the simulation.

2.2.3 Static simulation of cloth in commercial applications

Movement is important to assess the behaviour of fabric in a garment. For the animation of cloth based on fabric objective measurements the challenges are even higher. Yet some advances are made with the animation of cloth for the CAD area, in 2005 Volino and Magnenat-Thalmann introduced a method at the intersections of particle mesh and finite element modelling. Currently mainly static simulation based on mechanical parameters is offered in commercial applications for fitting and designing garments.

2.3. The textile area dealing with objective fabric measurement and drape

From the beginning of the previous century many researchers contributed to a better understanding of fabric behaviour. Pierce (1930; 1937) was one of the first to lay the foundation for the quantification of textile material. By introducing symbols and equations, he delivered a significant contribution to the geometry and construction of fabric. Pierce (1930) connected fabric handle to properties, arguing the latter was assessed by textile experts judging fabric handle by means of stiffness, smoothness, softness and compactness. Pierce recognised the need for objective measurement methods for the textile area, where purchaser's judgement of fabrics was subjective, influenced by season, place, fashion, personal and cultural preferences.

Many researchers in the textile engineering area followed up the work of Pierce. Researchers were able to derive mechanical parameters, such as bending, shearing, tensile, buckling and compression (Hu, 2004 p. 21).

2.3.1 Objective measurement of static fabric drape

Cusick (1965) made a distinction between the visual appearance of fabric drape and the mechanical interactions within the material. He specified the latter: '*The drape of a fabric may be defined as a description of the deformation of the fabric produced by gravity when only part of it is directly supported*'.

The quantification of fabric drape started with the development of drape meters, they enabled insight in the three-dimensional buckling of fabric, Chu, Cummings and Teixeira (1950) discussed typical drape diagrams for sateen and acetate. Moreover, the number and the shape of the nodes gives valuable information to characterise fabric drape as Chu, Platt and Hamburger (1960) pointed out in an abstract.

Yet drape measurement methods contribute to insight in the correlation between the real and virtual fabric drape. At the same time, multiple research is undertaken and ongoing to obtain insight in dynamical drape. This area is beyond the scope of this research, which concerns static virtual simulation and static drape measurement.

2.3.1.1 Measurement of two-dimensional fabric drape

In the 1930's Pierce found a relationship between the stiffness and weight of a fabric and its drapeability. Pierce argued that the haptically judged properties are objective, which makes it relevant to measure them. By introducing the Flexometer Pierce enabled measurement of the drape of fabric, expressed in bending length. Based on the cantilever principle, strips of fabric in warp and weft are tested. Under a certain angle the length of a fabric bends under its own weight, when pushed over the edge of the instrument. This method is appropriate to measure the bending of most fabrics, except for highly rigid or limp fabrics and fabrics which tend to curl up (Pierce, 1930).

2.3.1.2 Measurement of three-dimensional fabric drape

Chu, Cummings and Teixeira (1950) further refined drape measurement, to distinguish between textile and paper they developed the Fabric Research Laboratories (FRL) drape meter. According to the authors, fabric and paper can have the same two-dimensional measured properties and at the same time a complete contrast in appearance. To achieve a surround drape they placed a circular fabric specimen on a disc with a smaller diameter, allowing the fabric to hang over the edge under its own weight. Thus showing a closer relation with the drape of a skirt or a cape where the fabric folds and buckles around the human body. The fabric was clamped between a support and pressure disc and then lifted. A turntable, simultaneously rotating with the support, plotted the shadow of the drape which was captured with a camera. The used diameters on this instrument are 4-inch (10.16 cm) and 5-inch (12.7 cm) for the support discs and 10-inch (25.4) cm for the fabric specimen. In order to compare the various drape profiles, the authors introduced the term drape coefficient.

Cusick (1962, 1965) further developed three-dimensional drape measurement, following the principle of the FRL drape meter. He placed the support disc on a glass plate mounted above a table. The shadow was projected on the table by light reflected from a bulb through a spherical mirror. Below the bulb a screen was placed to avoid light on the specimen. The shape projected on the table was traced with paper and the drape coefficient calculated with a planimeter. The principle is illustrated in Figure 2.4.

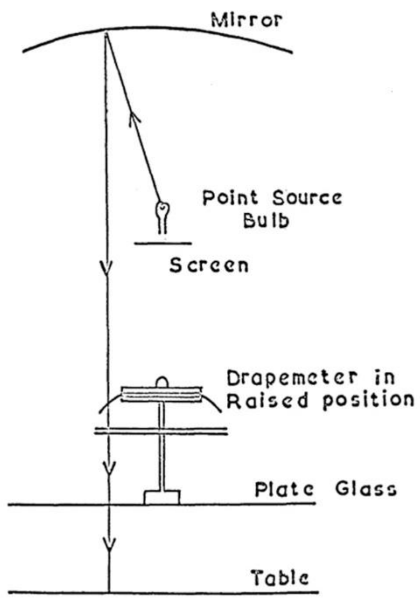


Figure 2.4: Schematic diagram of the preliminary Cusick's drape meter, source: Cusick 1965.

By testing a large range of fabrics with various stiffness on different support sizes Cusick (1962, 1965) found the combination of a 30 cm diameter fabric specimen and 18 cm diameter support disc suitable for most of them. Nevertheless, limp fabrics formed nodes under the support, whilst rigid material formed hardly any nodes. To measure limp fabrics with drape coefficients below 30% Cusick (1968) recommended a swatch with 24 cm diameter and for rigid fabrics with drape coefficients over 85% a swatch with 36 cm diameter. Moreover, he introduced the faster cut and weigh method to calculate the drape coefficient.

Cusick (1962, 1965) argued the drape coefficient is an objective measurement, expressing the percentage of the deformation occurring in the loose hanging part. Rigid material will have more and limp material less resistance to distortion, thus indicating the stiffness or limpness of the material. Cusick (1962, pp. 21-40) found good agreement between the drape coefficient and the subjective assessment by twelve judges, who assessed the most draping and most preferred drape of six skirts. Moreover, Cusick investigated the relationship between fabric mechanical properties and drape this will be explained in section 2.3.3.1.

The Cusick's drape tester is still used today, according to BS5058 (British Standards Institution, 1973)) the drape coefficient can be tested with fabric specimen of 30, 24 or 36 cm diameter. The current configuration consists of a support disc of 18 cm diameter with an outer ring to support the fabric before draping, a pressure disc of 18 cm avoids friction during draping, the outer ring is lowered enabling the fabric to drape under its own weight. A bulb is mounted under the support and the parabolic mirror, placed at the bottom, enables parallel projection of the shadow of the drape. The principle is illustrated in Figure 2.5.

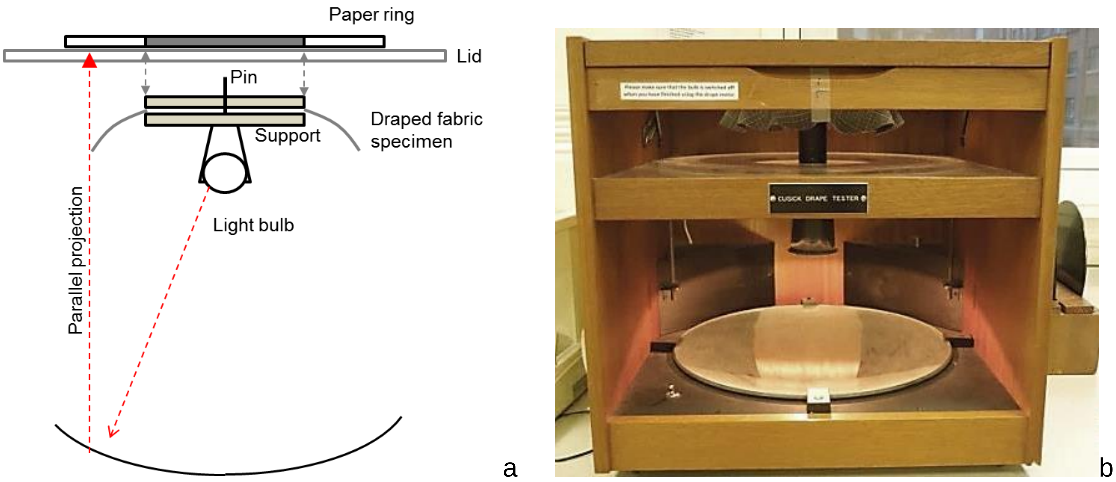


Figure 2.5: Drape meter principle; (a) schematic diagram adapted by the author from source: BS 5058 British Standards Institution, 1973, (b) photograph of Cusick's drape tester.

The drape coefficient is calculated with the cut and weigh method. A paper ring with the same diameter as the fabric swatch is placed on the lid. Firstly, the drape shadow is traced. Secondly the paper ring is weighed. Thirdly, the shadow is cut, fourthly the shadow is weighed. Hence the drape coefficient is calculated with the following equation:

$$DC = \frac{M_2}{M_1} X\ 100$$ (BS 5058 British Standards Institution, 1973).

Where M1 is the paper ring and M2 the shadow of the drape, as visualised in Figure 2.6.

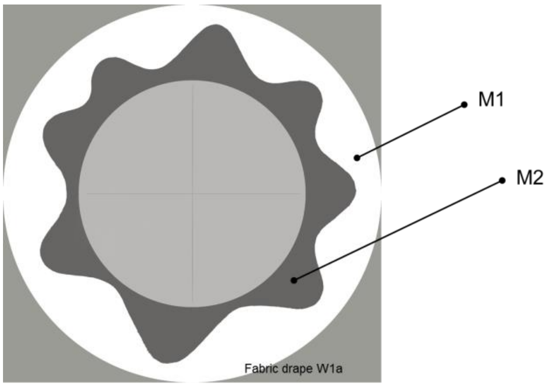


Figure 2.6: Paper ring and draped shadow; (M1) the white area of the ring with the shadow of the draped specimen (M_2) on it. The light grey area in the centre represents the support disc.

2.3.1.3 Computer analysed drape measurements

Today the cut and weigh method is often replaced by more accurate and faster image analysis methods. The principle of testing is equal, instead of tracing the shadow an image is taken with a digital camera mounted above the drape tester. Due to the fastness and the digital assessable data, this method opens new possibilities for researching fabric drape as the new drape parameters generate more insight in the drape and behaviour of fabric.

In 1993 Vangheluwe and Kiekens set up a configuration with a CCD camera mounted above the drape meter. The configuration further existed of a PC with frame grabber and a monitor, as illustrated in Figure 2.7.

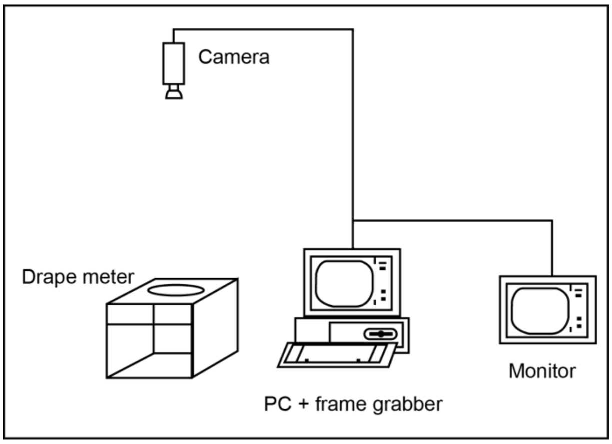


Figure 2.7: Schematic diagram of the configuration, source: Vangheluwe and Kiekens, 1993.

With image analysis Vangheluwe and Kiekens demonstrated a significant decrease of time and higher accuracy. They measured the drape coefficient in 10 seconds instead of 5 or more minutes. Next to that the coefficient of variation was half of the cut and weigh method. With at the same time high correlation for the compared drape coefficients of both methods.

The method, based on pixel count with an image resolution of 256 x 256 pixels, works as follows. The configuration is calibrated with an image without fabric specimen, next the white ring is calculated. After draping the number of pixels of the shadow is counted. Finally, the drape coefficient is calculated from the value of the calibration and the number of pixels of the drape shadow (Vangheluwe and Kiekens, 1993).

Jeong (1998) worked with the same principle, however the author calculated the drape coefficient based on boundary selection. Jeong argued that the boundary method is more reliable compared to the pixel count method. With the image of a square Jeong demonstrated that an original number of 48 pixels, increases with 41% if the image is rotated 45 degrees and calculated the drape coefficient with the formula:

$$DC = \frac{A_d - A_1}{A_2 - A_1} \text{ X } 100 \qquad \text{Jeong (1998)}$$

Where A_d represents the draped specimen, A_1 represents the support disc, A_2 represents the original fabric specimen, this is visualised in Figure 2.8.

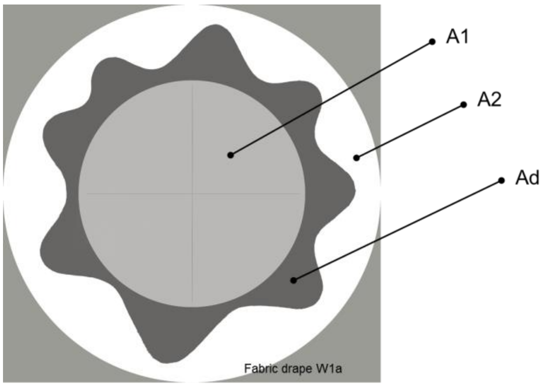


Figure 2.8: Draped specimen and boundaries as identified by the software, adapted by the author from source: Jeong, 1998.

With Adobe Photoshop® Kenkare and Plumlee (2005) retrieved the drape coefficient from digital images with a resolution of 2048 x 1568 taken with a camera mounted above the drape meter. They selected the drape shadow with the magnetic lasso tool and found a significant correlation with the cut and weigh method, Kenkare and Plumlee (2005) calculate the drape coefficient with the formula based on pixels:

$$DC\ \% = \frac{\left(total\ selected\ Pixels \div Pixels\ per\ CM^2\right) - Area\ of\ Support\ disk\ (cm^2)}{Area\ of\ the\ Specim\ (CM^2) - Area\ of\ the\ Support\ disk\ (CM^2)} X\ 100$$

A digital drape meter based on photovoltaic cells is developed by Collier et al.,(1988, cited in Collier, 1991, p.47). A digital voltmeter registers the amount of light. The same fabric swatch is draped on supports with diameters of 5-inch and 3-inch, this is in contrast to Cusick’s drape tester, where the swatch size varies according the fabric stiffness. Collier (1991) argued the effect on drape of the different support discs sizes might contribute to more insight in fabric drape. Collier found a high correlation between the drape coefficient and the subjective judgment of a panel consisting of thirteen advanced level apparel design students, who judged the attractiveness and the amount of drape. Moreover, Collier correlated the drape meter with mechanical measurements (section *2.3.3.1*).

The Sylvie three-dimensional drape tester based on 3D scanning technology, with 4 cameras and 4 laser transmitters is described by Al-Gaadi, Göktepe, and Haláz (2012). This drape tester is linked to a computer for storage and automated analysis of the images. The size of the fabric specimen and support disc is equal to the Cusick’s drape tester; however, the inner ring is pushed up to drape the fabric. Additionally, it is possible to measure the effect of force on the drape, by pushing the fabric through rings, with inner diameters of 21, 24 and 27 cm.

2.3.2 Fabric properties and instruments for objective fabric measurement

Pierce (1930) connected fabric behaviour to properties, next to the Flexometer to measure bending length (section 2.3.1.1) he describes different methods for measuring bending, such as hanging loops and heart loops, both more suitable for soft fabrics than the cantilever principle. Moreover, Pierce introduced flexural rigidity and bending modules, both calculated from the bending length. The bending modulus, converted from the flexible rigidity, defines the compactness of the cloth. Furthermore, the author presented and discussed methods for calculating parameters for thickness, hardness, compression and density and used Young's modulus for extensibility. In a next publication Pierce (1937) introduced yarn symbols and equations related to the construction of cloth, among others; yarn diameter, crimp, cover factor and twist factor.

After the work of Pierce, important research in methods and instruments to measure fabric properties emerged. A significant step was made when Kawabata (1980) introduced the Kawabata Evaluation System (KES); an overall concept for measuring fabric properties.

2.3.2.1 KES

In the 1970's Kawabata and Niwa researched methods to quantify the subjective measurement of 'fabric hand'. Fabric hand is an important way to judge the quality of the material. This is mostly done by experts in fabric finishing, but also by consumers. Kawabata set up an expert committee, with whom he defined the commonly used expressions for fabric hand. Kawabata sorted the expressions and divided them in four categories, with a sequence of importance. At the same time KES was developed. The objective measurements were correlated with the committee´s subjective measurements and total hand values, THV.

Table 2.1 gives an overview of the Japanese definitions and English translations, with the values for male and female fabrics, the number indicates the importance.

Table 2.1: Kawabata's primary expressions for hand values

		Winter fabrics		Summer fabrics	
Definition of Hand value		Male	Woman	Male	Woman
Japanese	English	Suit	Medium thick	Suit	Thin dress
Koshi	Stiffness	1	1	1	1
Numeri	Smoothness	2	2		
Fukarami	Fullness and Softness	3	3	4	4
Shari	Crispness			2	3
Hari	Anti-drape stiffness			3	2
Sofutosa	Soft feeling		4		
Kishimi	Scooping				5
Shinayakasa	Flexibility with soft feeling				6

Kawabata (1980)

KOSHI (stiffness), which is strongly related to bending (Kawabata, 1980, p.16), is for all four categories the first important hand value. The values for thin female dress fabrics express the most variety and are significantly different from the other categories.

The KES instruments quantify the essential mechanical parameters of a fabric which are the properties that determine fabric's handle, drape and formability. The low stress behaviour the material undergoes during wearing, garment assembly, finishing processes and weaving, are bending, shearing, tensile and compression. With four instruments, KES measures these parameters; Table 2.2 gives an overview of the instruments and the measured properties (Kawabata, 1980).

Table 2.2: KES instruments and the measured properties

Device	Property	Symbol	Unit	Measured
KES-FB1	Tensile	EMT	%	Tensile elongation, extensibility
		LT	-	Tensile linearity
		WT	gf . cm/cm^2	Tensile energy
		RT	%	Tensile resilience, the ability of recovering from tensile deformation
KES-FB1	Shear	G	gf/cm . Deg	Shear rigidity
		2HG	gf/cm	Hysteresis width at shear angle 0,5^0
		2HG5	gf/cm	Hysteresis width at shear angle 5^0
KES-FB2	Bending	B	gf . cm^2/cm	Bending stiffness / rigidity
		2 HB	gf . cm^2/cm	Hysteresis width at a bending curvature
KES-FB3	Compression	LC	-	Linearity of compression, thickness curve
		WC	gf . cm/cm^2	Compression energy per unit area
		RC	%	Compressional resilience
		T	mm	Fabric thickness at 0,5 gf/cm^2
KES-FB4	Surface	MIU	-	Coefficient of fabric surface friction
		MMD	-	Mean deviation of MIU
		SMD	mm	Surface roughness
X	Weight	W	mg/cm2	Fabric weight per unit area
Kawabata (1980)				

A fabric specimen of 20 by 20 cm, with warp direction marked, can be used for all the four instruments. Measurements are taken in standard conditions 20^0 and 65% RH (Kawabata, 1980).

The KES-FB1 Shear and tensile tester

Kawabata (1980) describes the instruments as follows. The fabric specimen is placed between the clamps, one of them slides on a bar, the measurements are taken over 5 by 20 cm, by replacing the specimen both warp and weft is measured.

Under 10 g/cm tensile force shear deformation of 8^0 is measured. The backward clamp slides sideward, thus shearing the fabric until the angle of 8^0 is reached. Hysteresis 2HG and 2HG5 is measured, as illustrated in Figure 2.09 and 2.10.

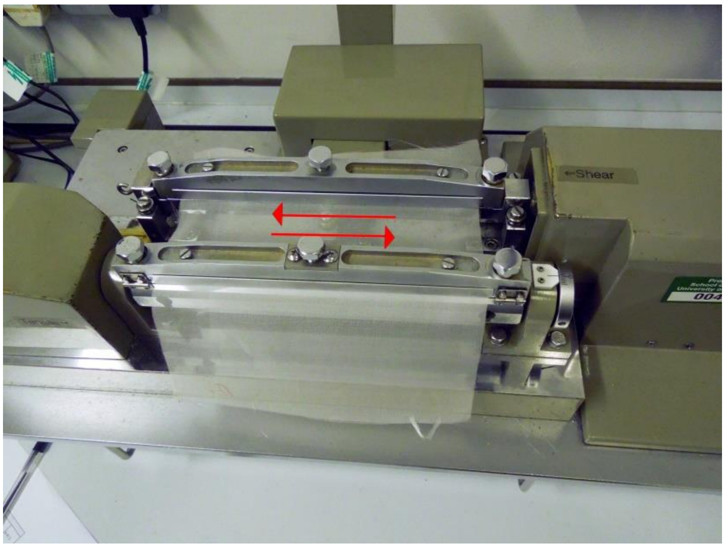


Figure 2.9: Photograph of the KES-FB1 shear measurement. Arrows indicate measurement direction.

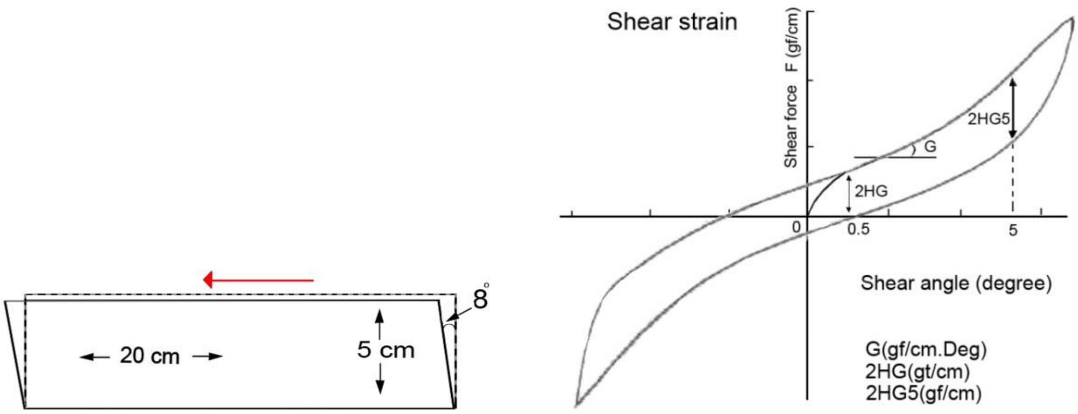


Figure 2.10: Diagram plot of the shear strain, adapted by the author from source: Kawabata, 1980.

To measure tensile rigidity the clamp moves backward by 500 gf/cm, both elongation and recovery are measured, as illustrated in Figures 2.11 and 2.12.

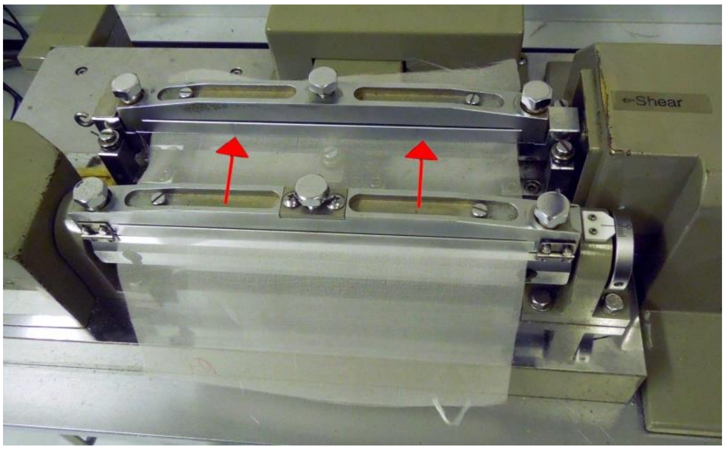


Figure 2.11: Photograph of the KES-FB1 tensile measurement. Arrows indicate measurement direction.

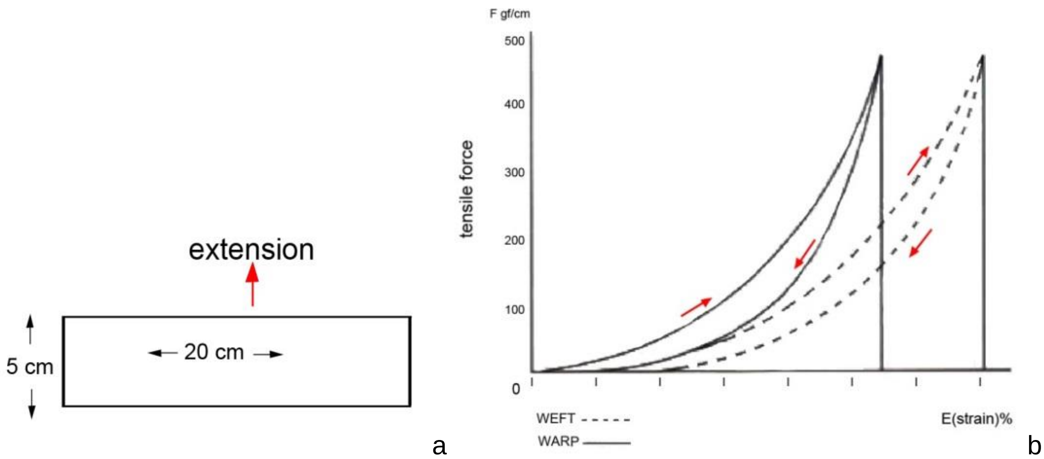
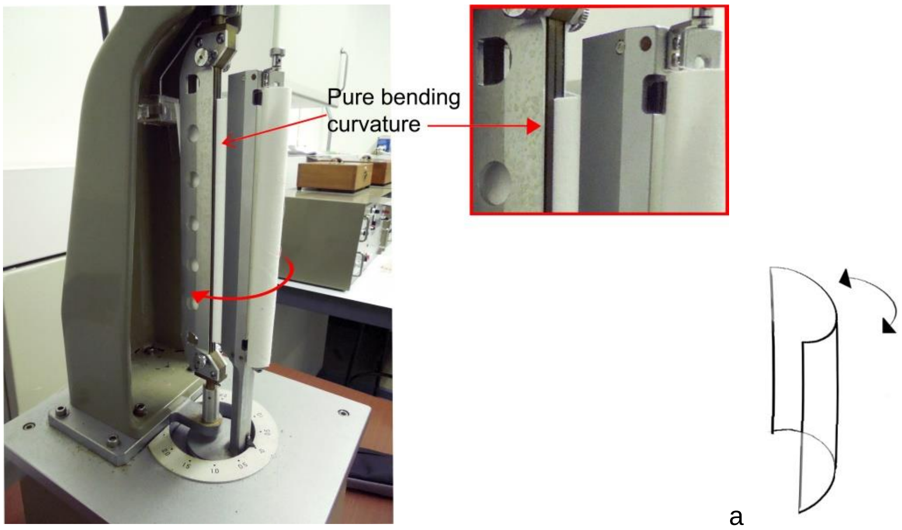


Figure 2.12: Nonlinear tensile measurement: (a) diagram, (b) tensile curve, adapted by the author from source: Kawabata, 1980.

KES-FB2 pure bending tester

The specimen is clamped between a fixed and a rotating clamp and pure bending is measured under an arc of constant curvature, as illustrated in Figures 2.13 and 2.14.



a b

Figure 2.13: KES FB2 bending measurement; (a) photograph, (b) diagram. Arrows indicate measurement direction.

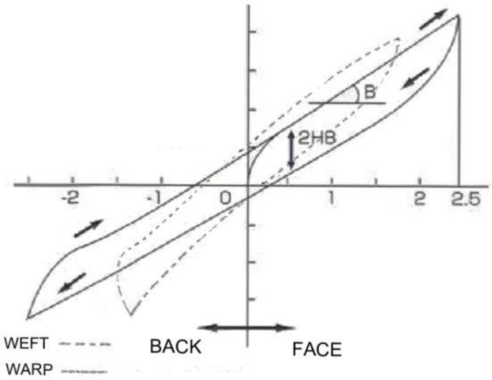


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Figure 2.14: Plotted bending slope, adapted by the author from source: Kawabata, 1980.

KES-FB3 Compression tester

Measures thickness (T), expressed in mm, the fabric is compressed under 0.5 g/cm² (T_0) and 50 gf /cm² (T_m), as illustrated in Figure 2.15. The result is plotted in a slope. WC, RC and LC are calculated.

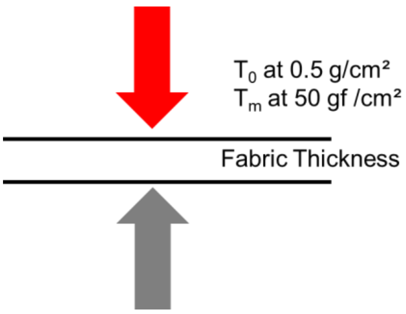


Figure 2.15: Diagram expressing the KES compression measurement, adapted by the author from source: Kawabata, 1980.

KES-FB4 Surface tester

The fabric specimen is under tension moved from left to right and from right to left, while the upper part with detector is lowered. The up and down movement of the friction is recorded with the detector. Hence a computer calculates MIU, MMD and SMD.

2.3.2.2 FAST

A few years later the Australian CSIRO Division of Wool Technology developed Fabric Analysis by Simple Testing, FAST. The instruments are developed for the wool industry to have an accurate, simple and relative cheap system for obtaining objective fabric properties. FAST provides information for cutting and garment assembly as well as performance in wearing. The system is based on thorough research carried out in Sweden, Holland, Japan, UK and Australia relating fabric properties to problems in clothing manufacturing. As well as 'compressibility and formability' both responsible for seam pucker through fabric buckling during sewing. FAST measures bending, tensile and compression properties, shear is calculated from the bias extension, formability is calculated from bending rigidity and extensibility at low loads. Further a method to obtain dimensional stability is incorporated. An overview of the measured properties is given in Table 2.3 (De Boos and Tester, 1994).

Table 2.3: FAST instruments and measured properties

Device	Property	Symbol	Unit	Measured
FAST 1	Compression	T2	mm	Thickness, measured under 2 g/cm^2
		T100	mm	Thickness, measured under 100 g/cm2
		ST	mm	Surface Thickness
		T2R	mm	= T2 released after steaming
		T100R	mm	= T100 released after steaming
		STR	mm	= Surface thickness released after steaming
FAST 2	Bending	B	µN.m	Bending Rigidity
		C	mm	Bending Length
FAST 3	Extension	E5	%	Extensibility at 5 gf/cm
		E20	%	Extensibility at 20 gf/cm
		E100	%	Extensibility at 100 gf/cm
		EB5	%	Bias extension at 5 gf/cm
	Shear	G	N/m	Shear rigidity = 123/EB5
FAST 4	Dimensional properties	RS	%	Relaxation Shrinkage
		HE	%	Hygral expansion
	Calculated	F		Formability
	Weight	W	G/m2	Weight
De Boos and Tester, 1994				

De Boos and Tester (1994) described the working of FAST as follows. For FAST 2 and FAST 3 the same fabric specimen is used, in total 12 fabric specimens of 5 by 15 cm are required. FAST 4 is tested with a specimen of 30 by 30 cm. For accurate results conditioning at 20^0 and 65%RH is required according the regular standards. In 8 hours 6-10 fabrics can be tested.

FAST 1 Compression meter

The thickness is measured at 2 g/cm² and 100 g-cm², from the output the surface thickness is calculated. The principle is illustrated in Figure 2.16.

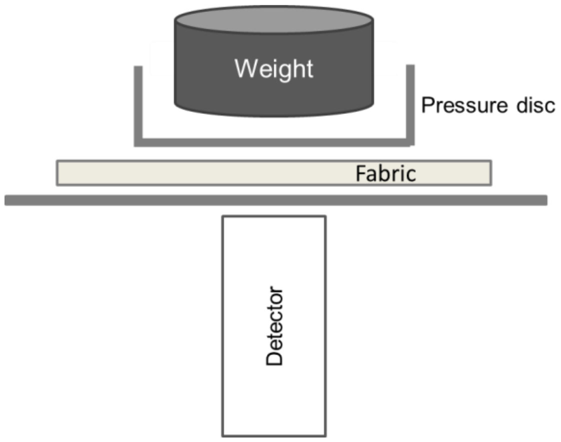


Figure 2.16: Diagram expressing FAST 1 compression measurement, adapted by the author from source: De Boos and Tester, 1994.

FAST 2 Bending meter

The bending length is measured based on a cantilever principle, the bending edge under $41{,}5^0$ is detected with a photocell, bending rigidity is calculated from this. The principle is illustrated in Figure 2.17.

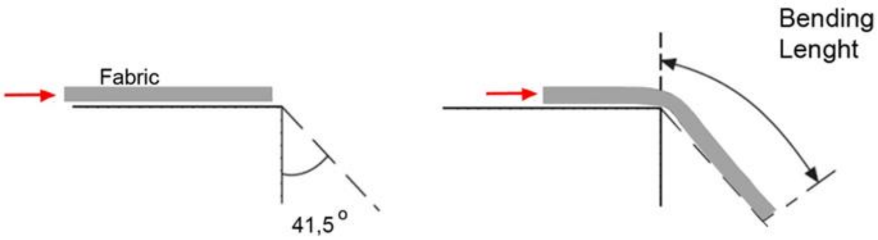


Figure 2.17: Diagram of FAST 2 bending measurement, adapted by the author from source: De Boos and Tester, 1994.

FAST 3 Extensibility meter

The instrument follows the principle of a balance, at the right side the fabric is positioned between a fixed clamp at the top and a moving one on the bottom. By taking off loads at the left side the fabric is extended and measured under 5 gf/cm, 20 gf/cm and 100 gf/cm. These loads represent deformation during cutting and sewing. The shear rigidity is calculated from the bias extension. The principle is illustrated in Figure 2.18.

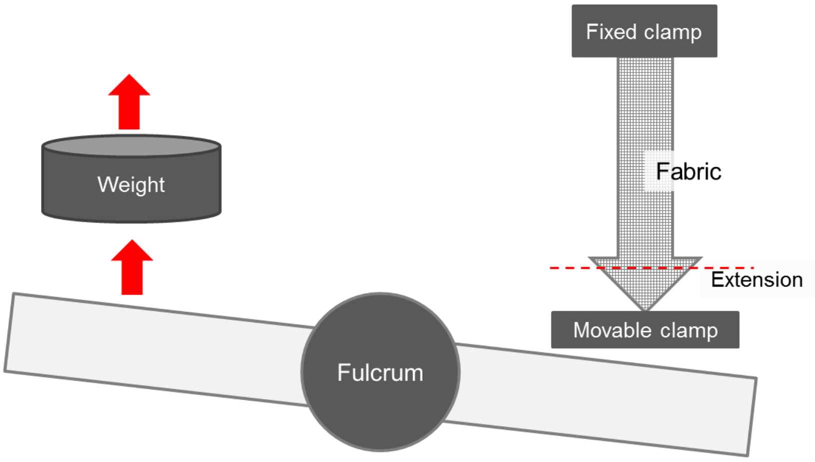


Figure 2.18: Diagram of FAST 3 elongation and shear measurement, adapted by the author from source: De Boos and Tester, 1994.

FAST 4 Dimensional stability test

The fabric specimen undergoes a 'dry-wet-dry' procedure and is measured in each stadium, hence relaxation shrinkage and hygral expansion are calculated.

2.3.2.3 Differences between KES and FAST

The results of both systems are investigated by extensive research throughout the world. KES is a very sophisticated system and requires qualified employees for operating. In Europe only a few universities are equipped with KES. Due to its nonlinear measurements more data are obtained about the behaviour of the fabric. FAST is in the lower price range, more robust and easy in use. FAST is used more often in the industry. The measurement principle is significantly different between the systems, as well as the measured area and the applied forces, resulting in different output. An overview of these differences is given in Table 2.4.

Table 2.4: Main differences between KES and FAST.

Property	KES	FAST
Tensile	500 gf/cm For jersey and stretch fabrics a lower force can be used. Nonlinear; elongation and recovery are measured.	5 gf/cm 20 gf/cm 100 gf/cm Linear Limitations for jersey and stretch fabrics: Maximum elongation 21%.
Shear	Shear angle of 8^0 10 gf/cm Nonlinear; hysteresis at 2HG and 2HG5	Calculated from the bias extension. 5 gf/cm Linear
Bending	Pure bending curvature. Nonlinear; bending hysteresis. Less suitable for very thick fabrics.	Cantilever principle. Linear. Has limitations with highly stiff and limp fabrics and fabrics which tend to curl up (Pierce, 1930).
Surface	Friction Roughness	Not measured
Compression	0.5 g/cm² (T_0) and 50 gf /cm² (T_m)	2 g/cm² and 100 g-cm²

2.3.2.4 Recent developments

The Fabric Touch Tester (FTT) is recently introduced to the market to measure properties related to fabric hand. The FTT measures thickness, compression, bending, roughness, friction and thermal properties (Zielenkiewicz, 2015) in warp and weft from a single swatch.

2.3.3 Influence of mechanical properties on fabric drape and variation of drape

2.3.3.1 Relationships between mechanical properties and drape

'Drape induced by gravitational force depends on the structural and mechanical properties of the fabric' (Jeong and Phillips, 1998).

Pierce (1930) connected bending stiffness with drapeability and handle. By testing the bending length, flexible rigidity and shear of 130 fabrics Cusick (1962, pp 105-109, 1965) demonstrated with statistical analysis that shear stiffness next to bending length influence the drape coefficient independently. By analysing the relationship between KES properties and the drape coefficients, of 138 fabrics, with residual-regression, Morooka and Niwa (1976) found that the drape coefficient was most influenced by bending and weight.

With the drape meter based on photovoltaic cells (section 2.3.1.3) Collier (1991) measured the drape coefficient of seventeen fabrics, Collier found that fabrics with a high amount of drape (section 2.3.1.3) have lower values for bending and shear resistance. Moreover, the author found a high significant correlation between the drape coefficient and KES bending rigidity, as well as shear rigidity and hysteresis at 0.5^0 and 5^0, with the highest correlation for the latter. Collier noted a significant difference between the support plates; on the 5-inch plate the bending modulus was dominant, where this place was taken by thickness and flexural rigidity on the 3-inch plate.

With multiple stepwise regression and correlation coefficients, Hu and Chan (1998) analysed the relationship of the drape coefficient with all KES measurements. With four different regression models, they found significant correlation for all shear and bending properties, weight, tensile linearity (LT) and the deviation of surface friction (MMD). The authors reasoned bending and shear hysteresis are closely related to internal friction and therefore might be more significant in complex fabric deformation.

Okur and Cihan (2002) correlated drape coefficients from Cusick's drape tester with FAST measurements of 44 women's suiting fabrics. With stepwise regression analysis they found all bending properties, shear properties strongly, and tensile properties under 5 g/m² and 20 g/m² somewhat related. No relationship was found for weight and compression. After examining the interrelationship between the properties they found bending length (B) in warp and weft, as well as bias extension (EB5), which is used to calculate shear rigidity, the most significant properties influencing the drape coefficient. Okur and Cihan argued that the differences found throughout various research might be caused by the variety in fabrics used, however, bending, shearing and extension are predominantly related to drape.

Kawabata and Niwa (1998) connected the KES system with the total appearance value (TAV) corresponding to formability, elastic and drape elements. In the same year Niwa et al. (1998) related KES data to three drape silhouettes by means of dresses; 'Tailored', 'Hari' (Japanese for spreading or anti-drape stiffness) and 'Drape. For 'Hari (anti-drape)' the fabric is pushed to stand from the body by pleats, gathering and flares, 'Tailored' follows the body and the shape of the garment has an adjusted fit, whilst 'Drape' has a loose fit with the fabric flowing around the body, as illustrated in Figure 2.19.

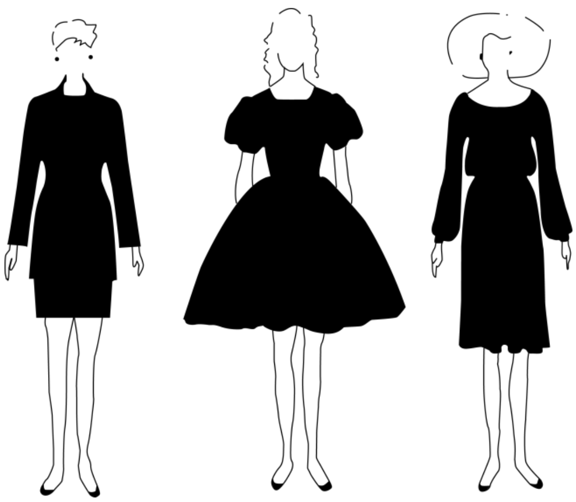


Figure 2.19: From left to right Tailored, HARI and Drape silhouette, source: Niwa et al., 1998.

To divide more than 300 fabrics into these categories Niwa et al. set up an expert panel consisting of eight designers. Based on their judgement Niwa et al. calculated the boundaries for the groups and based the classifications with equations on the KES data. An overview of the division over those 3 categories is given in Table 2.5.

Table 2.5: Fabrics categorised according the 3 defined drape silhouettes

	Tailored	HARI	Drape
Cotton		XX	
Heavy weight cotton	XX		
Cotton voile			XX
Silk		XX	XX
Polyester	XX	x	x
Wool	XX		

Data adjusted from source: Niwa et al. (1998)

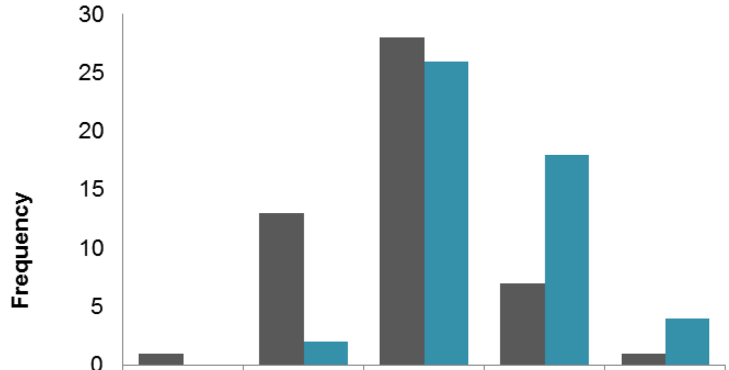
2.3.3.2 Influence of mechanical properties on variation of drape

Morooka and Niwa (1976) tested 138 male suiting fabrics on drape stability. They applied three different methods to drape the fabrics using the diameters from the FRL drape meter. Firstly, the support with fabric was three times shaken up and down before measuring the drape coefficient. Secondly, the fabric was manually shaped around the support into four nodes. Thirdly, the outer ring was lowered, whilst the fabric was pushed through a hole with a diameter equal to the support disc. The first method has the highest coefficient of variation for the drape coefficient, followed by the second, the third, without manual interference, was the most stable. The authors argued variation in drape coefficient is due to friction between yarn and fibre. They found higher drape variation by increasing bending hysteresis (2HB) per unit weight (W) with Kawabata's frictional term:

$$\sqrt{2HB/W}$$, (Morooka and Niwa, 1976).

Morooka and Niwa found that by increasing hysteresis in fabric shear and bending the drape stability decreased. Niwa and Seto (1986) confirmed this by testing 145 ladies dress fabrics according to the same principle. They also demonstrate that the drape coefficient is closely related with the primary hand values 'HARI' and 'SHINAYAKASA' (section 2.3.2.1)

During multiple tests Jeong (1998) found a significant difference in drape coefficient for the same fabric. To study this variation in drape further Jeong tested fabrics A and B repeated 50 times; first, with and second, without replacing the fabrics in between the tests. In general, both methods showed a large variation in number of nodes, which was higher for fabric B. Nevertheless, the first method showed for both more variation in number of nodes. Figure 2.20 illustrates the obtained nodes for fabric A with these tests.



	5 Nodes	6 Nodes	7 Nodes	8 Nodes	9 Nodes
With replacement	1	13	28	7	1
Without replacement		2	26	18	4

Figure 2.20: Fabric specimen A draped 50 times with and without replacement, graph composed with data from source Jeong, 1998.

Jeong (1998) also found the nuber of nodes is influenced by draping speed and the proportion between fabric and support disc.

With four pairs of weave from the same wool yarn with two different cover factors Jeong and Phillips (1998) studied the effect of weave construction and mechanical properties on drape behaviour. They argued that due to its effect on bending rigidity the cover factor highly influences drape, as bending rigidity and cover factor in- or decrease simultaneously. This is confirmed by the fact that for each set of weaves a higher cover factor resulted in lower drapeability. Moreover, a 3/3 twill and a 4/4 twill, with similar bending rigidity and cover, showed a large contrast in drapeability. Jeong and Phillps relate this to the interplay between the warp and weft yarns at the cross sections and thus to the effect of shear rigidity on the drape, where a fabric with a smaller shear rigidity has a higher drapeability. Another 3/3 twill and 4/4 twill weaves with equal cover and shear rigidity also have contrast in drape, the authors relate this to the difference in bending rigidity. The authors refer to research of Cusick in 1965 and Morooka and Niwa in 1976 that drapeability is influenced by the interaction between shear and bending rigidities. Jeong and Phillips demonstrated this with linear regression with bending and shear rigidity, as illustrated in Figure 2.21.

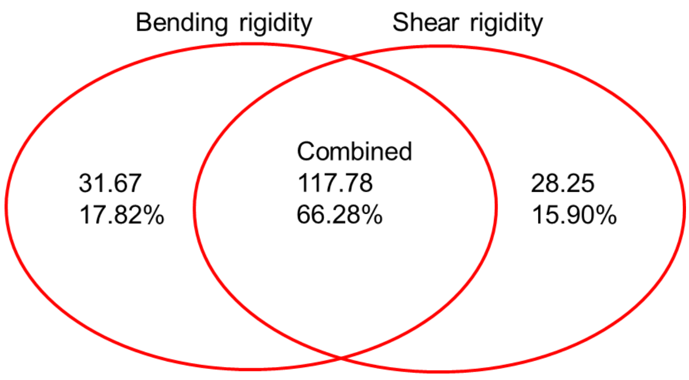


Figure 2.21: Venn diagram for regression sum of squares, adapted by author from source: Jeong and Phillps, 1998.

Al-Gaadi, Göktepe, and Haláz (2012) demonstrated the effect of twist on fabric drape. They developed three identical plain weave cottons, with equal weight, yarn density, yarn count. The only variance was in the twist of yarns as illustrated in Table 2.6.

Table 2.6: Twist variation in weft yarn

Warp	Weft
Z	Z
Z	S
Z	Z/S/Z/S

Data adjusted from source: Al-Gaadi, Göktepe, and Haláz (2012)

The authors found significant difference between the fabrics with Z/Z and Z/S twisted yarn. Where the Z/S twisted yarns have only surface contact at the intersections which increases the slippage among the yarns, the Z/Z twisted yarns merge in the folds, they ‘interconnect in the same way as the tooth of a gear’. This results in a slightly thinner fabric of 0.66 mm, whereas the Z/S twist combination is 0.79. Moreover, the drape of the Z/Z twist weave is more even and has slightly more nodes, as well as a higher drape coefficient, bending modulus, shear rigidity and hysteresis. The values of the weave with the alternating Z/S twisted weft yarns are in between the values of the other two weaves.

2.3.3.3 Other factors influencing fabric drape

The drape coefficient is influenced by humidity, unconditioned circumstances result in higher drape coefficients (Chu, Cummings and Teixeira,1950). In addition, time influences the drape coefficient, as it declines over a period of time (Vangheluwe and Kiekens, 1993; Jeong, 1998).

The drape coefficients drop more steeply at the beginning, Jeong (1998) assumed this is caused by the state of rest obtained by the mechanical properties.

2.3.3.4 Comparison of drape and drape parameters

The drape coefficient is commonly used to calculate the percentage a fabric is able to deform under its own weight. The drape coefficient is a validated and important factor to verify new measurement methods. Although drape coefficients draped from different disc or fabric sizes are not directly comparable. The proportion between swatches and discs varies per drape meter, on the FRL drape meter the fabric has more overhang than on Cusick's drape meter. Cusick (1962, pp. 13-16) found the number of nodes is highly influenced by the proportion between disc and fabric, this is illustrated in Table 2.7.

Table 2.7: Number of nodes by various disc sizes

	Disc diameter, cm			
Fabric diameter 30 cm	d10	d15	d18	d23
126 Spun viscose	5	7	8	11
119 Cotton	4	6	6	9
45 Courtelle dress	6	6	8	10
98 Worsted	4	5	8	8

Data adjusted from source: Cusick (1962, p.15)

Two fabrics with a different visual drape shape can have the same drape coefficient (Jeong,1998). Nodes, introduced by Cusick (1962, 1965), are important indicators for the drape of a fabric. The nodes are formed by the curve when the fabric buckles over the edge of the support. The number of nodes and certainly the shape, or distribution of nodes, provides valuable information concerning the drape of the material. A high number of nodes is an indicator for limpness and a low number for stiffness. Already in the 1950's Chu, Cummings and Teixeira emphasised typical drape diagrams for specific fabrics, as illustrated in Figure 2.22.

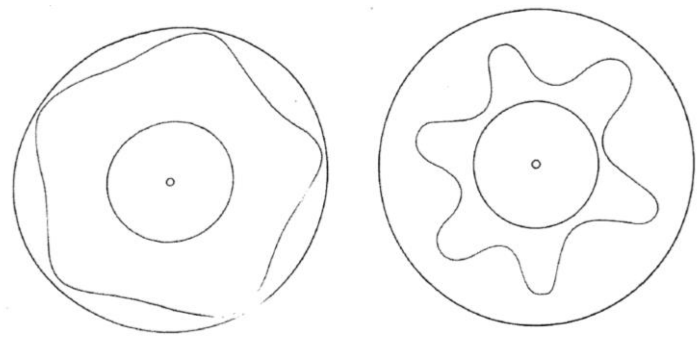


Figure 2.22: Typical drape diagram for sateen left and acetate right, source: Chu, Cummings and Teixeira, 1950.

Sanad et al (2013) indicated twenty-one drape characteristics and divided them in four groups. For a few of the drape parameters the authors obtained correlation between dresses and draped fabric specimen they compared. Namely; first, circularity, second, the number of nodes, third, area and fourth, perimeter. From their research the authors concluded the parameters are significantly influenced by the shape of the support.

2.4. Virtual fabric creation based on objective fabric measurements

Breen, House and Wozny (1994) created the first virtual fabrics based on physical properties measured with KES. Three $1m^2$ fabric sheets with a mesh size of 51 by 51 were simulated on 0.5 m^3 cubes, for each sheet one-week computation time was required. The prominent parameters in their model are bending as well as the friction at the intersections between warp and weft yarns, which they found most influencing the fabric drape. The stretch parameter is used to control the collisions. In spite of the imperfections Breen, House and Wozny (1994) found similar curve profiles between the physical and simulated drapes. During the physical tests the authors found variation in drape when placing the real material on the support. Nevertheless, they recognised for each fabric the typical drape profile in the simulations. They pointed out that due to the variation in drape of the real cloth the drape of the virtual cloth could never be exactly the same.

Eberhardt, Weber and Strasser (1996) further develop the model of Breen House and Wozny. They improved collisions management with a formula based on place, speed and acceleration, taking friction and compression from the KES measurements into account. Furthermore, they developed a method allowing precise modelling of the shear hysteresis from the Kawabata plots. The improved model is faster and allows direct insertion of KES data.

Implemented tensile, shear and bending properties in a quadrangular mesh are illustrated in Figure 2.23. The diagram of the deformed mesh is traced from a mesh based on simulated KES properties.

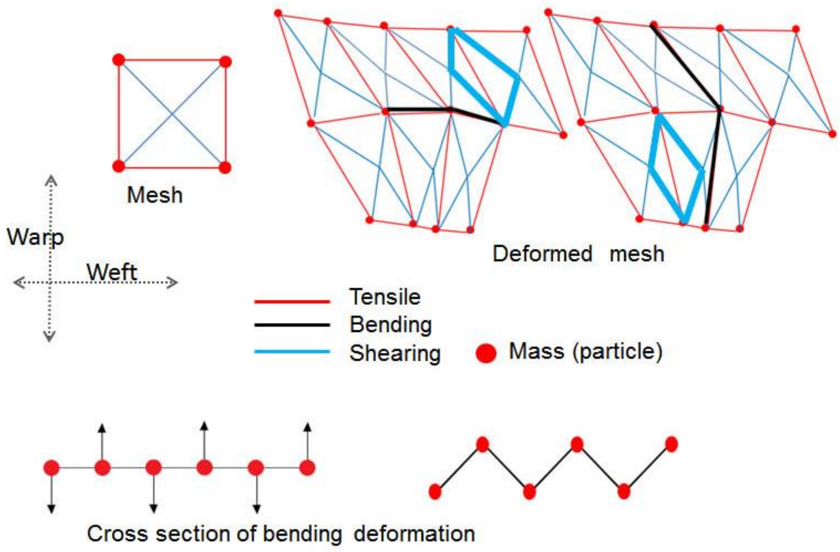
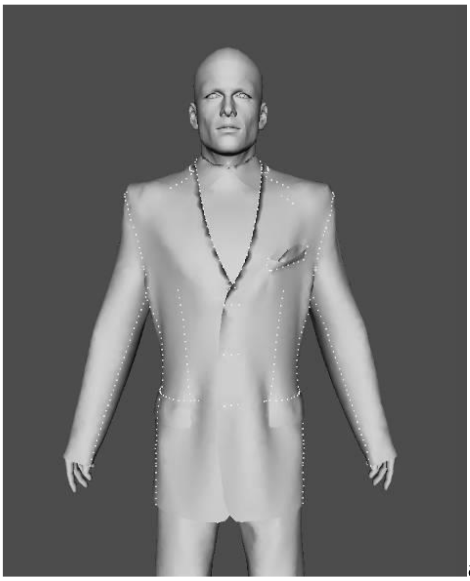


Figure 2.23: Diagram of a mesh with implemented tensile, shear and bending properties, drawing by author based on source: Breen House and Wozny, 1994; Volino and Magnenat-Thalmann, 2000, p. 54.

2.4.1 Suitability of fabric measurement technologies for providing input for creating virtual drape.

(Luible, 2008, p. 88) compared cotton simulated not based on fabric properties with cotton simulated based on objective properties measured with FAST. Comparisons of the properties revealed that the simulation based on the FAST measurements had much less elongation in the tensile and shear parameters, moreover the bending resistance was higher. This is illustrated in Figure 2.24.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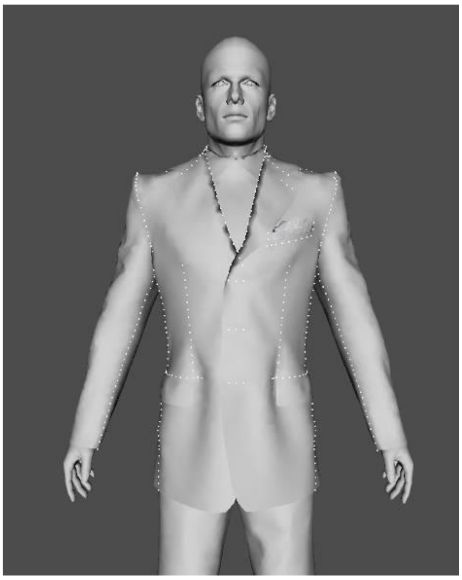

b

Figure 2.24: Simulation of cotton: (a) not based on fabric properties, (b) based on FAST data, source: Luible, 2008.

By testing six different fabrics with KES and FAST, Luible and Magnenat-Thalmann (2007) evaluated the appropriateness of the output of these instruments for virtual garment simulation. The KES data contains a strain-stress profile, which makes it possible to assess the non-linear behaviour in tensile and shear properties, whereas FAST data only contains linear behaviour. They conclude that the extension data retrieved from FAST, important for the comfort during wearing, does not show all the information.

Luible (2008 pp. 77-97) studied the suitability of FAST and KES parameters for static and dynamic garment simulation. Static simulation needs to be precise enough to obtain problems and mistakes like they would occur in the real garment, more precise the virtual fabric should exactly represent the faults in the 2D pattern. This requires exact representation of the fabric properties' behaviour in the same area on the body as it would occur in reality. To achieve this Luible defined, for the simulated cloth, precision criteria and tolerances for the differences.

Luible based the fabric parameters for accuracy in virtual simulations on two of the fabric performance categories defined by Kawabata and Niwa in 1998. For comfort and performance in static simulation, she listed tensile, shear, bending, and friction as highly important, weight and thickness as medium important.

Luible compared simulated KES and FAST properties based on these criteria. In static simulations, the fabric deforms under its own weight, which is comparable to the low forces in a KES plot. For the tests, Luible used six fabrics, which she simulated under low force (1% of the weight). The fabrics were represented as 1 m² rectangular sheets hanging in the virtual environment, with shear and tensile deformation visualised by colour scales in the software.

For tensile, tested in warp elongation, measured in the low force area at 2 N/m Luible found no visible differences between FAST and KES simulations of the hanging fabric, what makes both FAST and KES suitable for static simulation under its own weight.

For shear, Luible found differences between FAST and KES in the simulations for the linen and gabardine. Both fabrics and satin have nonlinear shear behaviour, however, the satin has a much lower weight. Therefore, Luible ascribes differences to the combination of weight and nonlinear shear behaviour, and advises to test fabrics with a weight above 150g/m² with KES.

With hanging loop tests Luible demonstrated dissimilarity between face and back bending of a fabric, which is not taken in consideration by FAST and the software Luible used. She tested simulated loop lengths of five fabrics with in general comparable lengths; the KES results for flannel and the FAST results for linen and statin are equal to the real fabric bending for both warp and weft, as illustrated in Figure 2.25.

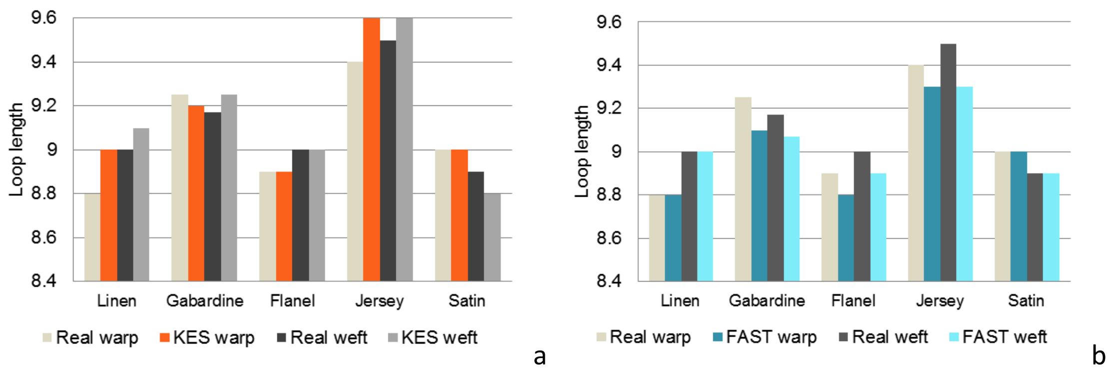


Figure 2.25: Real and simulated bending loops length; (a) based on KES data, (b) based on FAST data, adjusted by the author from source: Luible, 2008, p. 94.

However, in stretch and compression garment friction in the virtual simulation can cause higher forces in tensile and shear than by fabric deformation under its own weight, Luible concludes KES is sufficient to use for static garment fitting and prototyping.

In dynamic simulations body movement deforms the fabric, although dynamic simulation is beyond the scope of this research, Luible's investigation in fabric buckling is also interesting for gathered parts in static simulations. According to Luible (2008 p.123-128) the width of 1 cm and the 150° rotation KES uses to measure the bending makes the parameters more suitable for the simulation of small fabric gathering and buckling. The KES bending measurement is illustrated in Figure 2.13.

Kenkare, et al. (2008) developed an objective method for determining the correlation between a simulated and a physical fabric drape. They utilised a three-dimensional body scanner for this purpose. The authors tested a range of fourteen various white fabrics with KES and Cusick's drape meter. A set-up was made in a white light based 3D body scanner and a fabric specimen draped on a support disc was captured by the scanner. The authors demonstrated there was no significant difference between the drape coefficients obtained with the scanner and the traditional method. In part II of his paper Pandurangan et al. (2008) set up a drape configuration in Optitex Modulate^{TM} and imported the scans for comparison with the simulations. This will be described in section 2.4.2.

2.4.2 Fabric objective properties implemented in commercial applications

'*The clothing industry calls for a virtual simulation tool that not only satisfies the human eye with a realistic representation of the garment, but also mimics precisely the real physical and mechanical behaviour of fabrics so as to be able to truly judge a new garment design on the basis of a virtually calculated cloth*'. (Luible, 2008, p.5).

Since its market introduction academic research in the fidelity of commercial garment simulation software applications emerged. The accuracy to handle objective fabric parameters in virtual simulations is investigated from various angles.

2.4.2.1 Lectra Modaris

Lectra Modaris is based on the KES system, some KES measurements in gf/cm needs to be inserted in N/m, also the force used for the tensile measurements must be inserted. FAST measurements are inserted as they are measured.

Ancutiene, Strazdiene and Lekeckas (2014) analysed the effect of bending, shear, tensile and surface properties on the visual attractiveness in the body part of a tailored dress. With Lectra Modaris™ the dress was simulated based on the fabrics' mechanical properties measured with KES. Fabrics mainly composed of cotton were used, accordingly: fabric 16, 100% CO; fabric 17, 99% CO and 1% EL; fabric 21, 93% CO and 7% PC; fabric 22, 91% CO, 8% PAM and 1% EL; fabric 30, 100% CO; and fabric 66, 70% CO and 30% PES. An expert panel judged the 'visual quality' of the upperpart of the dresses based on the images illustrated in Figure 2.26.

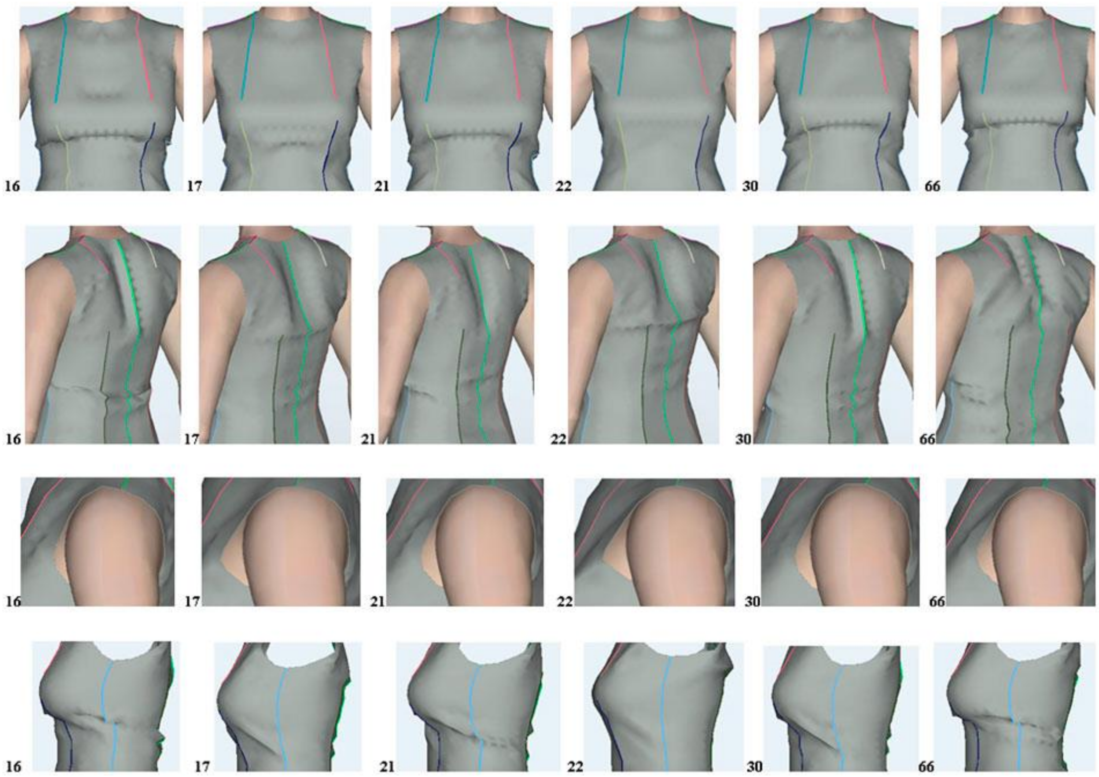


Figure 2.26: Images of different simulated cotton fabrics, source: Ancutiene, Strazdiene and Lekeckas, 2014.

Further, the authors analysed the mesh deformation and compression maps around the bust area, the armhole and the back, which they compared with the ratings of the panel. They found that the elastane containing fabrics 22 and 17 with higher tensile strains in weft, EMT, showed less deformation in the bias direction, with accordingly high rankings for the overall ‘visual quality’ by the panel. Fabric 22 was ranked the highest for the front, the bust and the side seam area, nevertheless the rating for the back was low and the armhole had the worst appearance. The individual areas of the dress simulated in fabric 17 were ranked similar to fabric 22, however, with less contrast between the lowest and the highest rating. The overall worst ‘visual quality’ was for fabric 66, which was followed by the dress simulated in fabric 16, nonetheless, the highest ranking was for the armhole of the latter. The authors assigned the better ranking for the armhole of those 100% cotton fabrics 16 and 30 to low EMT properties and a higher friction coefficient, MIU. Moreover, the low values in warp EMT, thickness, weight and warp bending rigidity of fabrics 16 and 30 resulted in a low ‘visual quality’ of the back part.

2.4.2.2 Optitex

To create virtual fabrics Optitex offers the Fabric Test Utility a manual test kit to measure shear from the bias extension, tensile, friction and only warp bending. Next to that, for FAST and KES data a conversion menu is available in the software. FAST bending, shear, and surface thickness are inserted as measured, for extensibility only E100 is used. Both warp and weft bending are inserted, which is converted to a single measurement. KES measurements are derived from the KES plots, shear and bending are both converted to a single value, (Optitex, 2009; 2013).

Pandurangan et al. (2008) simulated KES measurements in Optitex. According the same principle as described in the last paragraph of section 2.4.1, they correlated the scans with the simulations of the 14 fabrics. They found inaccurate representation of the drape for the inserted bending parameters. Due to the complexity of the simulation, Pandurangan et al. (2008) restricted the input parameters for the tests. They found the influence of bending and weight parameters most significant for the simulation, which they used as measured with KES, and kept the other measurements as a constant value. With linear regression Pandurangan et al. correlated KES bending measurements with Optitex bending measurements. They found a good correlation when they evaluated the method by comparing a scanned skirt and dress with the simulated counterparts.

With a flared skirt Wu et al. (2011) investigated the reliability of the virtual representation of twenty different draping fabrics. They used Optitex to simulate the skirts based on FAST data and made the real skirts. The latter was presented on a dress form and the virtual model adjusted to the same sizes as the dress form. The authors compared images and screen captures of front and side view of the virtual and real skirts. They converted the images and screen-captures to the same size based on pixels. On the images they measured waist, hip, hem and length. Wu et al. found significant inaccuracy for hip measurements, some inaccuracy for hem measurements, slight inaccuracy for length and waist measurements in the representation of the virtual skirts. Moreover, the three fabrics were represented differently.

Kim and La Bat (2013; Kim, 2009) compared real and virtual trousers simulated with FAST data in Optitex. A digital trouser pattern was graded in ten sizes and real samples were made in a cotton/polyester gabardine twill, the fabric was measured with FAST. From the thirty-seven judges a body scan was made and the digital pattern was stitched and draped on these scans, the fabric was simulated based on the FAST data. The panel fist assessed the virtual trousers on their own scanned body and secondly they fitted the real trousers. The overall visualisation of the trousers in relation to their figure was rated very good, with a well-represented length and positioning of the waistband, Figure 2.27. The material simulation was found inaccurate and resulted in large differences between real trousers with many wrinkles and virtual trousers having a very smooth look. Generally, the overall size of the virtual trousers was commented as being slightly tighter.

Figure 2.27: Comparison waistband and hem shapes, source Kim and La Bat, 2013.

2.4.2.3 Browzwear V-stitcher

At low cost's Browzwear offers the Fabric Test Kit, FTK, to measure bending, shear and tensile manually. The warp and weft bending length is measured according the cantilever principle. A clamped swatch is pushed over the edge of a 2.7cm high support until it reaches the lower level of the instrument. The height of the support is constant, the horizontal length and the length of the cloth are measured. The tensile property is tested by hanging the cloth vertically between two clamps, five tensile measurements are taken at 100g, 200g, 300g, 400g and 500g by hanging weights sequentially at the lower clamp. According to the same principle the shear is measured with a bias swatch. The Browzwear software converts some of the FTK measurements (Power, 2013).

Power (2013) selected six polyester knits to compare the FTK and FAST measurements in a simulated mail T-shirt. Both systems use different sample sizes, units and measurement principles. The measurements needed to be converted to the units Browzwear used for simulation. To compare the measurements of both systems Power converted them into equal units in the range where she found an overlap between the systems. For tensile properties Power found minor differences between the measurements compared at 20 gf/cm. Due to limit on maximum elongation of FAST it was not possible to test tensile in weft at 100 gf/cm, and therefore this was not used in the simulations. Bending and shear showed notable differences in the comparison between the measurements. In spite of those contrasts, no notable differences were visible in the simulations, although with the pressure mapping function some difference was visible. The outcome of the simulated results was unexpected, and it was not possible to retrieve them.

2.4.2.4 Browzwear V-stitcher and Optitex

Lim (2009) made a comparison between Browzwear and Optitex by using the same patterns, the same persons and the same fabrics. The fabric properties were measured with FAST, and inserted into the Optitex converter. Next Lim converted those properties to insert them into the Browzwear fabric properties field. In this fabric menu Browzwear again converts some of the properties. Lim found that the differences in the possibilities to insert fabric properties influenced the fit and the fabric drape. Next to this, the different methods may influence the drape differences. Lim remarked KES delivers more appropriate measurements to create virtual garments meeting the demands for online sales however this is cost and timewise not always an option.

2.4.2.5 Other commercial 2D/3D CAD system

With the 2D CAD software Kim (2016) constructed a pair of trousers in size 8 and graded it in eleven different sizes from size 5½ up to and including size 10½. The author fitted them on the same avatar in the same cotton fabric, both available in the 3D CAD software. The research focused on accurate representation of the sizes and the fit and not in particular on the simulated fabric properties. An expert panel consisting of thirty-seven pattern-drawing students assessed the trousers based on digital presented images. Kim found a significant positive correlation between the overall size of the garment and the judged trouser parts, such as waist, hip, crotch and abdomen. The panel ranked the trousers from small to large parallel to the increase in grading for the trousers with an interval of 1-inch between the sizes, for those with an interval of 0.5-inch this was weaker, which confirmed results of fittings with real garments according the author. For the investigation the same avatar is used, nevertheless the author stressed the benefits of the infinite availability of resizable avatars above body scanning technology and motion capture to fit size ranges meeting the demands of target markets.

2.5 Summary

As illustrated in this chapter the physical fabric drape is influenced by the interactions between fabric properties, and depending on the size and shape of the support, they may react differently upon each other. To capture the entire fabric in single properties and to translate this highly anisotropic material into computed equations is highly challenging.

However, the quadrangular particle system, as in a mass spring system allows accurate modelling and the representation of the real cloth in a virtual environment is acceptable. For static simulation, KES parameters are good when translated into virtual cloth. Results obtained with FAST are sufficient, however comfort during wearing is better represented based on KES measurements. Today some commercial software packages on the market are able to use the objective parameters from KES and FAST for modelling virtual cloth.

The work of Ancutiene, Strazdiene and Lekeckas (2014) demonstrated that the individual fabric properties interacting with the different body parts influence the ‘visual quality’ of the virtual dress differently depending on the different areas. Accurate representation of the fabric properties in the virtual garment enables testing of the suitability of fabrics prior to acquiring and to enable new possibilities for garment engineering to investigate the effect of fabric properties on fit and performance of garments.

Still the implementation and conversion of those measurements is rather complex, comparison is challenging and to have significant knowledge is required in the whole area as already stressed by Power (2013). Due to difficulties to measure the properties or to convert them, researchers leave measurements open or use them as a constant from available simulations (Pandurangan, 2008; Lim 2009; Power 2013). This may cause inappropriate representation of reality.

Fabric drape influences the fit of a garment and plays a decisive role in garment design. Yet comparison between the real and virtual fabric drape is intricate, as well as the comparison among simulations.

3 Materials and methods

3.1 Introduction

The research objectives, to obtain insight into cloth simulation, cloth measurement and the suitability of objective properties applied in virtual garments, as well as in the drape of fabrics outlined in chapter 1, section 1.2 are investigated through literature review as described in chapter 2. This chapter 3 deals with the materials and methods used to investigate the research questions and objectives outlined in chapter 1 further.

For this research qualitative and quantitative methods are combined with a greater emphasis on the latter. Subjective and objective data are acquired, the latter by empirical testing and the former through surveys and structured interviews. The relationships between the subjective and objective data are statistically examined.

The principle of the Cusick's drape meter has a central role in this investigation, next to the measurement function also the proportions between fabric and disc, as well as the views on the fabric contribute in the various stages of this research. The drape profile is used to investigate the variation in drape, which plays a role in the fabric selection process. The drape coefficient from the selected fabrics is measured and used to investigate the relationships between the subjective assessment of drape as well as the correlation between the real and virtual drape. The fabric selection will be described in section 3.2.1, whilst the role of the drape meter and its derivatives will be described in the various sections of this chapter. As the proportion between fabric and disc influences the drape (Collier, 1991) all fabrics are tested with a 30 cm diameter specimen, to obtain similarity in proportion between support and overhang, thus allowing equal comparison of the different fabrics.

The first part of this research will investigate the perception of drapeability through judgement of fabric drape images by expert panels. Following previous studies which have connected objective drape measurements with the human perception of fabric drape through subjective judgment of skirts (Cusick, 1962), or fabric specimens placed on support discs (Collier, 1991). The selection of judges is in line with the reasoning of Kawabata (1980) who argued that due to their profession the judgment of fabrics by textile experts is representative for consumers. Hence two different types of expert panels are composed for this investigation; a textile panel consisting of textile teachers as well as a user panel consisting of teachers and students who are both frequent users of 3D garment simulation software.

For the subjective judgement of drape, images of the drape are used. From practical and organisational points of view images of draped objects are preferable to the real draped objects (Cusick, 1962, p. 27). Another important reason to use images is the connection with the digital environment. Additionally, the images safeguard similarity during assessment over a period of time and variety in place. The methods applied for creating the images will be described in section 3.2.3.

Furthermore, the drape meter presses the fabric between two discs and at the edge of the support the material drapes under its own weight. A curved shape, however, enables the fabric to buckle free on the support which may lead to a different insight into drape. Moreover, Cusick (1962, p. 40) pointed out that the outcome of subjective assessment of fabrics may vary depending on how the fabrics are presented. With regards to this the fabrics are presented on two different supports and from different viewpoints, static and rotating, to enable the judges to obtain thorough insight in the fabric drape. What is more to increase understanding for presenting fabrics in a digital environment both panels are questioned about the preferred support and view to assess the drape of the fabric. The methods used to create the supports will be described in section 3.2.3.1.

In addition, Kawabata (1980) argued that standardising definitions for fabric hand would reduce confusion. As illustrated in the literature review Cusick (1968) divided the drape of fabrics based on their drape coefficients as follows very limp for fabrics with drape coefficients below 30% and stiff for fabrics with drape coefficients above 85%. Niwa et al. (1998) divided fabric drape in three drape silhouettes based on KES measurements. They described the silhouettes as follows; 'Hari' (anti drape) standing from the body, 'tailored' following the body and 'drape' with a loose hanging fit. By means of the drape coefficient Cusick connected the defined categories to a measurable quantity of the drape of the circular fabric sheet itself, whilst Niwa et al. connected the drape silhouettes with equations to individual KES properties. Considering these perspectives, definitions and categories to identify fabric drape might contribute to deeper comprehension specially towards identifying fabrics based on their drapeability in a virtual environment. Hence the textile panel is requested to define the fabric drape, and based on these definitions drape categories and fabric drape identifying keywords are derived. These drape categories and identifying keywords are judged by the user panel, who prior to their judgement grouped the fabrics based on drape. The purpose of the latter is to make the panel familiar with the assessment of the images and to obtain insight in the drape clusters made. Further, for each fabric the expert panels assess the stiffness and amount of drape on a rating scale. To obtain insight into the perception of drape the relationship between this stiffness and amount of drape is investigate, as well as the relationship with the drape categories and drape clusters and the role of the identifying keywords. The applied methods will be described in section 3.4.

Fabric drape depends on individual fabric properties (Hu, 2004, p. 199), whereas the overall drape of the fabric is expressed by the drape coefficient. The latter plays, together with the views of the drape, an important role in this investigation, although in relation to the individual fabric properties. The second part of this investigation presents the measured drape coefficient as well as the objective fabric properties measured with KES and FAST. The relationships between the objective measurements and the drape coefficient are investigated as well as how this relates to the subjective perception of drape.

Review of literature revealed that the KES instruments are currently the most suitable to obtain the parameters for static fabric simulation. Whereas the FAST system is sufficient, it has some limitations. A particle mesh is currently mainly used to simulate these measured fabric parameters. As described in the literature review the virtual representation of individual fabric properties has been investigated by Luible (2008) as well as by Power (2013). The third part of this research is to investigate the relationships between physical and virtual fabric drape simulated based on KES and FAST measurements with commercial software. The measured fabric mechanical and physical properties are used to create virtual fabrics, from those simulated fabrics the virtual drape coefficients are measured with image analysis, the applied methods will be described in more detail in section 3.3.4. To investigate the relationships between the real and virtual drape and to compare drape simulated with KES and FAST measurements the virtual drape coefficients are correlated with the drape coefficients of the real fabrics. Moreover, the relationship between virtual and physical drape is investigated through subjective judgement by the user panel of both real and virtual drape images, they will rate the stiffness and amount of drape. These ratings will be correlated with the drape coefficient, as well as the ratings between the real and virtual draped specimen, additionally the correlation between the drape simulated based on KES and FAST data is investigated based on this judgement. The applied methods will be described in section 3.5.

The work of Lim (2009) showed that comparison between virtual simulated garments is challenging due to the multiple aspects influencing virtual drape. The outcome of the surveys and objective comparisons are analysed and used for recommendations to improve the perception of fabric drape in a virtual environment.

In the next sections the methods and materials are described for the individual parts of this investigation, Figure 3.1 illustrates the above described research design, where the red arrows represent the investigated correlation.

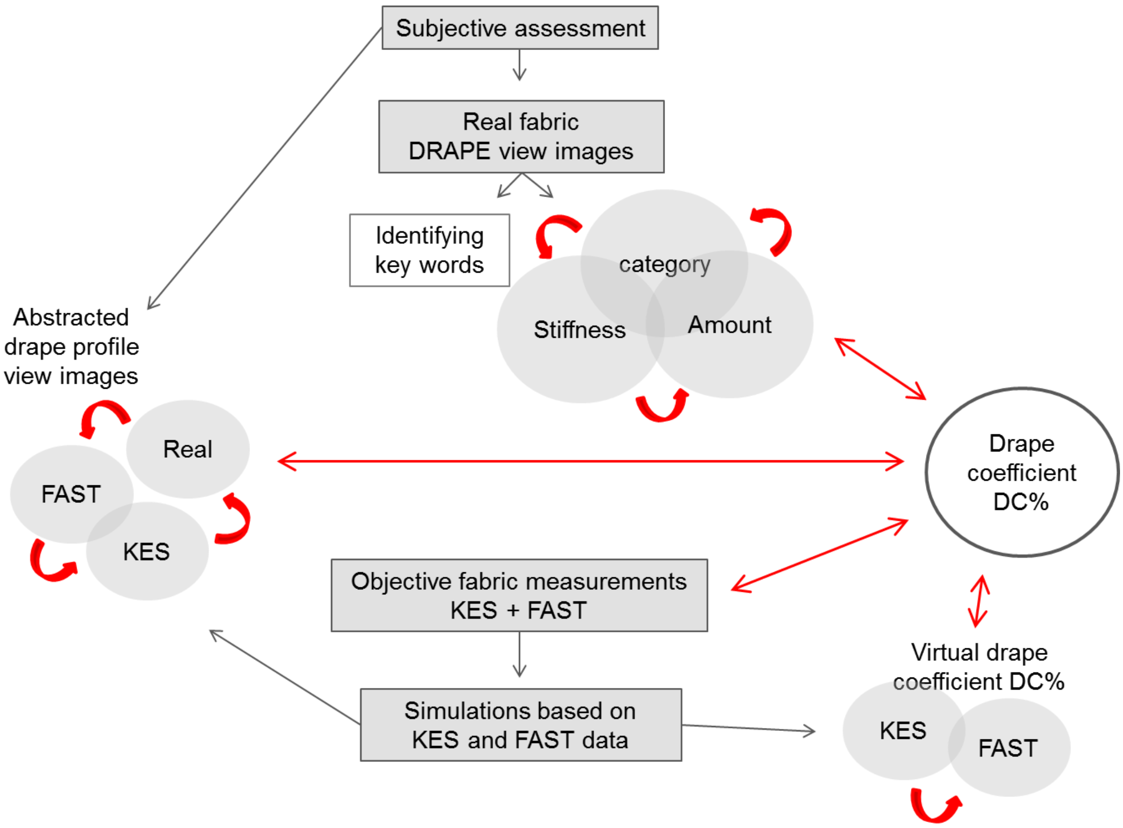


Figure: 3.1: Research design.

3.2 Materials

3.2.1 Fabrics selection and drape variation tests

With different behaviour in warp and weft, fabric is a highly anisotropic material, the drape and characteristics are influenced by its composition and the manufacturing process. For example, the fibre properties of silk and wool, both protein fibres, result, however, in significantly different material characteristics. Furthermore, the yarn construction and properties, as well as the weave construction, influence the end product, the finish can reinforce or diminish particular fabric characteristics. The behaviour of the fabric is an interplay between various factors, Figure 3.2 gives an impression of this.

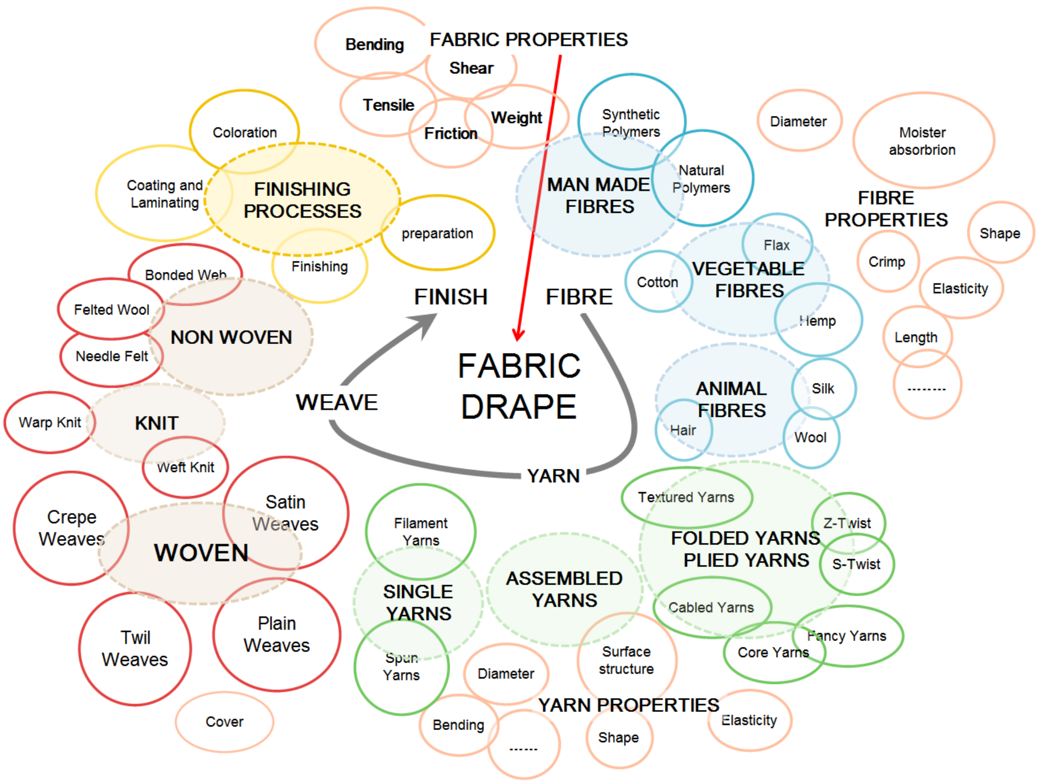


Figure 3.2: Factors influencing fabric drape.

Small differences in twist direction (Al-Gaadi, Göktepe, and Haláz, 2012) or cover and weave construction (Jeong and Phillips (1998) influence the fabric drape. Furthermore, two fabrics can have equal drape coefficients with at the same time contrasting drape profiles and node numbers, whereas some fabrics show variation in drape and number of nodes if the same swatch is draped multiple times (Jeong 1998). This behaviour depends on the fabric properties and friction between yarn and fibre (Morooka and Niwa, 1976; Niwa and Seto, 1986), as well as the interaction between warp and weft yarns (Jeong and Phillips; 1998). Despite this irregularity, Chu, Cummings and Teixeira (1950) pointed out that fabrics can have a typical drape profile. This typical nature of fabrics is considered during the fabric selection process, aiming to have contrasts and similarity in the fabric range, the selection criteria based on this are listed below.

- Woven.
- Finished state.
- Various weight ranges, from medium heavy to sheer.
- Variety in drape behaviour; fabrics with regular and irregular drape.
- Variation in drape profile; similar and dissimilar.
- Mainly pure compositions; cotton, silk, wool, polyester.
- Weave type.

The phases of the fabric selection process based on the above listed criteria are illustrated in Figure 3.3 and described in the next section.

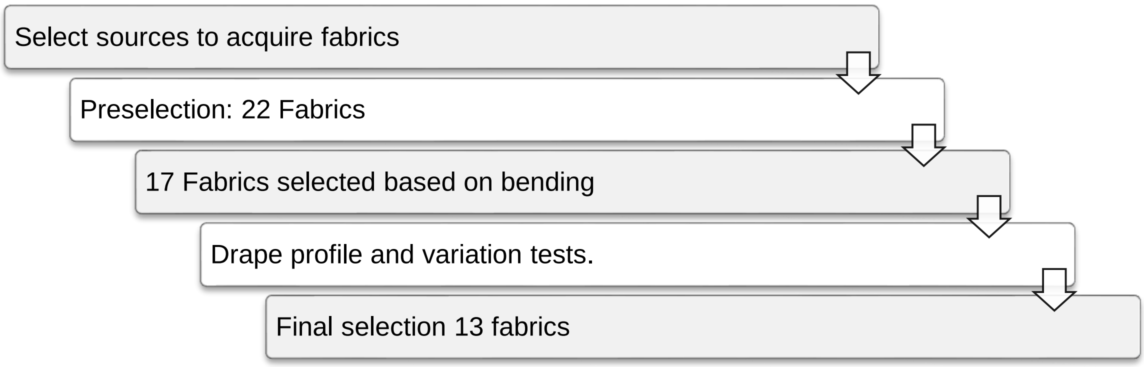


Figure 3.3: Overview of the fabric selection process.

A preselection of twenty-two fabrics based on weight and composition was made from the collection of Print-Unlimited and stock from iNDiViDUALS, who both expressed their commitment by sponsoring the fabrics. The fabrics from Print Unlimited are unprinted, to obtain end-use state they undergo exactly the same finishing process as is used for the printed fabrics. This selection is condensed to seventeen fabrics based on the visual differences in bending behaviour of the swatches. This visual bending assessment is obtained by clasping two edges of the fabric swatches together with a binder clip, as illustrated in Figure 3.4.

Figure 3.4: Visual assessment of bending.

These seventeen selected fabrics were tested for drape variation with Cusick’s drape meter by draping fabric swatches of 30 cm diameter multiple times. Directly after releasing the outer ring of the drape meter the drape shadow is drawn on the paper ring, this is repeated seven times without replacing the fabric specimen between the drape measurements, for each measurement the shadow is drawn on the same paper ring. By testing various fabric specimen multiple times, seven was found suitable to obtain variation in drape. A woollen twill fabric, W3, showed by seven drape relaxations exactly the same placement of the nodes, whilst for fabrics with a very high variation for each drape relaxation the nodes were placed in a different position. Based on this it was decided to drape the fabrics seven times. Figure 3.5 shows three fabrics draped seven times with the drape shadows traced on the same paper ring; fabrics FD with high variation, W3 without variation and C6 with some variation in drape profile. The drape variation tests of the selected fabrics are included in appendix 1.

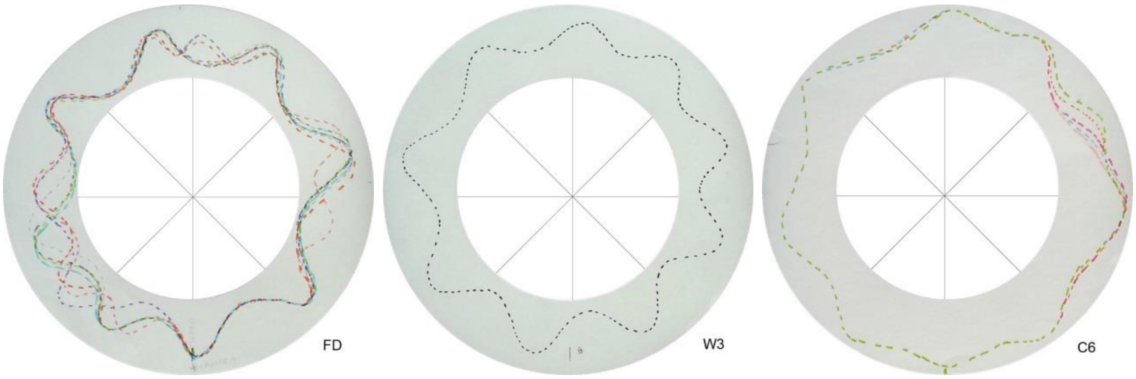


Figure 3.5: Plots of drape variation tests; repeated seven times without replacing the fabric.

Based on the fabric selection criteria listed above thirteen fabrics were selected from the drape variation plots, fabrics with high and low variation in drape, as well as based on their typical drape profile expressed by the differences between the highest and lowest amplitude. Figure 3.5 above shows three fabrics with a different drape profile, the plots for the selected fabrics are included in appendix 1. The selection process is aimed at selecting a wide range of drape profiles and, wherever possible, plain weave fabrics. Within three defined weight groups, light/sheer, medium light and medium heavy, the fabrics are selected in equal proportion. In the next section the data of the selected fabrics according to the set criteria is given.

3.2.2 Data of selected fabrics

The fabrics selected based on the set criteria are composed of wool, cotton, silk and polyester, the biggest share is for plain weaves and they are roughly divided into three weight groups. The specifications are given in Table 3.1 and the pie charts in Figure 3.6 show the proportions for composition, weight and weave.

Table 3.1: Overview of the selected fabrics

Code	Weight Group	g/m²	Composition	Weave	yarn/cm Warp	yarn/cm Weft
C3	Medium Heavy	279	100% CO	Plain	16	23
C2		272	97% CO 3% EL	Twill	30	20
P2		252	100% PES	Plain	32	17
W4		254	100% WO	Twill	14	18
W2	Medium Light	161	100% WO	Plain	24	19
W1		115	100% WO	Crepe	25	21
C4		90	100% CO	Plain	35	43
S2		88	100% SE	Satin	52	55
C5		81	100% CO	Plain	46	46
P1	Light Sheer	69	100% Pes	Plain	44	32
S3		54	92% SE 8% EL	Crepe	55	43
S4		27	100% SE	Plain	52	40
S1		25	100% SE	Plain	34	37

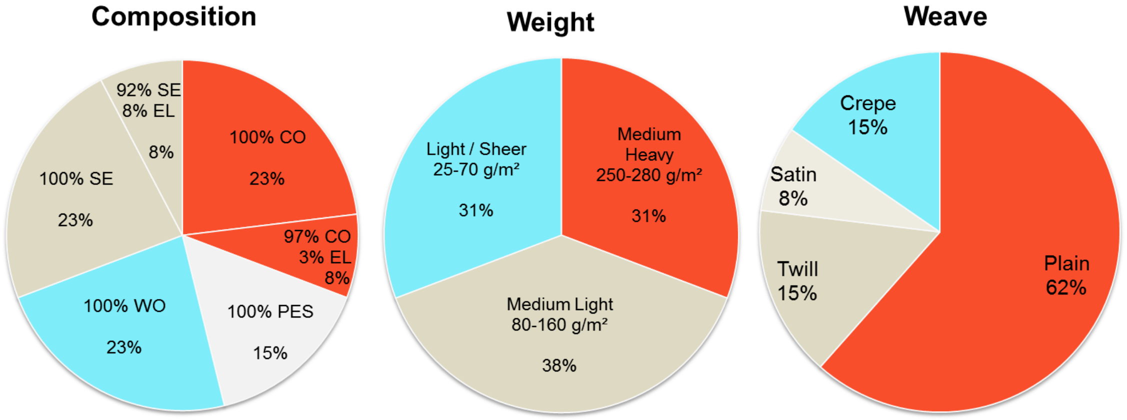


Figure 3.6: Proportions for composition, weight and weave of the selected fabrics.

Contrasting fabrics such as P2, a heavy polyester plain weave, and S1, a sheer organza with the lightest weight in the range, can have similarity in drape profile and variation. However, similar fabrics in weight, composition and weave can have opposite drape profiles and variation as illustrated by fabrics S1 and S4. The similarity and contrasts between pairs of the selected fabrics according the criteria set out in section 3.2.1 are illustrated in Table 3.2.

Table 3.2: Contrast and similarity between selected fabrics

Fabric	Criteria Drape profile	Drape variation	Weight	Composition	Weave
S1 / P2	Similar	Similar	Contrast	Contrast	Similar
S1 / S4	Contrast	Contrast	Similar	Similar	Similar
S3 / P1	Similar	Contrast	Indifferent	Contrast	Contrast
S2 / W2	Similar	Similar	Contrast	Contrast	Contrast
W1 / W2	Contrast	Similar	Indifferent	Similar	Contrast
C4 / C5	Similar	Similar	Similar	Similar	Similar
C5 / W4	Similar	Similar	Contrast	Contrast	Contrast
C3 / C2	Similar	Indifferent	Similar	Similar	Contrast

3.2.3 Supports and fabric drape views

As discussed in the introduction of this chapter visual materials, consisting of images and videos, are used for the subjective assessment of fabric drape. To enable the judges to obtain thorough insight, the images show the fabrics draped on two different supports and they present different viewpoints; static front and drape profile views, the videos show the rotating front views. To judge the drape of the different fabrics in equal relation to each other the images used during the surveys are all set to the same proportion. The methods used for the development of the images are described in the next section.

3.2.3.1 Supports

To enable static and rotating images of the front views separate support discs were developed following the principle of the drape meter. For accurate results two discs of 18 cm diameter were made in CAD with Lectra Modaris® and cut with a laser-cutter of PMMA, with the grainlines engraved for precise placement of the swatch. From the two discs, one is placed on a cylinder with a pin in the centre to centralise the fabric, the other is used as pressure disc on top of the fabric. Similarly to the drape meter, a plate is used to support the fabric before draping, to allow the fabric to drape this plate is manually lowered. For taking rotating images the supports are placed on a turntable, the set-up for the disc is illustrated in Figure 3.7.

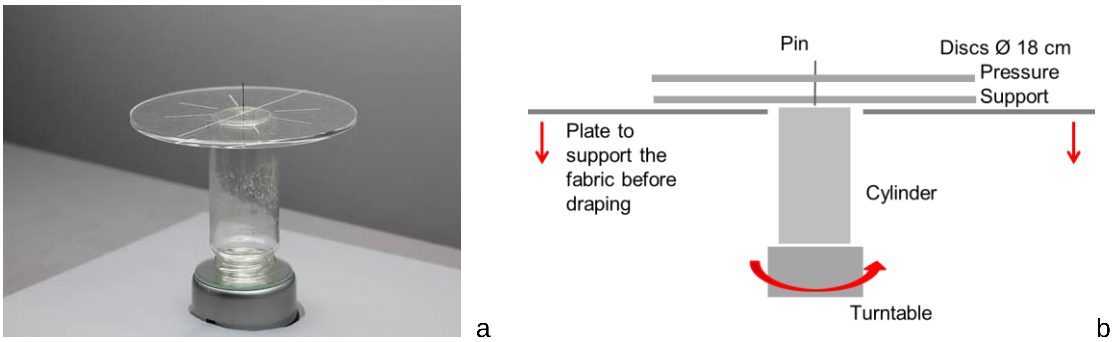


Figure 3.7: Set-up support disc: (a) photograph, (b) diagram.

For the other support a polystyrene sphere with a diameter of 12 cm was selected, which was pinned on a receipt spike. On the drape meter the fabric is supported by an outer ring, by lowering the ring the fabric is relaxed without manual interference. Placing the fabric on top of the sphere manually causes interference with the drape. To reduce this manual interference, the sphere support is shaken relative quickly up and down to relax the fabric and allow the fabric to drape more naturally. This method is similar to the ‘JIS method’ executed by Morooka and Niwa (1976), yet the sphere is shaken only once. This is still influencing the drape, however it is preferable to the interaction when placing the fabric manually on the sphere. Figure 3.8 illustrates the set-up for the sphere and how the fabric is draped by shaking it.

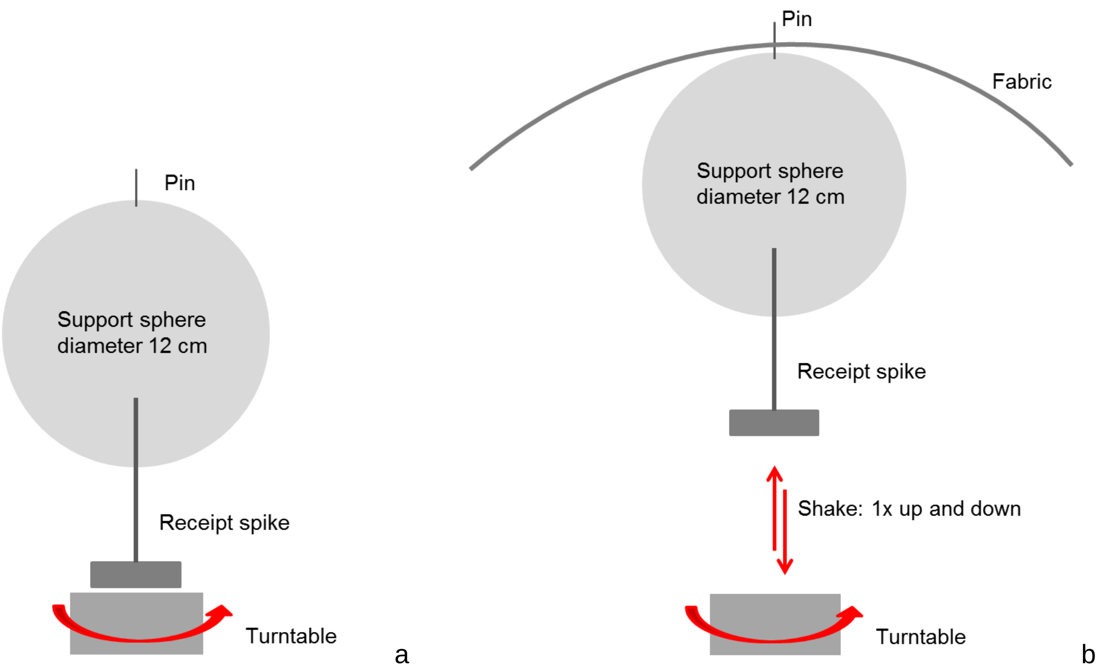
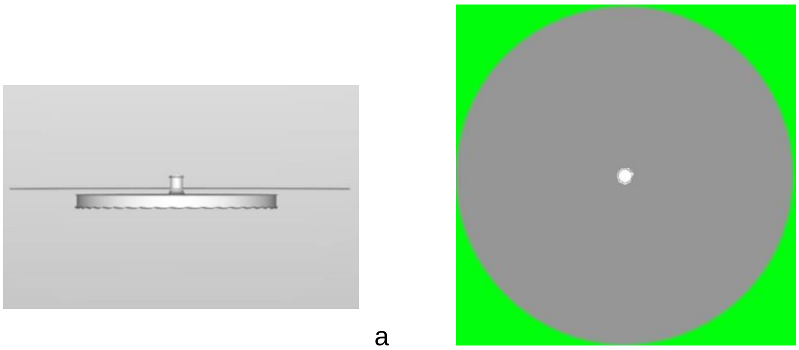


Figure 3.8: Set-up support sphere: (a) diagram, (b) shake to drape the fabric.

The virtual support disc is made in 3D Studio Max® and the saved OBJ file imported into Lectra Modaris®. The virtual support disc follows the principle of the real support disc, however lacks the pressure disc at the top as this is not within the purpose of the used software. To simulate the fabric a 30 cm diameter circular sheet is placed on top of the disc. The front and drape profile view of the support disc with the simulated fabric sheet on it are illustrated in Figure 3.9.



a b

Figure 3.9: Set-up virtual support disc with undraped fabric sheet: (a) front view, (b) drape profile view.

3.2.3.2 Front and drape profile *view images of the fabric drape*

The images of the front views of the real fabrics are taken in a VeriVide Light Cabinet using daylight, D65, as illustrated in Figure 3.10 below. The camera is placed on a tripod in front of the light cabinet.

Figure 3.10: VeriVide Light Cabinet used for the front view images.

From the rotating fabrics, on the disc and sphere, 16 images are made, the shots are taken based on the indicated grain lines on the edge of the fabric. These images are stitched to use as video during the survey, this method is preferred to videotaping directly in order to obtain similarity between the static and rotating images. The images used during the survey are all set to the same proportion, for the front views this is the width of the undraped specimen. The static front view images with 30 cm diameter swatches draped on the 18 cm diameter disc and 12 cm diameter sphere are illustrated in Figure 3.11.

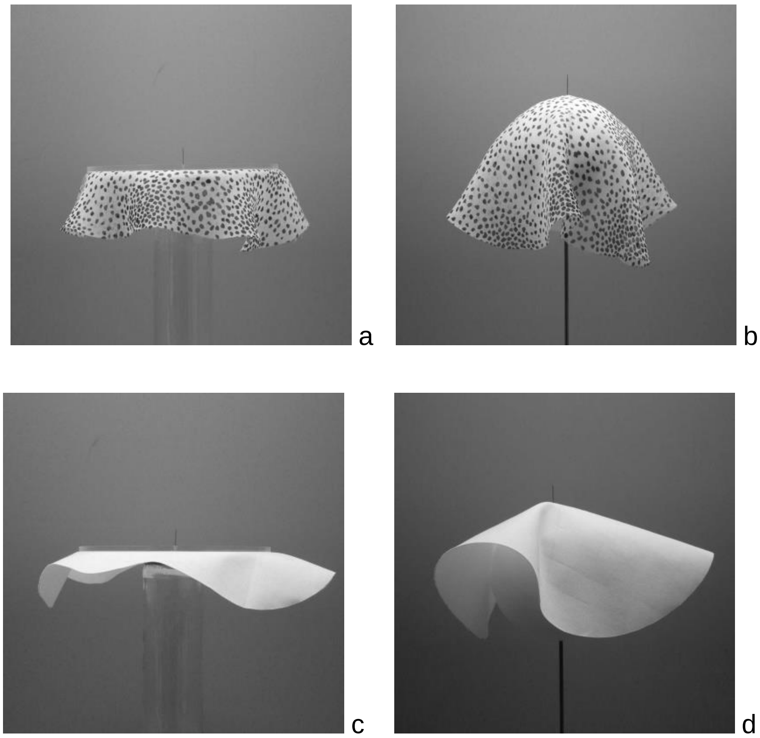


Figure 3.11: Front view images of disc and sphere support with different draping material: (a) disc with S4, (b) sphere with S4, (c) disc with C2, (d) sphere with C2.

The 16 frames used for the videos are illustrated in Figure 3.12, showing an example of a limp fabric on the disc and a rigid fabric on the sphere.

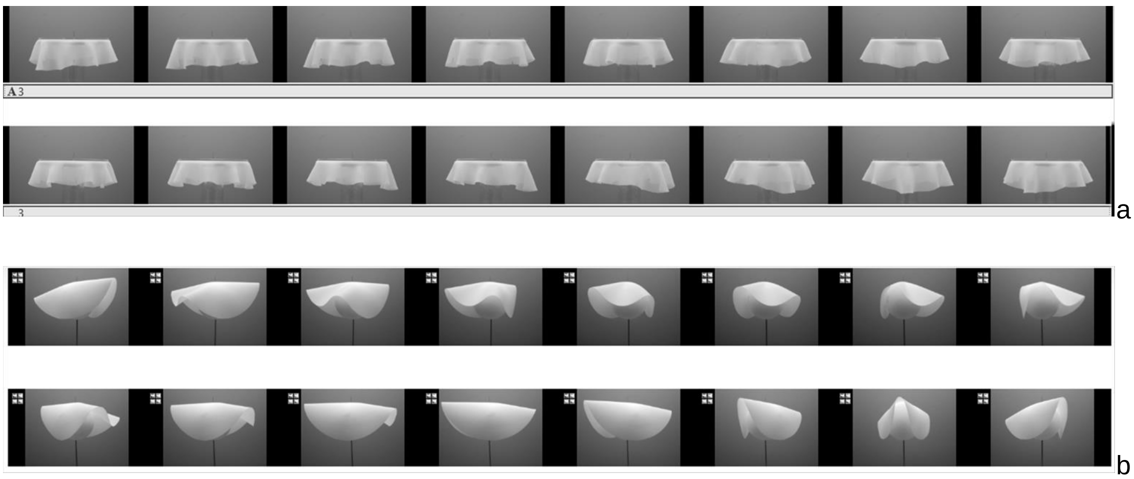


Figure 3.12: Individual frames stitched for the drape videos: (a) disc, (b) sphere.

To allow the judges to assess the typical fabric nature it was decided to take the pictures for the drape profile view images directly from the drape, as illustrated in Figure 3.13.

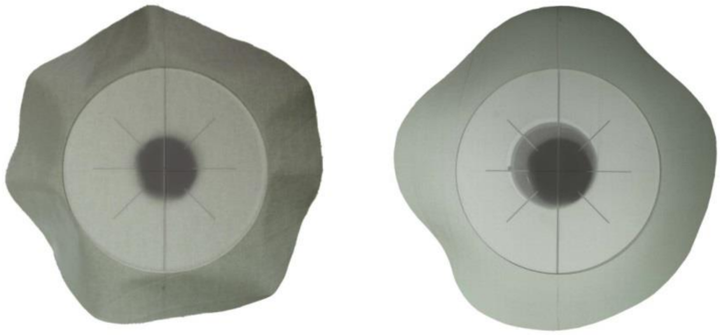
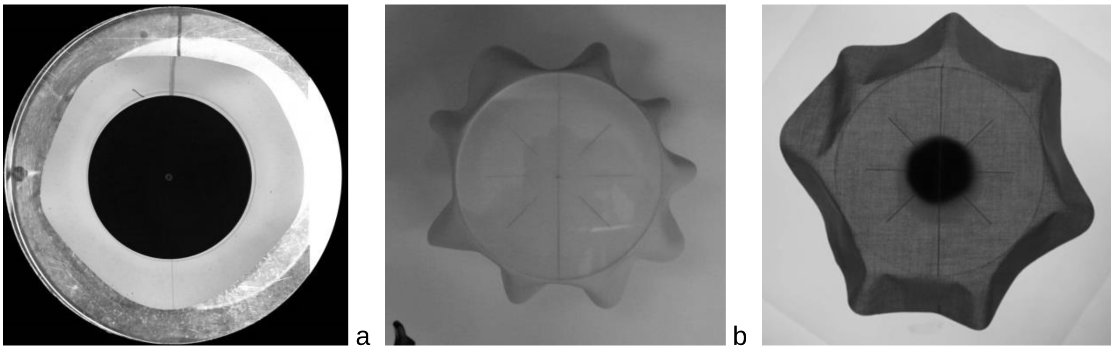


Figure 3.13: Drape profile view images of fabrics with different natures.

To have enough contrast and to reduce noise the images of the drape profile views are taken on a light box, this is illustrated in Figure 3.14. The used tripod is a Manfrotto art 161, which is stable and high enough to make an image of the entire drape, the image is taken at 80 cm distance from the draped specimen.



a b c

Figure 3.14: Contrast drape profile view images: (a) fabric on drape meter, (b) fabric on disc support without lightbox, (c) fabric on disc support placed on light box.

3.2.3.3 Preparation of the drape profile *view images for the surveys*

All images are converted to grey scale, the resolution is changed to 100 pixels/cm and the proportions between disc and fabric are set equal for all images. What is more the width and height of the drape profile view image represents the undraped fabric width, with a final image size of 30 by 30 cm. For some of the surveys a smaller image size is used, still the proportions are kept the same. The drape profile view images are all visualised in relation to the support disc and some in relation to the undraped specimen. For that purpose a digital drape test calibrator is made in Adobe Photoshop®, the drape tester is saved as a PSD with layers for the support, the undraped specimen and two for the draped specimen, the process is illustrated in Figure 3.15. First, a 30 cm diameter circle, indicating the undraped specimen, with an 18 cm diameter inner circle, indicating the support disc, with warp, weft and bias marked, is made in Lectra Modaris® and imported into Adobe Photoshop® (a). Second, separate layers are created and filled with different colours, the area outside the undraped specimen with a dark grey colour, the support disc area with light grey colour and the undraped fabric specimen with a white colour (b). To have the support disc visualised in all the drape profile view images the area is set slightly transparent and moved to the top in the 'layers window'. Third, by adjusting the image size the diameter of the support disc of the drape profile view image is set at 18 cm, the drape (Figure 3.14c) is selected with the magic wand and copied into the drape rings. The area of the support disc from the drape image is exactly placed on the inner ring (c). Fourth, a copy of the layer with the draped fabric image is made and abstracted by selecting the drape area which is filled with a dark grey colour, this abstracted drape profile images shows exactly the relationship between the disc, the draped and undraped fabric specimen (d). The drape images are created by selecting particular layers which are saved as JEPG files (e). The drape profile images show the draped fabric with the area of the support disc in the centre, but not the undraped fabric specimen (f).

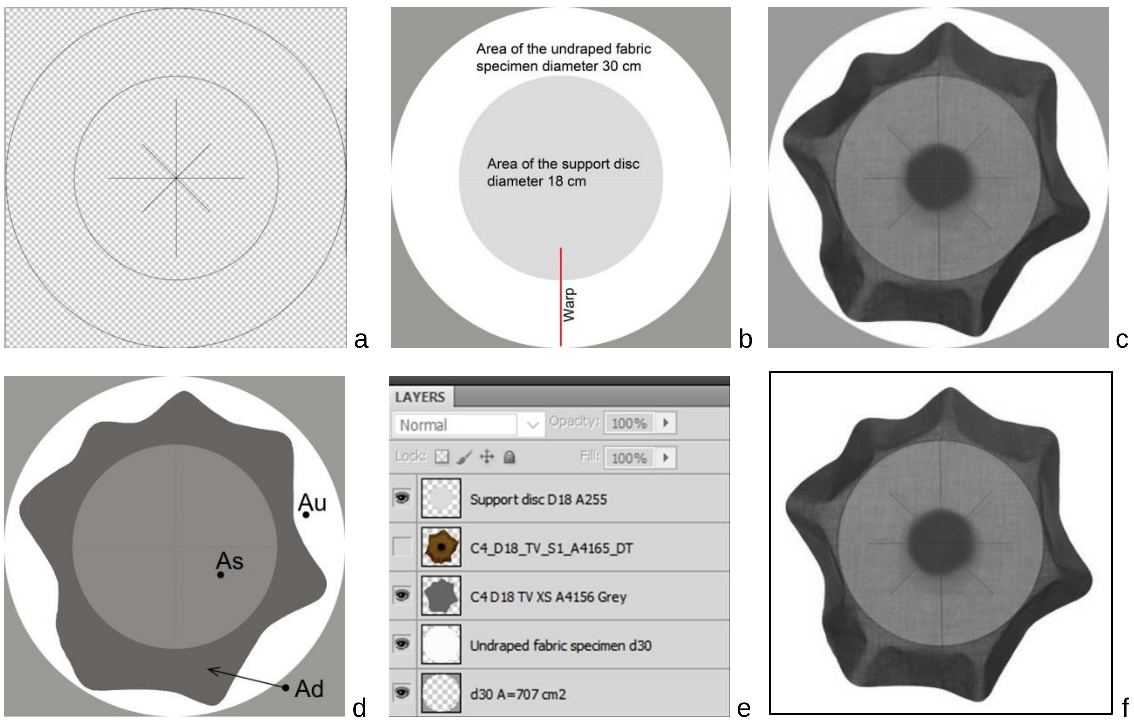


Figure 3.15: Process digital drape test calibrator disc: (a) imported circles with diameters of 18 and 30 cm with warp, weft and bias lines indicated, (b) area of the support disc and undraped fabric specimen coloured, (c) drape profile view image with imported drape, (d) abstracted drape profile image, where Au represents the area of the undraped fabric specimen, Ad the area of draped fabric specimen and As the area of the support disc, (e) organisation of the 'layer window' in Adobe Photoshop®, (f) fabric drape profile image.

The pressure disc on the fabric allows accurate placement, however for the sphere the placement is less precise. A circle of 12 cm is used to calibrate the area, the draped fabric specimen is placed on this circle based on the shape of the sphere. The further process to prepare the drape profile view images of the sphere is similar to the disc. This process is illustrated in Figure 3.16 below.

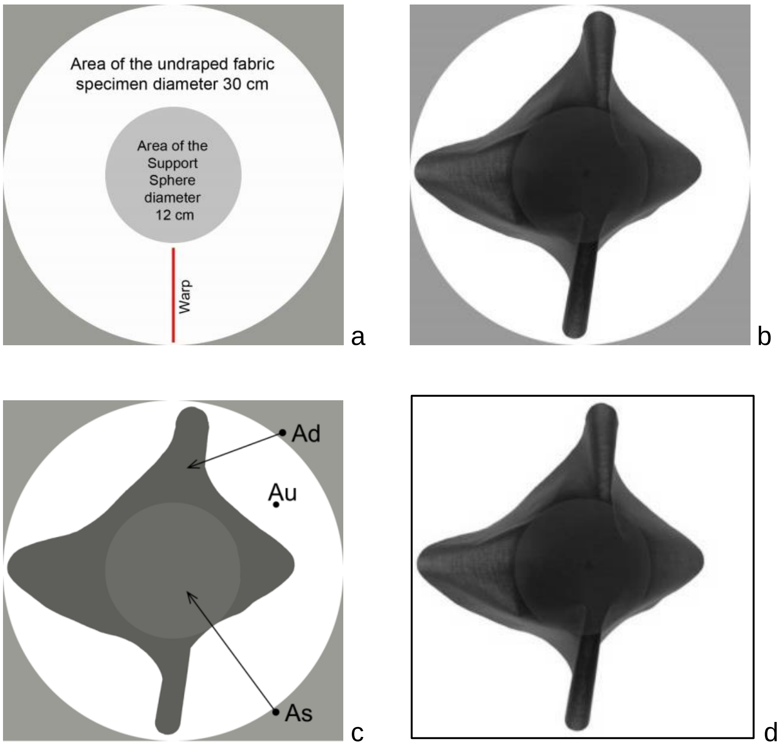


Figure 3.16: Process digital drape test calibrator sphere: (a) imported circles with diameters of 12 for the support and 30 cm for the undraped specimen in separate layers, (b) drape profile view image with imported drape, (c) abstracted drape profile image, where Ad represents the area of draped fabric specimen, Au the area of the undraped fabric specimen and As the area of the support disc, (d) fabric drape profile image.

The process for the virtual fabrics, illustrated in Figure 3.17, follows a similar process as described for the drape profile view disc images of the real fabrics. For the virtual drape profile view images the area of the support disc is used for calibration, to visualise this area the virtual fabric sheet is set slightly transparent, next to that the warp line is indicated and used for correct placement, with a green screen the contrast between specimen and outer area is optimised, a full screen zoom of the undraped specimen is memorised with the ‘memorise view’ function in the software to allow the reloading of the draped specimens in exactly the same position (a). To create the virtual fabric the file with KES or FAST properties is dragged on the virtual sheet, refreshed with a rough mesh size, and then refined and draped, next the memorised view is selected and the image saved at true size (b). This procedure is repeated six times with the KES properties and six times with the FAST properties. The measurement of the objective properties will be described in section 3.3. The virtual drape is selected and imported in the drape calibrator (c), then the abstracted drape profile image is created (d), this image is used for the assessment of the virtual drape by the user panel.

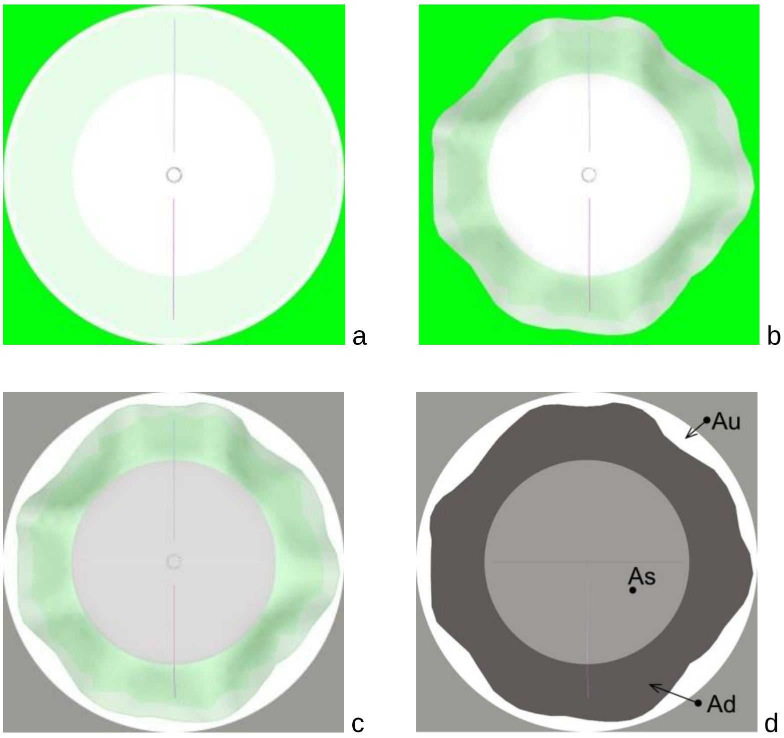


Figure 3.17: Process digital drape test calibrator virtual disc: (a) virtual fabric sheet with diameter 30cm showing the support disc of 18cm with warp line indicated, (b) virtual draped specimen based on KES properties, (c) drape profile view image with imported virtual drape, (d) abstracted drape profile image, where Ad represents the area of the draped fabric specimen, Au the area of the undraped fabric specimen and As the area of the support disc.

3.3 Objective measurements

3.3.1 KES measurements

KES measurements are taken under standard laboratory conditions with a relative humidity of 65% +/- 2% and a temperature of 20°C +/- 2°C, prior to the tests the fabrics are conditioned for 24 hours under the same conditions. Swatches of 20 by 20 cm are cut with the KES template and the warp is marked on the swatch. Accordingly, KES-FB3 Compression, KES-FB2 Bending, KES-FB4 Surface, KES-FB1 Shear and KES-FB1 Tensile are tested according to the principles described in section 2.3.2.1. The KES measurements are inserted into Modaris® and for each fabric a digital fabric file is created.

3.3.2 FAST measurements

FAST measurements are taken under standard laboratory conditions with a relative humidity of 65% +/- 2% and a temperature of 20°C +/- 2°C, prior to the tests the fabrics are conditioned 24 hours under the same conditions. Swatches of 5 by 15 cm are cut with the FAST template and the warp, weft and bias are marked on the swatch. Accordingly, FAST-1 compression, FAST-2 bending, FAST-3 tensile, FAST-3 shear are tested according to the principles described in section 2.3.2.2. The FAST measurements are inserted into Modaris® and for each fabric a digital fabric file is created.

3.3.3 Physical fabric drape coefficient

With Cusick's drape tester the drape coefficients are obtained according to the BS 5058 (British Standards Institution, 1973). The drape measurements are taken under standard conditions with a relative humidity of 56% +/- 2% and a temperature of 20°C +/- 2°C, prior to the tests the fabrics are conditioned for 24 hours under the same conditions. All tests are cut with the 30 cm diameter template to compare the various draping fabrics under the same proportion between the supported and unsupported part. With the template two specimen are cut from each fabric and they are both tested six times alternating face and back. The drape coefficient is calculated with the formula according to BS 5058 (British Standards Institution, 1973) as explained in section 2.3.1.2. From the twelve drape measurements the mean is calculated, these measurements are used throughout this research for the correlations. Additionally, the mean of the face up drape coefficients are calculated as they are required for the comparison between the real and the virtual drape coefficients.

3.3.4 Virtual fabric drape coefficient

Moreover, the virtual drape coefficient is calculated with image analysis in Adobe Photoshop® based on the pixel count method Kenkare and Plumlee (2005) used. The pixel size which is set to 10000 pixels per 1cm^2 avoids inaccurate pixel count by rotation (Jeong 1998), this is controlled by testing a rectangle which is illustrated in appendix 2. The drape area is selected with the magic wand and the pixel count is obtained with the histogram, the drape coefficient is calculated based on area as follows:

Pixel count square 30 cm^2 = 9,000,000 pixels, pixel count per 1cm^2:

$$P_c \quad \frac{9000000_P}{30\ x\ 30} = 10000 \text{ pixels per } 1\text{cm}^2. \qquad (3.1)$$

Where:

P_c = Pixel count per 1cm^2
p = pixel

$$DC\ (\%) = \frac{(P_d \div P_c) - A_s}{A_u - A_s} \quad (3.2)$$

Where:

DC = Drape Coefficient
P_c = Pixel count per 1cm^2
P_d = Pixel count of the draped specimen
A_s = the area of the support disc in cm^2
A_u = the area of the undraped specimen in cm^2

Figure 3.18 below illustrates those areas.

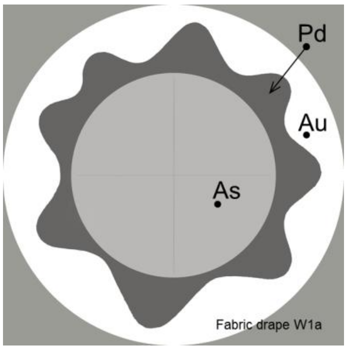


Figure 3.18: Indicated areas for calculation of the virtual drape coefficient: P_d draped specimen, A_u area of the undraped specimen, A_s Area of the support.

For each fabric the mean is calculated from the six measurements, the obtained virtual drape coefficients are statistically correlated with the face up drape coefficients of the real fabrics.

3.4 Subjective data collection

3.4.1 Introduction

As outlined in the introduction of this chapter fabric drape was assessed by expert judges, who defined the drape, rated the stiffness and the amount of drape based on drape profile and front view images, as well as rotating videos of the drape. This section explains the methods used in more detail, Figure 3.19 illustrate the design of the subjective data collection.

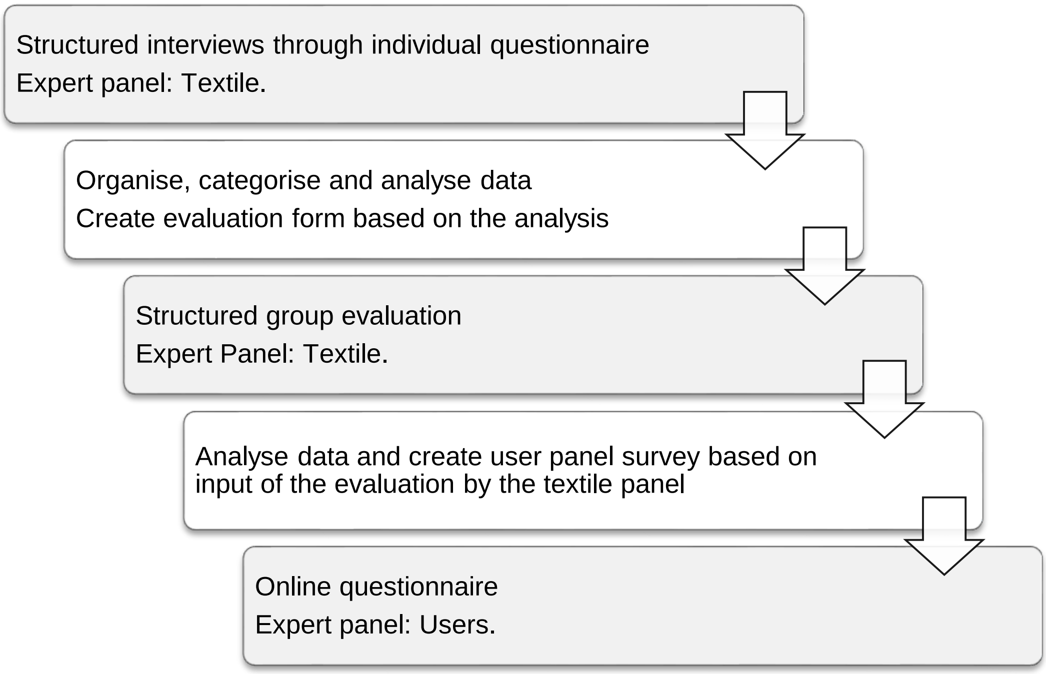


Figure 3.19: Design subjective data collection.

During the structured interviews textile experts defined the drape of the fabrics based on the images of the drape, their input given in the open-ended boxes was ordered, categorised and analysed, from these definitions drape categories were formed. Those drape categories were evaluated by the textile panel in a group discussion. The same was done with the selected keywords to identify the drape. Those keywords and categories were judged by the expert user panel in the main body of the online survey. The relationships between the drape coefficient and the defined drape categories were examined. Moreover, both panels were questioned to indicate the preferred support and view to assess the drape of the fabric. Further both the textile and user panels rated the stiffness and amount of drape, these ratings were correlated with the drape coefficient. Additionally, the measurements of the real drape were correlated with the judgement of the user panel, who further judged the similarity and rated the stiffness and amount of the virtual drape, simulated with KES and FAST data.

3.4.2 Organisation

At the start of each session the aim of the survey and what was expected were explained to the judges. To make the panel familiar with assessing the fabric drape, images representing an example of a limp (Figure 3.20a) and rigid (Figure 3.20b) drape used during the survey were shown, as well as an example of extremely limp (Figure 3.20c) and very rigid drape (Figure

3.20d). The purpose of the later was to provide a contrast for very limp or very rigid material with the material used in this research.

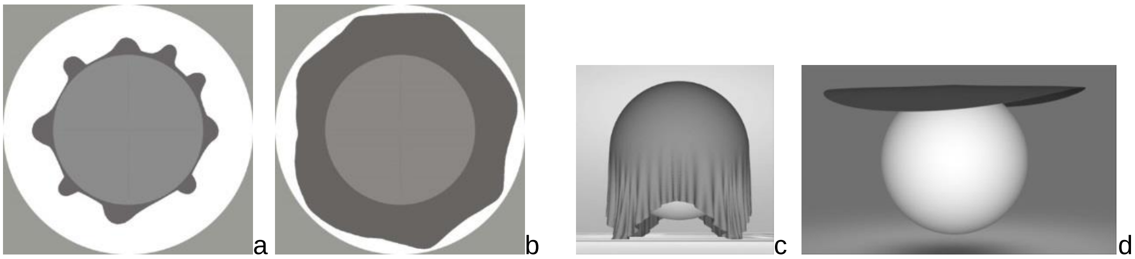


Figure 3.20: Examples of drape: (a) limp and (b) rigid material used in this research, extremely (c) limp and (d) rigid material.

The dimensions of the sphere, disc and fabric specimen, and how they relate to each other, as well as the size of the images were explained to the judges. All images of the drape were shown prior to the start of the survey. For each view type an overview was given showing images of all the thirteen fabrics as follows:

- Overview A1: Disc front views of the drape (Appendix 3).
- Overview A2: Disc abstracted drape profile views (Appendix 3).
- Overview B1: Sphere front views of the drape (Appendix 3).
- Overview B2: Sphere abstracted drape profile views (Figure 4.1).

Furthermore, to allow the judges insight into the drape, the questionnaire for each fabric included an overview of six images showing the fabric from different viewpoints followed by the questions. Moreover, the videos with rotating fabrics were accessible on a different computer or via a link on Vimeo, which is included in Appendix 4 and on DVD-R in the bound copy. For each fabric the following viewpoints were assessed:

a. Disc front view image.
b. Disc fabric drape profile view image.
c. Disc abstracted drape profile view image.
d. Sphere front view image.
e. Sphere fabric drape profile view image.
f. Sphere abstracted drape profile view image.
g. Video of rotating disc front view.
h. Video of rotating sphere front view.

Figure 3.21 gives an example of the images for one of the fabrics.

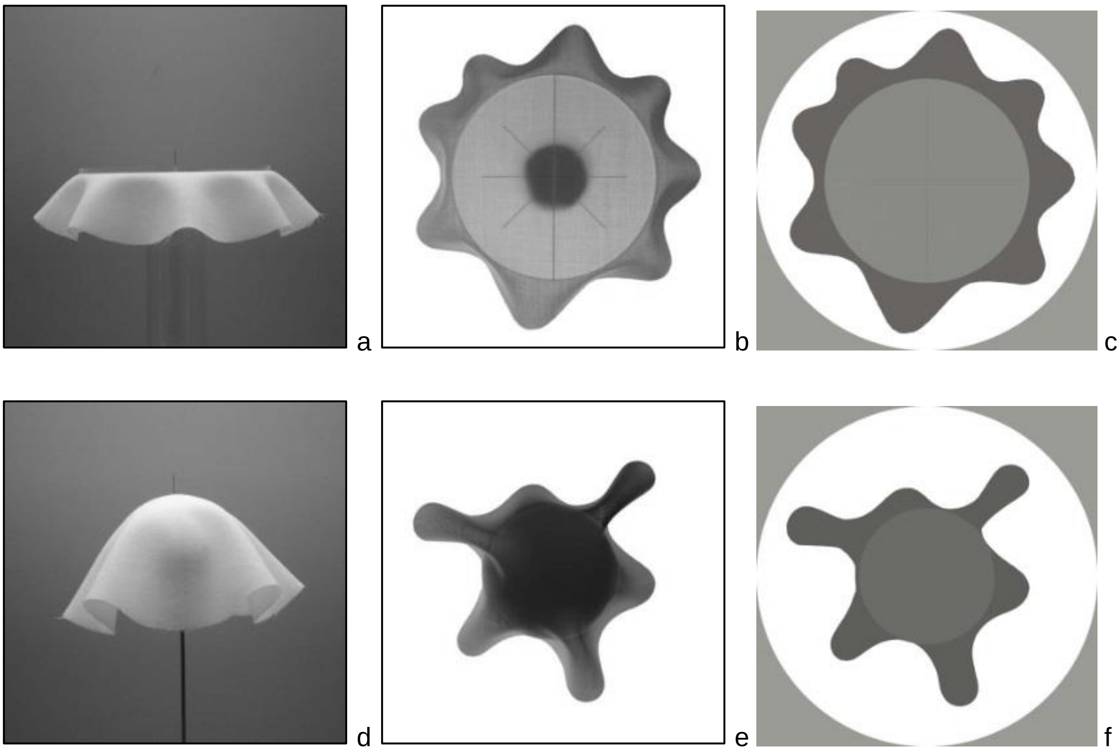


Figure 3.21: Images accompanying the questions in the questionnaire: (a) disc front view, (b) disc fabric drape profile view, (c) disc abstracted drape profile view, (d) sphere front view, (e) sphere fabric drape profile view, (f) sphere abstracted drape profile view.

3.4.3 Textile panel

A panel consisting of experts with advanced knowledge of textile and a fashion management student who had competent knowledge and interest in textiles was set up. The main purpose of this panel was to define the fabric drape, and to derive drape categories and fabric drape identifying keywords based on these definitions. Moreover, they assessed the stiffness and amount of drape of all the thirteen fabrics. An overview is given in Table 3.3.

Table 3.3: Textile panel

Background	Judges	Age
Teachers in textiles	3	45-65
Teacher in technical skills, patterns and garments	1	48
Student in Fashion and Management	1	24
Total number of judges	5	

3.4.3.1 Structured individual interview

In these individual sessions, the tasks of the textile panel were to define the drape of various draping fabrics, as well as to judge the stiffness and amount of drape. For this purpose, a questionnaire was used which was completed by each judge during the individual sessions. The structured interviews took place in a small room without any disturbance. The judges were individually questioned. This set up allowed the judges to fully concentrate and guided them through the process and made sure they assessed the drape as required.

Two laptops were used, one of them presented the rotating videos of the front views, the other laptop was used for the questionnaire. The Overviews A1, A2, B1 and B2 with the drape views for all the fabrics, described in section 3.4.2, were each printed on an A3 paper and spread on the tables. The duration of a session was between 90 and 120 minutes. Prior to the start the judges were made familiar with their tasks and the work they had to assess.

For each fabric the questionnaire consisted of nine questions which were accompanied by the six drape images illustrated in Figure 3.21. Except for the weight no additional information about the fabrics was given. First, the rotating video was shown to the judge, then the images were studied and the questions answered, each judge assessed thirteen fabrics. With open-ended questions, semantic differential scales and tick boxes, the following was assessed.

Open-ended questions:

- definition of the drape;
- explanation to the definition;
- composition of the material.

A seven point semantic differential scale was used for:

- classification of the stiffness of the drape: Limp-Rigid;
- amount of drape: Low-High.

Tick boxes:

- with various expressions used for hand (Bishop, 1996) and clothing movement (Griffiths and Kulke, 2001).

The survey ended with two questions based on tick boxes and a comment box for remarks.

Tick boxes:

- preferred support to judge the drape of the fabric;
- preferred view to judge the drape of the fabric.

Comment box:

- remarks.

3.4.3.2 Structured group evaluation

In this group session the task of the textile panel was to evaluate the defined categories and identifying keywords based on their definition of the drape, with the objective to avoid influence by the author and find overall agreement between the judges for the categories and identifying keywords. For this purpose, a questionnaire was used which was completed jointly by the textile judges.

For the structured group discussion, the judges were invited in a small room without disturbance. An evaluation form based on the questionnaire of the previous session was carried out. One laptop was used with the evaluation form. Prior to the start of the session, it was explained to the judges how the data, collected in the first round, was categorised and analysed, how it was processed in the evaluation form and what was expected from them. The duration was 60 minutes.

The evaluation form consisted of the six drape images for each of the thirteen fabrics as illustrated in Figure 3.21, provided with the derived categories and identifying keywords. Moreover, information about the fabrics such as weight, composition and weave was given. The panel was invited to discuss the categories and identifying keywords for every fabric and to insert their final judgement in the open-ended box next to the categories and identifying keywords. Finally, the panel was asked to indicate fabrics with a similar drape.

The comments and improvements for the categories and identifying keywords were analysed and used for the questionnaire in the next session with the user panel. The number of fabrics in the main body of the user panel session was condensed to eight based on the drape similarity indicated by the textile panel.

3.4.4 User panel

The purpose of setting up a panel with expert users of virtual garment simulation software was to let them judge the suitability of the drape categories and identifying keywords defined by the textile panel. It was also for judging the stiffness, amount of drape, and the drape similarity of the real and virtual drape.

This new panel consisted of users of the 3D garment simulation software for virtual fashion design, none of the members participated in the previous rounds. The panel worked highly intensively with the software and was used to select and work with materials in a virtual environment. Due to the time required for the assessment of the drape, and the time needed to prepare the virtual drape two sessions were held. Most of the judges participated in both sessions, however due to the time-frame, slight changes of participants were inevitable. Nevertheless, the similarity was safeguarded by keeping the knowledge and levels of the selected judges as much the same as possible. In both sessions the panels assessed the stiffness and amount of drape. Table 3.4 and 3.5 gives an overview of the judges.

Table 3.4: User panel judgement of real drape

Background	Judges	Age
Teachers in garment simulation	3	28-55
Students in Fashion & Design or Fashion & Management	9	20-26
Alumnus in Fashion & Design	1	26
Total number of judges	13	

Table 3.5: User panel judgement of virtual drape

Background	Judges	Age
Teachers in garment simulation	4	28-55
Students in Fashion & Design or Fashion & Management	7	20-35
Alumni in Fashion & Design or Fashion & Management	2	25-35
Total number of judges	15	

3.4.4.1 Online questionnaire real drape

In this first session the task of the user panel was to judge the suitability of the drape categories and identifying keywords defined by the textile panel, and also the stiffness and amount of the real drape. For this purpose, an online questionnaire was used.

The part considering the categories and identifying keywords of the questionnaire was made based on the output of the evaluation by the textile panel. The survey was first discussed in class with the participants. The survey started with the introduction discussed in section 3.4.2, explaining the purpose, what was expected and how the survey was built up, limp and rigid fabrics used in this research were shown, as well as the extremes of limp and rigid material. Furthermore, the proportions between the fabric, the support and the size of the images was made clear. The rotating drape videos were placed on Vimeo, and were accessible via a link.

The survey consisted of questions on a semantic differential scale, on a five point scale, tick boxes and open-ended questions, except the open-ended questions answering all the question on a page was compulsory to proceed to the next page. The duration was 60 minutes.

To make the participant familiar with reading the fabric drape as well as with the drape differences of the thirteen fabrics, the drape overviews described in section 3.4.2 were presented in the following order A1, A2, B1 and B2. For each overview the participant was asked to cluster the fabrics based on their drape, no extra information about the fabrics was given. The second purpose was to investigate if there was a relationship between the indicated drape similarity by the textile panel and the perception of the user panel. Moreover to collect data regarding the drape clusters made based on the different views and supports.

In the main body of the survey the number of fabrics was condensed to eight based on the selection made by the textile experts. Each fabric had a separate page with seven questions regarding the six images of the drape as previous illustrated in Figure 3.21. With open-ended questions, semantic differential scales, five point scales or tick boxes the following was assessed.

A seven point semantic differential scale was used for:

- classification of the stiffness of the drape: Limp-Rigid;
- amount of drape: Low-High.

A five point Scale; strongly agree, Agree, Neutral, Disagree, Strongly disagree was used for:

- drape category;
- keywords to identify the fabric drape.

Both questions were followed by a comment/suggestion box.

Tick boxes:

- preferred support to judge the drape of the fabric;
- preferred view to judge the drape of the fabric.

The question was followed by an open-ended question:

- the rationale for their preference.

3.4.4.2 Online questionnaire virtual drape

In this second session the task of the user panel was to judge the stiffness and amount of the real and virtual drape as well as the drape similarity. For this purpose, an online questionnaire was used, where the judges assessed the disc abstracted drape profile view images as illustrated in Figure 3.15d for the real drape and Figure 3.17d for the virtual drape.

Following the structure of the previous sessions the survey started with an introduction explaining the purpose, what was expected and how the survey was built up. Moreover, the extremes of limp and rigid material were shown, as well as limp and rigid fabrics used in this research. The questionnaire was split in two parts.

First, the respondents judged the stiffness and amount of drape of the real fabric, the fabric simulated with KES measurements and the fabric simulated with FAST measurements. The panel was not aware if they assessed real or virtual material. Each disc abstracted drape profile view image of the real or virtual drape was presented in random order and provided with two questions on a seven point semantic differential scale:

- the stiffness of the drape: Limp-Rigid;
- the amount of drape: Low-High.

Second the drape similarity was judged based on three sets of each two images of the fabric, provided with three questions. The real drape image used in the previous parts of the surveys was presented in combination with a second image of the same fabric:

- the physical drape; a second drape of the same fabric specimen;
- the virtual drape of the fabric simulated with KES measurements;
- the virtual drape of the fabric simulated with FAST measurements.

This resulted for each fabric in three sets of two images, which were presented in random order. For each fabric set the participants judged the similarity on a five point scale:

- very high: the drape is nearly identical;
- high: the drape is mostly similar;
- average: the drape is half similar and half dissimilar;
- low: the drape is mostly dissimilar;
- very low: there is no relationship between the drape of the fabrics.

3.5 Data analysis

Microsoft Excel® is used for the statistical analysis and to generate graphs and charts, the relationships are investigated with Pearson's correlation coefficient and regression to obtain the significance values, as well as descriptive statistics such as standard deviation, mean, minimum, maximum and mode.

In chapter 4, s*ubjective assessment of drape* the open-ended data from the textile panel to define the drape categories is analysed by ordering and classifying the definitions. The agreement of the user panel with these categories is analysed and presented in charts and tables. The analysis of the identifying keywords selected by the textile panel follows the same principle. Moreover, the panel ratings for stiffness and amount of drape for the real fabrics are correlated with the defined drape categories. Finally, the preferences for view and support are analysed and the open-ended answers supporting these preferences are ordered and classified.

In chapter 5, *relationships between subjective drape assessment and measured fabric properties* the drape coefficient as well as the fabrics' mechanical and physical properties measured with KES and FAST are examined. Furthermore, the properties measured with KES and FAST are compared with each other, and their correlations with the drape coefficient and the ratings of stiffness and amount of drape by the panels are analysed. Moreover, the relationship between the drape coefficient, drape categories and clusters formed by the panels, as well as how the drape categories and clusters relate to the divisions made by Cusick based on drape coefficient are investigated.

In chapter 6, *relationships between real and virtual drape* the virtual drape coefficient calculated from the simulations based on KES and FAST mechanical and physical properties are investigated. Furthermore, the subjective assessment of stiffness and the amount of virtual drape are presented and correlated with the assessment of stiffness and the amount of real drape. Moreover, the comparison between the real and virtual drape is analysed and set out.

4 Subjective assessment of fabric drape

4.1 Introduction

This chapter presents the analyses of the perception of fabric drape from the expert panels; a textile panel and a user panel, which have assessed images of the fabric drape presented from different perspectives. In individual sessions the textile panel brought in a rich vocabulary to define the drape of the selected fabrics and during the evaluation they gave jointly their opinion on the drape categories and identifying key-words derived from their input. The user panel assessed the suitability of the categories and identifying key-words for the particular fabric drape. They have organised the fabrics based on drape by creating drape groups. Both panels judged the stiffness and the amount of drape. Moreover, they gave their opinion for the preferred support and view to assess the fabric drape.

The analyses of the fabric identifying key-words and categories to define the fabric drape, as well as how the latter relates to the drape clusters made by the user panel are presented in section 4.2. This is followed by the analyses of the ratings of stiffness and amount of drape, as well as how they correlate with the drape categories in section 4.3. Furthermore, the analyses of the preferred support and view, as well as how the different perspectives on the drape contribute to a better understanding of fabric drape in a virtual environment are outlined in section 4.4. The coherence between the drape categories, drape clusters, identifying key-words, support and view is examined in section 4.5.

4.2 Definitions of fabric drape

For each fabric the contribution of the individual textile panel members to specify the fabric drape was combined and identical expressions grouped and categorised. Subsequently, for each fabric, coordinate categories and identifying key-words were derived and reviewed by the textile panel during the group evaluation. Upon agreement they refined the categories as well as the identifying key-words. Next, this outcome was judged by the user panel, who prior to this assessment created the drape clusters, the results are analysed and presented below.

4.2.1 Fabric drape categories and drape clusters

4.2.1.1 Fabric drape categories defined by the textile panels

During the group evaluation the textile panel simplified and reduced the number of categories, which were derived from their input during the individual rounds. This resulted in three drape categories; *well-draping* for the very limp and fluid draping fabrics, *soft drape* for fabrics combining softness and suppleness with a bit stiffness and finally *body* for fabrics with enough stiffness to create shape. The textile panel assigned a category to each fabric, the results are given in Table 4.1.

Table 4.1: Categories assigned to fabrics by textile panel

Category	Fabrics						
Well Draping	S4	S3	P1	S2			
Soft Drape	W1	W2					
Body	S1	C5	W4	C4	P2	C2	C3

Furthermore, the textile panel was asked to indicate similar draping fabrics. This selection is used to condense the number of fabrics in the main body of the questionnaire for the user panel. They are presented in Table 4.2, the fabrics marked with * are judged by the user panel, their agreement will be described in section 4.2.1.4.

Table 4.2: Fabrics indicated with comparable drape by the textile panel

Code	Weight	Comp	Comparable	Code	Weight	Comp
P1*	69 g/m²	100% PES	↔	S3	54 g/m²	92% SE-8% EL
W2	161 g/m²	100% WO	↔	W1*	115 g/m²	100% WO
C5	81 g/m²	100% CO	↔	C4*	90 g/m²	100% CO
C2*	272 g/m²	97% CO-3% EL	↔	C3	279 g/m²	100% CO

4.2.1.2 Fabric drape clustered by the user panel

Prior to the main body of the survey the expert user judges created clusters of similarly draping fabrics with the complete range of thirteen fabrics for each of the drape overviews A1, A2, B1 and B2, as described in section 3.4.2. Drape overview B2 with the sphere abstracted drape profile is given in Figure 4.1, the drape overviews A1 with the disc front views, A2 with the disc abstracted drape profile views and B1 with the sphere front views are given in appendix 3.

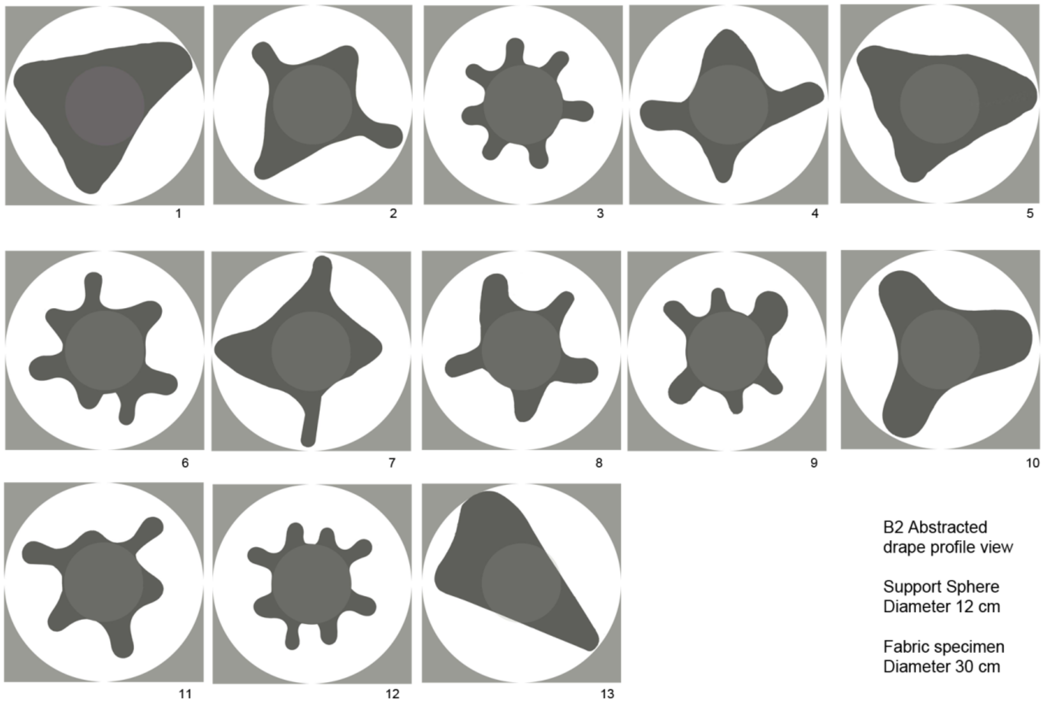


Figure 4.1: Drape overview B2: Sphere abstracted drape profile.

It is important to note that the drape clusters are composed from one view point, this is in contrast with how the textile panel defined the categories as they were able to judge the drape from different viewpoints as illustrated in Figure 3.2.1, and they had access to the videos of the drape. During the main body of the survey the user panel judged the drape categories under exactly the same conditions as the textile panel. The impact of the single and multiple views on the drape during the assessments are analysed in section 4.4. In the next section the relationships between fabrics with comparable drape indicated by the textile panel and the drape combinations made by the user panel are investigated, followed by how the drape clusters relate to the categories.

4.2.1.3 Drape clusters and relationships with drape categories

Table 4.3 indicates how the drape similarity indicated by the textile panel relates to the drape combinations made by the user panel, combinations made by more than 75% of the user panel are marked bold. With the means above 75% the drape similarity is subscribed by the user panel for fabrics S3 and P1, C5 and C4 as well as for C3 and C2, however, the different views lead to considerable differences in how the fabrics are clustered based on drape similarity. The Table illustrates that the user panel combines the same fabrics more often based on disc and sphere abstracted drape profile, whereas for some of the front views this uniformity is lacking.

Fabric W2 is combined with W1 by the majority of the user panel based on the abstracted sphere drape profile, however the mean stays below 75% due to only a few combinations on the abstracted disc drape profile.

Table 4.3: Similar draping fabrics indicated by the textile panel compared with drape clusters

	View				
	Front		Abstracted drape profile		
Combinations	Disc	Sphere	Disc	Sphere	Mean
S3 with P1	**85%**	69%	**100%**	**100%**	**88%**
W2 with W1	69%	62%	54%	**77%**	65%
C5 with C4	54%	62%	**100%**	**100%**	**79%**
C3 with C2	54%	**92%**	**100%**	92%	**85%**
Mean	65%	71%	**88%**	**92%**	

The bar charts in Figure 4.2 show all the combinations the user panel made with S3, C5, W2 and C3 based on drape similarity. Compared to fabric W2, the groups are more condensed for fabric S3, C5 and C3. The bar charts with drape clusters made on the different view types are included in appendix 5 for fabrics P1, S4, W1, W4, C4, S1, C2 and those for fabrics S2 and P2 in will be illustrated in Figure 4.14 and discussed in section 4.4.

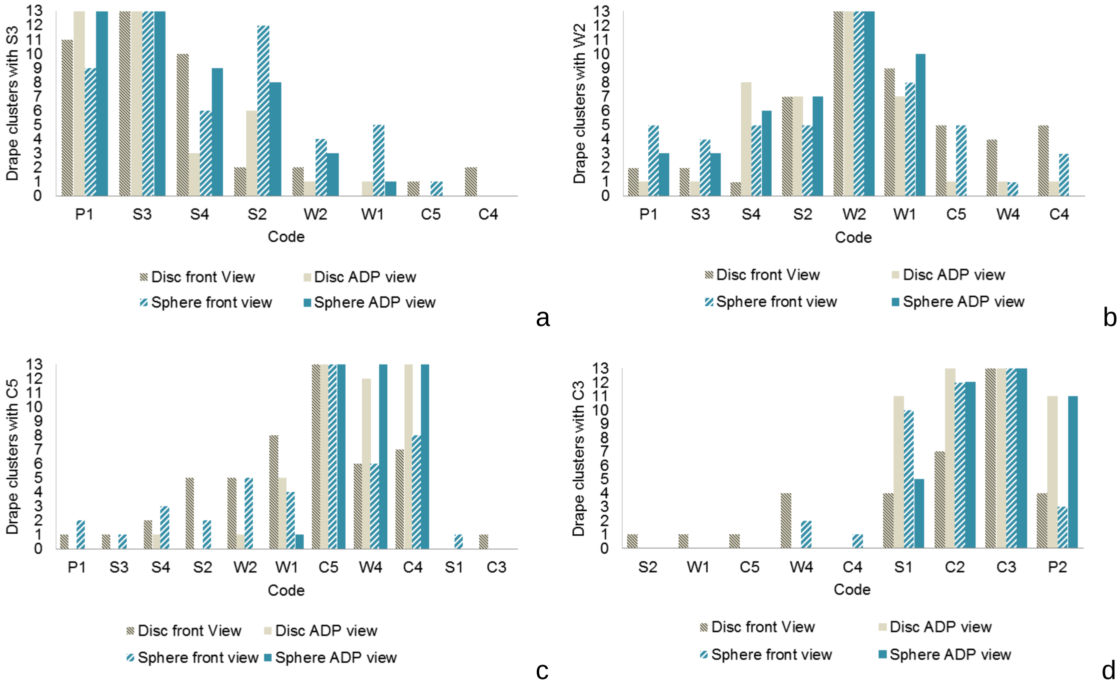


Figure 4.2: Drape clusters made by the user panel with fabrics: (a) S3, (b) W2, (c) C5, (d) C3.

Table 4.4 shows the average of the different views for all fabrics, as illustrated in the previous section. Depending on the view the combinations may differ. Taking this into consideration, combinations made by more than 50% of the judges are marked in bold. Comparison between the drape categories and clusters shows for the fabrics in the category *Well Draping* that the relationships between fabric P1, S3 and S4 is strong, whereas S2 is often combined with fabrics in the category *Soft Drape.* For the fabrics in the category *Soft Drape* the relationship with the drape clusters is strong, also they are often combined with fabrics in adjacent categories. The user panel divided the fabrics in the category *Body* in two drape clusters.

Table 4.4: Drape clusters in relationship to categories

	Well Draping				Soft Drape		Body						
	P1	S3	S4	S2	W2	W1	C5	W4	C4	S1	C2	C3	P2
P1	**100%**	**88%**	**60%**	42%	21%	12%	6%	...	6%	...	...	...	...
S3	**88%**	**100%**	**54%**	**54%**	19%	13%	4%	...	4%	...	...	...	...
S4	**61%**	**55%**	**100%**	47%	39%	20%	12%	2%	8%	...	...	...	...
S2	42%	**54%**	46%	**100%**	50%	40%	13%	13%	10%	...	...	2%	...
W2	21%	19%	38%	50%	**100%**	**65%**	21%	12%	17%	...	...	...	...
W1	12%	14%	20%	41%	**67%**	**100%**	35%	29%	29%	...	...	2%	...
C5	6%	4%	12%	13%	21%	35%	**100%**	**71%**	**79%**	2%	...	2%	...
W4	...	...	2%	14%	12%	29%	**73%**	**100%**	**73%**	8%	4%	12%	2%
C4	6%	4%	8%	10%	18%	30%	**82%**	**74%**	**100%**	4%	2%	2%	...
S1	...	...	...	...	...	...	2%	8%	4%	**100%**	**73%**	**59%**	**65%**
C2	...	...	...	...	...	...	...	4%	2%	**71%**	**100%**	**85%**	**67%**
C3	...	...	...	2%	...	2%	2%	12%	2%	**58%**	**85%**	**100%**	**56%**
P2	...	...	...	...	...	...	...	2%	...	**63%**	**67%**	**56%**	**100%**

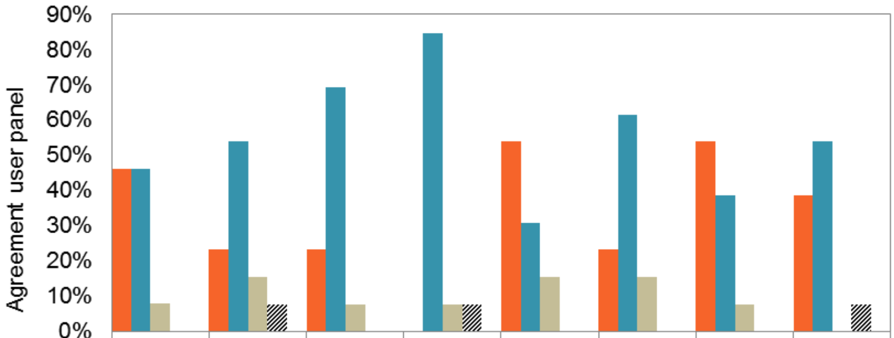
4.2.1.4 Agreement user panel with fabric drape categories

After they created the drape clusters the expert user panel judged the appropriateness of the drape categories defined by the textile panel, by assessing the images illustrated in Figure 3.2.1, as well as the videos. The fabric selection was reduced in accordance with the indicated drape similarity by the textile panel.

Table 4.5 shows the three categories and how the textile panel divided the fabrics among them, with the drape similarity indicated by the textile panel marked in superscript. Furthermore, the Table shows the agreement of the user panel with the defined drape categories for the particular fabrics. This agreement represents the sum of “highly agree” and “agree” responses, the bar Figure 4.3 shows the agreement of the user panel with the defined categories in more detail. Except for fabric W4, which is slightly below 78%, the agreement of the user panel with the defined categories by the textile panel is high for all tested fabrics.

Table 4.5: Agreement user panel with drape categories defined by textile panel

Code	g/m²	Comp	Textile panel category	User panel agreement
S1	25	100% SE	Body	**92%**
S4	27	100% SE	Well Draping	**92%**
$S3^{\sim P1}$	54	92% SE-8% EL	Well Draping	n/a
$P1^{\sim S3}$	69	100% PES	Well Draping	**85%**
$C5^{\sim C4}$	81	100% CO	Body	n/a
S2	88	100% SE	Well Draping	**85%**
$C4^{\sim C5}$	90	100% CO	Body	**85%**
$W2^{\sim W1}$	161	100% WO	Soft Drape	n/a
$W1^{\sim W2}$	115	100% WO	Soft Drape	**92%**
P2	252	100% PES	Body	n/a
W4	254	100% WO	Body	77%
$C2^{\sim C3}$	272	97% CO-3% EL	Body	**92%**
$C3^{\sim C2}$	279	100% CO	Body	n/a



Code and category >	C2 Body	W4 Body	W1 Soft Drape	C4 Body	P1 Well Draping	S2 Well Draping	S4 Well Draping	S1 Body
Strongly Agree	46%	23%	23%	0%	54%	23%	54%	38%
Agree	46%	54%	69%	84.62%	31%	62%	38%	54%
Neutral	8%	15%	8%	7.69%	15%	15%	8%	0%
Disagree	0%	8%	0%	7.69%	0%	0%	0%	8%
Strongly Disagree	0%	0%	0%	0%	0%	0%	0%	0%

Figure 4.3: Details of agreement of user panel with drape categories defined by textile panel.

4.2.1.5 Summary drape clusters and categories

The categories discussed in the previous section divided the fabrics roughly based on their drape, nevertheless they lack information to express the specific nature of the fabrics. Contrasting fabrics are combined in the same category as well as in the same drape cluster. Fabric W4 and C4 are clustered and assigned to the same category, however, their composition and weight are opposite. The same contrast applies to S1 and C2. The suitability of identifying key-words to distinguish more accurately between different fabrics is investigated in the following section. Moreover, the drape clusters made based on the overviews A1, A2, B1 and B2 with one perspective on the drape shows that different perspectives lead to different combinations, this is further analysed in section 4.4.

4.2.2 Fabric drape identifiers

4.2.2.1 Fabric drape identifying key-words

From the rich vocabulary brought in by the textile panel identifying key-words were derived to support the categories. Accordingly, the derived key-words were reviewed by the textile panel during the evaluation session. The final agreement of the textile panel was judged by the user panel during the main body of the survey. Below the analysed outcome is presented, the Tables show the agreement of the user panel with the defined identifying key-words for the particular fabrics. This agreement represents the sum of “highly agree” and “agree” responses. For some fabrics the word clouds of the definitions by the textile panel are given, the rest is included in Appendix 6.

For polyester fabric P1 classified in the category *well draping* the word clouds in Figure 4.4 show the diversity of the definitions, on the left side the definitions given in the open-ended boxes and on the right side the selected definitions. Part of them are more or less indicated by the category, such as; *floating, fluid, flowing, moveable, quite-wavy, soft flowy* and *drape*. In contrast to *well-draping* is the frequent use of *stiff* to define the drape with; *stiff-edges, stiff-suppleness, certain-stiffness* and *stiff*.

Figure 4.4: Definitions by the textile panel for fabric P1.

In the evaluation session the textile panel agreed to select *sheer* to cover the definitions; *transparent, transparency, flimsy* and *light*. Table 4.6 shows the agreement of the user panel with the selected key-words, where the agreement for *sheer* and *hanging* is above 78%, but the agreement is low for *grainy*, *springy* and *resilient stiffness*. One of respondents suggested *flowy*, which was also listed by the textile panel, another respondent proposed to use *drapy* instead of *springy*.

Table 4.6: Agreement of the user panel with identifying key-words P1

P1 Identifying key-words	Agreement user panel
Hanging	100%
Sheer	92%
Grainy	54%
Springy	46%
Resilient stiffness	46%

One of the textile judges remarked for S3: '*the fabric follows its own way*'. Fabric S3 classified in *Well draping* is not judged by the user panel. The similarity demonstrated in section 4.2.1.3, as well as the definitions; *sheer, transparent* and *light* presented in the word clouds in Figure 4.5, justify the use of *sheer* as the identifying key-word for S3.

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Figure 4.5: Definitions by the textile panel for fabric S3.

Table 4.7 shows the agreement of the user panel with the identifying key-words for silk fabric S4. The agreement was high for *swing* and *sheer*. In the comment boxes one of the judges noted down *silky* and another one *soft*, both words are listed by the textile experts as well.

Table 4.7: Agreement of the user panel with identifying key-words S4

S4 Identifying key-words	Agreement user panel
Swing	92%
Sheer	85%
Irregular	61%

Table 4.8 shows the agreement of the user panel with the identifying keywords for fabric S2. The agreement of the user panel was high for all identifying key-words. In the open-ended answer boxes some judges inserted additional expressions such as; *soft hand feel*, '*regular*' *smooth draping* and *satin*, the latter was mentioned by the textile experts as well.

Table 4.8: Agreement of the user panel with identifying key-words S2

S2 Identifying key-words	Agreement user panel
Smooth	100%
Silkiness	100%
Flowing	85%
Lustre	85%

One of the textile judges stressed the difference between a fabric revealing or *following the body shape* such as S2 and a *fabric drape hiding the body shape* such as W1 and W2.

For fabric W2 one of textile judges noted; '*the fabric looks very soft and light, and is rigid and limp at the same time*'. One of the textile judges typified fabric W1 as: '*a grainy wool crepe*'. The word clouds in Figure 4.6 illustrate the contribution of the textile panel for W1.

Figure 4.6: Definitions by the textile panel for fabric W1.

Fabrics W2 and W1 have equal composition and some difference in weight and are classified in the category *soft drape* by the textile panel. They indicated that the drape of the fabrics is comparable, however, this was not supported by how the user panel combined the fabrics in the drape clusters as described in section 4.2.1.3. Moreover, for all the identifying key-words the agreement of the user panel was below 78%, this is illustrated in Table 4.9.

Table 4.9: Agreement of the user panel with identifying key-words W1

W1 Identifying key-words	Agreement user panel
Fluid	77%
Grainy	69%
Resilient	69%
Slightly transparent	62%
Springy	54%

The drape similarity between fabrics C4 and C5, both classified in category *body*, is indicated by the textile panel and in the drape clusters made by the user panel. One of the textile panel members pointed out contradictions for fabric C5: '*stiffness though soft; a crispy softness*', and the latter she included in the questionnaire. For fabric C4 one of the user panel judges inserted *Paper-idea* and *crispy* in the open-ended answer boxes. One member of the textile panel noted for fabric C4 '*more a crease than a drape*'. Figure 4.7 shows the word clouds for fabric C4.

Figure 4.7: Definitions by the textile panel for fabric C4.

Table 4.10 illustrates the agreement of the user panel with the key-words for cotton fabric C4, which was strong for *fairly-stiff* and *creases.*

Table 4.10: Agreement of the user panel with identifying key-words C4

C4 Identifying key-words	Agreement user panel
Fairly stiff	92%
Creases	85%
Light	69%

As already pointed out in section 4.2.1.5, fabric W4 differs significantly from C4 and C5 although they are combined in the same drape cluster and classified in drape category *body.* The definitions in the word clouds in Figure 4.8 and the key-words derived from them distinguish between the fabrics.

Figure 4.8: Definitions by the textile panel for fabric W4.

The user panel inserted in the comment boxes the following; *warm, smooth, soft* and *firm,* except for the first, they are listed by the textile panel as well. Further, a good agreement was found for *slightly felted* and *fairly stiff* as illustrated in Table 4.11.

Table 4.11: Agreement of the user panel with identifying key-words W4

W4 Identifying key-words	Agreement user panel
Slightly felted	92%
Fairly stiff	85%
Compact	62%
Resilience	38%

Other fabrics allocated in category *body* are silk organza S1, cotton fabrics C2, C3 and polyester fabric P2. Fabric S1 has the lowest weight of the thirteen fabrics, whilst the weight of the other three fabrics is amongst the highest and, except for C2 and C3, their compositions differ.

For fabric S1 one of the textile judges commented on the drape: *'in spite of the stiffness the material was interacting with the shape of the support*'. During the group evaluation the textile panel agreed jointly with *adjusted rigid* as it covers the stiffness as well as the interaction with the support. Figure 4.9 shows the definitions for fabric S1 in the word clouds, where *heavy* is opposite to the weight of the fabric.

Figure 4.9: Definitions by the textile panel for fabric S1.

One respondent from the user panel inserted *strong shaping drape* in the open-ended boxes, another sugested *stiff open material* and *fragile*. For the key-words *adjusted-rigid* and *sheer* the agreement of the user panel was strong, whilst *resilience* stayed below 78%, as indicated in Table 4.12.

Table 4.12: Agreement of the user panel with identifying-key words S1

S1 Identifying key-words	Agreement user panel
Sheer	92%
Adjusted rigid	92%
Resilience	77%

As illustrated in the word cloud in Figure 4.10 the vocabulary of the textile panel for fabric C2 was less rich compared to the previous fabrics.

Figure 4.10: Definitions by the textile panel for fabric C2.

Moreover, the user panel agreed with the key-word *stiff*, whilst the agreement for *compact*, *creases* and *smooth* was negligible, they are illustrated in Table 4.13. Key-words brought in by the user panel are *heaviness*, *weight* and *shapeable*.

Table 4.13: Agreement of the user panel with identifying key-words C2

C2 Identifying key-words	Agreement user panel
Stiff	100%
Compact	38%
Creases	23%
Smooth	15%

Fabric C3, excluded from the main body of the user panel survey based on its similarity with C2, is indicated *stiff* and *heavy* by the textile panel. Fabric P2 is defined *stiff*, however, more *hard* and *sharp*. One member of the textile panel remarked that polyester fabric P2 was *curved through its stiffness*, another denoted *wimple*.

4.2.2.2 Value of fabric properties to identify fabric drape

After the judgement of the drape the user panel gave their opinion about the value of some specific fabric properties to identify fabric drape in a digital or virtual environment. Based on the sum of ‘very high” and “high” responses, weight was found valuable by the majority of the judges with 85%, fabric bending and the fabric drape coefficient both with 62% and shear with 54%, whilst Tensile obtained the lowest value with 38%, as illustrated in Table 4.14.

Table 4.14: Value of the fabric properties to identify fabric drape

	Weight	Composition	Weave	Drape coefficient	Bending	Shear	Tensile
Very High	**38%**	8%	0%	**31%**	**31%**	**8%**	0%
High	**46%**	38%	54%	**31%**	**31%**	**46%**	38%
Moderate	8%	23%	23%	23%	23%	23%	38%
Low	8%	23%	8%	8%	0%	8%	0%
Not relevant	0%	0%	0%	0%	8%	8%	8%

4.2.2.3 Summary identifying key-words

In the first instance, the aim was to generate fabric drape identifying key-words; however, the judges brought in many fabric specific aspects related to structure, weave and fibre, such as *grainy, crepe, woolly, transparent, satin, shiny* and *lustre*, apparently part of their perception and technical knowledge of the material. Although this examination to define identifying key-words is a first start and needs to be further investigated, the examples illustrate that the key-words give additional connotation about the drape of a fabric, such as *felted, light, heavy, stiff, sheer, swing, smooth, lustre, resilience* and *creases*, supporting the rough division of the categories, enabling to define the particular drape more precisely. Moreover, to increase the perception of drape in a virtual environment the weight is indicated as “highly valuable” and drape coefficient, bending and shear are “valuable to some extent”.

4.3 Relationship between drape categories and judgement of stiffness and amount of drape

On a seven point scale the panels rated the stiffness of drape as well as the amount of drape, both are illustrated in Figure 4.11 below. The stiffness of the drape of fabrics S4, P1 and S2 is rated between 2 and 2.5 indicating a limp drape, whilist the amount of drape is indicated as “high” for these fabrics. At the other side of the stiffness scale fabrics S1 and C2 have the highest ratings indicating a rigid drape, whlist the amount of drape is rated “low”. The stiffness of fabrics C4 and W4 is rated on the “stiff” side of the scale whilist fabric W1 is indicated “less stiff”. From the charts it can be obtained that the relationship between the stiffness and amount of drape is inverse.

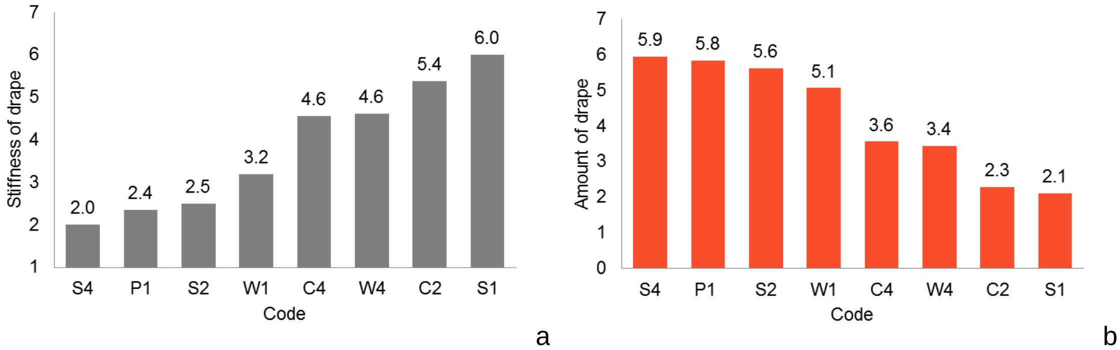


Figure 4.11: Subjective judgement of drape: (a) stiffness, (b) amount.

This inverse relationship is expressed in the scattergraph in Figure 4.12, as well as with the high negative correlation found with Pearson’s correaltion coeffiecient where r is -0,99 and which is statistically significant with p<0.0001.

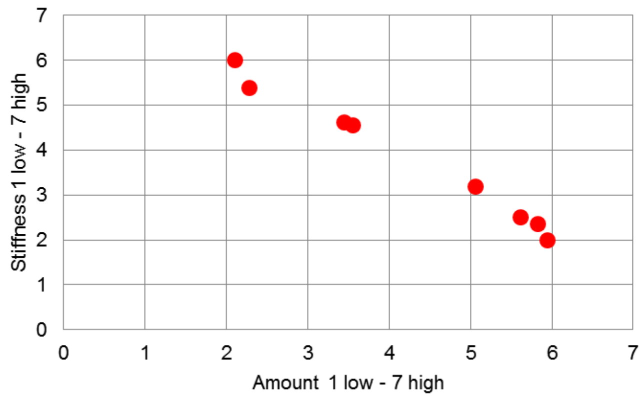


Figure 4.12: Correlation between stiffness and amount of drape.

Table 4.15 shows the relationship between stiffness of drape, amount of drape and drape category as indicated by the judges. Stiffness and amount of drape calculated as a percentage from the maximum amount of stiffness and amount of drape showes that fabrics with a stifness rating of 36% and lower are assinged to the category *well draping* and that they have an amount of drape of 80% and higher. In the category *soft drape* the rated stiffness is round 46%, whilist the amount is 72%. Fabrics with a stiffness of 65% and higher are classified in the category *body* and have an amount of drape of 51% and lower.

Table 4.15: Relationship between ratings of stiffness, amount of drape and drape categories

		Stiffness		Amount	
Code	Category	1 limp – 7 rigid	%	1 Low - 7 high	%
S4	Well draping	2.0	29%	5.9	85%
P1	Well draping	2.4	34%	5.8	83%
S2	Well draping	2.5	36%	5.6	80%
W1	Soft Drape	3.2	46%	5.1	72%
C4	Body	4.6	65%	3.6	51%
W4	Body	4.6	66%	3.4	49%
C2	Body	5.4	77%	2.3	33%
S1	Body	6.0	86%	2.1	30%

The following formual is used to calculate the percentage of stiffness and amount of drape:

$$\text{Stiffness} = \frac{S\,x\,100}{7} \qquad (4.1)$$

$$\text{Amount} = \frac{A\ x\ 100}{7} \qquad (4.2)$$

Where S is the mean of the ratings for stiffness of drape and A is the mean of the ratings for amount of drape.

The word “stiff” is used to express the quality of the drape (Pierce, 1930), the user panel assessed the stiffness of the drape as illustrated above. “Stiff” is used to indicate the most rigid fabrics in section 4.2.2.1. Nevertheless, for fabric P1, which is indicated as the most limp and with the highest amount of drape, stiff is frequently used to define the drape of the fabric.

4.4 Preferred support and view for the assessment of fabric drape

The panels were able to judge the fabric drape from different viewing ‘angles’; disc and sphere front views static or rotating, as well as disc and sphere abstracted drape profile views with the area of the undraped specimen marked, thus giving an extensive view of the drape. Nevertheless, in the first part of the survey the user panel had to combine the drapes from the overviews with the thirteen fabrics represented by one view type each time without any details about the fabrics. As discussed in section 4.2.1.3, this resulted in a large variety of drape clusters, with contrasting combinations made between sphere and disc as well as between front and abstracted drape profile views. Figure 4.13 present the number of drape clusters created with each fabric based on the different overviews. They illustrate that the combinations are condensed based on the abstracted drape profile views, especially for those of the sphere.

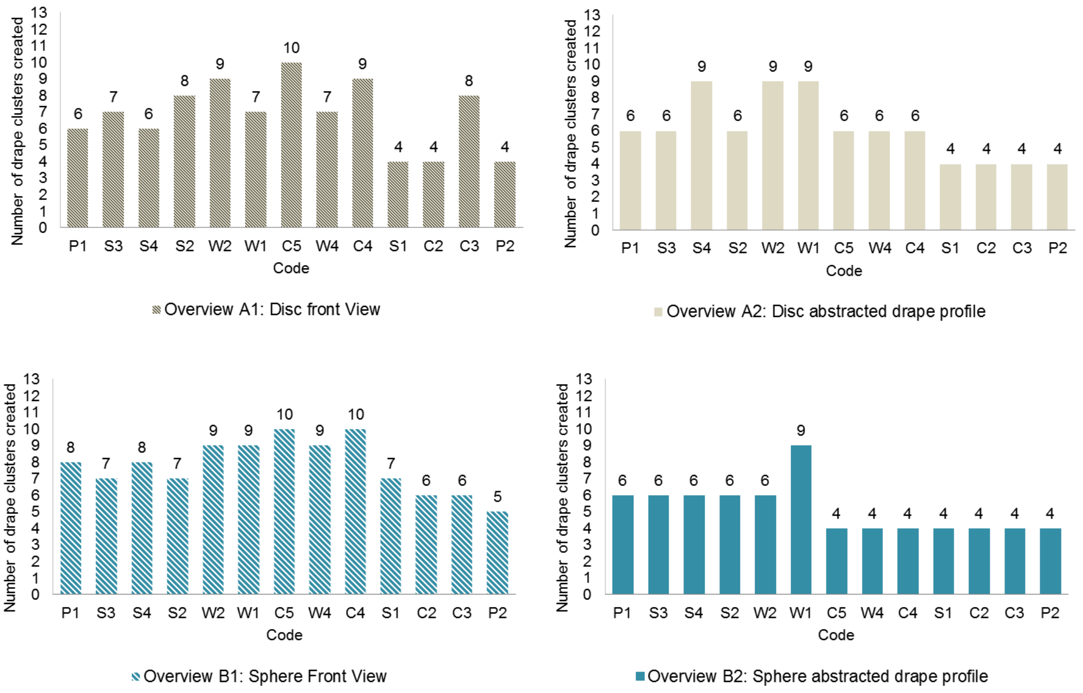


Figure 4.13: Number of drape clusters created based on the four drape overviews.

In particular cases different views enable the differentiation between fabrics, thus leading to different insights. The graphs in section 4.2.1.3 showed that some combinations are only made based on one view and never from another perspective on the drape. As illustrated in Figure 4.2.d fabric C3 is based on the disc front views clustered with S2, W1, C5 and W4, however, never based on the abstracted drape profile views of those fabrics. In contrast, C3 is frequently combined with P2 based on the abstracted drape profile views, whereas this is just a few times done based on the front views. Figure 4.14 illustrates the drape clusters made with fabric S2 and P2. Fabric S2 is by majority combined with S4 on the abstracted drape profile views, moderate on the sphere front view and never on the disc front view. Fabric P2 is a striking example that the different perspectives on the drape lead to different perceptions. The charts for fabrics P1, S4, W1, W4, C4, S1 and C2 are included in appendix 5, those for fabrics S3, W2, C5 and C3 in Figure 4.2.

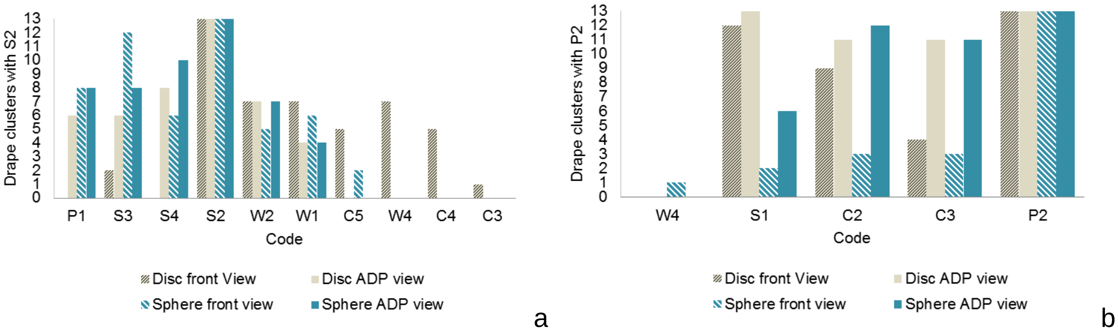


Figure 4.14: Drape clusters made by the user panel with fabrics: (a) S2, (b) P2.

At the end of the survey the panels gave their preferences and feedback on the different views, the analysis is illustrated in Figure 4.15 and the rationale of the panels is listed in Table 4.16. The sphere support was convincingly preferred, mainly due to its relationship with the curves of the body. From the views the rotating front view giving a surround view of the fabric was utmost favourite, the sum of both supports results in 50% for the video. Followed by the abstracted drape profile view with the proportion of the undraped specimen where the sum of both resulted in 23% preference. The disc front view was not selected, the sphere front view was preferred by 11% of the judges, the large number of drape clusters created based on this view, as illustrated in Figure 4.13, indicates a certain disagreement amongst the user panel members. The drape profile view with the fabric visible was preferred by 17% of the panel members.

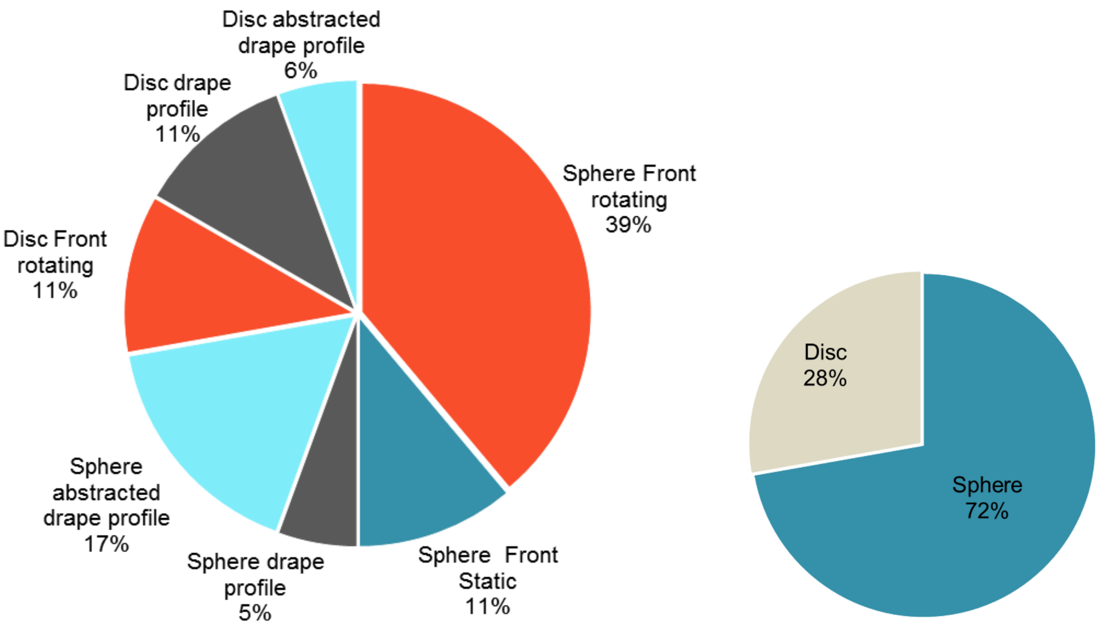


Figure 4.15: Preferred support and view.

Table 4.16: Rationale for support and view

Rationale textile and user panels for support and view	
General	
Rotating view	The film has more information on glance, texture, look and feel. Because it is 3D. I like the rotating, because you can see the whole drape. The video is the only medium offering a view around the entire fabric. Video gives the most information. You can see the drape the best in the video.
Static view	The static views lack information. The static front view is the best in the disc support version because you see more irregularities.
Drape profile view	Misses the communication of what is happening in between the edge of the sphere/disc and the edge of the fabric.
Abstracted drape profile view	You can see all sides and regular or irregularness. This disc view strips the presentation of distractions and leaves only the important shaping information. Sphere: Because of the differences in grayscale. Sphere: Gives me enough information on the drape.

Disc	
Disc	The disc offers more support to the fabric it seems and gives a delusional idea of how the fabric would actually fall.
Rotating front view	You see the irregularities, but also have the full view on the reaction of the fabric to the edge of the disk. Shows how the fabric behaves under true pressure.
Front view	The amount of overhang is just right; 2cm more will result in a different hang causing more similarity between the fabrics. More realistic view on fabric as applied in a garment.
Drape profile view	Clearly shows how the fabric falls all around equally. It is easy to see the stiffness (corners round or sharp) and the coverage of the surface area.
Sphere	
Sphere	Drape is much more extreme, image is more extreme (negative). Sphere gives more information. Most of our body parts are rounded and not flat so the sphere is more suitable.
Rotating front	The large curve shows how drapy the fabric is. It's best on a sphere because that's closest to the curves of an actual body. I don't consider the drape profile view as important as the side view when it comes down to evaluating the drape of a fabric. You see more drape on the sphere than on the disk. If you use the fabrics for 3D fit the sphere has the most natural drape for a garment. The sphere is having more influence on the drape of the fabric. Instead of falling over the edge it is following the shape. Makes it easier to visualise.
Front view	It is very visible what kind of drape the fabric has, fluent, soft, sharp and you can see the structure of the fabric because it is a photograph. Picture is clear. Realistic fall on a round shape such as the body. The drape is more visible.
Drape profile view	Picture and sphere give a good overview about the draping. You can see the outlines of the fabric, it makes it easy to recognise the drape. The shape tells you a lot about the drape. Overview from drape profile view is clear.

4.5 Coherence between drape categories, clusters, key-words and views

As illustrated in the previous sections of this chapter the perception of fabric drape is coherent between both panels. The drape categories correlate well with the perception of stiffness and the amount of drape and give a good indication of the drape of the fabric. However, the categories do not distinguish between particular differences in drape. The identifying key-words are apparently suitable to complement the categories to distinguish between equal draping fabrics with a dissimilar nature.

Moreover, the drape clusters showed that each perspective on the drape contributes to insight in the typical shape response some fabrics have to different supports. At the same time the drape clusters illustrated that lack of information leads to contrasting decisions. The sphere is preferred by the majority of the panels, however, the dissimilarity in the drape clusters indicate that the coherence found for the perception of drape increased by the multiple perspectives on the drape obtained from the different views used for the assessment of the fabric drape.

In the next Chapter the drape coefficient is measured as well as the fabric objective properties with both KES and FAST. The relationships between the fabric mechanical and physical properties and the drape coefficient will be investigated, as well the relationship between the subjective assessment of drape and the drape coefficient.

5 Relationships between subjective drape assessment and measured fabric properties

5.1 Introduction

This chapter presents the fabrics objective and mechanical properties and how they relate to the subjective judgement of fabric drape described in the previous chapter. In section 5.2 the measured drape coefficients and the number of nodes are presented. Furthermore, how the drape variation, observed during the fabric selection process, relates to the variance between the drape measurements. In section 5.3 the analyses of how the fabrics' mechanical and physical properties obtained with KES and FAST relate to the drape coefficient are presented. In section 5.4 the investigated relationships between the subjective judgement of stiffness and amount of drape, the drape coefficient and the fabric mechanical and physical properties are outlined. Moreover, how the drape categories defined by the expert panels relate to the drape coefficient. In section 5.5 a summary of this chapter is given.

The correlation between two series of variables is calculated with the Pearson Product-Moment Correlation Coefficient denoted by r and in short Pearson's correlation coefficient. Statistical significance is calculated with regression and denoted with *p*.

5.2 Drape measurements physical fabrics

5.2.1 Drape coefficient and number of nodes

The drape coefficient (DC) of the selected fabrics is measured with Cusicks' Drape Tester under standard conditions as described in section 3.3.3. The number of nodes is counted from the drape shadow. For each fabric the mean and the standard deviation of the drape coefficient and the number of nodes are calculated from the twelve face-up and back tests, and also from only the six face-up tests. The face-up measurements will be used to investigate the relationship with the virtual drape in chapter 6. All measurements are presented in Table 5.1, the fabrics are ordered based on increasing drape coefficient. As explained in section 3.3.3 the complete range of fabrics is tested with a 30 cm diameter specimen. Cusick (1968) recommended a 36 cm diameter fabric specimen for fabrics with drape coefficients above 85%, the author (1962 pp 16-18) found that very stiff fabrics with drape coefficients above 80% hardly form nodes on a support disc of 18 cm, and 'zero nodes' for fabrics with drape coefficients above 95%. Some of the fabrics, tested for this research, with drape coefficients above 85% formed undefined nodes.

Manual counting of the nodes of the fabrics with drape coefficients above 85% showed high inaccuracy as the nodes are not clearly defined, for that reason they are excluded. Fabric S1 is omitted for its face-up drape coefficient of 88%.

Some fabrics have a high variance between their measured drape coefficients. Silk organza fabric S1 has a considerable contrast between face and back measurements.

Table 5.1: Drape coefficient and number of nodes

	Both sides: 12 tests				Face-up: 6 tests			
Code	DC% Mean	DC% SD	Nodes Mean	Nodes SD	DC% Mean	DC% SD	Nodes Mean	Nodes SD
P1	20%	0.679	8	0.577	20%	0.686	8	0.516
S3	23%	2.090	10	0.798	22%	0.792	9	1.033
S4	28%	1.774	8	0.522	29%	2.130	8	0.548
S2	31%	2.043	8	0.452	29%	0.967	8	0.408
W2	36%	2.183	9	1.000	35%	2.252	8	0.516
W1	44%	2.079	9	0.622	43%	0.967	9	0.408
C5	56%	2.638	9	1.165	57%	2.505	9	1.329
W4	60%	1.682	9	0.669	60%	1.693	9	0.408
C4	74%	2.205	8	0.888	73%	2.212	8	0.753
S1	80%	8.878			88%	0.900		
C2	88%	3.661			85%	1.979		
C3	91%	1.639			91%	1.832		
P2	91%	1.336			91%	0.775		

Silk organza fabric S1 has a mean drape coefficient of 80%, the standard deviation of 8.878 and the minimum and maximum drape coefficient indicate a significant variance between the measurements. In contrast the mean of the face-up measurement has a low variance and a higher drape coefficient. The high variance in drape measurements of fabric S1 is caused by significant difference between the face and back measurements, they are illustrated in Table 5.2.

Table 5.2: Details of measured drape coefficient fabric S1

			DC Mean	DC SD	DC Min	DC Max
Specimen A	Back	3	70%	6.321	66%	77%
Specimen B	Back	3	74%	0.345	73%	71%
Specimen A	Face	3	87%	0.715	87%	88%
Specimen B	Face	3	89%	0.233	88%	89%

5.2.2 Variation in drape profile and drape measurements

The drape measurements are taken according to the standard procedure with replacement of the fabrics in between the measurements. During the fabric selection process the variation in drape profile is tested by draping each fabric specimen seven times without removing it from the tester. For each relaxation the shadow of the drape is drawn on the same paper ring. The drape variation tests show the largest variation in drape profile for fabrics P1 and S4. This variation in drape profile is illustrated in the chart in Figure 5.1. The traced drape profiles for fabric S4 and P1 are illustrated in Figure 5.2, the profiles for the other fabrics are included in appendix 1.

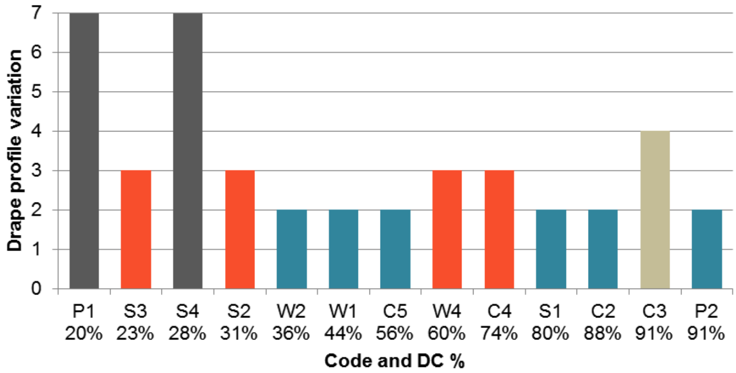


Figure 5.1: Variation of drape during repeated seven tests without replacing the fabric.

During the drape measurements there was considerable distortion of the fabric when turning the specimen in between the measurements, whilst for the drape variation tests the drape of the fabric was only influenced by gravity. Previous research demonstrated that distortion of the fabric during measurements influences the stability of the drape coefficient (Morooka and Niwa, 1976) and results in an increasing variance between the number of nodes (Jeong, 1998). Nevertheless polyester fabric P1 and silk fabric S4 showed a large variation in drape profile, as illustrated in Figure 5.1, and Figure 5.2; with at the same time a low variance between the measurements of the drape coefficient and number of nodes as illustrated by the standard deviation for those measurements in Table 5.1.

Investigation of the drape variation tests shows that the number of nodes is stable for fabrics P1 and S4, whilst the place where the nodes appear in the drape profile varies to a considerable extent as illustrated in Figure 5.2. The variance between the number of nodes of the drape variation tests, is comparable with the variance of the number of nodes of the drape measurements presented in Table 5.1. The comparison is illustrated in Table 5.3.

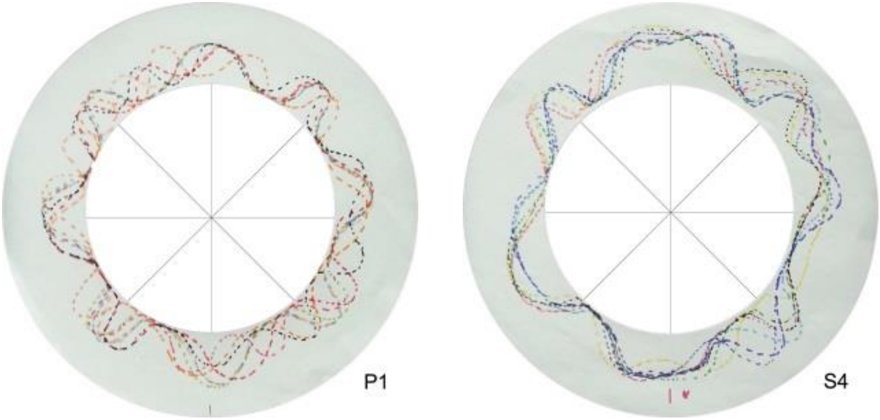


Figure 5.2: Drape variation tests for fabric P1, fabric S4.

Table 5.3: Comparison of number of nodes between drape variation and drape measurements

Code	Drape measurements	Distortion by turning	Number of nodes Mean	SD	Mode	Min	Max
P1	Both sides (12x)	Yes	8	0.577	8	7	9
P1	Face up (6x)	Yes	8	0.516	8	8	9
P1	Drape variation tests (7x)	No	9	0.690	9	8	10
S4	Both sides (12x)	Yes	8	0.522	8	7	8
S4	Face up (6x)	Yes	8	0.548	7	7	8
S4	Drape variation tests (7x)	No	8	0.518	8	7	8

5.3 Fabric mechanical and physical properties and correlation with drape coefficient

The fabrics' mechanical and physical properties are measured according the procedures described in section 3.3.1 for the KES properties and in section 3.3.2 for the FAST properties. The measurements are included in appendices 7 and 8. The following sections present the analysis of the relationship between the fabric properties and drape coefficient. The mean of warp and weft is used to investigate the relationships between the properties and drape coefficient, these relationships will be presented in scatter graphs. The first section presents the relationship between fabric weights and drape coefficient. Another purpose of the KES and FAST measurements is to create the virtual fabrics; this will be described in chapter 6. In the scatter graphs the data points indicating the fabric properties required to create the virtual fabrics have a red colour.

P2 is not measured with KES and FAST and thus not simulated. This heavy polyester fabric is most often used to make banners and is not very suitable to make garments. Nevertheless, sometimes P2 is selected by designers; Cootjans (2015) used this fabric for jackets because of its stiff properties. In the first instance this fabric was not selected, however, due to its contrast in weight and similarity in drape profile with silk organza fabric S1 it was decided to add it only to the survey range.

The tensile properties of fabrics S1 and S3 are not measured with KES and fabric S3 is beyond the maximum elongation of FAST. For that reason, the measurements of S1 and S3 have been removed for the correlations between drape coefficient and the tensile properties measured with both KES and FAST.

5.3.1 Relationship between weight and drape coefficient

In the scatter graph in Figure 5.3 the correlation between fabric weight and drape coefficient is presented. In general weight and drape coefficient increase simultaneously, however, the silk fabrics S4 and S1 illustrate that the lowest weights do not necessarily have the lowest drape coefficients. The correlation between weight and drape coefficient is significantly positive, although not very strong, with r = 0.64, $p<0.020$. Silk organza S1 with the lowest weight and one of the highest drape coefficients influences the correlation. The scatter graph in Figure 5.3 illustrates the large negative residual S1 has, if this outlier is excluded from the calculation the correlation is much stronger with r = 0.88, $p<0.002$. Moreover, cotton fabrics C5 and C4 have relatively low weights compared to their drape coefficients, whilst woollen fabric W4, having a drape coefficient in between C5 and C4, is the opposite with a relatively low drape coefficient in relation to its weight. These contrasts are illustrated by the opposite positions in the scatter graph.

Comparison of the wool fabrics; W1, W2 and W4, with the cotton fabrics; C5, C4, C2 and C3 shows that the cotton fabrics have relative high drape coefficients and the wool fabrics relatively low drape coefficients in relation to their weight.

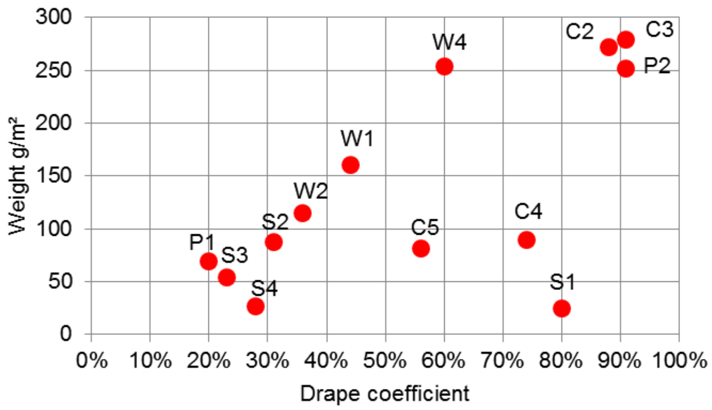


Figure 5.3: Relationship between weight and drape coefficient.

The correlation between weight and drape coefficient confirms the outcome of earlier research (Cusick,1962; Morooka and Niwa, 1976; Hu and Chan, 1998; Niwa et al., 1998) in which the authors demonstrated the relationship between weight and the drape coefficient. Okur and Cihan (2002) found no correlation between weight and drape coefficient, they suggested the correlation between fabric properties might depends on the selected fabrics, which is slightly supported by the influences S1 has on the correlation, as illustrated in the graph and the previous section.

5.3.2 KES bending properties and relationship with drape coefficient

A significant positive correlation between drape coefficient and KES bending hysteresis (2HB) is found with r = 0.73, p<0.007. Fabrics C2 and C3 have large positive residual and S1 has a negative residual. The fabrics with drape coefficients below 60% have low 2HB values, however, silk organza S1 with a drape coefficient of 85% has a low 2HB value too. Between KES bending rigidity (B) and drape coefficient a significant positive correlation is found with r = 0.75, p<0.005. Cotton C3 has a large positive residual. Fabrics with a drape coefficient below 60% have low B values, with the lowest values for fabrics with drape coefficients below 30%. Woollen fabric W4 has relatively high 2HB and B values compared to the cotton fabrics C5 and C4 with similar drape coefficients. This is illustrated in the scatter graphs in Figure 5.4.

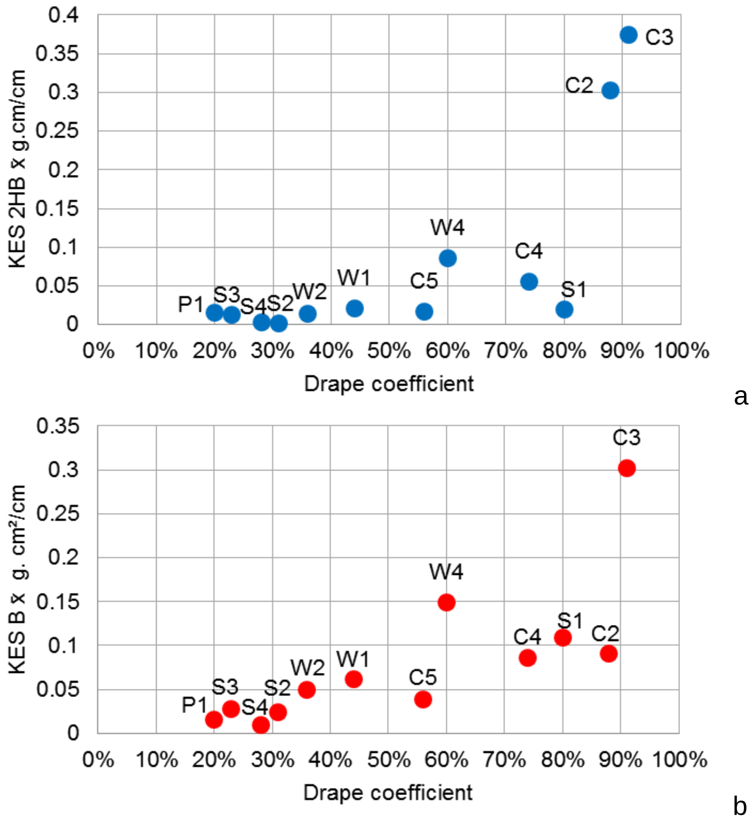
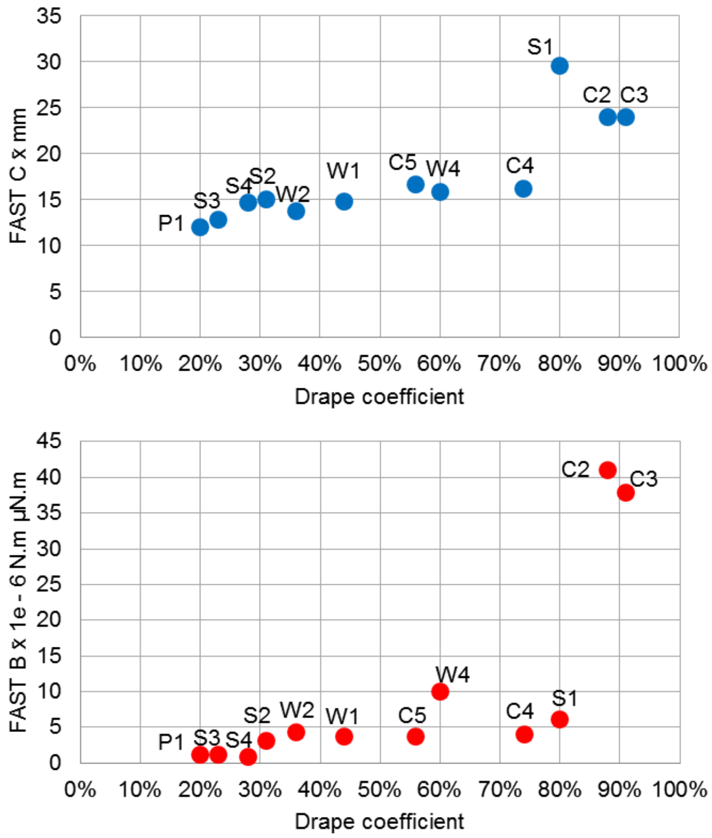


Figure 5.4: Relationship between drape coefficient and KES bending: (a) hysteresis, (b) rigidity.

5.3.3 FAST bending properties and relationship with drape coefficient

The correlation between drape coefficient and FAST bending length (C) is strong and significantly positive with r = 0.84, $p<0.007$, also the correlation with FAST bending rigidity (B) is significantly positive, with r = 0.74, $p<0.006$. The low weight silk organza S1 has the highest C value, whilst the wool fabric W4 has relatively low C values in relation to its weight. Cotton fabrics C2 and C3 have high drape coefficients and high rigidity of bending, whilst the silk organza S1 with a comparable drape coefficient has a low bending rigidity. Wool fabric W4 has in proportion to the cotton fabrics C5 and C4 with similar drape coefficients, a high bending rigidity. This is illustrated in the scatter graphs in Figure 5.5.



a

b

Figure 5.5: Relationship between drape coefficient and FAST bending: (a) length, (b) rigidity.

5.3.4 KES shear properties and relationship with drape coefficient

The correlation between drape coefficient and KES shear hysteresis at 0.5^0 (2HG) and at 5^0 (2HG5) and shear rigidity is positive and significant with r = 0.7 and, $p<0.020$ for 2HG, r = 0.73, $p<0.020$ for 2HG5 and r = 0.73, $p<0.008$ for G. For all KES shear properties silk organza S1 and cotton C3 have the highest residual. Fabrics with shear values (HB, 2HB and G) close to zero have drape coefficients below 50%, except for silk organza S1. Shear properties of woollen fabric W4 are relatively high compared to the cotton fabrics with similar drape coefficients.

Fabrics C2 and C3, with drape coefficients above 85%, have significantly higher values. This is illustrated in the scatter graphs in Figure 5.6.

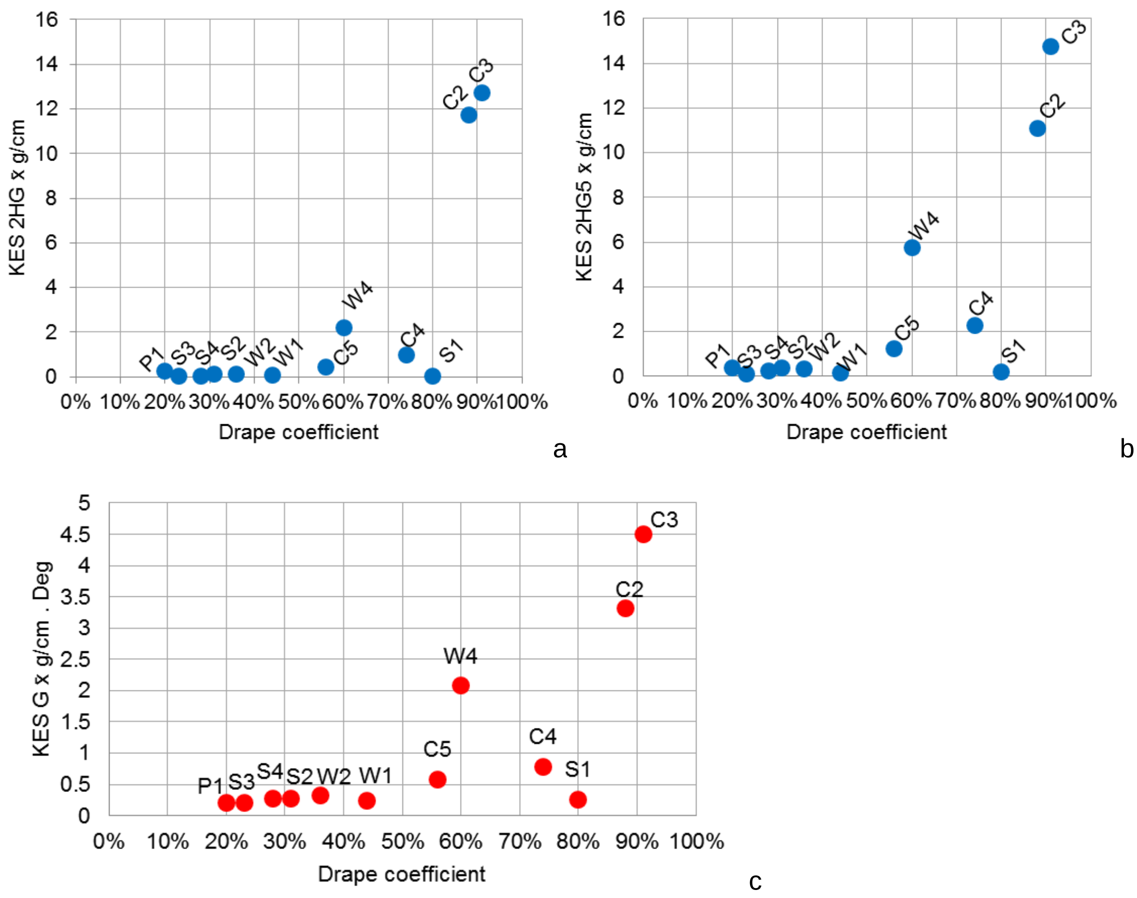


Figure 5.6: Relationship between drape coefficient and KES shear: (a) 2HG, (b) 2HG5, (c) G.

5.3.5 FAST shear properties and relationship with drape coefficient

The correlation between the drape coefficient and FAST shear rigidity (G) is found positively significant at r = 0.72, *p*<0.009. This is illustrated in the scatter graph in Figure 5.7.

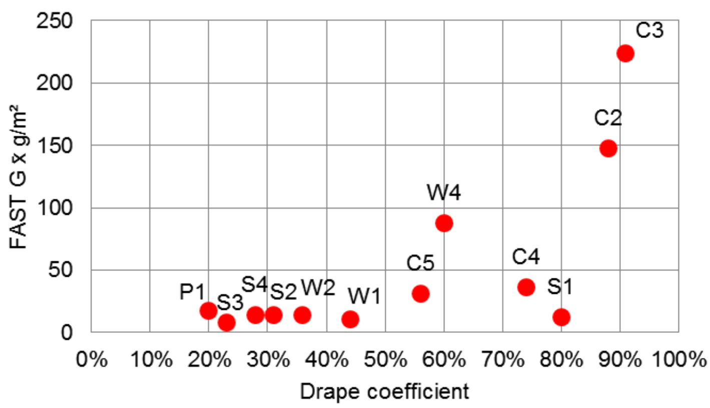


Figure 5.7: Relationship between drape coefficient and FAST shear rigidity.

As illustrated in the graph, silk organza S1 and cotton C3 have an outlier position, wool W4 has a contrasting position to cottons C5 and C4 with similar drape coefficients.

5.3.6 KES tensile properties and relationship with drape coefficient

Between drape coefficient and KES tensile properties the following correlations are found; zero correlation with r = - 0.1, *p*<0.800 for elongation (EMT), a positive significant correlation with r = 0.78, *p*<0.008 for linearity (LT), negative non-significant correlations with r = - 0.25, p<0.600 for energy (WT) and with r= -0.61, *p*<0.060 for resilience (RT). This is illustrated in the scatter graphs in Figure 5.8.

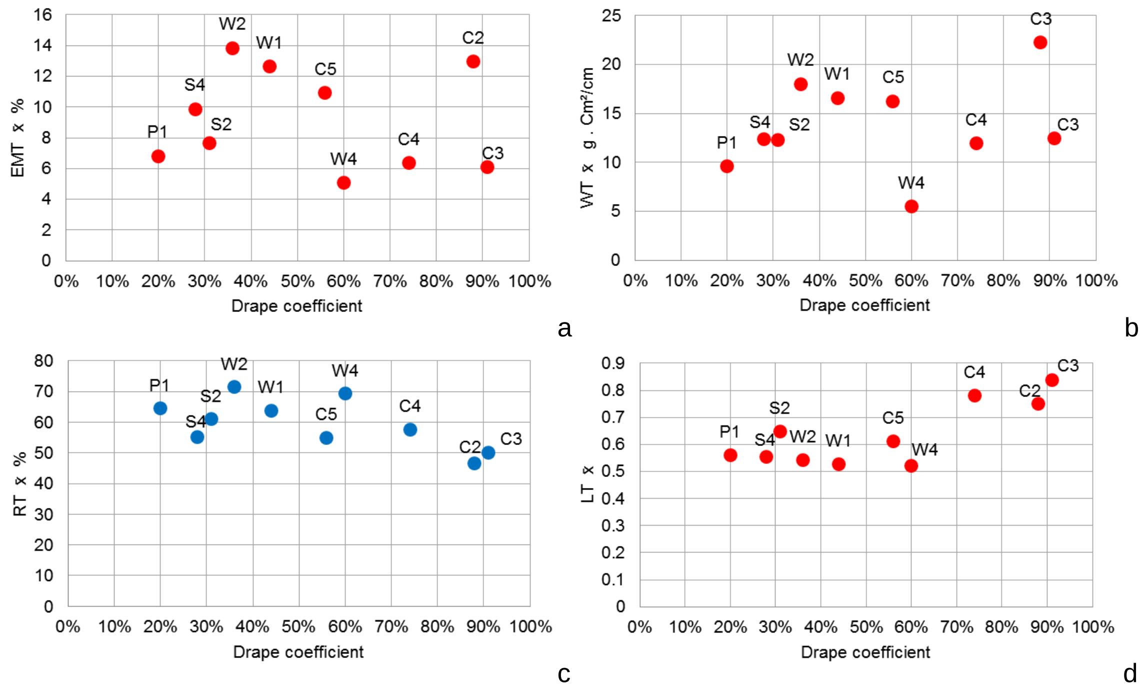


Figure 5.8: Relationship between drape coefficient and KES tensile: (a) EMT, (b) WT, (c) RT, (d) LT.

5.3.7 FAST tensile properties and relationship with drape coefficient

The following correlations are found between drape coefficient and FAST tensile; negative and significant with r = -0.68, *p*<0.040 for elongation at 5 gf/cm (E5), not statistically significant with r = -0.56, *p*<0.100 for elongation at 20 gf/cm (E20) and for elongation at 100 gf/cm (E100) no relationship is found with r = -0.15, *p*<0.700. This is illustrated in Figure 5.9.

A significant correlation with the drape coefficient is found for FAST elongation at 5 gf/cm but not for elongation at 20 and 100 gf/cm. The drape coefficient is measured at low force; the fabrics own weight influenced by gravity, which explains the correlation at low forces, the linear correlation will decrease by the nonlinear deformation of tensile property at different load levels.

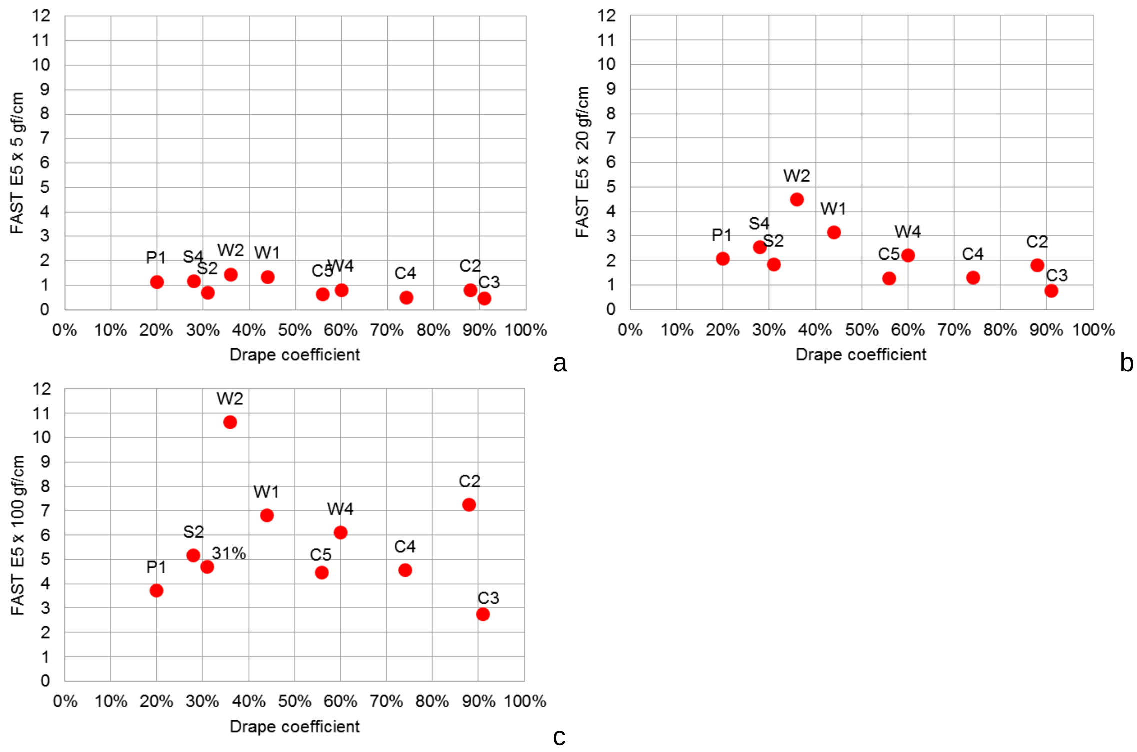


Figure 5.9: Relationship between drape coefficient and FAST tensile: (a) E5, (b) E20, (c) E100.

5.3.8 Analyses between KES and FAST properties related to drape coefficient

KES and FAST measure both bending rigidity, in spite of the different measurement principle the correlation with the drape coefficient is comparable with r = 0.75 and 0.74 respectively. The KES values show slightly more diversity compared to the FAST values. For both instruments the fabrics with low drape coefficients have low bending rigidity. Fabric C2 is an exception with low B values for the KES measurements, which are in contrast to the high values for FAST bending rigidity. Considering the similarity between the cotton fabrics C2 and C3 (Table 4.3), and the similarity between the patterns of the data points in the KES and FAST graphs for bending rigidity, the low bending rigidity of C2 may be a result of measurement error.

KES and FAST measure shear rigidity according to a different principle, nevertheless both systems have a strong positive correlation between shear rigidity and drape coefficient. The measured values show a similar pattern for both systems.

Cusick created a ‘fabric map’ by plotting the bending and shear properties against each other according the principle introduced by Lindberg *et al.* (1961, cited in Cusick, 1962, p.221). This is done with the bending and shear rigidity values measured with KES (r=0.84, p<0.00100) and FAST (r=0.94, p<0.00001) as illustrated in Figure 5.10. The red dots have drape coefficients below and the blue dots above 50%. It must be noted that the KES B value for C2 may not be accurate. The 'fabric map' shows the proportions between bending and shear rigidity and the distance C3 has to the fabrics with low values. The close up focuses on the fabrics with low values and marks the outlier position of organza S1 which agrees with the position Cusick found for organdie (1962, p.221).

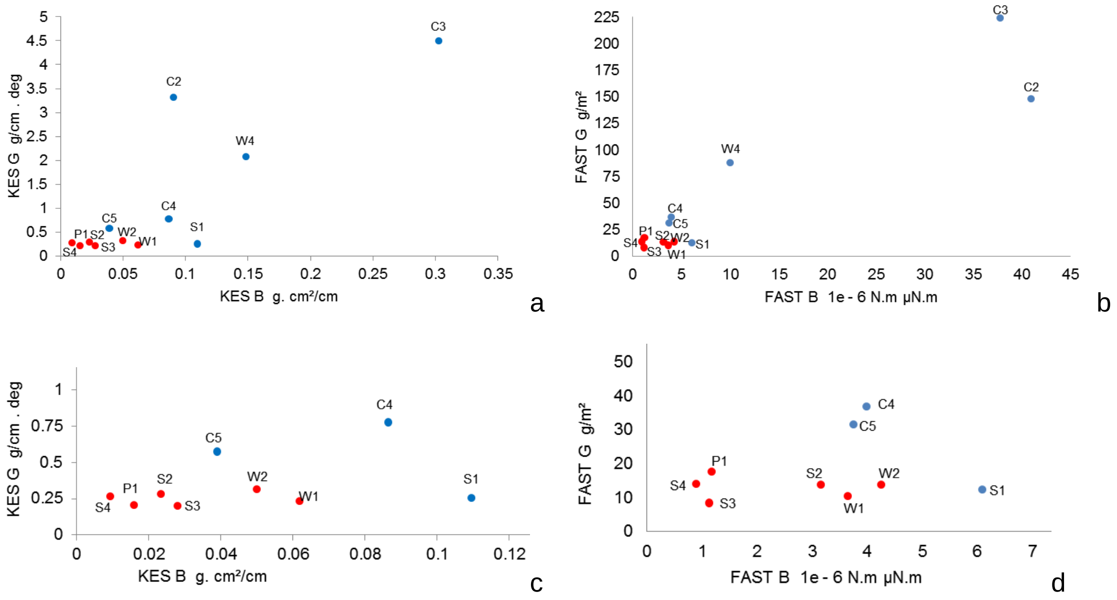


Figure 5.10: Relationship between bending and shear rigidity; (a) KES, (b) FAST, close up with lower values; (c) KES, (b) FAST.

The KES and FAST tensile properties and how they are measured are significantly different. Most closely related are KES tensile elongation and FAST E100, however, the applied forces are completely different. Tensile properties important for garment comfort (Luible, 2008) have for most of the measured properties of the selected fabrics no correlation with the drape coefficient.

The correlation of the drape coefficient with weight, bending and shear measurements confirms earlier research (Pierce, 1930; Cusick 1962; Morooka and Niwa, 1976; Collier, 1991) as well as with the correlation found between KES tensile linearity (Hu and Chan, 1998) and FAST tensile elongation at 5 gf/cm (Okur and Cihan, 2002) as described in section 2.3.3.1. Table 5.4 gives an overview of the correlation found between the measured properties and the drape coefficient.

As illustrated in the previous sections and in the 'fabric map', silk fabrics S1 and S4 have similar low weights and opposite drape coefficients, S4 has low values for bending and shear properties as well as a low drape coefficient, whilst organza S1 has, in relation to its very low weight high values for bending rigidity and low shear values. Its FAST bending length is the highest of the complete range of fabrics. Nevertheless, in general, fabrics with low drape coefficients have low values for KES and FAST bending and shear rigidity, as well as for KES bending and shear hysteresis and FAST bending length. Those properties increase for fabrics with higher drape coefficients.

The cotton fabrics have, in relation to their weights, higher drape coefficients than the woollen fabrics; cotton C2, C3 and wool W4 have similar high weights, C2 and C3 have (except from KES bending rigidity) high bending and shear properties and a high drape coefficient, whilst W4 has relatively low bending and shear properties and a relatively low drape coefficient, which is similar to the cotton fabrics C4 and C5 with significant lower weights. Woollen fabrics W1 and W2 have higher weights than C4 and C5 but lower properties for bending and shear. For the cotton and wool fabrics the influence of the bending and shear is stronger than the influence of the weight on the drape. However, the bending rigidity value of silk organza S1 in comparison to cotton C3 and wool W4 illustrates that the weight influences the drape as well. This may be due to the interplay between the bending and shear properties, as well as the fabrics' weights as pointed out by Cusick (1962 p.16, 106-109) and Jeong and Phillips (1998), who also discussed the this interplay in relation to the variation in drape.

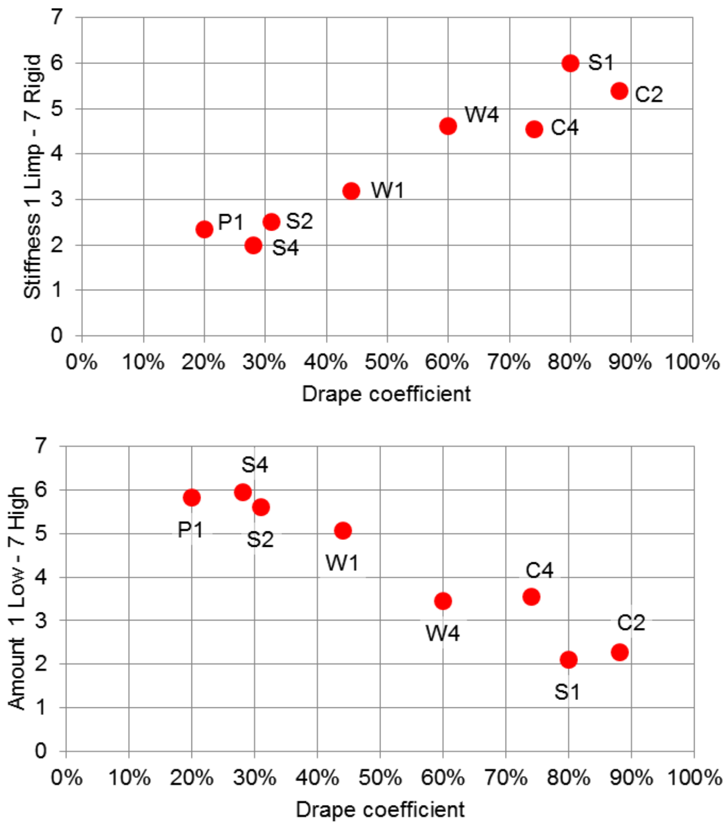
Table 5.4: Overview correlation between objective fabric properties and drape coefficient

Property			r	*p* <
Weight			0.64	0.020
Bending	KES	Bending hysteresis	0.73	0.007
		Bending rigidity	0.75	0.005
	FAST	Bending rigidity	0.74	0.006
		Bending length	0.84	0.007
Shear	KES	Shear hysteresis at 0.5°	0.70	0.020
		Shear hysteresis at 5°	0.73	0.020
		Shear rigidity	0.73	0.008
	FAST	Shear rigidity	0.72	0.009
Tensile	KES	Tensile elongation	. . .	. . .
		Tensile linearity	0.78	0.008
		Tensile energy	. . .	. . .
		Tensile resilience	. . .	. . .
	FAST	Elongation at 5 gf/cm	-0.68	0.040
		Elongation at 20 gf/cm	. . .	. . .
		Elongation at 100 gf/cm	. . .	. . .

5.4 Relationships between drape coefficient, fabric objective properties and subjective assessment of drape

5.4.1 Relationship between drape coefficient and judgement of drape

The correlation between drape coefficient and judgment of the stiffness of the drape is significant and positive with r = 0.959, $p<0.0002$. Fabric S1 was considered slightly more stiff compared to C2 with a higher drape coefficient. Whereas S4 was judged slightly more limp compared to P1 with a lower drape coefficient. Also fabric W4 is judged more stiff compared to C4. The correlation between drape coefficient and amount of drape judged by the expert panels is negative and slightly higher with -0.970, $p<0.0001$. Fabric S4 is assessed with slightly more amount of drape then P1, whilst S1 is rated with a lower amount of drape than C2. This is illustrated in the scatter graphs in Figure 5.11.



a

b

Figure 5.11: Correlation between subjective assessment of drape and drape coefficient; (a) stiffness of drape, (b) amount of drape

The high correlation between drape coefficient and the subjective judgement of the stiffness of drape demonstrates the panels ability to identify the fabric drape based on the images.

5.4.2 Relationships between objective fabric properties and judgement of drape

The fabrics with low drape coefficients have low bending and shear properties as illustrated in the previous sections, moreover, according the expert panels they have a higher amount of drape. This relationship confirms the findings of Collier (1991). The low shear properties of fabric S1 seem to contrast with these findings, however, the bending properties are in proportion to the weight of S1 and are relatively high.

Furthermore, woollen fabric W4 and cotton fabric C4 have contrasting properties, nevertheless the panels ratings for stiffness and amount of drape are closely related. The FAST bending length values for fabrics W4 and C4 are quite similar. Silk organza S1 was rated most stiff by the panel and has the highest bending length. The statistically significant correlation of r = 0.84, $p<0.009$ between FAST bending length and the judgement of stiffness of the panel is high (Figure 5.12) and similar to the correlation found between FAST bending length and the drape coefficient, as illustrated in Table 5.4. The correlation between the stiffness of drape judged by the panels and drape coefficient is higher, however, the perception of the panel of the drape of fabrics S1, W4 and C4 correlates better with the FAST bending length.

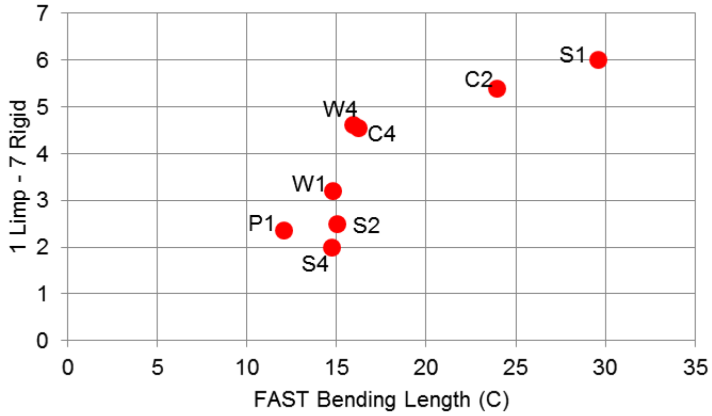


Figure 5.12: Correlation between subjective stiffness of drape and FAST bending length.

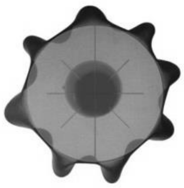
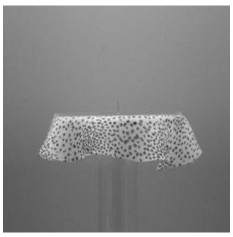
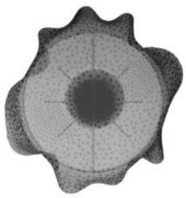
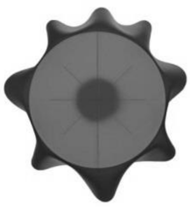
5.4.3 Relationships between drape categories, drape coefficient and objective fabric properties

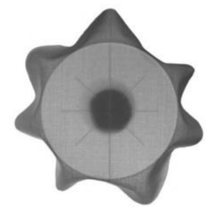
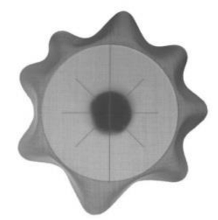
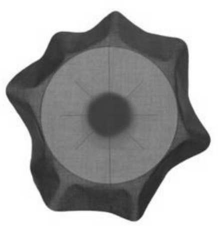
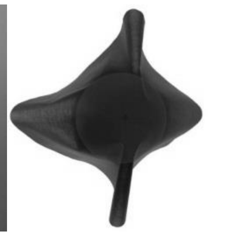
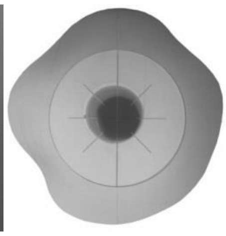
The previous chapter established the agreement of the user panel with the defined categories as well as the relationship between the panels' judgement of stiffness and amount of drape with the drape categories, the former is illustrated in Table 4.5 and the latter in Table 4.15.

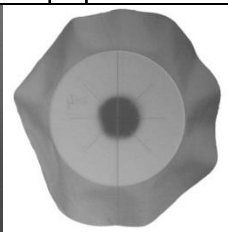
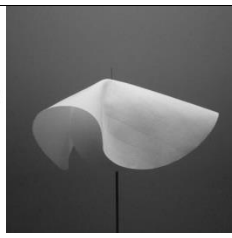
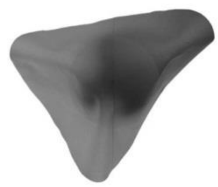
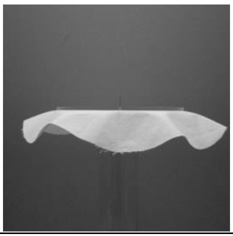
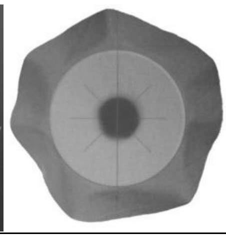
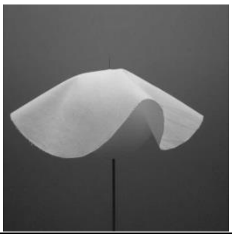
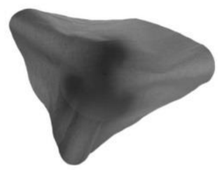
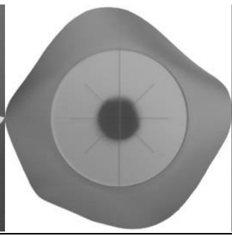
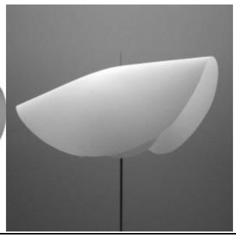
This chapter demonstrates the correlation between drape coefficient and perception of stiffness and amount of drape of the panel as evidenced in section 5.4.1, as well as, the relationship between the judgement of stiffness and amount of drape of the panel with particular fabric properties in section 5.4.2.

Table 5.5 shows the fabrics ordered by increasing drape coefficients. Fabrics in the category *well draping* have drape coefficients between 20% and 31%, fabrics in the category *soft drape* have drape coefficients between 36% and 44%, fabrics in the category *body* have drape coefficients between 56% and 91%. The exact borders between the categories are not defined, however, the border between *well draping* and *soft drape* is close to 31%. In the drape clusters made by the user panel fabric S2 is often combined with W2 and W1 both in the category *soft drape*.

Table 5.5: Overview of drape categories.

	Disc d18 cm Front view	Disc d18 cm Drape profile view	Sphere d12 cm Front view	Sphere d12 cm Drape profile view
P1 69 g/m² DC 20% Category Well Draping (WD)				
Key Words:	Hanging - Sheer			
S3 54 g/m² DC 23% Category: Well Draping (WD)				
Key Words:	Sheer			
S4 27 g/m² DC: 28% Category: Well Draping (WD)				
Key Words:	Swing - Sheer			
S2 88 g/m² DC 31% Category: Well Draping (WD)				
Key Words:	Smooth - Silkiness - Flowing - Lustre			

	Disc d18 cm Front view	Disc d18 cm Drape profile view	Sphere d12 cm Front view	Sphere d12 cm Drape profile view
W2 161 g/m² DC 36% Category: Soft Drape (SD)				
W1 115 g/m² DC 44% Category: Soft Drape (SD)				
C5 81 g/m² DC 56% Category: Body (B)				
W4 254 g/m² DC 60% Category: Body (B)				
Key Words	Slightly felted - Fairly stiff			
C4 90 g/m² DC 74% Category: Body (B)				
Key Words	Fairly stiff - Creases			
S1 25 g/m² DC 80% Category: Body (B)				
Key Words	Sheer - Adjusted rigid			

	Disc d18 cm Front view	Disc d18 cm Drape profile view	Sphere d12 cm Front view	Sphere d12 cm Drape profile view
C2 272 g/m² DC 88% Category: Body (B)				
Key Words	Stiff			
C3 279 g/m² DC 91% Category: Body (B)				
P2 252 g/m² DC 91% Category: Body (B)				

As pointed out in section 2.3.1.2, Cusick (1962, 1968) divided the drape of fabric based on drape coefficient, the author distinguished between very limp fabrics with a drape coefficient below 30% and very stiff material with drape coefficients higher than 85%. The category *well draping* fits with the first, for category *soft drape* and *body* this relationship is not found. As illustrated in Table 4.4 the drape clusters are in the category *body* divided into two groups; one cluster with drape coefficients of 56%, 60% and 74%, and the other with drape coefficients above 80%. The latter is fabric S1 with a mean drape coefficient of 80% and face up drape coefficients between 87% and 89% as discussed in section 5.2.1, based on this the border may be defined between 74% and 87%, which is close to the border defined by Cusick (1968).

For both KES and FAST bending rigidity the fabrics in the category *well draping* have the lowest values, the majority of the fabrics in the category *body* have high values, whilst fabrics in the category *soft drape* have values in between, however, with more dispersion. KES bending hysteresis and FAST bending values have a slightly weaker but similar relationship with the categories. Fabrics in the category *body* have the highest values for all shear properties, except from fabric S1. Fabric C3 has the highest values for all the KES shear and bending values.

5.5 Summary chapter 5

The drape coefficient is reversely related with the subjective judgement for the amount of drape and simultaneously with the perception of stiffness of drape. In general, all KES and FAST bending and shear properties increases parallel with the drape coefficient.

High variance in drape profile is not related to a high variance in drape coefficient and number of nodes, they can both be stable with a low standard deviation between the measurements, whilst the variation in drape profile is high.

Fabrics with low drape coefficients have in general low values for KES and FAST bending and shear rigidity, as well as KES shear hysteresis and FAST bending length; these values increase more or less in parallel with the drape coefficient, the same is the case for the fabric weight.

Borders between the category *well draping* and *soft drape* are found between 31% and 36%, and for *soft drape* and *body* between 44% and 56%.

The next chapter deals with the relationships between the real and virtual fabric drape. The abstracted drape profile images of the virtual fabrics created with the KES and FAST properties presented in this chapter, will be correlated with the measured drape coefficient. Furthermore, the subjective assessment of the real and virtual drape will be examined.

6 Relationships between real and virtual drape

6.1 Introduction

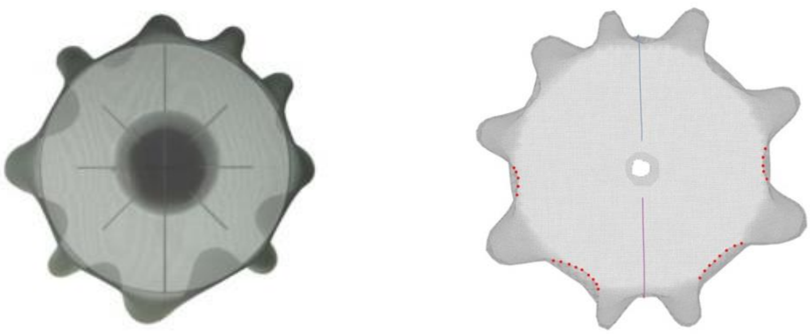
In the previous chapter the analyses of the relationship between the fabric drape and the fabric mechanical and physical properties measured with KES and FAST are presented. This chapter presents the relationships between the real and the virtual fabrics created with those measured properties. In section 6.2 the virtual drape coefficients based on the KES and FAST measurements are presented as well as the analyses on how they relate to the physical drape coefficient. Moreover the accuracy of KES and FAST properties for the simulation of cloth are discussed. In section 6.3 the analyses of the judgement of stiffness and the amount of the real and virtual drape by the expert user panel are outlined, and how this relates to the drape coefficient of the real drape. Moreover, the judgment of drape similarity between real and virtual duplicates of the same fabric are analysed and presented. In section 6.4 the relationship between the real and virtual drape with the drape categories is discussed. Additionally a wrap up of the chapter is given in section 6.5, but first the differences found between real and the virtual environment are presented in the next section.

6.1.1 Differences between real and virtual environments

As discussed in section 3.2.3.1 the virtual drape meter lacks the pressure disc on the top of the draped specimen. During the simulations it is found that the fabric does not lay flat on the virtual disc, this might result in differences between the real and virtual drapes. Figure 6.1 illustrates a simulated drape.

Figure 6.1: Simulated fabric without pressure disc.

Owing to the fact that very limp fabrics form nodes under the support, Cusick (1968) recommended a fabric specimen with a diameter of 24 cm for fabrics with drape coefficients below 30% and a fabric specimen of 36 cm for fabrics with drape coefficients above 85%. For this research it was decided to use only the 30 cm diameter fabric specimen, as described in section 3.3.3. It was found that the virtual fabrics developed hardly any nodes under the support, whilst the physical fabric swayed to both sides; this is illustrated with a transparent fabric in Figure 6.2. The virtual support is 10mm, significantly thicker than the real support, this thickness might influence the drape of the virtual fabric and prevent the nodes from flipping over.



a b

Figure 6.2: Formed nodes under the support; real (a) and virtual (a) specimen.

6.2 Drape measurements virtual fabrics

In the previous chapter the relationship between fabric drape and the following measurements was demonstrated; fabric weights, KES and FAST bending properties, KES and FAST shear properties, KES tensile linearity and FAST extensibility at 5 gf/cm. To create the virtual fabrics the fabrics weights and the KES and FAST measurements given in Table 6.1 are used.

Table 6.1: KES and FAST properties used to create the virtual fabrics

Property	KES		FAST	
Bending	B	Bending rigidity	B	Bending rigidity
Shear	G	Shear rigidity	G	Shear rigidity
Tensile	EMT	Tensile elongation	E5	Extensibility at 5 gf/cm
	LT	Tensile linearity	E20	Extensibility at 20 gf/cm
	WT	Tensile energy	E100	Extensibility at 100 gf/cm
Surface	MIU	Coefficient of surface friction	. . .	. . .

The virtual fabric drape is created and the virtual drape coefficient calculated as explained in section 3.2.3 and 3.3.4. The virtual fabrics are draped face-up and they are compared with the face-up measurements of the real drapes, the mean face-up drape coefficients differ for some fabrics from the mean of face and back, as illustrated in section 5.2.1.

A general advice of the software supplier is to simulate the more stiff fabrics with a higher mesh size and the more limp fabrics with a lower mesh size. For this investigation it was decided to use a mesh size of 6 mm for fabrics with a face-up drape coefficient of 30% and lower, and a mesh size of 15 mm for fabrics with a face-up drape coefficient of 60% and higher. Fabrics with drape coefficients between 30% and 60% are simulated with a mesh size of 10 mm.

6.2.1 Relationship between real and virtual drape created with KES and FAST data

The chart in Figure 6.3 presents the mean number of nodes for the real and virtual fabrics created with KES and FAST data. Five of the eight virtual fabrics created with KES properties have exactly the same number of nodes as the physical fabrics, for the virtual fabrics created with FAST properties this is one of the eight fabrics.

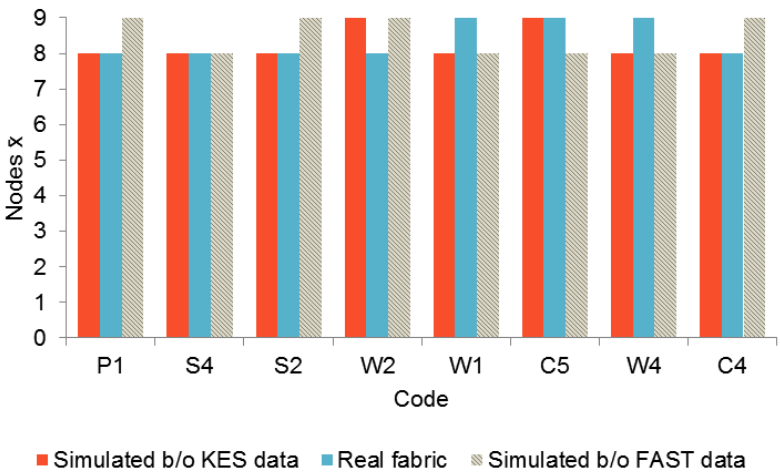


Figure 6.3: Number of nodes real and virtual.

Table 6.2 presents the measured drape coefficients and the standard deviation for the real and the virtual fabrics created with KES and FAST data, as well as the used mesh size.

The simulated fabrics with drape coefficients below 50 % have the best fit with the real drape coefficients, however, the drape coefficient of fabrics C2 and S1 both simulated with FAST are also comparable to the real drape coefficient. For fabric C2 the simulation based on KES data is far below the real drape coefficient, in section 5.3.8 the measured bending rigidity values of C2 are significant lower for KES than for FAST, this is possibly due to a measurement error which will be discussed in section 6.2.2.The drape coefficient of C2 created with FAST data is similar to the real drape coefficient, however, the variance between the measurements is high with a minimum drape coefficient of 64% and a maximum of 94%. Fabric C3 has a large standard deviation for both virtual drape coefficients; for the simulation with KES data the minimum drape coefficient is 58% and the maximum 92%, for the simulation with FAST data the minimum drape coefficient is 61% and the maximum is 80%. This high variance might be due to the missing pressure disc or simulation errors. In general the drape coefficients simulated with FAST have a higher variance between the measurements.

Table 6.2: Face-up drape coefficient of the real and virtual drape

	Real drape		Virtual drape				
			Mesh	created with KES data		created with FAST data	
Code	x̄ DC	SD	size	x̄ DC	SD	x̄ DC	SD
P1	20%	0.686	6	25%	0.416	22%	1.268
S4	29%	2.130	6	34%	1.577	33%	1.661
S2	29%	0.967	6	27%	0.603	32%	1.348
W2	35%	2.252	10	33%	0.400	33%	1.542
W1	43%	0.967	10	41%	1.959	35%	0.585
C5	57%	2.505	10	49%	3.229	43%	3.055
W4	60%	1.693	15	47%	1.596	45%	3.883
C4	73%	2.212	15	61%	2.769	55%	3.389
C2	85%	1.979	15	58%	0.415	83%	10.663
S1	88%	0.900	15	. . .	. . .	90%	3.270
C3	91%	1.832	15	73%	13.514	69%	7.723

The correlation between the real and virtual drape is illustrated in the graph of Figure 6.4, fabric S1 is omitted in the graphs and the calculation of Pearson's correlation coefficient, as S1 is not simulated with KES. Except from P1, S4 and C2 the virtual drape coefficients created with KES properties are more close to the drape coefficients of the physical fabric, as visualised in the graph.

Statistically significant and very strong positive correlations are found between the real and virtual drape coefficients with $r = 0.97$, $p<0.0001$ for the cloth simulated with KES data, and for the cloth simulated with FAST data with $r = 0.94$, $p<0.0001$.

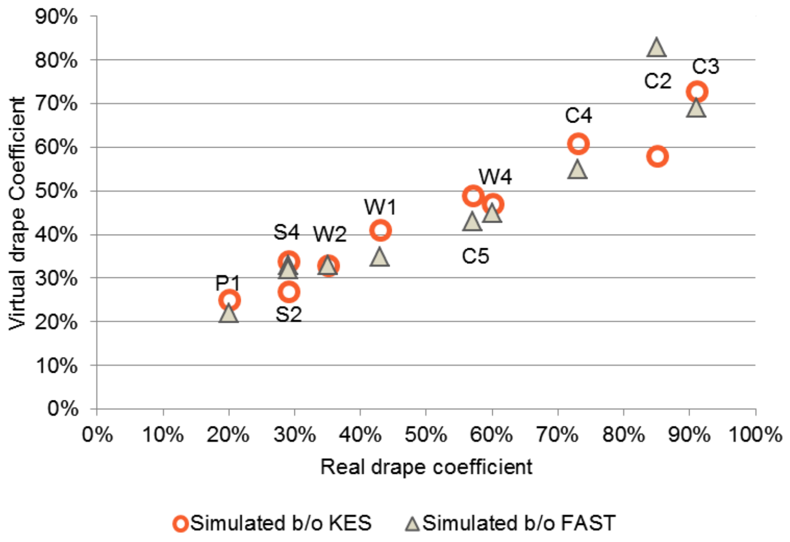


Figure 6.4: Correlation between real and virtual drape coefficients.

6.2.2 Accuracy of the drape created with KES and FAST data

The drape coefficients are simulated with commercial software Lectra Modaris® and the simulations depend on the formulae used to simulate the cloth with the fabric mechanical and physical measurements. Nevertheless, the methods used to validate the drape simulated based on these properties can easily be applied in other software packages.

As illustrated in the previous sections the correlation between the drape coefficients of the real and virtual fabrics created with KES and FAST properties is high. For both measurement systems drape coefficients above 50% have more dissimilarity, except for silk organza S1 and cotton C2 both created with FAST data. Fabrics C2 and C3 are difficult to handle during measurement; they easily crease and fold. The inaccuracy of virtual fabric C2 created with KES properties is expectedly due to an error during measurement, this is based on the following; the physical fabrics C2 and C3 are indicated with a similar drape by the textile and user panel (Table 4.3) and have similar drape coefficients (Table 6.2), the measured properties for shear and bending with both KES and FAST are comparable for the two fabrics except for the bending rigidity, an important property for the simulation, for which KES has a significantly lower value compared to FAST (section 5.3.2, 5.3.3, 5.3.8 and appendices 7 and 8). The high standard deviation for the virtual simulated fabrics C2 and C3 might indicate handling difficulties during simulation as well. For the other dissimilar virtual fabrics, it is not found if this is due to the missing pressure disc, the thickness of the support disc, caused by errors during measurement of the fabrics, or simulation errors.

6.3 Relationship between drape coefficient and judgment of real and virtual drape

During the subjective assessment of the physical and virtual drape the user panel assessed the images of the abstracted drape profile view (Figure 3.15d and 3.17d).

6.3.1 Judgement of stiffness and amount of the real and virtual drape

The user panel judged the stiffness and amount of drape of the physical as well as the drapes simulated with KES and FAST properties. Each image was presented in random order according the methods described in section 3.4.4.2.

The chart in Figure 6.5 presents the results of the assessment of the stiffness of the real and virtual drapes by the user panel. The judged stiffness of the real and virtual fabrics increases with the drape coefficient. Most of the data points of the real and virtual fabrics are positioned closely to each other. Significant positive correlations between the stiffness of drape and the drape coefficient are found with; r = 0.97, p<0.00001 for the real drape, r = 0.95, p<0.00010 for the drape simulated with KES data and r = 0.96, p<0.00010 for the drape simulated with FAST data.

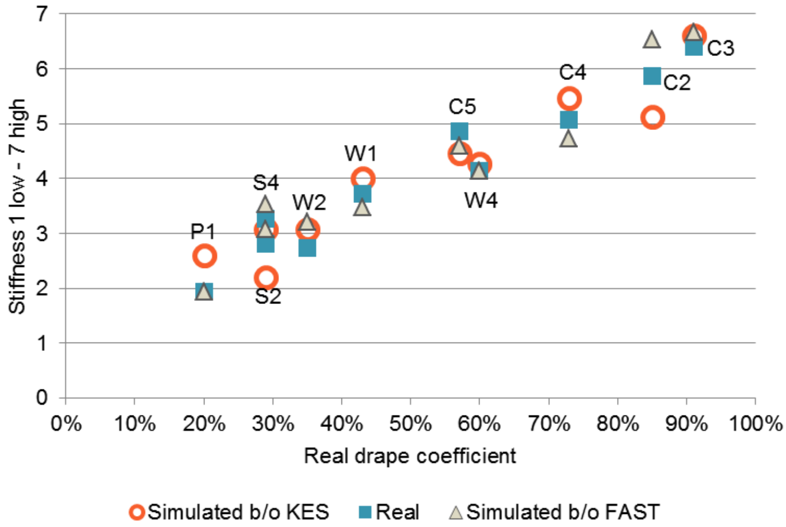


Figure 6.5: Correlation between real drape coefficient and judgement of stiffness of drape.

The chart in Figure 6.6 presents the results of the assessment of the amount of the real and virtual drape by the user panel. The judgment of the amount of the physical and simulated drape is opposite to the judged stiffness of drape. Significant negative correlations between the amount of drape and the physical drape coefficient are found with; r = -0.95, p<0.0001 for the real drape, r = -0.88, p<0.0100 for the drape simulated with KES data and r = -0.94, p<0.0001 for the drape simulated with FAST data.

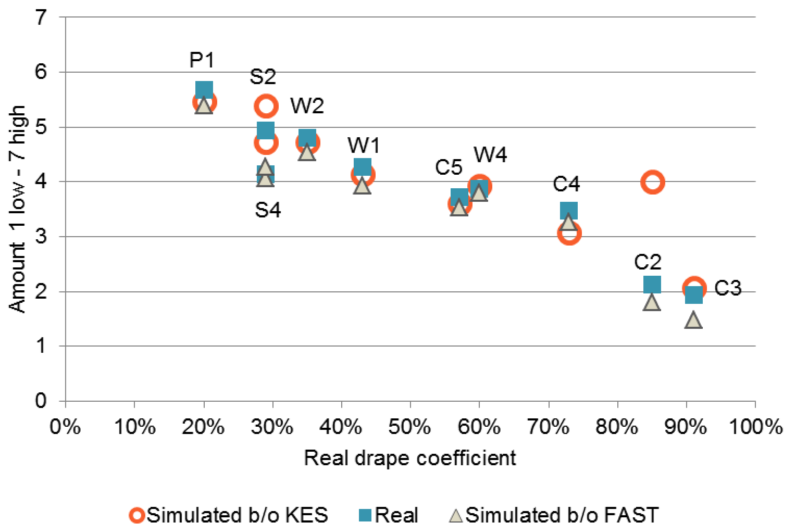


Figure 6.6: Correlation between real drape coefficient and judgement of amount of drape.

The correlation presented in this section is comparable to the correlation between the physical drape coefficient and the judgement of the stiffness and amount of the physical drape based on the different perspectives of the drape (Figure 3.21) presented in section 5.4.2.

6.3.2 Judgement of similarity of drape profile

Another task of the user panel was to indicate similar draping fabrics based on the abstracted drape profile views of the virtual and real fabrics. They judged the similarity of drape based on pairs of two images of the same fabric consisting of the real drape image used throughout the survey (real[1]) in combination with:

a) the physical drape; a second drape of the same fabric specimen (real[2]);
b) the virtual drape of the fabric simulated with KES measurements;
c) the virtual drape of the fabric simulated with FAST measurements.

The images were presented in random order. The judgement of the user panel was given as the following.

Very high: The drape is nearly identical.
High: The drape is mostly similar.
Average: The drape is half similar and half dissimilar.
Low: The drape is mostly dissimilar.
Very low: There is no relationship between the drape of the fabrics.

Figure 6.7 present the sum of “very high” and “high”, ”average”, as well as the sum of “low” and “very low” similarity indicated by the textile panel for the drape combinations described above. The user panel found 65% of the drapes of the same real fabric specimen similar, which is considerably below 78%, what is more, a quarter of the fabrics drape half similar/half dissimilar, whilst 10% of the fabrics drape is mostly dissimilar according to their judgment. This dissimilarity between two drapes of the same physical specimen needs to be taken in consideration regarding the virtual simulated drape. Compared to the similarity between the two drapes of the real specimen the similarity with the real fabrics is 33% lower for the virtual fabrics created with KES data and 17% lower for the fabrics created with FAST data. If C2 with the assumed measurement error is omitted the similarity for the simulations based on KES would increase, nevertheless, those measurement errors are ineluctable with difficult to handle fabrics. The virtual fabrics created with FAST have more similarity with the real drape according the panel, this is in line with their judgment of the stiffness and amount of drape and in contrast with the objectively measured drape coefficients, where the highest correlation is found between the drape simulated with KES data and drape coefficient.

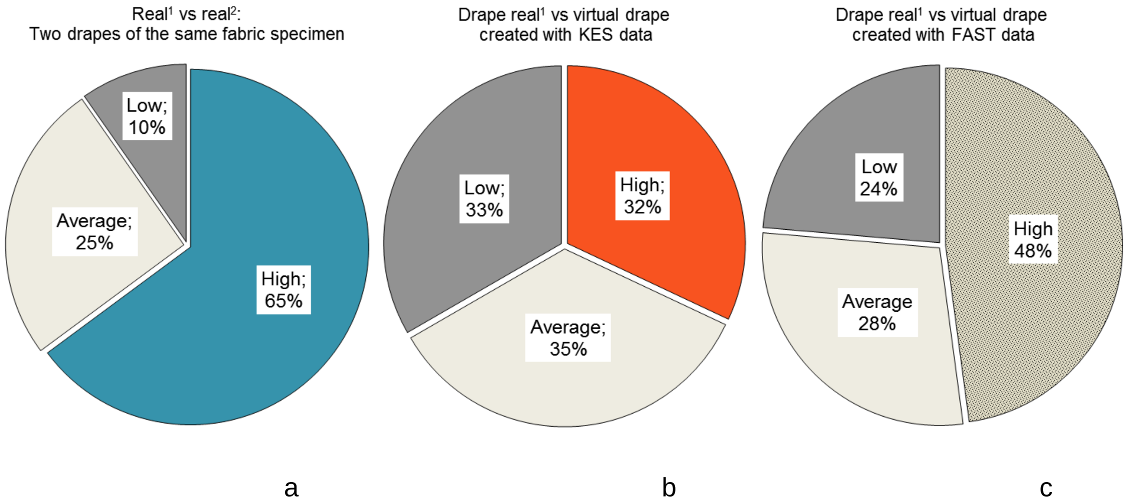


Figure 6.7: Similarity between drape profiles in proportion: (a) two drape relaxations of the same fabric specimen (real¹ vs real²), (b) real¹ drape and virtual drape b/o KES data, (c) real¹ drape and virtual drape b/o FAST data.

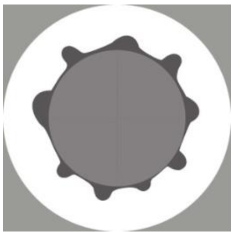
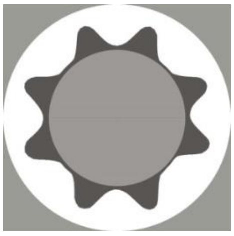
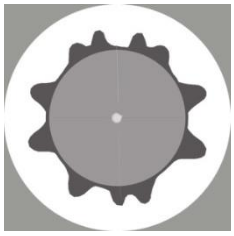
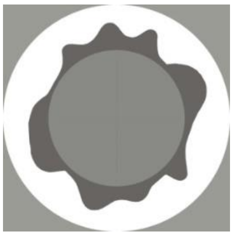
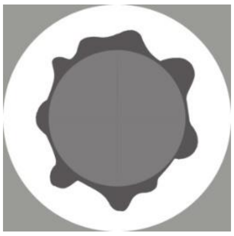
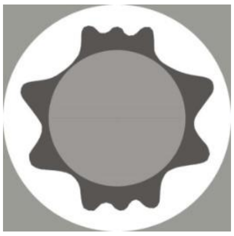
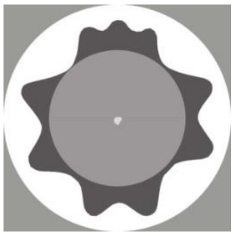
Table 6.3 shows more details of how the user panel judged the drape similarity. They indicated that only for a few fabrics the virtual drape was nearly identical with the real drape. Moreover, they found that the drape was highly similar for a quarter of the drapes of the real fabric with the same swatch, which is basically very low for the drape of exactly the same fabric specimen.

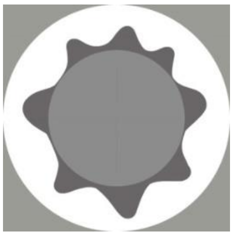
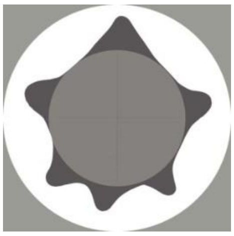
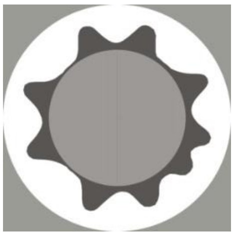
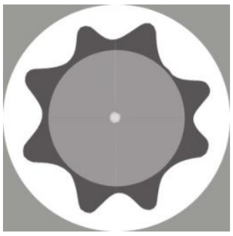
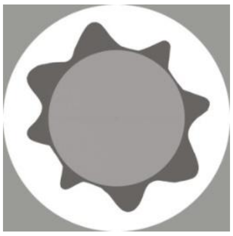
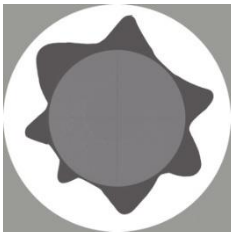
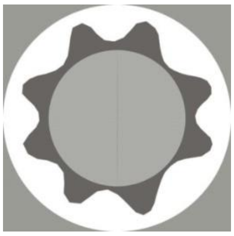
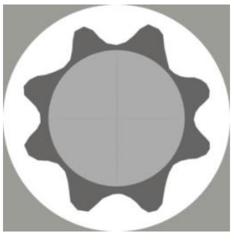
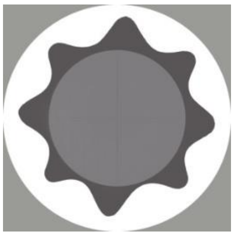
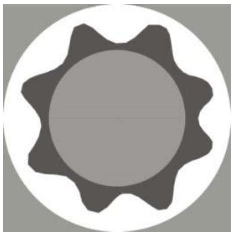
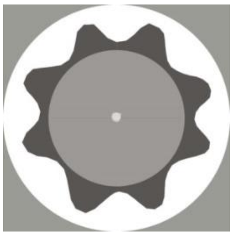
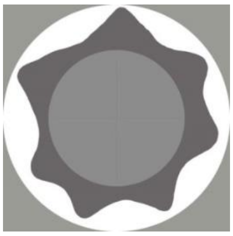
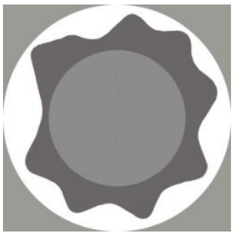
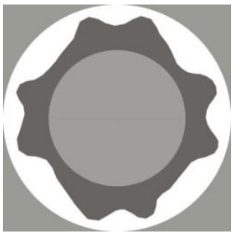
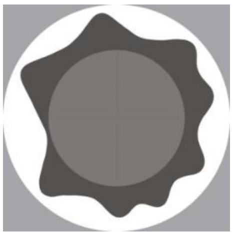
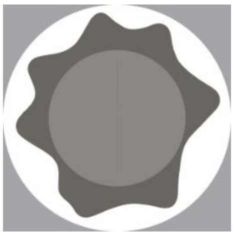
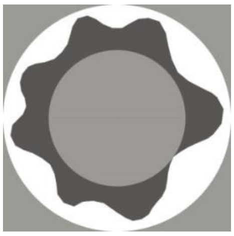
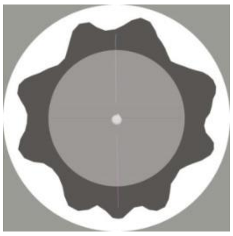
Table 6.3: Similarity between drape profiles

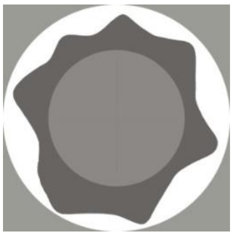
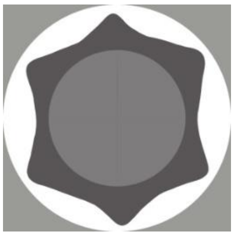
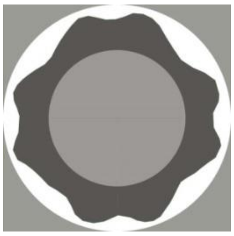
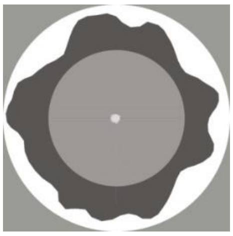
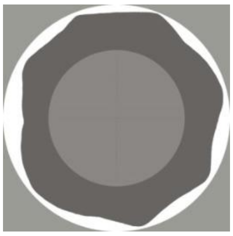
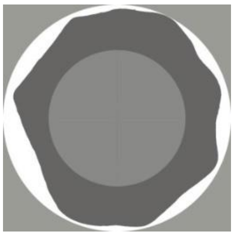
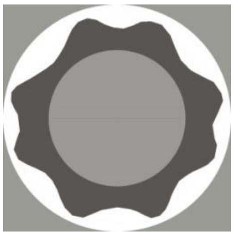
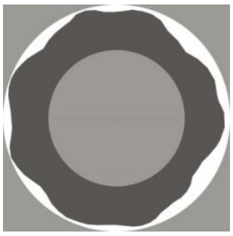
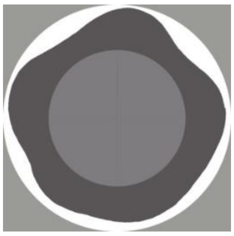
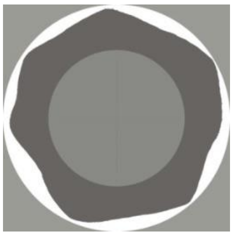
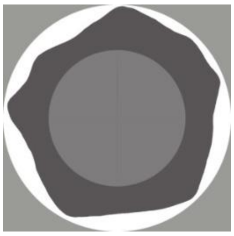
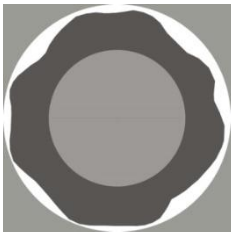
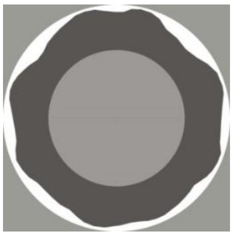
	Similarity of drape profile between drape real^1 and:		
	Real^2 (a)	Virtual b/o KES data (b)	Virtual b/o FAST data (c)
Very High	24%	4%	6%
High	41%	28%	42%
Average	25%	35%	28%
Low	9%	20%	20%
Very low	1%	13%	4%

Table 6.4 below illustrates the similarity between the drape profiles of individual fabrics indicated by the user panel, next to the “average”, the sum of “very high” and “high” as well as “low” and “very low” are given, for “average” the arrows mark if the second larger part is indicated high ↑ or low ↓. During the survey the image of real drape^1 in the first colon was always assessed in combination with one of the other images, they were presented in random order to the user panel.

Table 6.4: Similarity of drape profile of real drape with real and virtual drape per fabric

Real drape^1 Specimen x Drape 1	Real drape^2 (a) Specimen x Drape 2	Virtual drape (b) based on KES properties	Virtual drape (c) based on FAST properties
			
P1^1	P1^2 ~ P1^1: High 87%	P1$^{V\ b/o\ KES}$ ~ P1^1 Low 87%	P1$^{V\ b/o\ FAST}$ ~ P1^1: High 47%
			
S4^1	S4^2 ~ S4^1: High 53%	S4$^{V\ b/o\ KES}$ ~ S4^1: Average 53%↓	S4$^{V\ b/o\ FAST}$ ~ S4^1: Low 53%

Real drape[1] Specimen x Drape 1	Real drape[2] (a) Specimen x Drape 2	Virtual drape (b) based on KES properties	Virtual drape (c) based on FAST properties
			
$S2^{1}$	$S2^{2}$ ~ $S2^{1}$: Low 53%	$S2^{V\ b/o\ KES}$ ~ $S2^{1}$: High 60%	$S2^{V\ b/o\ FAST}$ ~ $S2^{1}$: High 67%
			
$W2^{1}$	$W2^{2}$ ~ $W2^{1}$: High 67%	$W2^{V\ b/o\ KES}$ ~ $W2^{1}$: High 53%	$W2^{V\ b/o\ FAST}$ ~ $W2^{1}$: High 47%
			
$W1^{1}$	$W1^{2}$ ~ $W1^{1}$: High 87%	$W1^{V}$ b/o KES ~ $W1^{1}$: High 73%	$W1^{V\ b/o\ FAST}$ ~ $W1^{1}$: High 73%
			
$C5^{1}$	$C5^{2}$ ~ $C5^{1}$: Average 47% ↑	$C5^{V}$ b/o KES ~ $C5^{1}$: Average 53% ↓	$C5^{V\ b/o\ FAST}$ ~ $C5^{1}$: Average 53% ↑
			
$W4^{1}$	$W4^{2}$ ~ $W4^{1}$: High 67%	$W4^{V\ b/o\ KES}$ ~ $W4^{1}$: High 40%	$W4^{V\ b/o\ FAST}$ ~ $W4^{1}$: Low 53%

Real drape^{1} Specimen x Drape 1	Real drape^{2} (a) Specimen x Drape 2	Virtual drape (b) based on KES properties	Virtual drape (c) based on FAST properties
			
$C4^{1}$	$C4^{2}$ ~ $C4^{1}$: High 40%	$C4^{V\ b/o\ KES}$ ~ $C4^{1}$: Average 53%	$C4^{V\ b/o\ FAST}$ ~ $C4^{1}$: High 47%
			
$C2^{1}$	$C2^{2}$ ~ $C2^{1}$: High 73%	$C2^{V\ b/o\ KES}$ ~ $C2^{1}$: Low 93%	$C2^{V\ b/o\ FAST}$ ~ $C2^{1}$: High 53%
			
$S1^{1}$	$S1^{2}$ ~ $S1^{1}$: High 100%		$S1^{V\ b/o\ FAST}$ ~ $S1^{1}$: High 60%
			
$C3^{1}$	$C3^{2}$ ~ $C3^{1}$: High 80%	$C3^{V\ b/o\ KES}$ ~ $C3^{1}$: High 53%	$C3^{V\ b/o\ FAST}$ ~ $C3^{1}$: High 80%

In general, the virtual fabrics follow the amplitude of the real fabrics, however, the distribution of the nodes may differ. This typical behaviour is also obtained from the real fabrics, the draped specimen of fabric S2 forms 3 nodes in the warp in drape profile $S2^{1}$ and they coalesce in one node in drape profile $S2^{2}$, as illustrated in Table 6.4 above. The light weight silk organza S1 and heavy weight cotton fabric C3 have very similar drape coefficients, however, their drape profiles show a different amplitude, which is also mimicked in the virtual drapes. Nevertheless, the particularly irregular drape of fabric S4 is apparently difficult to represent, although the virtual draped counterpart shows a typical irregularity, and the minimum amplitude follows the original drape, the distribution of the nodes is different and the typical shape of the nodes in the real fabric are unequalled in the virtual specimen of S4.

6.4 Drape coefficient versus drape profile

Table 6.5 below gives an overview of the correlations presented in the previous sections. The correlation for the objectively measured drape coefficients and the subjective assessment of stiffness of drape are quite similar, whilst this is for the amount of drape slightly lower.

Table 6.5: Overview correlation between real and virtual drape

Correlation between:		r	*p* <
Real and virtual Drape coefficient	b/o KES data	0.97	0.00010
	b/o FAST data	0.94	0.00010
Judged stiffness of drape and drape coefficient	Real	0.97	0,00001
	b/o KES data	0.95	0.00010
	b/o FAST data	0.96	0.00010
Judged amount of drape and drape coefficient	Real	-0.95	0.00010
	b/o KES data	-0.88	0.01000
	b/o FAST data	-0.94	0.00010

In Table 6.4 the fabrics are ordered by increasing drape coefficient, the drape profile expands in parallel with the drape coefficient, whilst the differences between the minimum and maximum amplitude decreases. The drape coefficient is a good indicator of the stiffness of the drape which aligns well with the panel's perception. The drape profile, however, is more sophisticated as it reveals additional information about the nature of the drape. The real drape coefficients of the silk fabrics S4 and S2 are equal, although the real drape profiles are different. The same is the case for physical fabrics C2, S1 and C3, in spite of their nearly identical drape profiles, the amplitude of the drape profile of silk organza S1 is dissimilar from cotton fabrics C2 and C3.

6.5 Summary chapter 6

The analysed correlations between the real and virtual drape presented in this chapter are high and statistically significant. The perception of stiffness as well as the amount of the virtual and real drape is closely related. Moreover, they correlate highly with the measured drape coefficient, however, the investigated drape profile allows more accurate distinction to be made between the particular fabric drapes as well as revealing the similarity and dissimilarity between the drapes. The drape similarity assessment agrees with the statement of Breen, House and Wozny (1994) who pointed out that due to the variation in drape of the real cloth the drape of the virtual could never be exactly the same.

For users of virtual technology software, the methods applied in this investigation could easily be applied to verify the drape of virtual fabrics with the real drape.

As demonstrated with the correlations the fabrics mechanical properties measured with KES and FAST are suitable to represent the fabric drape in commercial virtual garment software based on a particle mesh system.

As indicated by the standard deviation the fabrics with drape coefficients above 50% have a high variance between the measurements and the average drape coefficient is generally lower, it needs to be further investigated if the dissimilarity is due to the missing support disc or that the software supplier needs to improve the equations. Furthermore, the mesh size used influences the simulation, a higher mesh size of 15 mm results in a better simulation of stiff fabrics with drape coefficients from 60%, nevertheless the results are more rough and angular. For limp draping fabrics with drape coefficients below 30% the results with a mesh size of 6 mm are appropriate, however, this will require computational power and longer simulation time for large parts of cloth. Future research on these topics will be discussed in section 7.3.

Measurement errors cause inaccuracies, an easy to use measurement principle with accurate and reliable results would facilitate users of 3D virtual technology.

Another aspect is the limited availability of the KES and FAST equipment for users of 3D virtual technology. In an ideal situation fabric suppliers provide the fabrics with the mechanical and physical properties, users could fit and visualise the designs prior to ordering the fabrics, which would contribute to a more responsible design process. This would require a standard for the units and properties used by the software developers.

7 Conclusions, limitations and future work

7.1 Conclusions

This research studied the suitability of KES and FAST data to represent fabric drape in a virtual environment by using commercially available software to simulate the cloth, as well as how to increase insight into the perception of fabric drape in a virtual environment.

The investigation has been executed with a range of woven fabrics with weights varying from sheer to medium heavy, selected on their drape profile as well as drape variation. Images, showing the physical fabrics on different supports and from different perspectives, were presented to an expert textile panel to define the drape. These definitions were validated by an expert user panel. Moreover, both panels judged the stiffness and amount of drape, as well as their preference for the support and view to read the drape. The relationships between drape coefficients, obtained with Cusick's drape tester, and the fabrics' mechanical and physical properties, retrieved with the KES and FAST instruments, were examined, as well as the relationships between drape coefficients and the panel's judgement of stiffness and amount of drape. Furthermore, based on the fabric mechanical and physical properties the drape was simulated on the virtual support disc, developed for this research. The virtual drape coefficient was derived and correlated with the drape coefficient of the physical fabric. Moreover, the user panel assessed the disc abstracted drape profile view images of the real and virtual drape to judge the stiffness and amount of drape, as well as the similarity of the physical and simulated drapes of the same fabric. Based on the results a number of conclusions can be drawn.

1. Relationships between physical and mechanical properties and drape

a) Correlation between physical and mechanical properties and drape coefficient

Statistically significant correlations with the drape coefficient are found for fabric weights, for KES bending hysteresis, bending rigidity, shear hysteresis, shear rigidity and tensile linearity, as well as for FAST bending rigidity, bending length, shear rigidity and tensile elongation at 5 gf/cm. Fabrics with low values for KES and FAST bending and shear rigidity as well as for KES bending and shear hysteresis have in general low drape coefficients. These correlations confirm with earlier research, nevertheless, they differ to some extent due to the contrasts in the range of fabrics as illustrated with silk organza fabric S1.

b) Variation in drape

Fabrics with a high variation in drape profile can have a low variance in drape coefficient. Apparently, the nodes are differently divided over the drape profile, whilst the drape's surface area remains equal. The variation in drape profile and variance in drape coefficient may be influenced by the interference between bending and shear properties in relation to the fabric weights per unit area.

c) Correlation between drape coefficient and subjective evaluation of drape

The judged stiffness of drape is inversely related to the amount of drape, which confirms with previous research. Moreover, statistically significant correlations between drape coefficient and the subjective evaluation of drape are found, a positive correlation for stiffness of drape with $r = 0.959$, $p<0.0002$ and a negative correlation for amount of drape with -0.970, $p<0.0001$.

2. Suitability of KES and FAST data to represent fabric drape in a virtual environment

a) Correlation between real and virtual drape coefficient

The accuracy of fabric mechanical and physical properties acquired with KES and FAST to represent the drape of a measured fabric is demonstrated with a statistically significant correlation. For the cloth simulated with KES properties the correlation between the real and virtual drape coefficient is high with $r = 0.97$, $p<0.0001$, also the virtual fabrics created with FAST data have a high correlation between the real and virtual drape coefficient with $r = 0.94$, $p<0.0001$.

b) Correlation between the evaluation of the virtual and real drape

The subjective judgement of the virtual and real drape confirms the suitability of KES and FAST data to accurately represent fabric drape in virtual cloth. All correlations are statistically significant, the correlation between stiffness of real and virtual drape is positive with $r = 0.95$, $p<0.00010$ for the simulations based on KES data and $r = 0.96$, $p<0.00010$ for the simulations based on FAST data. The correlation between amount of real and virtual drape is negative with $r = -0.88$, $p<0.01000$ for the simulations based on KES data and $r = -0.94$, $p<0.00010$ for the simulations based on FAST data.

Based on the objective measurements the correlations for the simulations with KES data are higher, whilst the simulations with FAST data are judged higher by the user panel.

The statistically significant correlation verifies the suitability of both KES and FAST data for creating virtual fabric drape. The found drape similarity was in general relative low, also for two drapes of the same physical fabric; 65% of the two real drapes of the same specimen was found highly similar, 32% of the drapes simulated with KES data, and 48% of the simulations based on FAST data was found highly similar to the real drape. The drape dissimilarity within the fabric itself stresses the intricateness of measuring fabrics and to represent them in a virtual environment. This is in line with Breen, House and Wozny (1994) who argued that virtual drape could not exactly mimic real drape through the variation occurring in the real drape.

For some of the simulations the drape is similar, whilst others have no similarity with the real drape, some fabrics are better represented in the simulation with KES data, others in the simulation with FAST data. It is not found if this is due to measurement or simulation errors.

3. Contribution to increasing perception of fabric drape

a) Fabric drape categories

Fabrics can be divided into categories based on the way they drape. Those categories are related to the drape coefficient. Three drape categories are defined by the textile panel and validated by the user panel: the first category is *well draping* for fabrics with limp and fluid drape. The second category is *soft drape* for fabrics with soft and supple drape but with some stiffness. The third category is *body* for fabrics with a stiffer drape and having enough body to give shape.

Moreover, a relationship is found between the categories and the rated stiffness and the amount of drape. Fabrics with category *well draping* are judged limp, with category *body* are judged stiff and with category *soft drape* are judged in-between limp and stiff. For the amount of drape the relationship is inverse.

Furthermore, the drape category *well draping* aligns with the division Cusick made to measure the drape coefficient for limp fabrics with drape coefficients below 30%. The border between the categories *well draping* and *soft drape* is close to a drape coefficient of 31%, and for *soft drape* and *body* between 44% and 56%.

By ordering the fabrics in the drape clusters, the user panel created four drape groups by splitting the category *body* in two, with a sharp border between 74% and 87%, which is close to the border defined by Cusick (1962; 1968). Nevertheless, their agreement for the fabrics in the category *body* was high.

b) Identifying key words

The tentative investigation showed that identifying key words can distinguish between contrasting fabrics with a similar drape, such as a felted wool and a crisp cotton, or a weighty cotton and a sheer organza. In combination with the drape category they may contribute to a better understanding of fabric drape when searching, assessing and selecting fabrics in a virtual environment.

c) Support and view

The perception of stiffness and amount of drape are highly correlated with the drape coefficient, which is a good indicator for the stiffness of drape, nevertheless, the found similarity between drape profiles illustrates that the amplitude and shape of the nodes gives a more complete insight into the particular drape of some fabrics.

The user panel's judgement of the fabric drape based on the images with the abstracted drape profile view was equal to their judgement of the drape based on the different perspectives of the drape, where the fabric was presented on the sphere and disc with front view, drape profile view and abstracted drape profile view, as well as the videos with the rotating front views. These results show the panel's ability to read the drape from the disc abstracted drape profile view only.

From the two supports used to present the drape, the sphere was highly preferred to the disc. From the views, the video with the rotating view of the drape was the most preferred, with 50% for the rotating disc and sphere together. Second preferred, with 23% for the disc and sphere together, was the abstracted drape profile view showing the proportions between the support, the undraped and the draped specimen. The video with the rotating view is highly preferred because it is in 3D and offers the most information. Nevertheless, the rationale and the drape clusters created illustrate that the combination of all the views together contribute to an increased insight into the drape and facilitate drape perception. For the static views the drape clusters created by the user panel show that the abstracted drape profile views enable the differentiation between fabrics, whereas the sphere front view has the opposite effect.

7.2 Possible research limitations

In this investigation there are several sources for error, they are listed below.

1. Parallel light error

The drape profile and abstracted drape profile view images, described in section 3.2.3, are taken on the light box without a paper ring and parallel light. This is in contrast with the principle of Cusick's drape meter, which is based on the projection of the drape shadow on the paper ring by the parallel light reflected through the parabolic mirror, as described in section 2.3.1.2, this optical distortion is visualised in Figure 7.1.

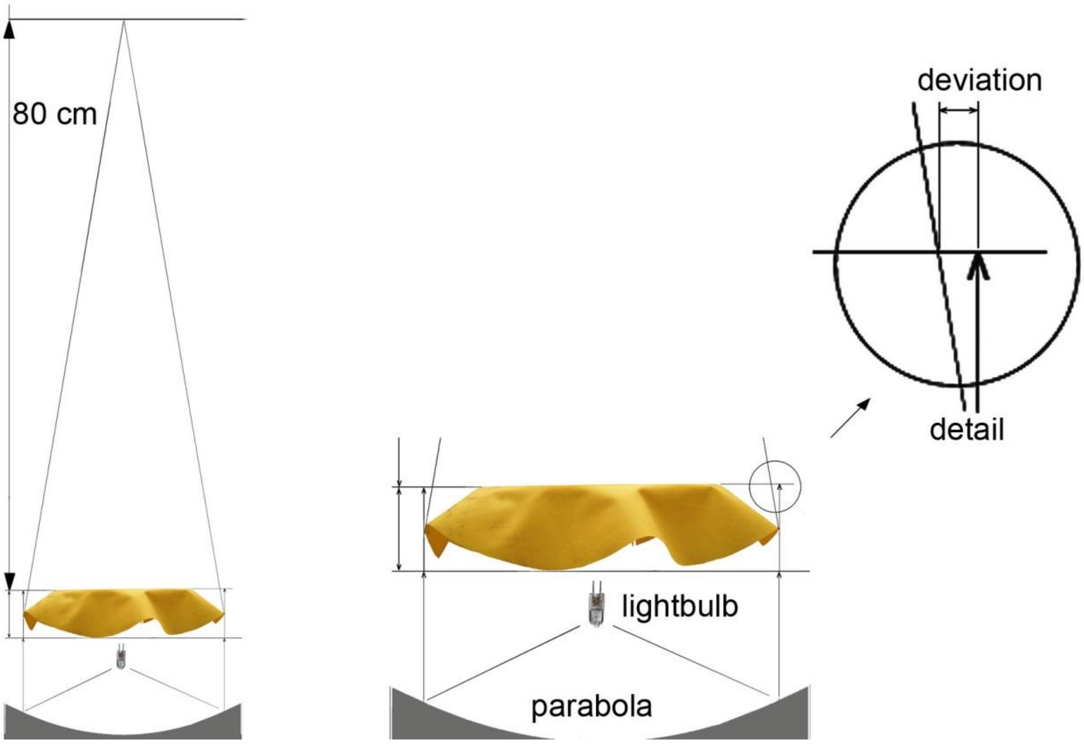


Figure 7.1: Optical distortion through parallel light error.

2. Availability of the textile panel

Due to limited availability, different schedules and working days, for the group session with the textile expert judges to evaluate the defined drape categories, were used with 3 of the 5 judges.

3. Virtual drape and top disc

a) The outcome of the comparison of virtual and real drape coefficients is limited by how the fabric objective measurements are interpreted by the used software.

b) The options to apply fabric objective parameters, as well as the results vary per software package, as discussed in section 2.4.2.

c) During the research period access to multiple commercial software packages able to interpret fabric objective measurements was not available, three available software applications were tested, from which one met the aims of this study and had the option to insert objective properties measured with KES and FAST.

d) The possibility to exactly mimic the real situation in a virtual environment.

e) The pressure disc at the top is missing for the virtual drapes, as described in section 3.2.3.1. Tests without the top disc showed that the real fabric bounces on the plate when lowering the outer ring, resulting in high drape variation and inaccuracy of the grainline, thus it was decided to measure the drape coefficient according the BS5058 (British Standard Institution,1973) with the pressure disc on top. In the case of the images of the drape used for the survey, the pressure disc is used to calibrate and control the proportions of the image, as well as to keep the fabric fixed.

7.3 Suggested future work

1. Relationships between physical and mechanical properties and drape

a) Correlation between physical and mechanical properties and drape coefficient

Further investigation of the effect of tensile measurements on drape might be executed with different draping stretch and jersey fabrics, preferably containing similar light and medium to heavy weight jersey fabrics with some elastane to investigate the influence of extensibility and weight on drape. A jersey viscose fabric with some elastane has a relatively high weight in relation to its thickness and might therefore have a different drape from a similar lighter fabric.

b) Variation in drape

How the variation of the drape profile is influenced by the mechanical and physical properties was not a particular aim of this study, nevertheless, inspired by the literature and some drape tests the variation in drape profile became a vital selection criterion and was partly studied. Future research in how the fabric mechanical and physical properties interact and influence the drape would contribute to increasing the insight into fabric drape and the anisotropic nature of the material. For this research a large group of fabrics is recommended, consisting of groups with similar draping fabrics and dissimilarity in drape between the groups.

2. Suitability of KES and FAST data to represent fabric drape in a virtual environment

The fabrics selected for this research were selected based on variety and similarity in drape, with drape coefficients ranging from low to high, to obtain more insight into the representation of fabric in a virtual environment it is recommended to test a larger range of fabrics.

Some fabrics are not well represented; to retrieve the cause further investigation is recommended. A cause for inaccuracies might be the lack of the pressure disc on top of the virtual drape or the thickness of the disc. To establish a thinner virtual drape disc including a pressure disc is suggested for further investigation. Nevertheless, the software provider may need to facilitate this, as well as an examination to find out if the cause is a simulation error.

Another option to retrieve the cause of the inaccuracies might be further testing with nearly identical fabrics to obtain measurement errors.

The tests were executed with one software supplier, Lectra Modaris®, the representation of the KES and FAST data depends on the used formulas. Future testing with a wider range of suppliers to investigate how fabric drape is represented based on different calculations will enlarge insight.

The function of the pressure disc is not negligible, however, an investigation can be executed with and without pressure disc to measure the impact of the disc on the drape.

The mesh size influences the drape results and draping time, for limp draping fabrics the results are more refined and accurate with lower mesh sizes, however, a large amount of computation time or computer power is required. For stiff fabrics a larger mesh size results in a more accurate representation of the fabric drape and a faster simulation time, however, the visual effect is rough. The computation time and computer power are most likely a matter of time. Nevertheless, improvement of the visualisation of the rough mesh size is recommended. Moreover, a rule of thumb for the best usable mesh size will speed up the digital work processes. Future investigation may focus on a relationship of the mesh size with the drape coefficient and/or the drape categories, also the bending length may be suitable due to the high correlation with the drape coefficient, as well as with the perception of stiffness, moreover it is relative fast to measure this property.

3. Contribution to increasing perception of fabric drape

Further research with international expert panels could contribute to establish an internationally recognised drape vocabulary consisting of fabric drape categories and fabric identifying key words.

a) Fabric drape category

To define the exact borders between the categories a larger range of fabrics with drape coefficients between the borders of the categories, defined in section 5.4.3, needs to be judged by subjects.

Based on the contrasts between the created drape groups and the ordering of the fabrics in the categories a preliminary investigation was undertaken. The results of the present research were discussed with a group of experts consisting of two participants of the textile panel, four participants of the user panel, completed with three new subjects who were not involved in the previous assessments, namely; one textile and two design teachers. They came up with the suggestion to work with four categories, for a trial they divided the fabrics into the same clusters as the user panel during the survey, thus splitting the category *body* in two. To deal with the split category *body* they suggested *rigid* and *semi-rigid*, also *fluid* was opted for in combination with *semi-fluid*. Further investigation is recommended to refine the categories and to examine if the category *body* is an overarching category over *rigid* and *semi-rigid*.

b) Identifying key words

It is recommended to continue this first endeavour to assign identifying key words with a larger variety of fabrics. With the expert group mentioned in the previous section a first step was undertaken; the key words found in this research are discussed and their suggestions are listed in the Table 7.1. Further investigation with a broader range of fabrics judged by a lager panel is recommended.

Table 7.1: List with suggested identifying key-words

Identifying key-word and antonym	Identifying key-word
Crease - Crease resistance	Flowing
Open weave - Closed weave	Springy
Loose weave - Tight weave	Sheer
Body concealing - Body revealing	(Slightly) transparent
Hard - Soft	(Slightly) felted
Rough - Smooth	Grainy
Regular - Irregular	Paper-like
	Crisp

c) Support and view

The different views show from different perspectives how the fabric falls and drapes, this investigation revealed that both supports have their pro's and con's and the intuitive clustering of drapes by the user panel showed that some fabrics are never combined based on the images of the abstracted drape profile views of the sphere and disc, whilst those fabrics are frequently combined on the front view images of both supports. The results demonstrated that the sphere drape profile and abstracted drape profile views enable quick selection based on fabric drape. Further research may involve investigation to provide more accurate draping according to a standard and to retrieve a sphere drape measurement.

Another future research area might be tests with a thicker support disc in real and virtual environments, the thickness of the plate may prevent the fabric from forming nodes under the disc, and ideally make the tests with a 24 cm diameter fabric specimen superfluous.

For this investigation the disc support is cut with a laser, however water-jet cutting would be preferred; there is no heat to wrap up the plate. In combination with 3D printing technology the supports can be effortlessly made, and a similar real and virtual setting can be used for a simple and quick comparison between real and virtual drape, as well as between two virtual environments. Moreover, the disc can easily be validated with the drape coefficient. Software suppliers could collaborate on a virtual drape meter configuration based on Cusick's drape meter for relatively quick and accurate validation, comparison and selection of fabrics based on their drape.

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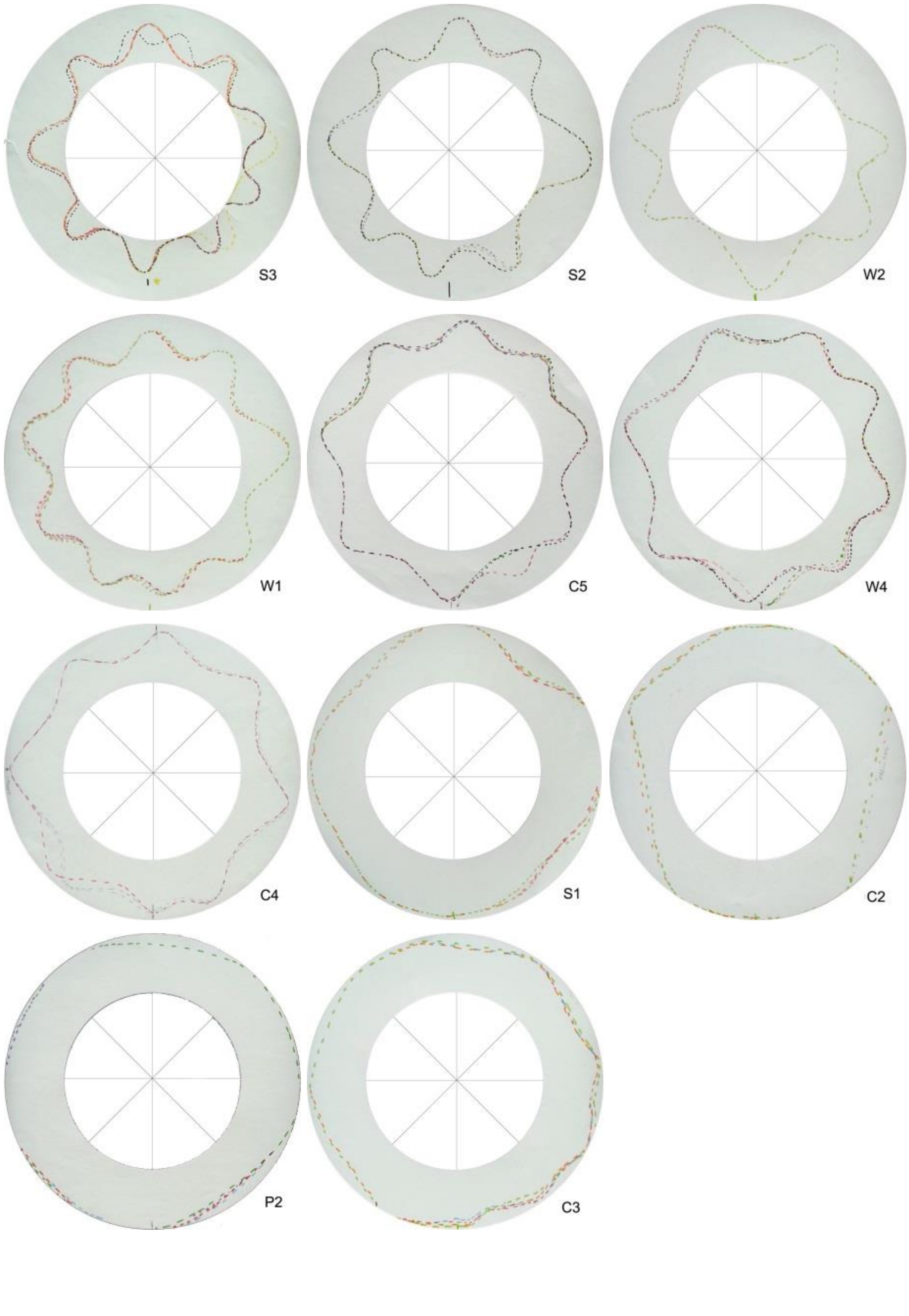
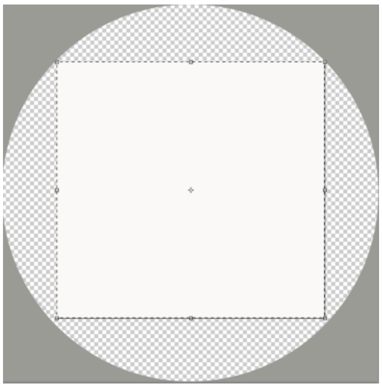
Appendix 1:

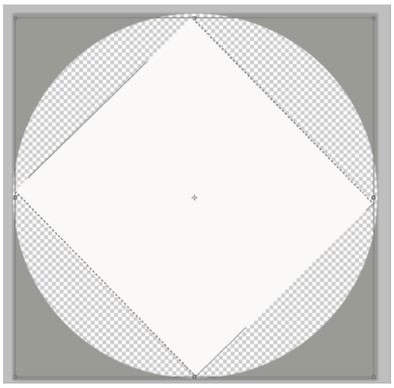
Plots of drape variation tests; repeated seven times without replacing the fabric



Appendix 2:

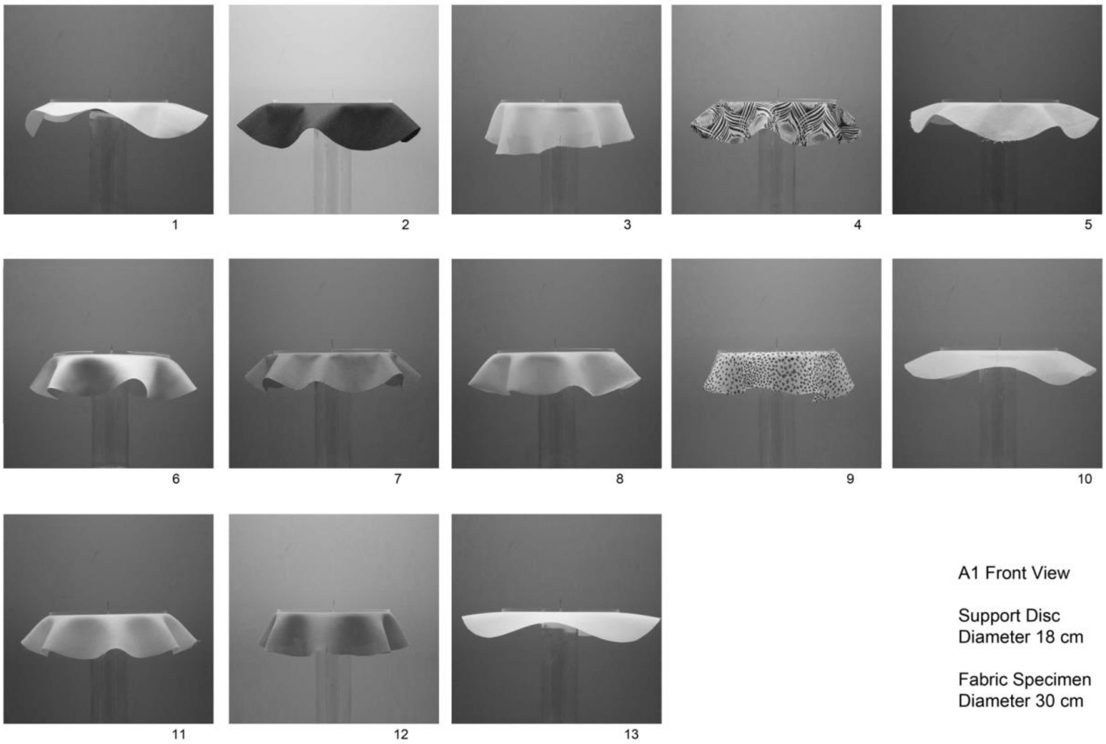
Negligible difference between original and rotated rectangle


Original rectangle counted pixels: 4357440


Rotated rectangle counted pixels: 4357464

Appendix 3:

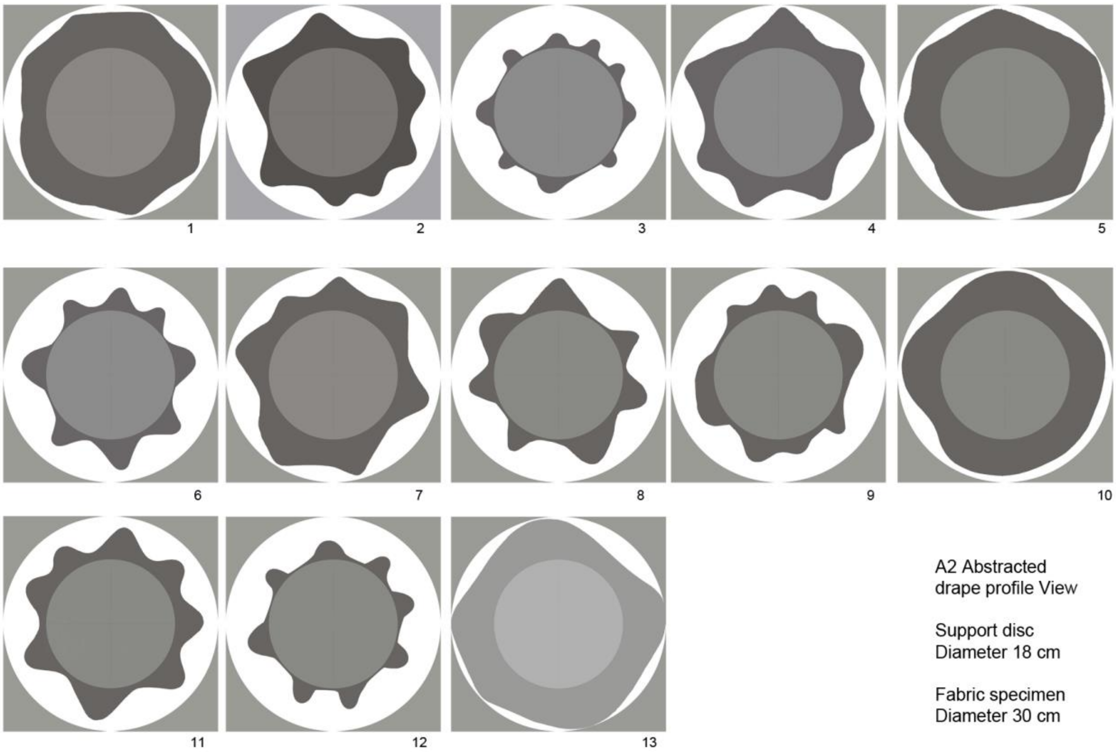
Drape overview A1, A2 and B1



A1 Front View

Support Disc
Diameter 18 cm

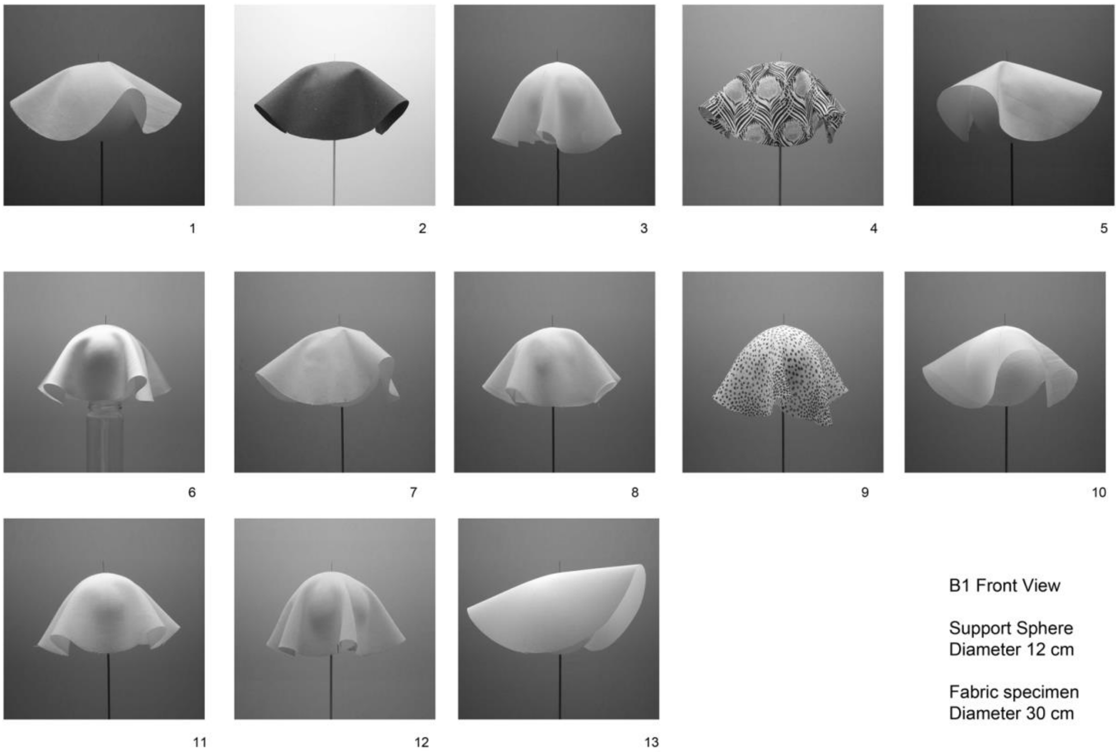
Fabric Specimen
Diameter 30 cm



A2 Abstracted
drape profile View

Support disc
Diameter 18 cm

Fabric specimen
Diameter 30 cm



Appendix 4:

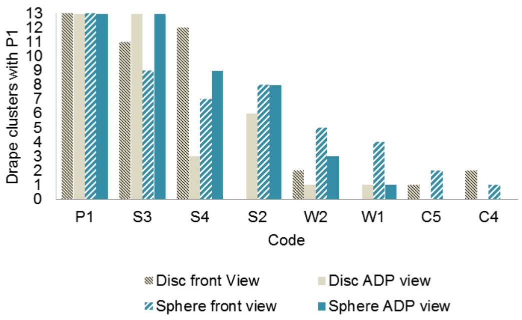
Link and password to the drape videos

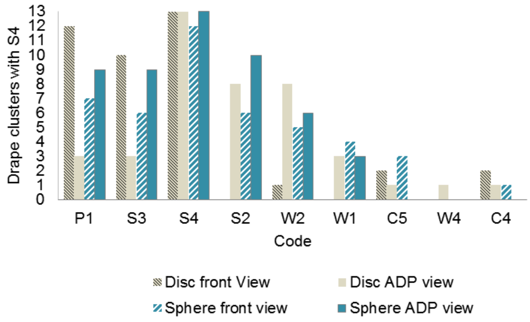
https://vimeo.com/album/3229076

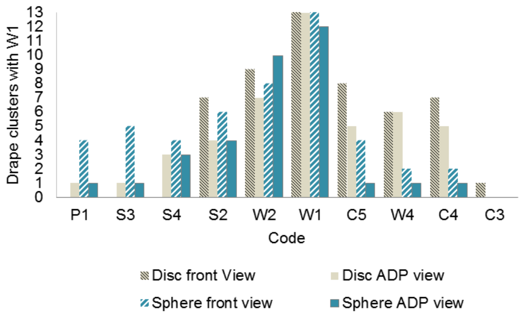
Password: *eup2!!*

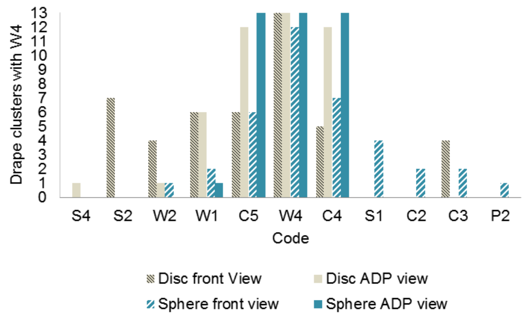
Appendix 5:

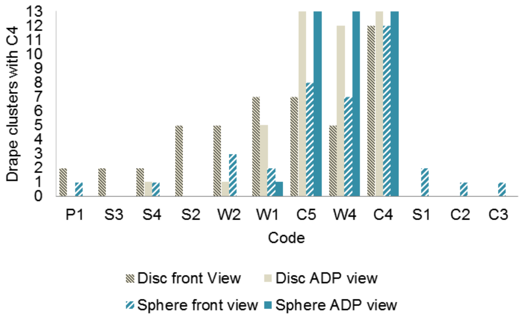
Drape clusters made by the user panel with fabrics P1, S4, W1, W4, C4, S1 and C2

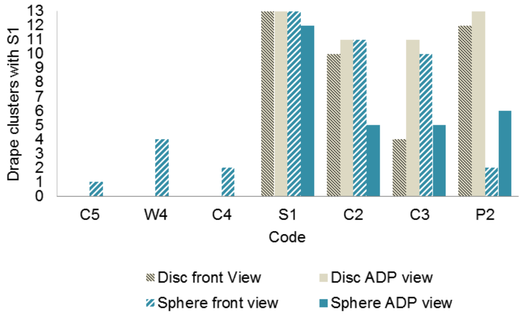


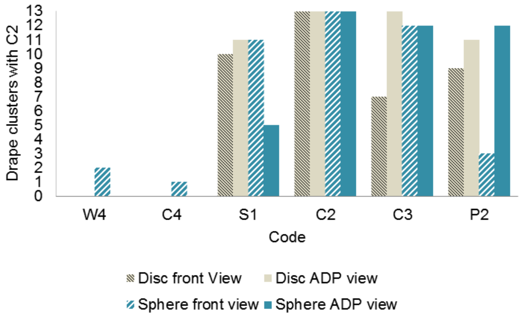






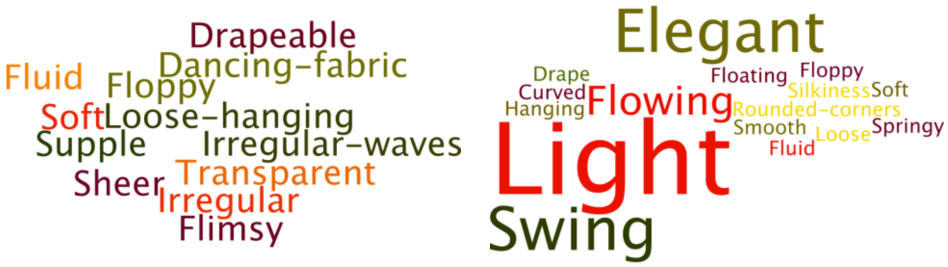






Appendix 6:

Word clouds with definitions by the textile panel fabrics S4, S2, W2, C5, C3 and P2



S4

S2

W2

C5

C3

P2

Appendix 7:

KES measurements

	KES bending properties			
	2HB g.cm/cm		B g. cm²/cm	
Code	Warp	Weft	Warp	Weft
C3	0.3969	0.3519	0.330	0.275
C2	0.1531	0.4513	0.118	0.063
W4	0.1112	0.0598	0.196	0.101
W2	0.0174	0.0095	0.050	0.050
W1	0.0264	0.0147	0.069	0.055
C4	0.0808	0.0291	0.131	0.042
S2	0.0000	0.0023	0.035	0.012
C5	0.0259	0.0086	0.056	0.022
P1	0.0233	0.0077	0.022	0.010
S3	0.0158	0.0083	0.041	0.015
S4	0.0062	0.0010	0.017	0.002
S1	0.0200	0.0179	0.118	0.101

	KES shear properties					
	2HG g/cm		2HG5 g/cm		G g/cm . deg	
Code	Warp	Weft	Warp	Weft	Warp	Weft
C3	11.96	13.47	14.41	15.11	4.58	4.41
C2	13.12	10.33	11.25	10.94	3.20	3.43
W4	2.07	2.35	5.22	6.30	2.21	1.94
W2	0.03	0.21	0.34	0.33	0.29	0.34
W1	0.07	0.06	0.24	0.08	0.24	0.22
C4	1.14	0.78	2.50	2.03	0.88	0.67
S2	0.20	0.02	0.53	0.22	0.31	0.25
C5	0.45	0.42	1.25	1.23	0.57	0.58
P1	0.14	0.35	0.40	0.31	0.22	0.19
S3	0.02	0.00	0.09	0.13	0.19	0.21
S4	0.01	0.01	0.24	0.28	0.22	0.31
S1	0.00	0.08	0.23	0.14	0.27	0.24

	KES Tensile properties							
	EMT %		LT -		WT g.Cm²/cm		RT %	
Code	Warp	Weft	Warp	Weft	Warp	Weft	Warp	Weft
C3	4.16	8.03	0.905	0.773	9.40	15.50	51.72	48.36
C2	5.02	20.87	0.851	0.648	10.67	33.80	45.06	48.13
W4	2.07	8.07	0.666	0.374	3.45	7.55	78.26	60.26
W2	11.17	16.53	0.493	0.593	13.77	22.27	74.80	68.03
W1	11.07	14.20	0.541	0.515	14.93	18.27	62.99	64.77
C4	2.21	10.53	0.827	0.735	4.57	19.33	61.48	53.78
S2	7.01	8.31	0.724	0.572	12.70	11.87	65.29	56.73
C5	6.40	15.47	0.652	0.573	10.42	22.13	56.60	53.15
P1	6.20	7.45	0.528	0.591	8.18	11.00	68.22	60.66
S3	12.40	. . .	0.484	. . .	15.00	. . .	65.16	. . .
S4	4.85	14.90	0.645	0.466	7.82	17.00	56.76	53.79
S1	5.47	. . .	1.109	. . .	16.60	. . .	42.83	. . .

	KES Compression				KES Surface					
	LC -	T mm	RC %	WC g.cm/cm²	MIU -		MMD -		SMD mm	
Code	-	-	-	-	Warp	Weft	Warp	Weft	Warp	Weft
C3	0.391	0.881	39.36	0.260	0.194	0.171	0.0611	0.0304	8.03	15.25
C2	0.400	0.884	43.78	0.298	0.183	0.190	0.0821	0.0179	8.96	2.35
W4	0.289	0.874	48.96	0.241	0.153	0.159	0.0145	0.0123	2.28	2.53
W2	0.319	0.647	61.14	0.205	0.207	0.184	0.0436	0.0227	12.75	10.46
W1	0.367	0.797	58.44	0.333	0.261	0.224	0.0359	0.0219	7.55	6.74
C4	0.329	0.345	40.18	0.146	0.124	0.109	0.0585	0.0106	4.78	1.95
S2	0.478	0.234	40.99	0.044	0.126	0.171	0.0076	0.0120	1.11	1.79
C5	0.342	0.329	56.66	0.146	0.128	1.131	0.0109	0.0118	1.23	1.56
P1	0.622	0.232	59.10	0.064	0.143	0.157	0.0105	0.0151	3.21	2.43
S3	0.650	0.241	73.67	0.096	0.216	0.168	0.0133	0.0075	1.29	1.66
S4	0.345	0.160	50.08	0.045	0.152	0.143	0.0120	0.0102	0.90	1.86
S1	0.936	0.121	75.44	0.039	0.124	0.119	0.0230	0.0294	3.77	4.68

Appendix 8:

FAST measurements

	FAST Bending properties				FAST Shear property
	C mm		B 1e - 6 N.m µN.m		G N/m
Code	Warp	Weft	Warp	Weft	-
C3	23.400	24.500	35.200	40.400	223.600
C2	28.600	19.300	62.700	19.200	147.700
W4	15.500	16.300	9.300	10.800	88.000
W2	14.500	13.000	4.900	3.600	13.800
W1	15.750	13.900	4.300	3.000	10.400
C4	18.700	13.800	5.700	2.300	36.700
S2	17.500	12.580	4.622	1.684	13.717
C5	18.330	14.917	5.027	2.498	31.538
P1	12.250	11.833	1.232	1.111	17.655
S3	13.418	12.250	1.278	0.973	8.367
S4	17.000	12.417	1.286	0.501	14.057
S1	29.300	29.900	5.900	6.300	12.300

	FAST Elongation					
	E5 %		E20 %		E100 %	
Code	Warp	Weft	Warp	Weft	Warp	Weft
C3	0.400	0.500	0.700	0.800	3.200	2.300
C2	0.600	1.000	0.800	2.800	1.900	12.600
W4	0.900	0.700	2.200	2.200	6.000	6.200
W2	1.300	1.600	3.900	5.100	8.300	13.000
W1	0.900	1.800	2.100	4.200	4.400	9.200
C4	0.400	0.600	0.700	1.900	1.500	7.600
S2	0.600	0.800	1.700	2.000	3.800	5.567
C5	0.600	0.633	0.967	1.600	2.633	6.300
P1	1.400	0.900	2.633	1.533	4.733	2.700
S3	1.200	3.833	3.267	10.933	8.300	21.300
S4	0.600	1.767	1.000	4.100	2.067	8.267
S1	0.200	0.200	0.300	0.400	0.700	0.900

The elongation of fabric S3 in weft is beyond the maximum elongation of FAST, the real value at 100 gf/cm is plausibly higher than 21.3%.

	FAST thickness		FAST Surface thickness
Code	T2 mm	T100 mm	ST mm
C3	0.789	0.571	0.218
C2	0.965	0.536	0.429
W4	0.717	0.508	0.209
W2	0.556	0.391	0.165
W1	0.485	0.316	0.169
C4	0.308	0.153	0.155
S2	0.223	0.194	0.029
C5	0.285	0.148	0.137
P1	0.225	0.189	0.036
S3	0.225	0.173	0.052
S4	0.141	0.105	0.036
S1	0.116	0.092	0.024