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Fabric and Garment Drape Measurement - Part 1

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Abstract

This paper aims to make a comprehensive review of measurement methods developed for evaluating fabric and garment drape. Drapemeters used for evaluating drapeability since Pierce's bending length tester are reviewed. Parameters proposed for measuring drapeability are also considered. The authors propose that using flat fabric methods does not accurately reflect the drape of fabrics when worn. The paper is a pre-cursor to a new image analysis technique which will be reported in Part 2.

Keywords: Fabric; Drape; Parameter; Drapemeter

1 Introduction

Fabric drape is the ability of a fabric (circular specimen of known size) to deform when suspended under its own weight in specified conditions [1-3]. Fabric drape along with lustre, colour, texture, etc. defines fabric and garment appearance.

Drape is normally subjectively evaluated by textile and apparel workers in the design and manufacturing industry. Due to the limitations of individuals' assessments, from the lack of reproducibility to inconsistent agreement between assessors etc, researchers have worked on interpreting drape quantitatively. To measure this quality, it is important to find a reliable, efficient and accurate method to reflect fabric real drape characteristics properly. Different studies have been carried out concerning the development of drapemeters to make the measurement process easier, more accurate, less dependent on operator skills and to find a satisfactory presentation for drape and proposing alternative fabric drape parameters (which was sometimes a result of drapemeter development). Moreover, the development of dynamic drapemeters enabled researchers to study dynamic drape behaviour similar to the human body motion.

2 Drapemeters

Measurement of fabric drape started with Pierce in 1930. He developed objective tests for measuring fabric bending length which was proposed as a measure of fabric draping quality [4].

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Bellinson set a drape tester (called Drapeometer) at the M. I. T. Textile Research Laboratory (see Fig. 1 and Fig. 2). A fabric specimen was attached to the edge of a horizontal circular disc movable vertically and supported on a column to be suspended vertically. The specimen width equals the semi-circumference of the disc. A circle of diameter equals the supporting disc and concentric with it is drawn on the base of the tester. A straight line tangent to this circle is drawn. The departure of a fabric lower edge from the drawn circle identifies fabrics drapeability. The low drapeable the fabric was, the nearer its edge to the straight line was. The drape length could be measured by shortening the samples height progressively and determine its length making a definite degree of departure from the straight line. The greater the drape length the more flexible the material would be. The radius curvature of the sample and its variation along sample tested length was also used to compare between fabrics drapeability. It had negative relation with fabric drapeability [5, 6].

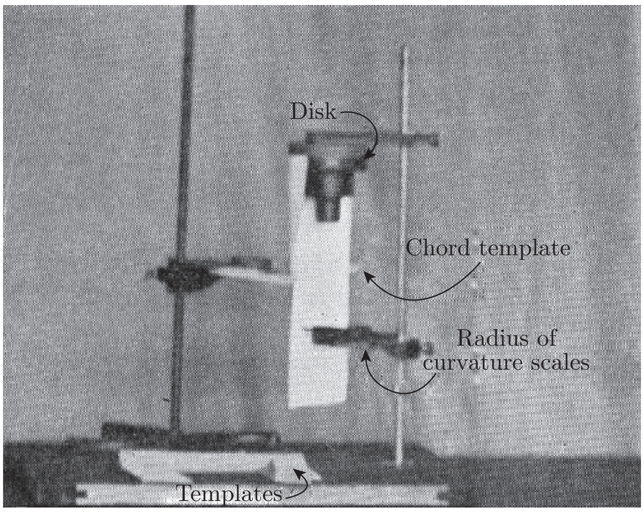


Fig. 1: Drapeometer developed by Bellinson [6]

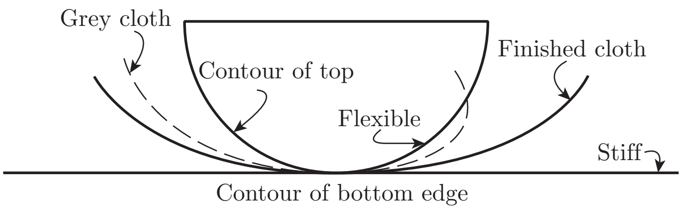


Fig. 2: Top view of the Drapeometer showing different fabrics measured [6]

Fabric drape was not clearly determined by those tests based on two-dimensional distortion of sample tested, as they measured bending properties rather than drape.

2.1 Static Drape Testers

Monoplanar drapemeters were not reliable testers for fabric drape measurement. Consequently, a three-dimensional distortion apparatus was introduced by the Fabric Research Laboratories in Massachusetts. This tester measured drape quantitatively in a way which shows its significant anisotropic properties [7].

In this optical apparatus, the sample tested was sandwiched between two circular plates mounted on a movable (up and down-wards) pedestal, and positioned so that it could not touch the apparatus base (see Fig. 3). The optical system of this apparatus was used to cast the image of the sample draped on the ground glass – it was placed above the circular plates - which was traced by the operator.

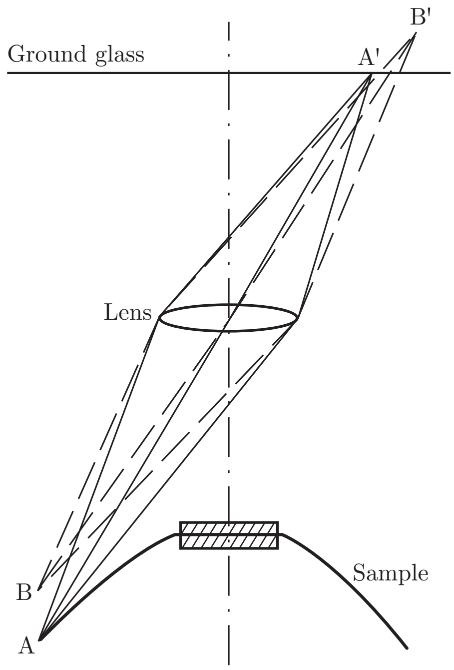


Fig. 3: Schematic diagram of F. R. L. optical drapemeter [7]

The first "Drape coefficient" F was developed as a parameter to analyze drape test data/image. It was defined as the fraction of the area of the annular ring placed concentrically above a draped fabric covered by the projection of the draped sample (see Fig. 4). The higher the drape coefficient, the less drapeable the fabric [7]. It is noteworthy that this drape coefficient was used in most drape studies.

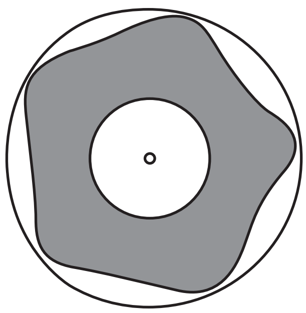


Fig. 4: Drape diagram (the dark grey area is the shadow of the draped sample on the annular ring) [7]

A study on the accuracy of this apparatus reveals that there were errors which reached 17% in the measured area for 1 inch different elevation levels of fabric edge. (as fabric drape occurs with double curvature). The principle of F. R. L. drapemeter of draping the sample tested on a circular disc was the basis of all/most of the further developed drapemeters. Improvements were carried out only to obtain more expressive and accurate data easily.

An improved F. R. L. drapemeter was developed to cope with the error in the original drapemeter (see Fig. 5). In the improved tester, a sample (25 and 30 cm diameter samples were able to be measured) was draped on a circular disc (10 or 12.5 cm in diameter) which was one of two synchronized turn tables and a standard circular chart was mounted on the other one. An optical system mechanically connected to a pen was used to scan the edge of the sample tested continuously and automatically in order to draw/trace the scanned edge on the chart. A planimeter was used to obtain the drape coefficient using area ratio [7].

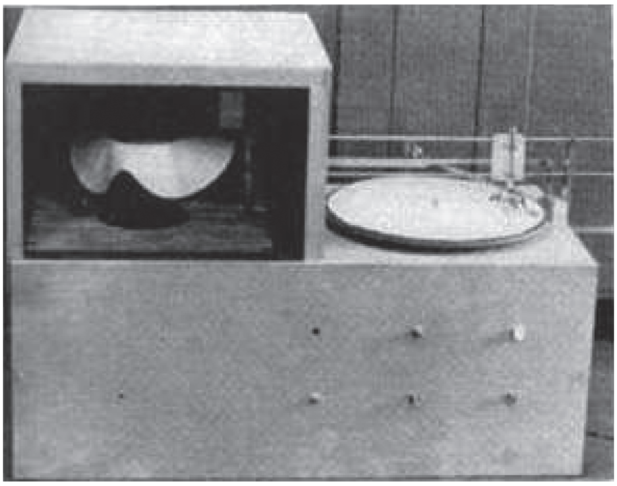


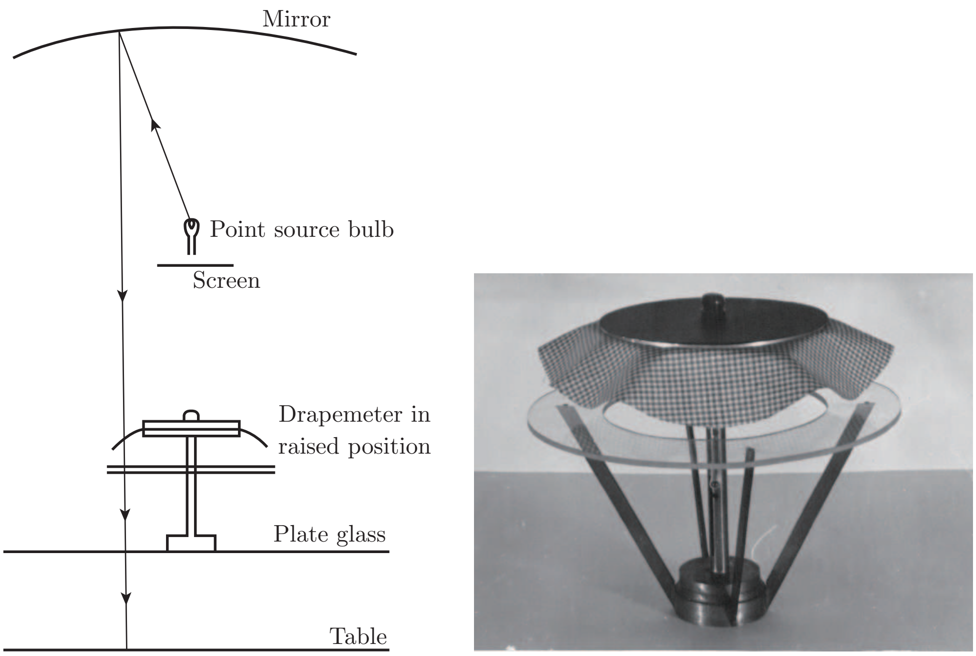
Fig. 5: Improved F. R. L. Drapemeter [7]

A further upgrade was carried out for the F. R. L. drapemeter by Cusick in 1962. In this tester, the sample tested was also sandwiched between two horizontal sample discs. The sample's shadow was projected on a table underneath the apparatus by means of a light source and spherical mirror positioned above it which produced near parallel vertical light. The projected shadow was drawn on a sheet of paper placed on the table. A planimeter was used to measure the drape coefficient DC. The sample disc with 18 cm diameter and the sample with 30 cm diameter were found to be the best standards and the most sensitive to a wide range of fabrics from limp to stiff which produced DCs from 30 to 98 %. Drape coefficient value errors were greatest at high values.

Cusick in 1968 further improved the F. R. L. drapemeter in terms of obtaining more accurate drape coefficients with less tedious and costly procedures. He suggested three proposals in this drapemeter development. First, three different samples sizes, 24, 30 and 36 cm in diameters were chosen. They were chosen as the smallest and largest samples. It turns out that the smaller sample were more sensitive for limp and stiff fabrics. A second, alternative proposal is the use of a less expensive optical system (divergent of light). Third, a cut and weigh method was proposed to measure the drape coefficient rather than using a planimeter. This drape coefficient was measured using weight ratio [8].

In 2003, Behera and Pangadiya developed a drapemeter with an optical system based on the principle of Cusick's 1962 drapemeter but in a turned over position, and it was devised with a camera to capture images of tested fabrics [9].

Three British standards published by the British Standards Institution were found for measuring fabric drape coefficient. First: Method for the assessment on the drape of fabrics (BS 5058:1973), second: Textiles - Test methods for nonwovens - Part 9: Determination of drape Coefficient (BS EN ISO 9073-9:1998), and third: Textiles - Test methods for nonwovens Part 9: Determination



(a) (b)

Fig. 6: An F.R.L drapemeter improved by Cusick in 1962, a) Schematic diagram b) Photograph [8]

of drapability including drape coefficient (ISO9073-9:2008). These standards were inspired by Cusick's work in 1962 and 1968. The optical system and apparatus were based on Cusick's 1962 but in an overturned position as the shadow was cast above the sample on a paper ring placed centrally above the supporting discs. However, the cut and weigh method was inspired by Cusick 1968 (an alternative image analysis method was used in BS: ISO9073-9:2008) (see Fig. 7) [1-3].

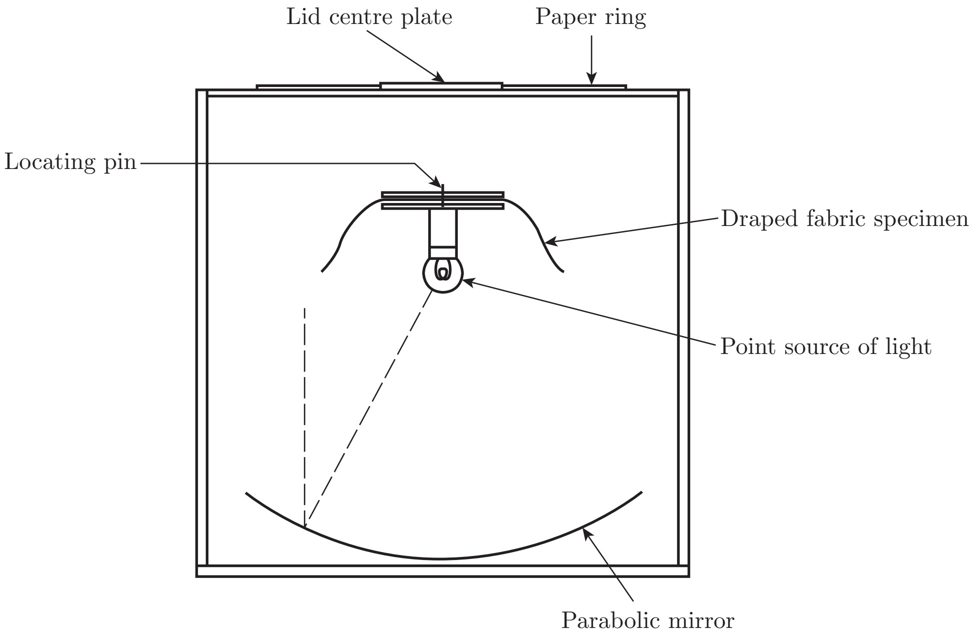


Fig. 7: Drapemeter used in British Standards with codes: BS 5058: 1973, BS EN ISO 9073-9: 1998 and BS: ISO9073-9: 2008

2.2 Integrated Drapemeters

Limitations, inaccuracy, poor data and tedious measurement using the conventional drape testers encouraged drape researchers to adapt static traditional drapemeters to obtain more data with higher accuracy, repeatability and ease. Therefore, several adaptations were carried out for conventional drape testers.

2.3 Image Analysis Technique

Researchers investigated the use of image processing technology in studying drape. In this method a digital camera is attached to a drape tester in order to capture images for draped samples. By means of computer software detailed data such as drape shape parameters and statistical information including drape wave amplitude, wavelength and number of nodes were developed and computed from drape profile image.

Moreover, it enabled researchers to carry out studies such as fabric drape dependence on time from minutes to hours and investigate drape value instability and repeatability. Studying the relation between the rotation speed of the fabric tested and its drapeability was difficult without employing an image analysis method [10-16].

The relation between cut and weigh (conventional) and image analysis methods for drape coefficient measurement was studied by several researchers. Vangheluwe and Kiekens found that image analysis method had several advantages over cut and weigh method, as the first takes less time, independent from operator and less dispersion (half the image analysis method) which means it was more accurate [17].

Jeong found that conventional measurement of drape coefficient was very time consuming and needs skilled operator. Correlation between conventional method and image analysis method for measuring DC was found with R^2=0.8 and good agreement p value > 0.05. However, image analysis method had better repeatability [12].

Kenkare and Plumlee investigated the correlation between cut and weigh and image analysis techniques. The overall drape coefficients of 10 fabrics were calculated using both methods. Pearson product-moment correlation was 0.99. Differences between digital and conventional drape coefficients of each fabric tested were calculated. They found that the differences were 3 percent or less [14].

Also, Behera and Mishra found good correlation between conventional and image analysis methods [11].

Farajikhah et al studied the virtual reconstruction of draped fabric using shadow moiré topography employing front lighting and linear grating. A captured image's centre and points located in the fringes were determined. The intensity and height of all pixels in the fringes were determined and plotted against the radius of the fabric edges. Using the radius (x), intensity (y) and height (Z) values calculated by given equations, 3D profiles of draped fabrics were generated [18].

An image analysis technique was used in the British Standard: Textiles - Test methods for nonwovens, Part 9: Determination of drapeability including drape coefficient with code number BS EN ISO 9073-9: 2008 [1].

There were two methods of fabric draped image acquisition; namely projection capture and direct acquisition. Tsai et al argued against the accuracy of the first method. They proposed an alternative method to enhance the image using the second method (directly acquired images). This method exhibited higher speed in finding the image contour and better efficiency in obtaining drape images [15].

2.4 Photovoltaic Drapemeters

In 1988 Collier and his colleagues developed a photovoltaic drapemeter. A drape coefficient was measured by means of a voltmeter which determined the amount of unblocked/sensed light by a sample tested by means of the photovoltaic cells. The DC was measured directly from the machine without any calculations [19].

2.5 Dynamic Drapemeter

Drape researchers were concerned with obtaining drape values which correlated with real fabric drape and movement. Different fabrics would have similar static drape behaviour, while differ in dynamic drape behaviour. The dynamic drape presented the real fabric performance and would help textile, clothing and design workers in quantifying realistic drape behaviour of fabrics.

Ranganathan et al used a dynamic apparatus to measure fabric drape (see Fig. 8). The test procedure was inspired by the shape and dimensions of the sample from the bending behaviour and shape of real folds constructing fabric drape. The sample was clamped in the apparatus using a needle and an arm, and was used to rotate the sample. The movement of both the arm and the response of the needle (sample) were recorded by means of a protractor to obtain a hysteresis diagram. The maximum value at 45° rotation and the area of the hysteresis loop were used as parameters of drape behaviour (see Fig. 9) [20].

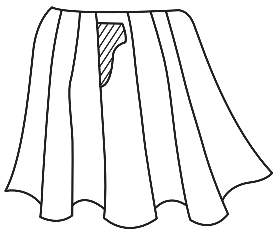


Fig. 8: Contour of a specimen on a vertically draped fabric [20]

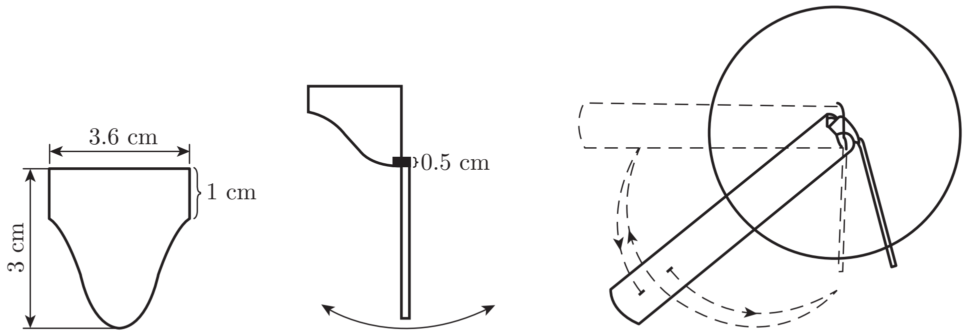


Fig. 9: a) sample dimensions, b) Needle suspended on the specimen, c) The sample mounted on the apparatus [20]

Dynamic drape behaviour was studied later using a system consisting of a drapemeter with a circular rotatable supporting disc and image processing devices (CCD camera and PC). The camera used should be able to capture images for the tested sample at very short intervals (perhaps) at every $1/30^{\text{th}}$ second. The range of the revolution speed changes according to the investigation.

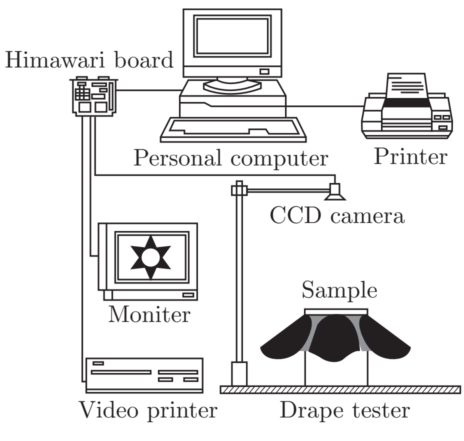
Stylios and Zhu developed a 3D drapemeter called "The Marilyn Monroe meter" (M^3) to work on the modelling of the dynamic drape of garments. They proposed an efficient parameter correlated with subjective assessment of fabric drape called a feature vector V expressed as ($\bar{p}_{\max}$, $\bar{p}_{\min}$, S), where was the average of the maximum fold's length (peak), $\bar{p}_{\min}$ is the average of the minimum fold's length (trough) and parameter S was an indication of how balanced or even the folds/nodes were.

$$S = \sum_{i=1}^{n} = \frac{(p_{\max(i)} \times \bar{p}_{\max})^2}{\bar{p}_{\max}^2} \tag{1}$$

$p_{\max(i)}$ is the maximum length of the i th fold/node, and $\bar{p}_{\max}$ is the average of the maximum length of the folds that make up the drape projection. S is equal to 0 when the folds are even and S is equal to 1 if the variation in the fold length is in the order of a fold length. Two more parameters $\alpha_{\max}$ and $\alpha_{\min}$ were proposed, these were the slopes of lines connecting overhang points on the circular disc and the free ends at maximum and minimum node length respectively [21].

Matsudaira and his colleagues published a series of papers focused on dynamic drape (see Fig. 10). Their tester consisted of rotatable circular supporting disc with speed ranged between 0 - 240 r. p. m. An image analysis system was employed to capture and analyze the images of the tested draped samples. New dynamic drape parameters were developed. The first property was the revolving drape-increase coefficient (DCr) which presented the overhanging fabric's degree of spreading with increasing revolutions (presented by the slope of the curve of the relation between revolutions and drape coefficients at the stage between 50 - 130 r. p. m.). High DCr value indicated a fabric's ability to change easily with revolutions. Drape coefficient at 200 r. p. m was selected for the dynamic drape coefficient (DC200) which presented fabric saturated spreading at rapid revolution, as the change of the drape coefficient became lower than the previous stage [22].

(a)



(b)

Fig. 10: a) Dynamic drape tester, b) System of measuring dynamic drape using an image analysis method [22]

Lin et al studied the dynamic drapeability of four natural fabrics at a wider range of revolution speeds (0 - 450) r. p. m. for a sample disc with 18 cm diameter. The resultant curve (presented the relation between drape coefficient and revolution speed) showed four stages of dynamic drape behaviour by the tangent partition method. These were initial growth, fast growth, slow growth and the last stage was the stable dynamic drape coefficient. Plots of experimental drape coefficients showed that the order of the fabrics was dependant on the revolution speed at which the DC was measured. Their order was changed three times in the fast growth stage and returned to the initial growth order and became stable at the two periods following the fast growth (slow growth and dynamic stable) [23].

Sylvie 3D drape tester based on 3D scanning of the fabric tested was developed by Al-Gaadi *et al* (see Fig. 11). The software was developed to reconstruct a virtual image for the scanned fabric from which ordinary drape parameters were calculated. Annular supporting discs with 21, 24 and 27 cm were used to exert dynamic impact (similar to real dynamic effect of a garment) on the fabric tested, which was already supported by a circular disc (18 cm diameter). Using this tester they studied fabric drapeability in terms of the effect of composite yarns twisting direction and exerting dynamic effect on fabric tested [24].

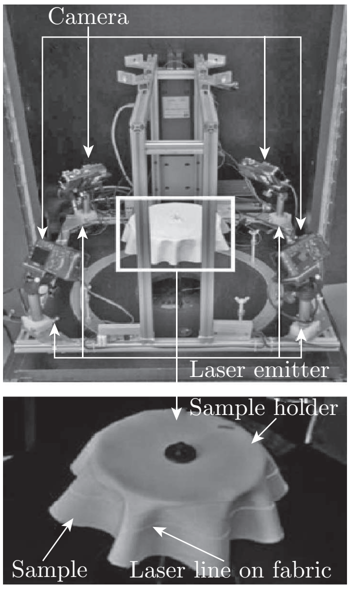
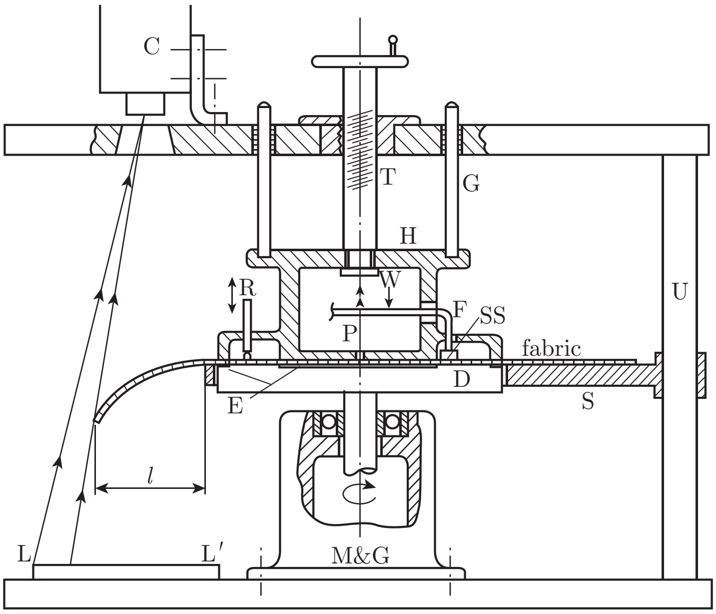


Fig. 11: 11Sylvie 3D Drape tester [24]

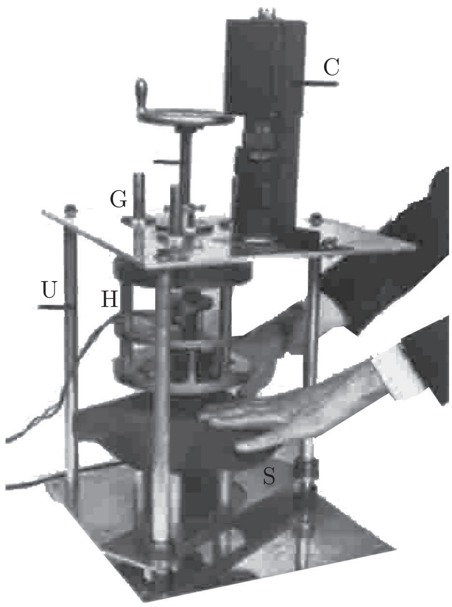
2.6 Alternative Drapemeters

Hearle and Amirbayat developed a new multipurpose fabric tester for measuring different physical and mechanical fabric properties such as surface properties, drape coefficient, and bending stiffness by means of simple adjustments to its functional parts (see Fig. 12). When a sample tested rotated for 1 r. p. m by means of supporting disc, 600 readings at regular intervals were recorded for space/distance between the sample centre and its edge by a camera fixed above the rotating disc. The readings were used to obtain the projected area of the draped sample from which the drape coefficient was calculated [25].

According to Mizutani et al, the conventional Japanese drape test (JIS L-1096 1999) included a drape apparatus based on the Fabric Research Laboratories drapemeter features. However, it was adapted to be a closed drapemeter with a 12.7 cm diameter rotatable sample disc. The measurable sample dimension was 25.4 cm in diameter. The tested sample rotated after mounting for 10 seconds at 120 r.p.m. rotation speed to hang down under its own weight. A photoelectric tracing method was used to record the vertically projected shadow of a draped sample.



(a)



(b)

Fig. 12: a) Schematic diagram and b) photo of Hearle and Amirbayat 1988 multipurpose tester of drapeability

Mizutani et al. developed a drape elevator to investigate the effect of the initial state of the measured sample on its drape, in addition to the stages of drape generation (see Fig. 13). It is similar to the conventional Japanese drape tester but they replaced the rotatable sample disc with a fixed one and attached an elevator table to it, which was capable of moving downwards and upwards by means of a lever. A test started with both table and disc at the same level and ended with sample became completely free and hung under its own weight. They determined that there were three stages of drape formation. These were node appearance (early stage), drape growing from the nodes (next stage) and stabilized drape (final stage) [26].

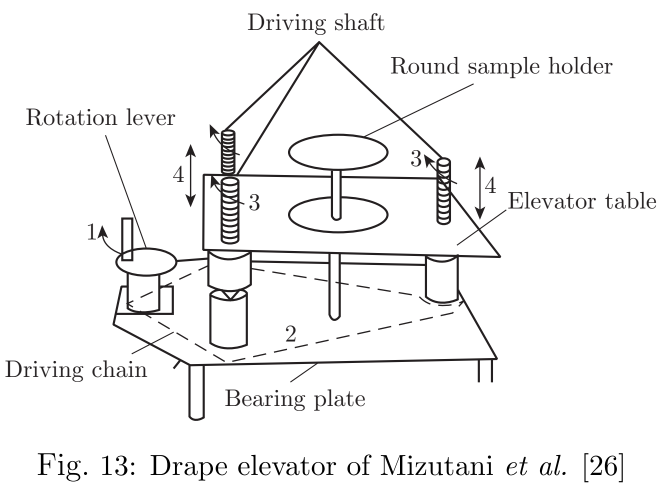
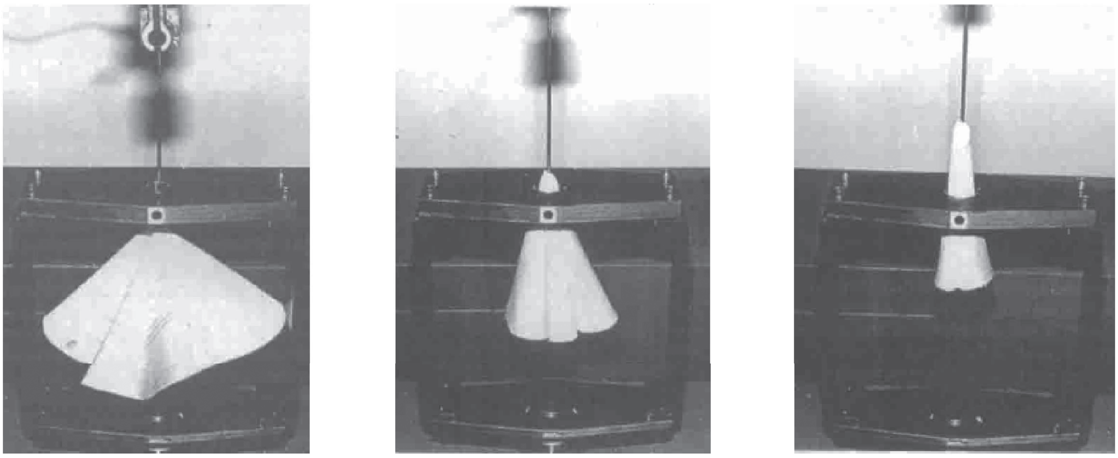


Fig. 13: Drape elevator of Mizutani *et al.* [26]

Researchers correlated fabric drapeability with its hand property measured by fabric extraction test (see Fig. 14). The load - displacement extraction curve were proposed to compare between fabrics drapeability [27, 28].



(a) Handle force device on tensile tester

(b) Initial portion of fabric specimen being withdrawn through the ring

(c) Later portion of fabric specimen being withdrawn through the ring

Fig. 14: Stages of extraction tests used by Grover *et al.* 1993

3 Drape Parameters

Researchers aimed to find parameters which could be reliable and representative of fabric drape. Conventionally, a drape coefficient has been used to determine fabric drapeability. While integrating, devising and/or adjusting the conventional drapemetres allowed drape researchers to develop alternative parameters. A reciprocal relationship existed between developing alternative parameters and drapemeters.

3.1 Drape Coefficients (DC)

Generally, drape coefficient was used as the traditional fabric drape parameter. It is expressed as the ratio of a draped fabric's shadow when it is partially supported to its undeformed flat state in terms of area. This ratio was calculated using weight or area (pixels [17]/length) units measured by a planimeter [7], weigh [8], image processing software [17] or photosensitive cells [19]. It basically ranges between 0 – 100%.

In 1998, Jeong argued against the accuracy of Vangheluwe and Kiekens's method (based on using the number of pixels occupying the drape profile shadow in calculating DC), as different drape coefficients resulted for similar shapes with different directions relative to the camera. He proposed an alternative drape coefficient calculated using these boundaries as follows:

$$\mathrm{DC} = \frac{\text{Fabric's shadow area} - \text{support disc's area}}{\text{the area of the region outside the supporting plate} - \text{support disc's area}} \times 100 \qquad (2)$$

This method showed good correlation with the cut and weigh (conventional) method and high repeatability [12].

Frydrych et al used the Polish standard for measuring fabric drape coefficient. It was defined as the ratio of the area between two edges of original and draped sample's shadow to the area of its flat unsupported part (0.027 m^2). This ratio was considered to be more comprehensive than the conventional DC as it correlated directly with fabric drapeability [29].

Gider proposed scanning the drawn shadow of a draped sample using a 2D digital scanner after reducing its scale to 70 % on a photocopying machine to fit on the scanner pad. The DC was calculated using the number of pixels of the fabric shadow employing image processing software [30].

Kenkare and Plumlee modified the digital calculation of drape coefficient and applied the following formula [14].

$$\mathrm{DC} = \frac{\text{Total shadow pixels} \div \text{pixels/cm}^2 - \text{area of supporting Disc (cm}^2)}{\text{Area of the specimen (cm}^2) - \text{area of supporting Disc (cm}^2)} \tag{3}$$

3.2 Static Drape Profile/Image Analysis

Drape researchers aimed to obtain more representative drape parameters. Further analysis of the draped fabric shadow image was their approach to generate their proposed parameters.

In 1960, Chu et al indicated that one of the most important aspects of understanding the drape mechanism was studying fabric drape geometry. The drape diagram contains three items of significance: the area, the number of nodes and the shape of the nodes [31].

Hu and Chung determined and compared the drape behaviour of seamed woven fabrics in terms of drape coefficient, node analysis and drape profile. The variability of number of nodes was used as an indicator of fabric drape stability. Regularity of node arrangement, their orientation, location and highest and lowest node length were proposed as drape parameters [32].

Rodel et al characterized the drape configuration by area, form and amplitude of the folds, the number of folds and their position with regard to warp and weft directions [33].

Jeong proposed "Drape distance ratio" as an alternative measure of drape. It increased as the fabric becomes more flexible and was calculated using the following formula:

$$R_d = \frac{r_f - r_{ad}}{r_f - r_d} \times 100 \tag{4}$$

R_d is the drape distance ratio, r_f is the radius of the undraped sample, r_{ad} is the average radius of draped sample's profile, r_d is the radius of the supporting disk [12].

Four virtual parameters were used by Stylios and Wan to define the drapeability of textile materials as follows: virtual drape coefficient, drape fold number, fold variation, and fold depth [34].

Robson and Long used imaging techniques to analyse fabric drape profile using number of nodes NN, mean node severity MNS (node height/node width) (similar to Chu et al's 1960 "shape factor"), the variability of node severity VNS and circularity of the drape profile [35].

Behera and Pangadiya proposed using a combination of drape parameters namely: Drape coefficient, average, maximum and minimum radius, drape distance ratio (DDR) $\left[\frac{r_2-r_s}{r_2-r_1}\right]$, amplitude to average radius ratio (ARR) $\left[\frac{A}{\bar{r}}\right]$, number of nodes and fold depth index (FDI) $\left[\frac{r_{\max}-r_{\min}}{r_2-r_1}\right]$, where $r_1, r_2, r_s, \bar{r}$, were the radii of the supporting disc, flat sample, draped sample, average of draped sample and A was the amplitude $[r_{\max} - r_{\min}/2]$ [9].

Ucar et al investigated the drape behaviour of seamed knitted fabrics using image analysis in terms of drape coefficient, drape profile and node analysis [16].

Jevšnik and Geršak investigated using finite element method for fused panel simulation. Experimental drape parameters including drape coefficient, number of folds, minimum and maximum amplitude and the distance between folds, fold distribution G_p were used.

$$G_p = \sum_{i=1}^{n} \frac{(l_{G_{\max}(i)}\bar{l}_{G_{\max}})^2}{l^2_{G_{\max}}} \tag{5}$$

New parameters were proposed; namely Maximum hang of fabric sample $f_{\max}$, Minimum hang of fabric sample $f_{\min}$ and the fold's depth d_G

$$f_{\max} = \sqrt{p^2 - (l_{G_{\min}})^2} \tag{6}$$

$$f_{\min} = \sqrt{p^2 - (l_{G_{\max}})^2} \tag{7}$$

$$d_G = l_{G_{\max}} - l_{G_{\min}} \tag{8}$$

where $l_{G_{\max}}$ is the maximum depth of the fold and $l_{G_{\min}}$ is the minimum depth of the fold and P is the perimeter/length of the circular sample (60 mm) draped over the pedestal [36].

Mizutani et al proposed an alternative drape shape parameter (R) presented complexity degree of tested sample drapeability with positive correlation between them. It was calculated using the following formula:

$$R = \frac{\sqrt{\overline{(r - r_0)^2}}}{r_0 - r_s} \tag{9}$$

$(r - r_0)$ is calculated along the whole contour of the drape projection. r, r_0 and r_s are radial coordinates of the drape projection, the radius of a circle with an area equal to that of the drape projection, and the radius of the sample holder [26].

Kenkare and May-plumlee used the number and dimensions of nodes as alternative parameters to drape coefficient to quantify drape [14].

Jevsnik and Zunic-Lojen proposed using the maximum amplitude of folds $I_{G_{\max}}$, minimum amplitude of folds $I_{G_{\min}}$ and the angle between two neighbouring peaks of the folds α_i to measure drape [37].

Ngoc and Anh converted the polar coordinates constituting the drape profile into rectangular coordinates using 32 coordinates at 11.25 degrees regular interval over the 360 degrees to study fabric drape. The X axis presented the angle of measurement and the Y axis presented the displacement of each coordinate from the origin [38].

Behera and Pattanayak used a combination of drape parameters including: drape coefficient, drape distance ratio, amplitude to average radius ratio, number of folds and fold depth index. This measurement was based on an Indian standard [10].

British Standard for determination of drapeabilty of nonwovens stated using image processing technology to analyze fabric drape. The shape parameters were defined as the number of nodes (waves or folds), the positions of nodes, wavelength and amplitude data. Various statistical information were obtained using image processing technology and frequency analysis as well as the traditional drape coefficient [1].

Shyr et al calculated the fabric drape profile ratio (DPR) as follows

$$\mathrm{DPR} = \frac{r - r_0}{r_f - r_0} \tag{10}$$

where r is the distance from the drape profile's edge to the origin, r_0 is the radius of the small disk (9 cm) of the drapemeter, r_f is the radius of the circular fabric profile (15 cm) [39].

Al-Gaadi et al studied fabric drapeability using drape parameters including: drape coefficient (DC), drape unevenness (DU), number of waves, and maximum, minimum, deviation of amplitudes. The drape unevenness was calculated as follows:

$$\mathrm{DU} = \frac{\sqrt{\dfrac{\sum_{i=1}^{n}(\mathrm{WL}_i - \overline{\mathrm{WL}})^2}{n-1}}}{\overline{\mathrm{WL}}} \tag{11}$$

where WL_i is the central angle between two adjacent maximum amplitudes (i.e. the wave length of single waves), $\overline{\mathrm{WL}}$ is the average central angle on one wave (i.e. average wave length, $\overline{\mathrm{WL}} = 360/n$) and n is the number of waves. DU had a reverse/negative relation with drape profile evenness [24].

3.3 Fourier Analysis

Fourier transform was proposed as an alternative approach for drape analysis. Fourier coefficients were proposed as an alternative drape values to obtain information about the drape profile in terms of wave amplitude, number of waves and the curvature of the waves [40], drape coefficient, minimum, maximum and average radius, and average amplitude [41].

Behera and Pangadiya studied the correlation between drape coefficients which was measured using different image analysis techniques. Pixel counting (number of pixels occupying a draped fabric shadow), boundary approximation (area of the shadow calculated using its edge's points at 10 or 1 degree(s) interval 36 or 360 points respectively), Fourier approximation and conventional methods were compared. The first two techniques showed significant difference. The pixel count method and the conventional method showed good correlation and agreement. The image processing methods showed lower variation than the conventional method. The pixel count had higher variation than boundary approximation and Fourier series methods [9].

Kokas-Palicska et al proposed using Fourier transform plot of drape projection as an easy and fast approach/method for drape comparison.

This approach was tested on fabrics treated with a soft finish and showed efficiently the effect of that treatment [42].

British Standard (BS EN ISO 9073-9:2008) proposed using Fourier analysis in studying drape. Fitness factors was proposed to verify the fit of the Fourier transformation and to determine the dominant wave, expressed as percentages. These were ratios of the following:

$$\text{Fourier transform/original} = \frac{B_f}{B_0} \times 100 \tag{12}$$

$$\text{Dominant/original} = \frac{B_d}{B_0} \times 100 \tag{13}$$

where B_0 is area of the original captured draped image, B_f is the B_0 Fourier transformed shape, B_d is the ideal shape recomposed from a determined dominant wave [1].

3.4 Standard Drape Values

Jeong proposed what was called the standard drape values. These were the values with the most frequent number of nodes obtained, since the variation of the drape values within the same node was not large/high [12].

3.5 Measurement of Number of Nodes Objectively

Since, subjective node numbers were determined by visual judgment of drape image, different results could be obtained by different fabric personnel. Shyr et al developed an objective approach for this measurement/test. The objective node numbers were determined by the threshold node value resulting from the following equation, the distance between peak and trough (P – T) > TN, a node was defined as:

$$\text{TN} = \bar{x}_{(p-T)} - z_{(1-\alpha)} \times s_{(p-T)} \tag{14}$$

where: TN is the threshold of the node, $\bar{x}_{(p-T)}$ is the sample mean of the difference between peak and trough, $z_{(1-\alpha)}$ was the $(1-\alpha)$ percentile of a standard normal variable, and $s_{(p-T)}$ is the sample standard deviation [39].

3.6 Dynamic Drape Parameters

Drape researchers proposed studying dynamic drapeability of fabrics as more representative for actual dynamic real- life performance of draped fabric.

Dynamic drape coefficient with swinging motion (D_d) was proposed and calculated as follows

$$D_d = \frac{S_{\max} - S_{\min}}{\pi R_1^2 - \pi R_0^2} \times 100 \tag{15}$$

where $S_{\max}$ = maximum projected area at the turn-round angle, $S_{\min}$ = minimum projected area at the turn-round angle, R_0 was radius of the circular supporting stand, R_1 is radius of the fabric sample [43].

Tandon and Matsudaira developed a new parameter, "Index of Drape Fluidity (I)" which expressed the drape fluidity better than static and dynamic drape parameters. This was the ratio of the dynamic drapeability to the static drapeability as static drape coefficient was separated from the dynamic drape coefficient values. The higher the I was, the softer the fluid drape that the measured fabric displayed [44].

3.7 Garment Drape Parameters

Moore et al characterized the drape profiles of four-gore skirts worn by a mannequin using the area of the profile of each quadrant, the distance between the apexes of adjacent nodes, the maximum distance in each quadrant between node apexes and the intersection of the axes, and the asymmetry of the right and left sides of the profile [45].

Kenkare studied the evaluation and presentation of garment drape virtually by using its properties. Three drape parameters were developed: garment drape coefficient (GDC), number of nodes (NON) and drape distance coefficient (DDC). The amount of garment drape was defined using the first two parameters while the last represented the lobedness of the garment drape. These parameters were used to compare virtual and actual garment drape (measured using a 3D scanner). GDC was defined by the following equation:

$$\mathrm{GDC} = \left[\frac{\text{Volume of the draped garment}}{\text{Full geometrical volume of the garment form}}\right] \times 100 \tag{16}$$

The garment's waist and hem line contours were projected on the bottom surface to obtain a diagram with which the ratio DDC was calculated using the following formula:

$$\mathrm{DDC} = \left[\frac{\frac{\sum Y_i}{n}}{\frac{\sum X_i}{n}}\right] \tag{17}$$

where: Y = maximum distance of a node from the edge of the waistline contour, X = minimum distance of a node from the edge of the waistline contour, n = number of nodes [46].

4 Conclusion

The purpose of this paper is to overview the various developments, in a close to chronological sequence, in techniques devised for the measurement of drape. The authors have not stressed the data provided, the statistical measures of that data and the detailed claims made. The reader can use this as an introduction to the subject which is clear and very readable. This review shows that extensive research has been carried out by many researchers over most of the twentieth century. Many findings are consistent with each other but some contradict or conflict with each other. The authors suggest a growing concern that the measurement of flat fabric parameters does not enable the accurate measurement of the many parameters which influence garment drape both subjectively and objectively. A new method will be introduced in Part 2 and this paper is suggested as an introductory review of what has been before.

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