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Enhancing accuracy of drape simulation. Part I: Investigation of drape variability via 3D scanning

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Abstract: The objective of this two part paper is to present a method of enhancing accuracy of fabric drape simulation using commercially available software. In Part I, we report results of an investigation of drape variability for a set of fabrics having varied mechanical properties, an essential step in defining accuracy for drape simulation. Results illustrate that fabric drape behaviour is highly variable and thus provide no single drape configuration to target with simulation. Development of a revolutionary method for capturing drape of actual fabrics and measuring that drape in a virtual three-dimensional (3D) environment is also presented. The method allows identical drape measurement processes to be implemented for actual and simulated fabrics and provides opportunity for use of additional measures to assess fabric drape in three dimensions. The accomplishments presented in this paper are utilized to demonstrate, in Part II, development of a relationship that enhances realism of particle model simulations generated using the commercial drape simulation software.

Key words: Simulation, drape measurement, 3D body scanner, fabric drape behavior, fabric mechanics.

INTRODUCTION

Fabric drape response is an important property due to its influence on the appearance of clothing. Drape determines the configuration of fabric when supported by the human form. Drape is defined as "the extent to which a fabric will deform when it is allowed to hang under its own weight" (BS 5058: 1973; British Standard Institution, 1974b). This unique characteristic provides a sense of fullness and a graceful appearance that distinguishes fabrics from other sheet materials. When a fabric is draped, the fabric can bend in one or more directions based on its configuration. For example, curtains usually bend in one direction, whereas garments and upholstery exhibit a complex three-dimensional (3D) draped form with double curvature. Hence, fabric drape is a complex mathematical problem involving large deformations under the influence of relatively low stresses (Postle and Postle, 1993).

Simulating drape of a particular fabric is challenging. This is due in part to limited understanding of 3D behaviour of draped fabric. The most common method of quantifying drape, drape coefficient, reduces drape configuration to a ratio based on two-dimensional (2D) measurements. A single drape coefficient value may be shared by two fabrics that differ in draped appearance. Also, a reported drape coefficient is typically an average of several measurements, providing no insight into the range of measurements or the consistency of the draped configuration with repeated draping.

Another challenge is that fabric drape simulations using mass-spring or interacting particle based models have limited ability to produce accurate virtual representations of a particular fabric, unless the material property values obtained from standard testing like the Kawabata evaluation system (KES) are input and utilized correctly. Typically, the input parameters used in such models do not correspond directly to material testing parameters such as load-deflection or moment-curvature. Breen *et al.* (1994) were pioneers in addressing this issue for the interacting particle approach, and in particular pointing out the importance

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Table 1 **Physical characteristics of chosen fabrics**

Sample no.	Sample name	Weight (g/m^2)	Fabric thickness (mm)	Yarn density (cm)		Yarn count (Ne)	
				Warp (wale)	Weft (Course)	Warp	Weft
1	Plain1	110	0.32	28	24	29.52	29.52
2	Interlock 6	202	0.88	28	27	–	36.90
3	Rib	211	0.84	17	15	–	23.61
4	Lawn	95	0.26	35	31	42.17	36.90
5	Plain 2	194	0.40	38	22	18.45	21.87
6	Challis	153	0.38	24	24	19.05	18.45
7	Twill 1	190	0.45	44	21	21.09	21.09
8	Plain 4	168	0.38	38	18	42.17	10.54
9	Oxford 5	211	0.55	37	11	15.96	8.20
10	Polytwill	254	0.81	19	17	8.81	8.68
11	Corduroy	217	0.81	19	23	16.40	22.71
12	Momie	180	0.47	24	20	18.45	15.96
13	Twill 3	292	0.70	28	17	8.68	9.23
14	Plain20	256	0.54	35	13	11.58	7.29

of including nonlinear moment–curvature response. Bhat *et al.* (2003) used an optimization technique to select input parameters for a mass-spring model that would result in realistic simulations and avoided addressing real mechanical properties altogether. In practice, an ad hoc selection of input parameters is often chosen to make a simulation appear more similar to the drape of a particular fabric. Even then, the assessment of similarity is quite subjective. Methods for evaluating simulation accuracy by comparing a simulation to a specific draped fabric have not been developed.

Fabrics may drape in dramatically different ways, depending on the fibre content, type of yarn, fabric structure and type of finish. Each fabric has its own distinct set of properties and drapes in its own characteristic way. Experience shows that each time a fabric is draped it hangs in a slightly different configuration; the reason being that drape of fabric is governed by a large number of factors that exhibit behaviour sensitive to environmental and other conditions. By studying the range of variation exhibited in actual fabric drapes, one can begin to develop quantitative measures for evaluating how representative a simulation is of a particular fabric.

This paper presents a method for enhancing accuracy of drape simulations considering the variability inherent in fabric drape behaviour and using 3D scanning technology. This was done by evaluating, for a variety of fabrics, the range of variation in drape behaviour exhibited by circular fabric samples repeatedly draped over a cylindrical support. Experiments performed to document the range of variation exhibited by the selected fabrics are detailed in this paper. Part II utilizes these accomplishments to develop a simple and systematic way of relating fabric mechanical properties measured by the KES to input parameters required for the particle model simulation.

There have been numerous instruments, ranging from a simple cantilever bending tester measuring stiffness of the fabric (Peirce, 1930) to a dynamic drape tester (Yang and Matsudairs, 1999), used to measure fabric drape. Most of them developed specifically for that purpose. In this paper, we demonstrate the application of a 3D body scanner for translating actual fabric drape to a 3D virtual environment and the measurement of drape in that environment. 3D scanning technology has been adapted in the last decade for use in the apparel industry to capture the measurements of the human body and represents a revolutionary technology to that industry (DesMarteau, 2000). Scanning technology developed for capturing measurements of the human body has not been used to evaluate drape in the past. We demonstrate the usefulness of white light based 3D scanning technology for capturing the drape characteristics of not only simple draped circular samples but also its potential for complex forms such as garments (Part II). The output image from the 3D body scanner can also be compared with the particle model simulations to evaluate how effectively the simulations represent drape of actual fabrics.

MEASUREMENT OF FABRIC MECHANICAL PROPERTIES

To initiate the investigation, a broad spectrum of white fabrics was identified and procured from the market. Details of the 12 woven and 2 knitted fabrics selected for study are given in Table 1. White fabric samples were preferred to dyed or printed samples for their assistance in capturing the point cloud data in the 3D body scanner. The scanner acquires data from white objects more easily than from multicolored objects. All of the fabrics were conditioned in standard atmospheric conditions before testing (BS 1051: 1972; British Standard Institution, 1974a).

The literature (Collier, 1991; Cusick, 1965, 1968; Hu and Chan, 1998) suggests that bending, extension, shear

Table 2 **Kawabata evaluation system test results for selected fabrics**

Fabric samples	Fabric weight (W) (g/m^2)	Bending stiffness (B) (dyne-cm)*	Shear stiffness (G) [gf/(cm-deg)]†	Surface friction coefficient (MIU)	Linearity of load (LT)	Tensile energy (WT) ($gf\text{-}cm/cm^2$)‡	Tensile resilience (RT) (%)
Plain1	110	35	1.110	0.21	0.570	11.700	49.270
Interlock 6	202	38	0.552	0.29	0.779	3.394	45.573
Rib	211	38	0.949	0.30	1.713	12.701	47.483
Lawn	95	68	1.812	0.24	0.653	13.100	52.607
Plain 2	194	82	2.297	0.16	0.631	13.120	47.430
Challis	153	91	0.741	0.26	0.620	14.887	50.842
Twill 1	190	122	2.060	0.20	0.660	6.710	58.540
Plain 4	168	129	2.634	0.22	0.696	11.308	44.174
Oxford 5	211	129	2.093	0.19	0.658	6.561	52.122
Polytwill	254	213	0.793	0.37	0.619	37.392	66.736
Corduroy	217	251	2.461	0.23	0.592	19.094	50.652
Momie	180	470	3.082	0.28	0.704	12.057	58.002
Twill 3	292	551	6.045	0.25	0.775	8.200	52.787
Plain20	256	580	4.368	0.19	0.856	28.678	39.903

*1 gf cm = 9.8×10^{-5} NM.
†1 gf /(cm-deg) = 9.8×10^{-1} N/(cm-deg).
‡1 gf /cm = 9.8×10^{-1} N/M.

behaviour, and weight of fabrics contribute to the draped shape of fabrics. Hu and Chan (1998) investigated the relationship between fabric drape and its mechanical properties derived from standard testing methods. The results of their study suggest that the influence of mean deviation of friction coefficient and tensile linearity from KES values along with bending and shear properties relate closely to drape coefficient.

The KES was used to measure the mechanical properties of all selected fabrics. The KES uses four testing instruments to measure 16 mechanical properties on fabric samples of standard dimensions. The first instrument measures tensile and shear properties, the second measures thickness and compression, the third measures bending properties, and the fourth instrument measures surface roughness and friction (Kawabata, 1980). On the basis of previous research (Collier, 1991; Cusick, 1965; Hu and Chan, 1998; Morooka and Niwa, 1996) that established which mechanical properties most influence drape, the number of KES parameters were narrowed to seven for this work. Results of the Kawabata evaluation are summarized in Table 2. The compression test was not conducted because of the expected negligible influence on drape (Hu and Chan, 1998). The fabric samples in Table 2 are arranged in ascending order of bending stiffness value, which ranges from 35 to 580 dyne-cm. Kawabata testing was carried out only in the low deformation region under an assumption of purely linear elastic behaviour. This makes deriving various stiffness values from plots by reducing the data with linear regression and calculating the slopes of the plotted lines relatively easy.

Fabric mechanical properties are not easy to derive considering that fabrics exhibit anisotropic and nonlinear properties. Standard tests like the KES only measure average mechanical properties governing fabric deformation because the time and cost requirements of a comprehensive evaluation make it impractical. The mechanical properties of fabric are roughly divided into three regions: the initial resistance region, region of low deformation, and a region of high deformation (Breen *et al.*, 1994). The mechanical behavior of fabric throughout the region of deformation is nonlinear. It is only in the region of low deformation that the mechanical properties follow a reasonably regular pattern and can be represented by a linear mathematical model. The data obtained from the KES only represent the mechanical properties of fabric in the low-deformation region of 0.5 cm^{-1} sec. When these parameters are used in the particle model simulations, it severely limits the accuracy of the 3D simulations where large deformations are expected and present. Hence, there is a need to develop a relationship between measured fabric properties and input parameters to the particle model simulations, as we have done in Part II.

MEASUREMENT OF DRAPE

Peirce (1930) developed the "cantilever method" for measurement of fabric stiffness. This measurement was used initially to assess fabric drape. To overcome the limitations of using a 2D measurement of stiffness as the estimating parameter of drape, researchers at the Fabric Research Laboratories developed the FRL drapemeter (Chu *et al.*, 1950). Later, Cusick (1968) developed a drapemeter (Fig. 1), based on similar principles, to measure drape of the fabric. Chu *et al.* (1950) and Cusick (1961, 1965, 1968) made significant contribution to the practical determination of fabric drape.

Figure 1 (a) Cusick drapemeter. (b) Configuration of draped image on the Cusick drapemeter.

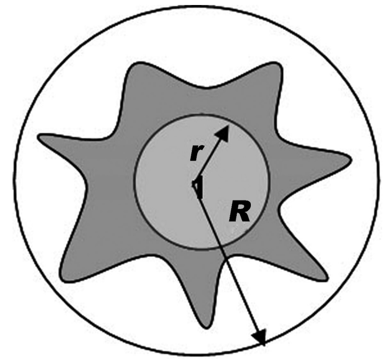

Figure 2 Definition of drape coefficient.

Conventionally, drape is measured using a Cusick drapemeter resulting in a drape coefficient. Drape coefficient is defined as the ratio of the area of the portion of the annular ring obtained by vertically projecting the shadow of a draped specimen to the total area of the annular ring, expressed in percentage (Fig. 2). To determine this drape coefficient, a circular fabric sample is supported horizontally by an inner circular disk and an outer annular disk. During the drape test, fabric is placed over the two disks and the outer annular disk is lowered gradually, whereas the inner disk is held stationary, allowing only an annular ring of the fabric to drape. This results in deformation of fabrics into a series of folds supported by the circular disk.

Even though drape is not completely parameterized by the drape coefficient, most of the research related to fabric drape considers drape coefficient as one of the primary attributes explaining drape in fabrics. Drape coefficient is, however, insufficient to completely describe fabric drape particularly as considered in three dimensions including depth, length, size, and density of the lobes that are formed. Two fabrics sharing the same drape coefficient may have different drape forms and may look very different in the draped configuration. Hence along with drape coefficient, other parameters such as number of nodes (folds) and node dimensions were measured (Fig. 3) in the current investigation.

DRAPE MEASUREMENT USING THE 3D BODY SCANNER

An alternative method of measuring the fabric drape was accomplished by using a white light based 3D body

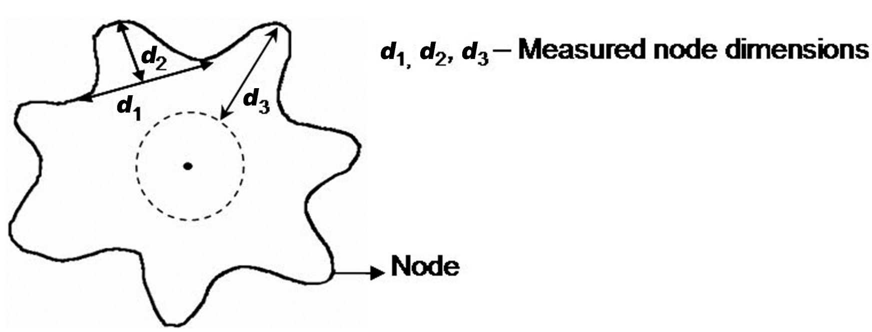

Figure 3 Measurement of nodes and node dimensions.

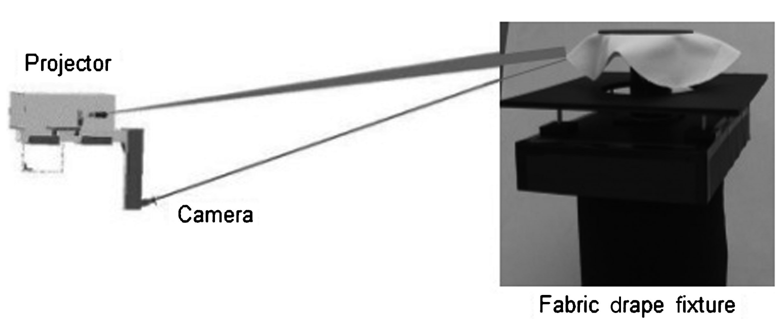

Figure 4 Drape fixture for circular fabric samples.

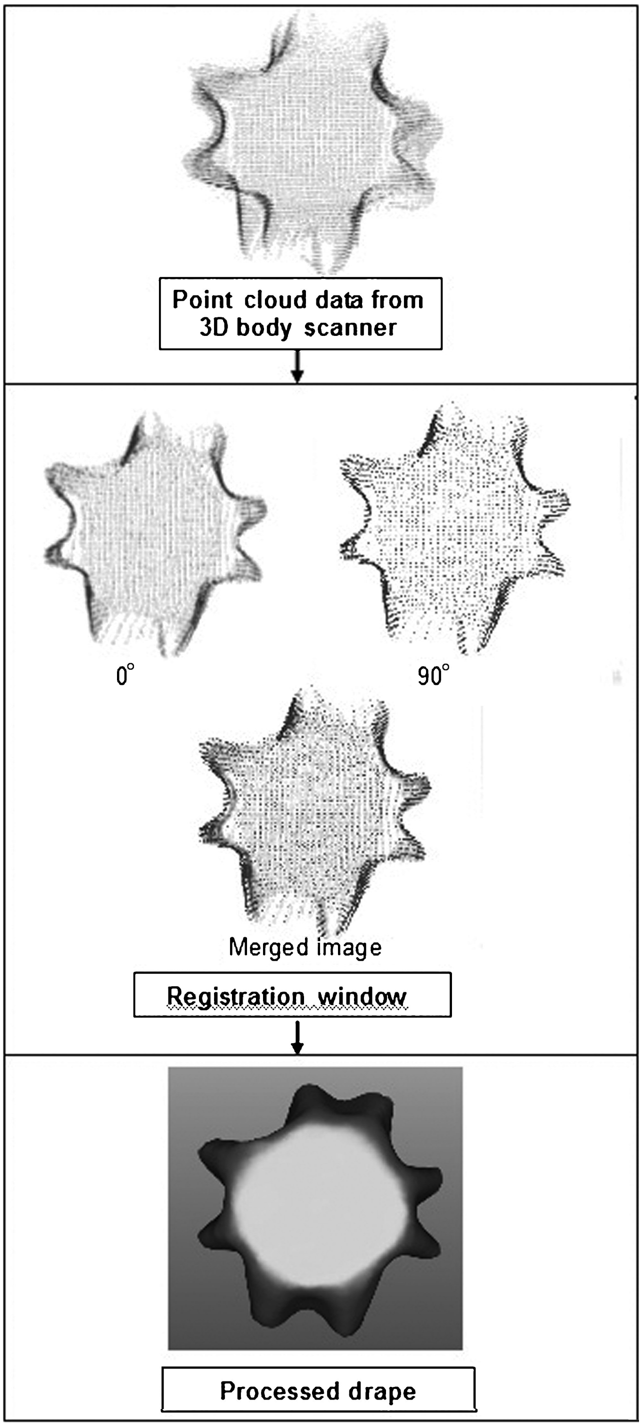

Figure 5 Processing of point cloud data of the two scans in Geomagic.

scanner.* A circular piece of fabric was draped over a circular disk on a fixture built to be accommodated in the 3D body scanner. The fixture, shown in Figure 4, performs the function of holding the circular fabric sample on a circular disk and allowing the fabric sample to drape as in

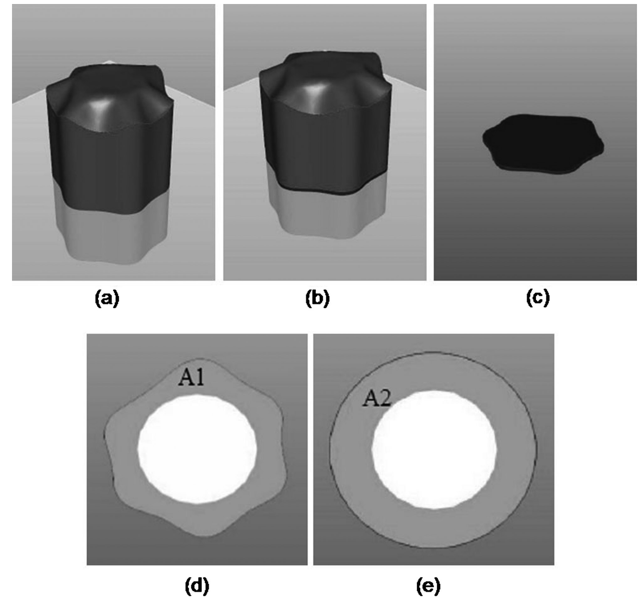

Figure 6 Steps in the calculation of the drape coefficient by scanning and processing in Geomagic.

the Cusick drapemeter. The scanner takes approximately 12 seconds to capture the point cloud data of the draped sample. The captured point cloud data are then processed using Geomagic^{TM}software to generate a 3D surfaced virtual representation of the scanned object. Drape coefficient along with other useful drape parameters can then be extracted from the processed scan in Geomagic.

The body scanner utilized in this research effectively captures only the front and back of the object being scanned, and when used as designed for body measurement, it interpolates data for the sides of the body. In capturing drape characteristics of fabrics, it is difficult for the body scanner to capture the complete configuration of a draped sample in a single scan. Hence, two scans (one rotated 90° from the other) were used to capture the complete configuration of the draped fabric.

Using Geomagic software, the point cloud images were cleaned to remove any extraneous points (points that do not lie on a smooth surface). Then, 0° and 90° images of each drape, captured using the body scanner, were merged into one complete image. The scans were subjected to a registration process (Fig. 5) that properly aligns the two images and allows the user to generate a surface from the point cloud image. The resulting processed 3D model was used for extracting the drape parameters.

Steps involved in calculating drape coefficient from a processed body scan image are shown in Figure 6. First (Fig. 6a), the processed scan is projected onto a parallel plane. Then (Fig. 6b), a thin slice of cross section is cut from the perimeter. Figure 6(c) shows the cut cross section alone. Figures 6(d) and 6(e) show the areas whose ratio multiplied by 100 yields drape coefficient. The node dimensions (Fig. 3) were also acquired. To verify the efficacy of measuring drape using the 3D body scanner, several

*[TC]^2 3D Body Scanner, for additional information refer to www.tc2.com

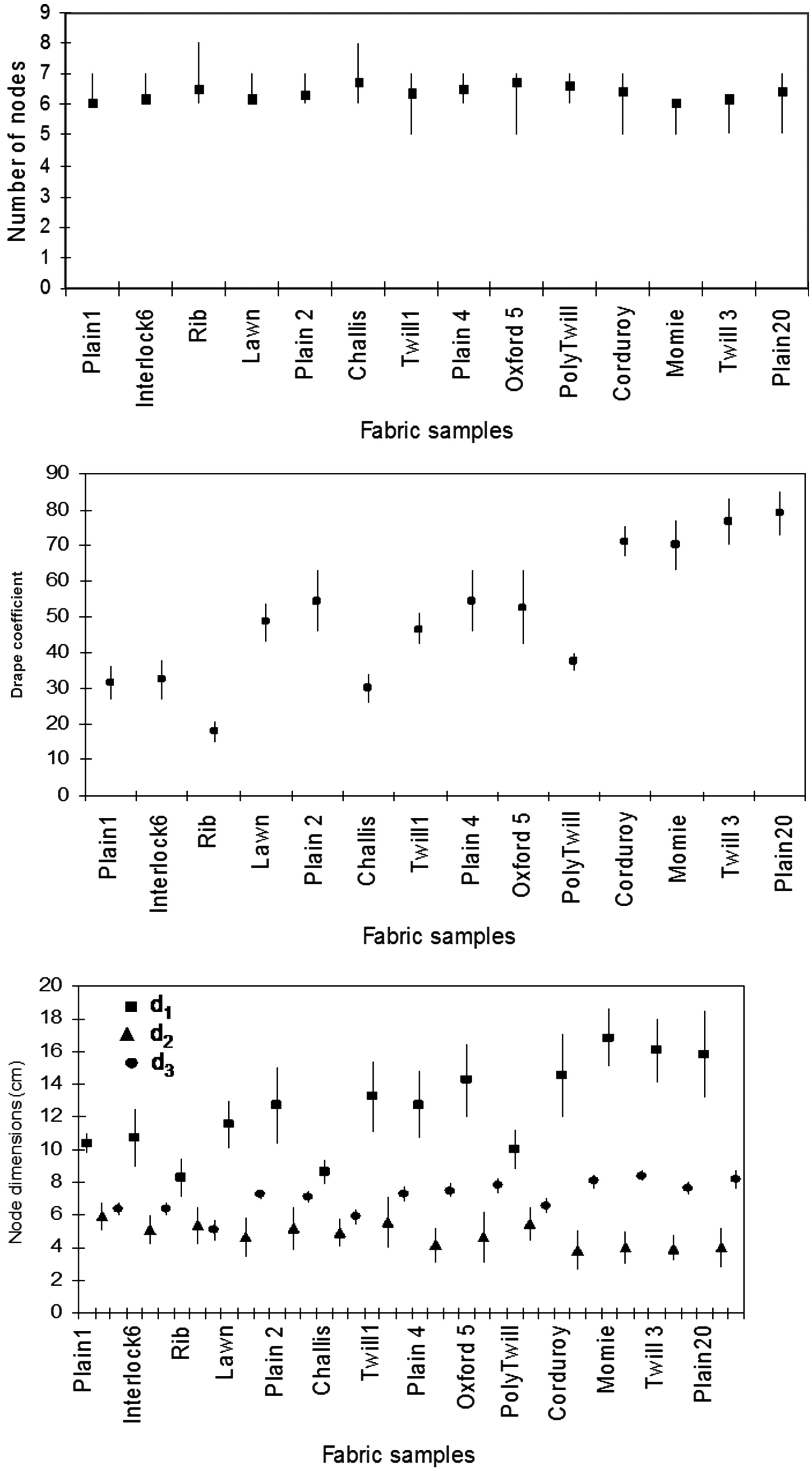

Figure 7 Variation in drape parameters exhibited during the variability tests.

Table 3 **Variation exhibited in drape parameters**

Fabric	DC (%)		Number of nodes	d_1(mm)		d_2(mm)		d_3(mm)	
	Range	Average	Average	Range	Average	Range	Average	Range	Average
Plain1	27–36	33	6.08	98–110	104.76	51–67	58.43	60–67	64.42
Interlock6	27–38	35	6.23	89–125	105.06	42–60	52.06	60–67	64.22
Rib	15–21	19	6.54	71–95	85.79	42–65	56.4	45–57	53.19
Lawn	43–54	50	6.23	101–130	114.96	35–58	45.62	70–75	73.67
Plain 2	46–63	52	6.31	104–150	126.72	38–65	51.66	67–75	73.79
Challis	26–34	29	6.77	79–94	89	41–57	53.17	55–64	60.55
Twill1	42–51	49	6.42	111–154	135.59	40–71	60.4	68–77	76.19
Plain 4	46–63	59	6.54	107–148	133.24	31–52	45.22	71–79	77.92
Oxford 5	42–63	58	6.77	120–165	138.4	31–62	47.49	74–83	77.44
Polytwill	35–40	36	6.62	88–112	102.68	45–65	57.86	61–70	67.13
Corduroy	67–75	71	6.46	120–171	151.98	26–50	39.73	76–85	82.44
Momie	77–83	79	6.08	151–186	166.76	30–50	39.85	81–87	85.77
Twill 3	70–83	76	6.23	141–180	164.68	32–47	40.26	73–80	83.12
Plain20	73–85	79	6.46	132–185	170.74	28–52	45.06	76–87	83.75

experiments comparing drape coefficients obtained from the Cusick drapemeter with those obtained from samples scanned in the 3D body scanner were conducted. A correlation of 0.9842 between the two methods of measuring drape coefficient was found. The results from a paired t-test ($t(23) = -1.35$, $p = 0.188$) verify that there is no significant difference between the drape coefficients obtained using the traditional Cusick drapemeter and the 3D body scanner. This shows that measurement of drape using the 3D body scanner is a viable alternative to using the Cusick drapemeter.

VARIABILITY EXHIBITED IN FABRIC DRAPE

Drape measurement was carried out using 36 cm diameter fabric samples draped on an 18-cm diameter disk. To estimate the variation that occurred during repeated draping of the same fabric sample, a total of 12 trials were conducted. The readings were blocked in two sets of six, one set captured using the 3D body scanner and the second captured at a different time using the Cusick drapemeter. Use of 12 trials is consistent with standard procedures for determining drape coefficient (BS 5058, 1973; British Standard Institution, 1974b), although two samples would be used in determining drape coefficient. The fabric samples were maintained in standard atmospheric conditions before the trials. The range of variation exhibited by each fabric in the number of nodes, drape coefficient, and the nodal dimensions were recorded and are plotted in Figure 7.

IMPROVED ACCURACY IN REPRESENTATION OF A FABRIC

To evaluate the virtual appearance of fabric drape simulation, the meaning of accurate representation of a specific fabric must be defined. Draped fabric exhibits a fairly wide range of variation when draped repeatedly, as the experimental results showed in the previous section. The variation exhibited in the drape parameters is summarized in Table 3.

The mean variation for the tested fabric samples was in the range of ±15% for drape coefficient and ±25% for the node dimensions. The variation in node numbers was as high as three nodes. Considering the wide variation in drape exhibited by fabrics, it is apparent that there is no single target value for a simulation to match for it to be considered a good match to the actual fabric. Instead, if a simulation falls within a region of acceptance, it could be considered a good match to an actual fabric drape.

CONCLUSIONS

A new technique for the measurement of fabric drape using the 3D body scanner was developed and validated. We found that the 3D body scanner can be successfully used to measure parameters of a draped circular fabric sample by capturing the image of the draped fabric and processing the image in Geomagic software. The significance of this new method of evaluating drape lies in the ability to translate drape of actual fabrics to the virtual 3D environment, where drape can be measured identically for actual and simulated fabrics. Furthermore, use of additional measures and metrics for describing fabric drape in 3D become feasible in the virtual environment.

Fabric drape is dependent on large number of variables including fabric properties, shape of the object over which it is draped, and environmental conditions. Each of these is in turn dependent on more variables, which exhibit chaotic behaviour. Hence, fabrics do not fall in the same configuration each time they are draped. The variability test results for the selected fabrics show that on an average they exhibit a ±15% variation from the mean in drape coefficient, and ±25% variation from the mean in the nodal dimensions. A large variability in the number of nodes formed from trial to trial was also documented.

In simulating the drape of fabrics, it must be remembered that fabrics do not drape the same way each time. Hence, there is no precise target that the simulation of a particular fabric should achieve in order to be representative of that fabric. This complicates efforts to simulate particular fabrics accurately. In Part II of this paper, we demonstrate the applicability of variability test results for matching fabric simulations to actual fabric drape.

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