THE MEASUREMENT OF FABRIC PROPERTIES FOR VIRTUAL SIMULATION—A CRITICAL REVIEW

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THE MEASUREMENT OF FABRIC PROPERTIES FOR VIRTUAL SIMULATION—A CRITICAL REVIEW

Authored by

Sandra (A.A.M.) Kuijpers, *Amsterdam Fashion Institute, Netherlands*

Christiane Luible-Bär, *University of Art and Design Linz, Austria*

R. Hugh Gong, *University of Manchester, UK*

IEEE

3 Park Avenue | New York, NY 10016-5997 | USA

TRADEMARKS AND DISCLAIMERS

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This work is undertaken as part of the key area focus of the 3D Retail Coalition Innovation Committee to gain insight in the measurement of fabric properties for virtual simulation to pave the path for standardization of the measurement methods and its output data.

The Institute of Electrical and Electronics Engineers, Inc. 3 Park Avenue, New York, NY 10016-5997, USA

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ABSTRACT

This investigation is undertaken based on the indicated improvements for fabric simulations, defined during the panel discussion “Driving the Uniformity of Material Measurements for Accurate Virtual Simulation” at the Product Innovation Apparel Conference (PI Apparel) in Berlin 2017, by experts from industry and academia. According to the expert panel, there is no coherency between methods used to measure the fabric properties and the simulated results of the same fabric among the different software packages. In praxis, fashion brands use different 3D software packages and need to measure a fabric with different methods to obtain the same fabric properties. In addition to the time investment, the simulated results for the same fabric vary significantly between the different software packages. The experts indicated the lack of standardization in material measurements, the lack of correlation between the data of the different measurement systems, and the lack of correlation between the simulated results of the different software packages for the same material. The contributions of the panel were followed up during the next edition of PI Apparel in the United States and resulted in the 3D Retail Coalition (RC) innovation committee to work on the indicated areas to improve the efficiency of material measurements. Moreover, this topic was further discussed during the PI Apparel Conference at Lago Maggiore in 2019 within the panel discussion "How Can We Collectively Achieve the Standardisation of Fabric Measurements for Digital Materials?"

This paper investigates, on the one hand, the suitability of the current available measurement technologies for retrieving fabric parameters for precise virtual fabric and garment simulations. The focus is on the main properties required by the software packages—bending, shear, tensile and friction—aiming to identify and specify the most suitable methods to retrieve mechanical fabric properties and to start a standardization process for fabric measurements for virtual simulations.

Seven fabric measurement methods and their output data are reviewed, namely the Kawabata Evaluation System (KES), the Fabric Assurance by Simple Testing (FAST), the Fabric Touch Tester (FTT), the CLO Fabric Kit 2.0, the Fabric Analyser by Browzwear (FAB), the Optitex Mark 10, and the cantilever principle. A set of fabrics with different mechanical behavior and physical drape has been tested with the FAB method. Other measurement methods have been discussed with expert users. In addition, fabrics have been tested with ZwickRoell’s (ZwickRoell) measuring systems applying various standard measurement methods, developed for similar materials. This publication will give for each property an overview of the different measurement methods, as well as recommendations based on their accuracy. Further, a SWOT analysis is provided. The outcome of this research can be used to pave the foundation for further work on the standardization of the fabric measurement.

1

INTRODUCTION

1.1 BACKGROUND

In recent years, the fashion industry has been increasingly shifting to use simulations for virtually assessing new products before they are actually produced [1], [2], [3].[1] Even if it is impossible to simulate a product with 100% accuracy since all real influencing factors cannot be known, the virtual prototype has to be precise enough so that important decisions can be taken within the product development process. For a 2D pattern optimization, which is done with millimeter precision, the virtual prototype should be in the same range of precision. Depending on the field of application, simulations approach reality with various mechanical models that consider forces and impulses and reduce the influencing factors to the most important ones. Fabrics are complex non-linear viscoelastic materials that, when subjected to stress, flow and only gradually come to rest when the force is removed. Their simulation is not easy, as their behavior is difficult to describe and predict. Fabrics must have sufficient strength and at the same time they must be flexible, elastic, and easy to pleat and shape. The knowledge of the viscoelastic behavior of a material is based on empirical data from characterization experiments. The accuracy of virtual garment simulations is dependent on the mechanical model of the simulation system and the precision of fabric input parameters, derived from fabric physical and mechanical fabric properties [4].

With regards to the accuracy of the mechanical model of simulation systems, earlier cloth simulation systems were not able to precisely simulate garments and, therefore, largely simplified the complex fabric behavior. Accurate fabric input parameters were not needed. More recently, algorithms are optimized to such an extent that more accurate simulations have become possible (see [5]−[15]).

As defined during the panel discussion “Driving the Uniformity of Material Measurements for Accurate Virtual Simulation” [16], a few of the struggles the industry faces regarding the implementation of 3D virtual technology are the lack of uniformity in measurement technology, the lack of uniformity in units, and the lack of correlation between virtual samples created based on the same fabric when using different software solutions.

The purpose of this investigation is to find the most suitable method to retrieve mechanical properties required for simulation in order to achieve a standard. In doing so, a good collaboration between simulation companies, garment companies and mills, as well as researchers, is essential. Software providers have to share the information about underlying mechanical models of their computation system so that a standardization process can take into account how a fabric property is integrated in different simulation systems. An example of this is, with regards to the tensile parameter, whether the tensile behavior is linearly or non-linearly modeled. Only if most simulation systems are able to calculate precisely the non-linear fabric behavior, a standard can be envisaged to capture it. With regards to shear, it is important to know if the parameter is measured by extension in the bias (45°) direction of a fabric (FAST) or is measured by shear deformation of the fabric (KES). With regards to bending, it is important to know if the parameter is integrated in a way so that there is a correlation to other properties. An example of which is whether the interplay between bending, shear and weight properties is considered [17], [18], [19]. For friction, it is essential to know whether static or dynamic friction is considered. As long as this information is not made transparent and discussed by simulation companies, the development of a standard will be challenging. The simulation itself is a necessary simplification of reality, in order to obtain a complex garment simulation in a reasonable time. However, in the development of a standard measurement, it is important that the fabric properties and the conditions of their measurement match the need of the mechanical models of the simulation systems so that the virtual garment is accurate enough to base important decisions upon it.

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[1] Numbers in brackets refer to Citations list in Section 5.

1.2. RESEARCH AIM AND SCOPE

The aim of this research is to investigate the principle and methods applied by the currently used measurement technologies for retrieving fabric parameters for virtual garment simulations. The main focus is on bending, shear, tensile, and friction properties because these are widely considered to be among the most important fabric properties determining fabric behavior. The following fabric measurement methods are studied:

- Kawabata Evaluation System (KES)
- Fabric Assurance by Simple Testing (FAST)
- Fabric Touch Tester (FTT)
- CLO Fabric Kit 2.0,
- Fabric Analyser by Browzwear (FAB)
- Optitex Mark 10

In addition, fabrics have been tested with ZwickRoell's measuring systems applying various standard measurement methods, developed for similar materials. With regards to the bending property, the fabric stiffness tester (FST) is additionally assessed.

1.3. RESEARCH QUESTIONS AND METHODOLOGY

The leading research question is as follows:

What is the most suitable fabric measurement method to retrieve mechanical properties required for precise virtual fabric and garment simulations?

The sub questions addressed are as follows:

1) What is, for each property, as defined in the aim, the measurement principle for each system?
2) What are, for each property, the characteristic values for each system?
3) What are, for each principle, the strengths, weaknesses, opportunities, and threats?

Secondary and primary research methods were applied.

For each measurement system and/or principle, questions 1) and 2) were answered through review, observation, and testing as follows: all measurement methods were reviewed based on publications, some instruments were discussed with an expert user (Optitex Mark 10) and users (FAB),and two instruments were tested and observed (ZwickRoell, FAB).

To answer the third question, SWOT analysis were made based on the findings for each system.

1.4. STRUCTURE

Section 2 will give for each system an overview of the different measurement methods and principles used, as well as the data by means of the characteristics values for each property. In Section 3, a SWOT analysis is given for each system or method, as well as recommendations based on the findings. This is followed by the conclusions, the research limitations and suggestions for future work.

2

FABRIC PROPERTIES, EXISTING MEASUREMENT PRINCIPLES, AND DEVICES

2.1. FABRIC MEASUREMENT BACKGROUND

Pierce ([20], [21]) was one of the first to lay the foundation for the quantification of textile material and to connect fabric behavior to properties, as well as to relate the subjective assessment of drape and handle to objective properties. By introducing the Flexometer, Pierce [20] enabled measurement of the drape or stiffness of fabric, expressed in bending length. This method, explained under BS 3356:1990 [22], is appropriate to measure the bending of most fabrics, except for highly rigid or limp fabrics and fabrics that tend to curl up. To measure the bending of soft fabrics, Pierce describes hanging loops and heart loops. Moreover, Pierce discussed formulas based on the bending length to quantify handle properties such as flexural rigidity, thickness, hardness, bending modulus, compression modulus, density, and extensibility.

Research in the textile engineering area emerged. Physical and mechanical parameters where derived, such as bending, shearing, tensile, buckling and compression [23]. Bending and shear properties closely relate to fabric drape, [24], [7], [19], tensile properties are responsible for comfort and movement in the garment [25], [26], [27], the same properties are related to fabric hand [20], [28] and today used to simulate garments [29].

2.2. BENDING PROPERTIES ACCORDING STANDARD CANTILEVER METHOD

The Fabric Stiffness Tester (FST) follows the Flexometer with the cantilever principle as developed by Pierce [20]. The FST is a simple manual device and various standards are available to execute the measurements, as among others BS 3356:1990 [22] and ASTM D1388-96 (2002) [30]. Fabric specimens (specific cut pieces of fabric for the testing) supported on the dedicated area of the instrument are pushed over the edge to bend under the fabrics own weight until an angle of 41.5° is reached, (Figure 5). Test material used is five warp and five weft specimens of 25 mm × 200 mm each, according BS 3356:1990 [22]. The bending length (C) indicates the stiffness of the fabric and is measured from the overhanging part, expressed in cm. Stiffer fabrics have higher values. Flexural rigidity (G) indicates the resistance to bending as if a strip of fabric is bent between finger and thumb, it is calculated based on C and the mass (weight) of the material, expressed in mg cm. A significant step was made when Kawabata [28] introduced the Kawabata Evaluation System (KES); a more systematic concept for measuring fabric properties.

2.3. KAWABATA EVALUATION SYSTEM (KES)

In the 1970s, Kawabata conducted research on fabric mechanical properties; however, his main achievement was the concentration of the so far obtained fundamental knowledge on fabric mechanics in one standardized fabric characterization method. His achievements represent the most widespread and well-known method for the objective assessment of fabric hand. Until then, fabric hand experts in factories, sales engineers or consumers executed fabric hand assessments subjectively without any common concept or definition of hand, despite its importance [28].

Kawabata's standardization study was two-staged. First, he organized an expert committee with different people from the apparel industry, who assessed using traditional methods in total around 1500 different fabric materials. According to the expert team, a "good" hand meant, for example, that to the touch the fabric is extremely smooth and both stiffness and fullness/softness are moderate. The main goal of the expert team was to identify the most important hand expressions and to relate these touch sensations to measurable fabric properties. Kawabata then developed a method of measuring the fabric properties (KES) that were considered relevant to fabric hand. There were in total 16 characteristic values (Table 1). The fabric hand values subjectively evaluated by the panel were then correlated with the objectively measured fabric properties. The equations developed could then be used to calculate fabric hand from the fabric properties measured using the KES system. This part of Kawabata's studies can be seen as the standardization procedure [28].

TABLE 1: FABRIC PROPERTIES MEASURED BY THE KES-F SYSTEM

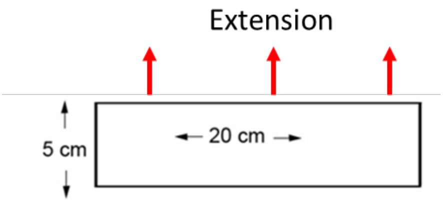
PARAMETER		DEFINITION	UNIT
Tensile	LT	Linearity	—
	WT	Tensile energy	gf cm/cm^2
	RT	Resilience	%
	EM	Max. extension	%
Bending	B	Bending rigidity	gf cm^2/cm
	2HB	Hysteresis	gf cm/cm
Shearing	G	Sheer stiffness	gf/cm^{-0}
	2HG	Hysteresis at 0.5°	gf/cm
	2HG5	Hysteresis at 5°	gf/cm
Compression	LC	Linearity	—
	WC	Compressional energy	gf cm/cm^2
	RC	Resilience	%
Surface	MIU	Coefficient of friction	—
	MMD	Mean deviation of MIU	—
	SMD	Geometric roughness	µm
Weight	W	Weight/unit area	mg/cm^2
Thickness	T	Thickness at 0.5 gf/cm^2	mm

Besides his studies on the standardization of objective fabric hand assessment, Kawabata went on with research on measuring mechanical and physical fabric properties. This part of research was driven by the question of how a broad variety of fabrics should be tested in the same way so that the obtained data represents a significant statement about that textile. When a fabric is touched and squeezed during subjective hand assessment, only small forces occur. For example, no fabric would break during this manipulation. For this reason, Kawabata designed his measurement standard for small deformation regions. In conclusion, Kawabata considered six measurement blocks, which were improved in 1980, named KES-FB and reduced to only four machine blocks, KES_FB 1, 2, 3, and 4 [28].

2.3.1. KES-FB 1 = TENSILE AND SHEARING TEST

Tensile deformation is applied along both the warp and weft directions. The specimen size is 5 cm length to 20 cm width. This is illustrated in Figure 1. The strain in the width direction becomes approximately zero because the force is applied to the long sides of a rectangular specimen. This type of deformation is also called “strip biaxial deformation.” After the tensile force attains the maximum stress F_m= 500 g f/cm, the recovery process starts. The tensile and shear tests can be conducted with velocities of either 0.1 mm/sec or 0.2 mm/sec.

FIGURE 1: DIAGRAM KES-FB 1: TENSILE MEASUREMENT



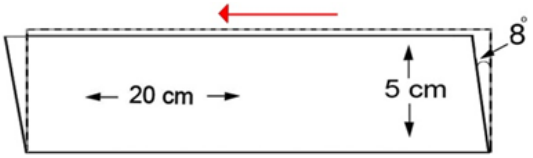
The derived characteristic values are as follows:

- EM: extension at maximum load (%)
- LT: Linearity
- WT: Tensile energy per unit area (gf*cm/cm^2)
- RT: Resilience (%), (to which degree the fabric recovers, after the release of the force)

In addition, KES has a sensitive setting that allows the testing of stretchy fabrics such as knits with a maximum load of 50 gf/cm.

Shear properties are obtained by shearing the same specimen 8° in one direction, moving it back to the origin, and shearing it in the opposite direction until an angle of −8° is reached. The first movement is illustrated in Figure 2. Applied forces are recorded. A constant tension of W = 10 gf/cm along the orthogonal direction of shearing is applied, to minimize fabric crease during shearing.

FIGURE 2: SHEAR DIAGRAM



The derived characteristic values are as follows:

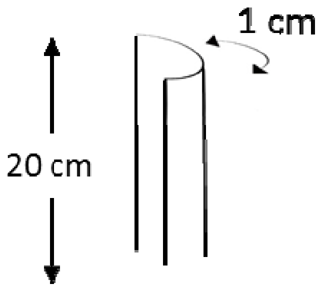
- G: Shear rigidity (gf/cm * degree)
- 2HG: Hysteresis at shear angle Ø = 0.5 degree (gf/cm)
- 2HG5: Hysteresis at shear angle Ø = 5 degree (gf/cm)

G is defined as the (shear force per unit length) * (shear angle). G can also be defined as the slope of the shear force (F_s) minus phi, F_s – Ø, where Ø is between 0.5° and 5°. If the curve is not linear in this region, the mean slope over this region is taken. For fabrics with a non-symmetric weave structure, the curves are different between positive and negative regions. The G value is the average value of the two regions. 2HG and 2HG5 are the sum of HG and HG5 measured in the two regions, respectively.

2.3.2. KES-FB 2 = PURE BENDING TEST

Kawabata measures bending with an apparatus that bends the whole sample in an arc of constant curvature, where the curvature is changed continuously. This allows the detection of the relationship between bending momentum and curvature. The bending tester measures the forces to bend the specimen up to 150° followed by the opposite direction. (K = −2.5 cm^{-1} and 2.5 cm^{-1}). K is the bending angle in radians. For example, 150° = −2.5 cm^{-1}. The specimen size is 20 cm by 1 cm width. This principle is illustrated in Figure 3. The rate of curvature change is 0.50 cm^{-1}/sec.

FIGURE 3: KES FB2 BENDING MEASUREMENT



See also Kawabata [28].

The derived characteristic values are as follows:

- B: Bending rigidity per unit length (gf.cm^2/cm)
- 2 HB: Momentum of hysteresis per unit length (gf.cm/cm)

Four types of bending are important: Face (Bf), Back (Bb) in weft and warp. 2HB is taken between K= 0.5 and 1.5 for HBf and between K= −0.5 and −1.5 for HBb. B is the average of Bf and Bb while 2HB is the sum of HBf and HBb.

2.3.3. KES-FB 3 = COMPRESSIONAL TEST

Compression tests measure the compressibility of a textile as well as physical characteristics such as thickness. Thickness T in mm is measured with a fixed pressure of P = 0.5 gf/cm^2. The LC, WC, and RC values are also calculated. In addition, the fabric specific weight W (mg/cm^2) is measured separately.

2.3.4. KES-FB 4 = SURFACE TEST

Within the surface tests, friction is measured with a sensor made from piano-wire. The sensor travels 30 mm, but the measurement is taken over the middle 20 mm. The sample size is 20 cm × 20 cm.

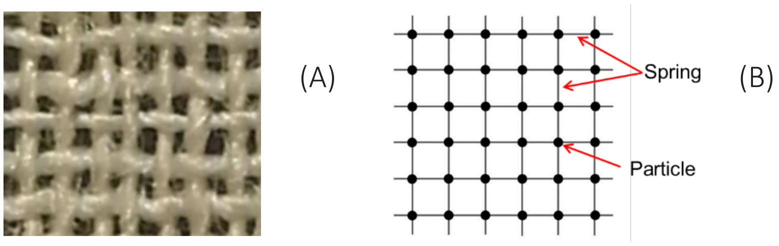
The derived characteristic values are as follows:

- MIU (mean value of the coefficient of friction).
- MMD (mean deviation of MIU).

In addition, the fabric surface roughness, SMD, is also measured by a separate sensor.

The Kawabata data were used in 1994 by Breen, House and Wozny [29] when they delivered a significant contribution to cloth simulation for the CAD area by applying objective fabric measurements into a particle grid or mesh (Figure 4). They stressed the complexity of textile materials, which are a compound of fibers 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.”

FIGURE 4: **PARTICLE MESH PRINCIPLE; (A) PLAIN WEAVE, (B) PARTICLE-SPRING MESH, THE PARTICLES REPRESENT THE YARN INTERSECTIONS**



Statistically, significant and positive correlations are found between real and virtual drape coefficients with $r = 0.97$, $p<0.0001$ for the cloth simulated with KES data [19].

2.4. FABRIC ASSURANCE BY SIMPLE TESTING (FAST)

Although Kawabata’s objective assessment method is precise from a mechanical point of view, it was not widely adopted by the textile and clothing industry. Many companies still used the subjective evaluation to assess fabric hand. The main reason for this situation was the repetitive and lengthy process of measurements and expensive equipment. In the late 80s, CSIRO Division of Wool Technology in Australia realized the importance of a simpler and cheaper alternative to KES-f and developed the FAST-method. The SiroFAST characterization standard resulted in three instruments (FAST1, FAST2, and FAST 3) and one test method (FAST4), returning 16 measured and calculated characteristic values (Table 2). FAST provides information for cutting, garment assembly, performance in wearing, as well as ‘compressibility and formability’ both responsible for seam pucker during sewing. For FAST2 and FAST3 the same fabric specimen is used—in total 12 fabric specimens of 5 cm by 15 cm are required. FAST4 is tested with a specimen of 30 cm by 30 cm. For more consistent results, conditioning at 20 °C and 65% RH is required according the regular standards. In 8 hours, 6–10 fabrics can be tested [31], [32].

TABLE 2: FAST MEASURED AND CALCULATED CHARACTERISTIC VALUES

Property	Symbol	Measured	Unit
Compression	T2	Thickness, measured under 2 g/cm^2	mm
	T100	Thickness, measured under 100 g/cm^2	mm
	ST	Surface Thickness	mm
	T2R	= T2 released after steaming	mm
	T100R	= T100 released after steaming	mm
	STR	= Surface thickness released after steaming	mm
Bending	B	Bending Rigidity	µN.m
	C	Bending Length	mm
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	Shear rigidity = 123/EB5	N/m
Dimensional properties	RS	Relaxation Shrinkage	%
	HE	Hygral expansion	%
Calculated	F	Formability	—[a]
Weight	W	Weight	G/m2

[a] There is no unit of measure given for this calculation.

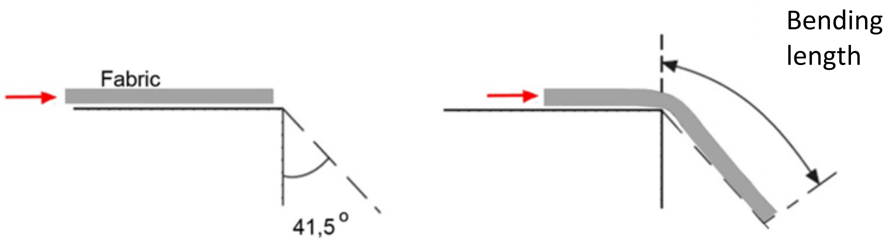
2.4.1. SIROFAST-1: COMPRESSION METER

Compression is taken at two loads, 2 g/cm^2 and 100 g/cm^2, to obtain T2 and T100, respectively. The difference between T2 and T100 is calculated to obtain ST. The measurements are then repeated after the fabric has been relaxed with steam for 30 seconds. Original surface thickness (ST) and the released surface thickness (STR) can be used to assess the stability of the finish of the fabric under garment manufacturing conditions such as pressing and steaming.

2.4.2. SIROFAST-2: BENDING METER

This instrument measures the bending length using the cantilever bending principle. The bending edge under 41.5° is detected with a photocell, bending rigidity is calculated from the bending length. The principle is illustrated in Figure 5. Bending is usually measured in the machine and cross directions.

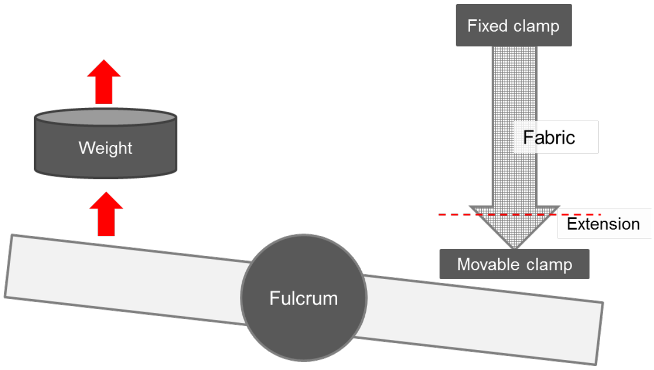
FIGURE 5: FAST 2, DIAGRAM OF THE BENDING MEASUREMENT [19]



2.4.3. SIROFAST-3: EXTENSIBILITY METER

The Extensibility meter measures the extensibility of a fabric under three different loads (5 g/cm, 20 g/cm, and 100 g/cm). These loads are chosen to simulate the level of deformation that a fabric is likely to undergo during garment manufacture. This device is also used to measure the bias extensibility of the fabric (= shear) under a low load 5 gf/cm. Bias extensibility is not used directly but rather it is used to calculate shear rigidity. This principle is illustrated in Figure 6. In addition, formability parameters can be derived from SiroFAST-3 measurements in conjunction with data from SiroFAST-2.

FIGURE 6: DIAGRAM OF FAST 3 ELONGATION AND SHEAR MEASUREMENT, SEE ALSO [31]



2.4.4. SIROFAST-4: DIMENSIONAL STABILITY TEST

SiroFast-4 is a procedure for measuring dimensional stability properties of fabrics, such as hygral expansions and relaxations of fabrics (important for wool).

Statistically significant and positive correlations are found between the real and virtual drape coefficients with r = 0.94, p<0.0001 for the cloth simulated with FAST data [19].

2.5. FABRIC ANALYZER BY BROWZWEAR (FAB)

Recently 3D software developers have brought their own devices to the marked to measure shear, bending, and tensile properties. To replace their manual Fabric Testing Kit (FTK) Browzwear introduced at the end of 2017 the Fabric Analyser by Browzwear (FAB). On a single device, one long fabric specimen can be used to measure mass, thickness, tensile, shear, and bending [33], [34], [35], returning eight measured and calculated characteristic values (Table 3). Friction is part of the data but apparently not measured. This conclusion is based on the measurements obtained by the expert user during the past year. It is also based on the measurements obtained from the six tested fabrics, which have dissimilar values for friction measured with KES.

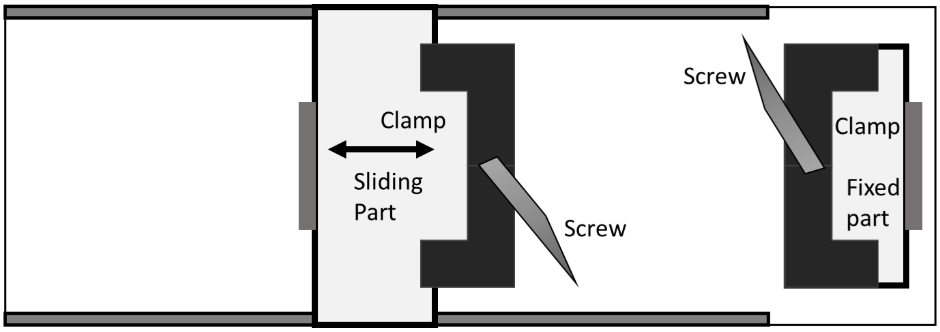
TABLE 3: FAB MEASURED AND CALCULATED CHARACTERISTIC VALUE

Property	Symbol	Unit	Measured
Stretch (Tensile)		N/m	Stretch (warp/weft)
		%	Stretch linearity
Shear		N/m	Shear
		%	Shear linearity
Bending		Dyn*cm	Bend
		Dyn*cm	Hysteresis
Thickness (Compression)		mm	mm
Friction		—[a]	Is part of the data, but apparently not measured and set as default on 0.20
Mass Density (Weight)		g/m2	An external digital scale is required

[a] There is no unit of measure given for this calculation.

The fabric is placed on a surface between two clamps, one of them is able to slide along the long side of the device (Figure 7). The specimen is attached with screws and the left over part is rolled up at the end of the movable part. The fabric specimen has a width of 5 cm and a recommended length of 25 cm. This length is required in order to be able to use the other side of the specimen for the bending test. Another option is to use shorter fabric specimens for which the minimum length depends on the distance between the clamps.

FIGURE 7: SCHEMATIC DIAGRAM IN BIRD VIEW OF THE FAB



The first step in the testing sequence is the calibration of the device. Then, the testing order is as follows in 2.5.1 through 2.5.4.

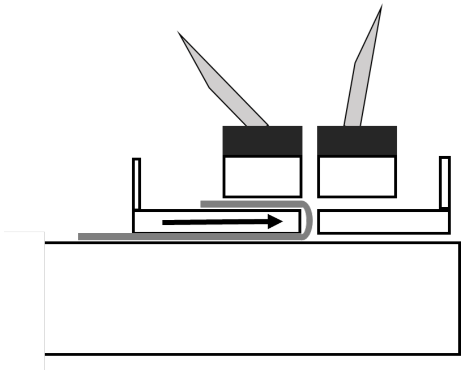
2.5.1. FAB 1 MASS

With an external digital scale, the weight of the specimen is obtained and input into the software. Based on the weight and inserted specimen size the software calculates the fabric area and hence the mass density.

2.5.2. FAB 2 THICKNESS OR COMPRESSION

The width of the specimen is specified and the fabric is positioned between the clamps. To measure thickness, the movable part slides towards the fixed part. Figure 8 shows a schematic diagram of the FAB thickness test.

FIGURE 8: SCHEMATIC DIAGRAM OF THE FAB THICKNESS MEASUREMENT

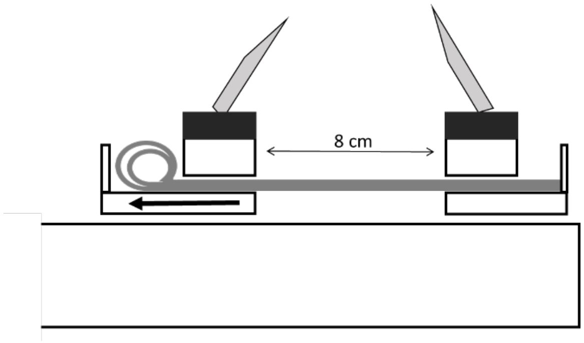


The software produces a curve with the thickness measurement as illustrated in Browzwear's Thickness Test [36]. This graph is hard to interpret, if the vertical axis shows the force, it appears that the thickness decreases with increasing force, which is plausible, but then the thickness increases with force, which is illogical.

2.5.3. FAB 3 LONG SEGMENT TEST OR TENSILE AND SHEAR TEST

After activating the tensile test the movable part slides from the fixed part until a distance of 8 cm is reached between the parts. To support the fabric during placement a block is placed between the movable and the fixed part, which is removed after positioning the fabric. A sensitive needle indicates correct placement of the fabric. The moveable part slides away from the fixed part to extend the fabric. The principle is illustrated in Figure 9. The load cells register the tension (force), which is plotted in a graph with the extension in mm on the x-axis and the force on the y-axis as in Using the FAB [37]. The shear test follows the same principle and is executed with a bias cut fabric specimen.

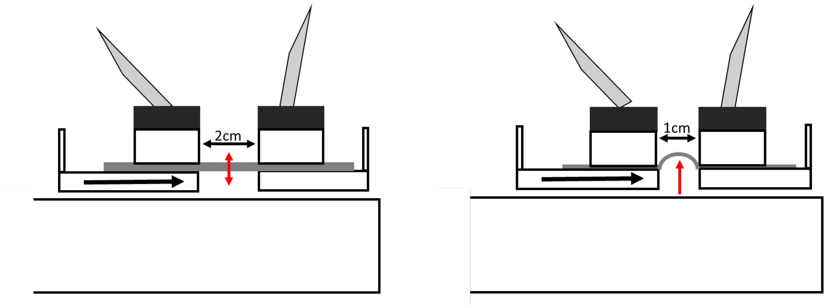
FIGURE 9: SCHEMATIC DIAGRAM OF THE FAB TENSILE AND SHEAR MEASUREMENT



2.5.4. FAB 4 SHORT SEGMENT TEST OR BENDING TEST

After activating the bend test the moveable part slides into its start position with 2 cm between the clamps. A temporary support is placed between the sliding part and the fixed part during placement of the unused part of the fabric between the clamps. A sensitive needle indicates correct placement of the fabric. After starting the test, the moveable part slides a bit towards the fixed part. The fabric needs to be pushed with a pen to help it bend in the right direction, upward and downward. After activating the test, the sliding clamp moves until 1 cm distance is reached. The principle is illustrated in Figure 10. From warp, weft, and bias fabric specimens, the upward and downward (face and back) bending measurements are tested. During testing, a graph with the force on the Y-axis and the bending length in cm is visible [38]. With regards to the sensitivity of the bending measurement, a warning is given to avoid any vibrations during the tests.

FIGURE 10: SCHEMATIC DIAGRAM OF THE FAB UPWARD BENDING MEASUREMENT



The FAB review is based on manuals and videos [34]–[38], as well as observations during the testing of six fabrics together with expert users.

2.6. CLO FABRIC KIT 2.0 (CFK2.0)

The measurement tools consist of a digital scale, digital thickness gauge, a bending tester, for the tensile test a short and a long fabric feed, and a digital force gauge, which are attached to a long base with ruler. The kit needs to be assembled by the user (Figure 11).

FIGURE 11: OVERVIEW OF THE CLO KIT

In total, one warp, one weft, and one bias fabric specimen, each of 22 cm by 3 cm, are required to measure the weight, thickness, bending, and tensile properties.

All measurements need to be read from the rulers and/or devices, next written on a form, and then input into the fabric emulator of the software; the characteristics are given in Table 4 [39].

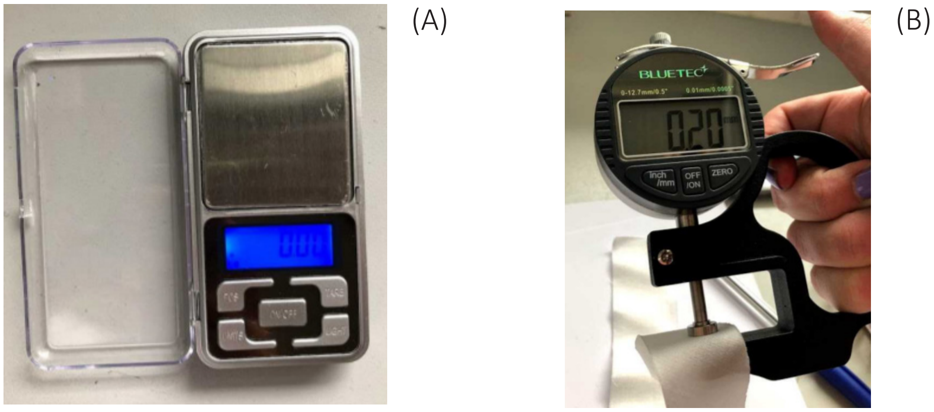
TABLE 4: CLO MEASURED CHARACTERISTIC VALUE

Property	Symbol	Unit	Measured
Stretch test (Tensile)			Length (mm) / Force (kgf)
Bias stretch test (Shear)			Length (mm) / Force (kgf)
Bending test		mm	Contact distance
		mm	Length
Thickness		—	mm
Mass Density (Weight)		g	The three cut specimen are weighted on a scale provided with the Fabric Kit

2.6.1. WEIGHT AND THICKNESS

First, the three required fabric specimens are folded and put on the scale [Figure 12(A)] to measure the weight. Second, the thickness is measured with a digital thickness gauge [Figure 12 (B)], in both cases the values are written on the form.

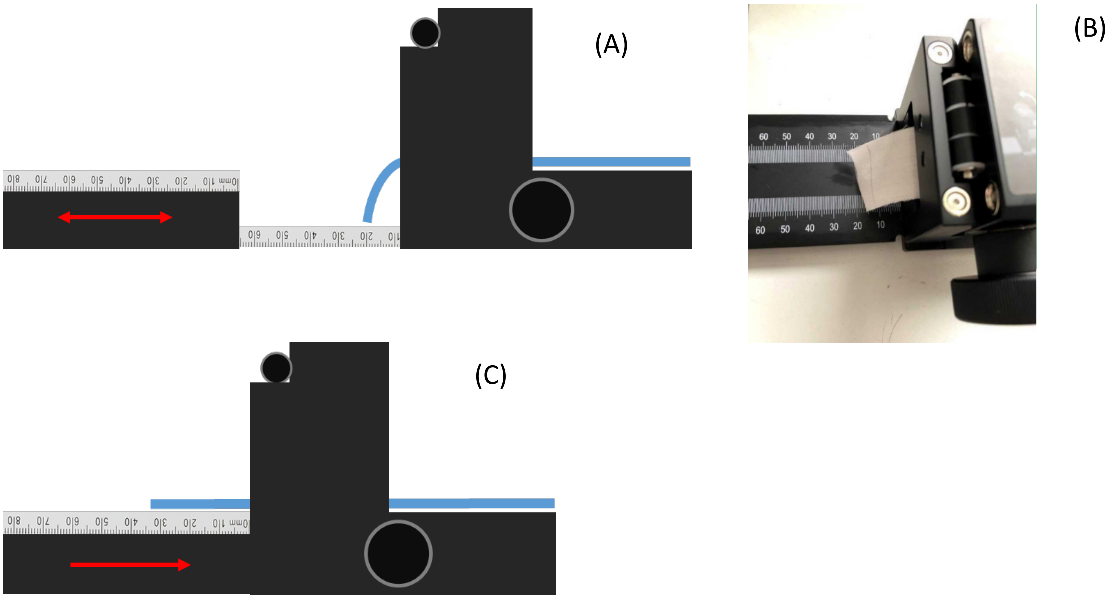
FIGURE 12: MEASURING (A) WEIGHT AND (B) THICKNESS


(A)
(B)

2.6.2. BENDING

The contact distance and the bending length is obtained by testing one warp and one weft swatch. The procedure follows the cantilever principle; however, in contrast to the standard, the fabric is fed into the instrument and rolled outside the canal with a wheel. Next to this, the contact length is taken as soon as the fabric specimen reaches the ruler instead of under a corner of 41.5° [Figure 13(A), (B)]. The fabric is manually lifted and the higher sliding ruler is moved under the fabric to obtain the bending length [Figure 13(C)], as see in CLO3D [39]. The bending measurements are manually obtained and written on the form by the user.

FIGURE 13: BENDING, (A, B) CONTACT DISTANCE, (C) BENDING LENGTH



The CLO KIT does not distinguish between face up and down and fabrics can be tested randomly. This is in contrast with the standard procedures, such as BS 3356:1990 [22] and ASTM D1388-96 (2002) [30], where both sides are tested. As well as to the significant differences between the face and back drape coefficient (DC) that some fabrics have, the DC is closely related to the bending length [19].

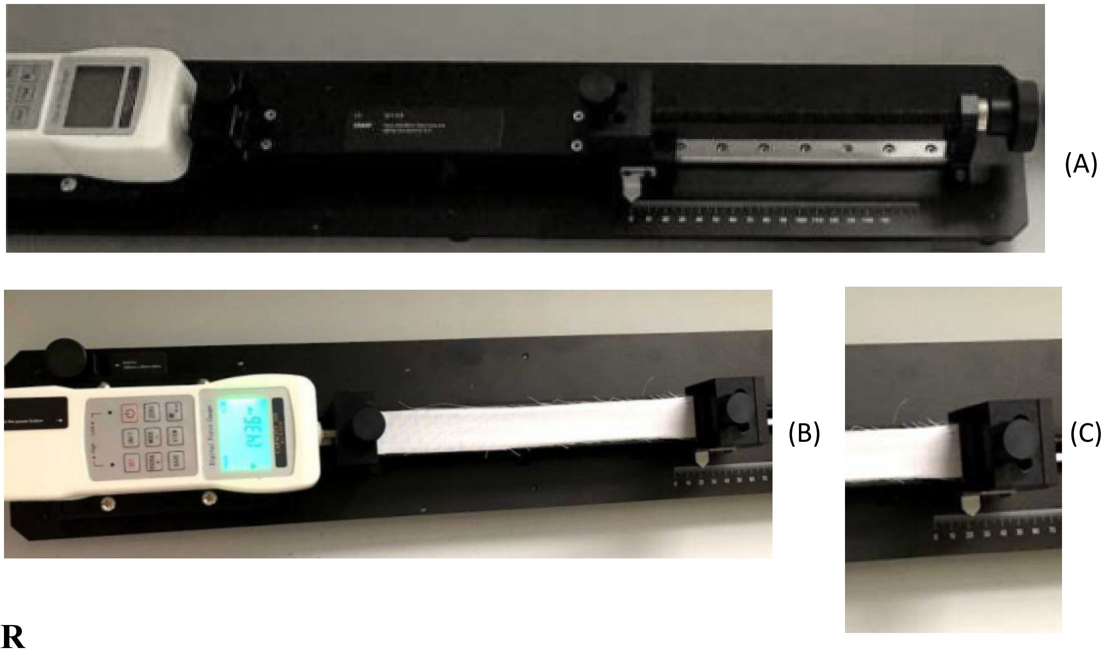
A general deficiency of the cantilever principle is the limitations with jersey fabrics, which tend to curl up [20]. CLO advises to solve this by manually pulling the fabric further outside the device and rolling it back until it is hanging free from the ruler. It is unclear how the bending measurement is influenced by the manual interaction and/or by dragging the specimen over the ruler surface, especially given the intricacy of the bending measurement described in the comment at the bottom of Table 5 in Chapter 2.10. Another deficiency of the cantilever is visible in Figure 12(B), where two contact distances can be obtained.

2.6.3. TENSILE (STRETCH TEST)

Figure 14 illustrates the stretch tester with a digital force gauge to record how much force is applied to the fabric (Figure 14A). The knob on the right (Figure 14A) is used to move the fabric and has a ruler on its surface. The combination of the ruler and the digital force gauge will result in one set of measurements. The device has a threshold at 2 kg force, when this is reached it stops testing. In total one warp, one weft, and one bias fabric specimen (each) are tested, through increasing the length for each specimen a minimum of three measurements and a maximum of five measurements are taken, depending on the elongation in the material. The length increments differ for stretch and woven fabrics—for woven 1 mm and for high stretch fabrics 10 mm is advised, for a woven bias specimen 10 mm could be used.

The start position of the ruler is on 0, with the digital gauge switched off, the fabric specimen is placed in the center between the grips (Figure 14B). First the length to use as a constant is determined with the force gauge switched on, the knob (Figure 14C) is turned to stretch the fabric until the force gauge reaches approximately 0.00, slight differences are due to destabilization. The reached length value at the ruler and the gauge value represent the first set of measurements and are manually obtained and written on the form by the user. To obtain the following sets of measurements the knob is turned with the required length increment from the previous value, thus extending the fabric each time with the defined increment. All values are manually obtained and written on the form by the user.

FIGURE 14: TENSILE TESTING



2.6.4. SHEAR

This property is not mentioned, but we assume this can be calculated based on the bias extension of the stretch test.

The CLO fabric kit is reviewed based on the instruction video [39] and observed during testing of fabrics.

2.7. OPTITEX FABRIC TESTING UNIT (FTU)

Regular and independent instruments are used by Optitex according to the following industry standards: bending obtained with the manual Fabric Stiffness Tester (FST) as described in Section 2.2; thickness obtained with a Digital Thickness Gauche; tensile and shear obtained with a motorized tensile (tension) tester from Mark 10 in combination with a Force Gauge; and weight obtained with a high precision digital scale [40]. The manual does not include the friction test. According to the Mark-10 website [41] the motorized test stands are dedicated for tensile and compression testing. Moreover, they are configurable; on the website they offer an attachment for friction measurement [42]. According to the Optitex fabric testing guide [40], the thickness is measured according to ASTM D1777-96 [43].

During a Skype interview, the device is discussed with an expert user responsible for fabric testing at a large company and who had worked with the instrument for 3 years. In a similar way as described in the Optitex fabric testing guide [40] tensile and shear are tested with the Mark 10. In contrast, friction is measured with the device and part of the bending measurement. For both measurements, additional parts are installed at the Mark 10, which are removed prior to the tensile and shear measurement. Each property is tested three times. In total 12 fabric specimens are needed as follows—three specimens of 15 cm in warp by 10 cm in weft to test friction and three fabric specimens in warp, weft, and bias of 3 cm by 10 cm to test accordingly bending, tensile, and shear with the same specimen. This process is described in 2.7.1, 2.7.2, and 2.7.3.

The output data and units are not yet investigated.

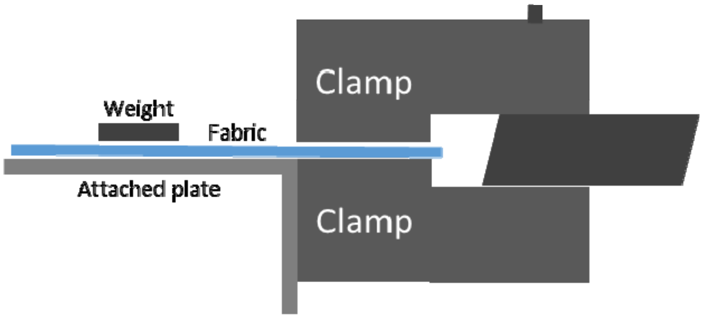
2.7.1. OPTITEX MARK 10 FRICTION

Friction is measured with the fabric specimen on a horizontal plate clamped between the grips and a weight is placed on top of it (Figure 15). After the specimen sizes are inserted in the program, the friction is measured and the coefficient of friction is calculated. This data is copied from the computer into an excel document to register the data.

This test is repeated two times. In the Optitex fabric testing guide [40] the measurement of friction is not included.

How the friction is exactly measured needs to be investigated further.

FIGURE 15: **OPTITEX MARK 10, ATTACHMENT CONFIGURATION FOR FRICTION MEASUREMENT**



2.7.2. OPTITEX MARK 10 BENDING

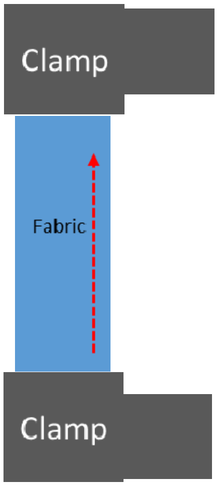
According to the user, significant differences are found when the same fabric is measured multiple times.

Recently, Optitex improved their bending method, the bending is now measured in the Optitex fabric testing guide [40] with the manual FST, as already described in 2.2, fabric stiffness and flexural rigidity is obtained based on five warp and five weft specimens. For this publication, this system is not reviewed in combination with the objectives of this study. The previous system Optitex used is discussed with a user. The previous used system was not found sufficient and we recommend updating to the system as described in the Optitex fabric testing guide [40].

2.7.3. OPTITEX MARK 10 TENSILE AND SHEAR

After the bending test, the device needs to be reconfigured to be used for the tensile and shear tests. The tensile measurement principle is illustrated in Figure 16. For the shear test, use the bias cut specimen of 3 cm by 10 cm. For the tensile, the warp and weft fabric specimen of 3 cm by 10 cm each are used The instrument is put to start position with a width of 6 cm between the clamps, the software is set at 20 mm per minute to slide the upper clamp upwards and stops when the maximum tension is reached. The force is measured and the measurement copied into the Excel data sheet. The shear is measured following the same procedure with the bias swatch and calculated from the bias extension. Due to the maximum reach, fabrics with a lot of stretch usually give error messages.

FIGURE 16: **OPTITEX MARK 10 TENSILE TESTING**



2.8. FABRIC TOUCH TESTER (FTT)

In 2013 the Fabric Touch Tester (FTT) was introduced, the instrument was developed by HKRITA research institution at the Hong Kong Polytechnic University and brought to the market by SD Atlas [44]. From one L-shaped fabric swatch the FTT measures hand values, aiming to be a simpler and cheaper alternative to KES-F [45]. The FTT characterization standard resulted in one instrument and one test method, returning 13 measured and calculated characteristic values. All the characteristic values are measured and calculated for warp and weft directions, as well as from face and back side within 5 minutes from one swatch. Due to the recent introduction the validation of the FTT is still very limited [46], [47].

As the FTT is designed for a haptic purpose, more investigation is needed to test suitability of the data for the simulation of cloth. Moreover, the obtained properties do not contain shear and tensile.

Measured and calculated characteristics consider the following:

- Bending: Bending Average rigidity (BAR); Bending Work (BW).
- Thermal conductivity: thermal conductivity under compression (TCC), thermal conductivity under recovery (TCR), thermal maximum flux (QMAX).
- Compression: compression work (CW), compression recovery rate (CRR), compression average rigidity (CAR), recovery average rigidity (RAR), thickness (T).
- Surface roughness: Surface roughness amplitude (SRA); Surface roughness wavelength (SRW).
- Surface friction: Surface friction coefficient (SFC).

Test specimen details are: 310 mm for the long sides and 110 mm for the short sides of the L, thickness max 5 mm. The details of the apparatus are: size of the test plate 120 mm × 120 mm, max pressure 70 g/cm^2, standard pressure 42 g/cm^2, test travel 0–50 mm [45].

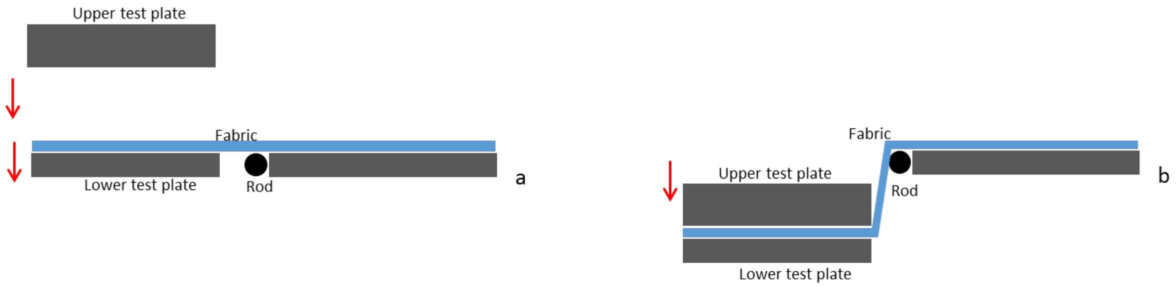
To obtain more reliable results, the recommendation is to test 10 specimens of the same fabric, as well as condition the samples under standard conditions of 20°C ± 2°C and relative humidity of 65% ± 2% for at least 24 hours prior testing [46].

2.8.1. FTT BENDING

The fabric is placed on the lower test plate, over the bending rods at the same level (Figure 17a). The lower test plate is pushed down (Figure 17b) and the sensors under the bending rods capture the bending forces, which are converted into a bending moment. The bending curve is plotted with the bending moment against the radian, representing the Bending Work (BW). The value at different angles is used to calculate Bending Average Rigidity (BAR). FTT uses a different approach to measure bending compared to the cantilever principle according BS 3356:1990. Direct comparison between the methods is not possible; nevertheless, a correlation is found between FTT bending measurements and data derived from the measurements obtained with the BS 3356:1990 method [46].

During the measurement of bending average rigidity (BAR) the force needed to bend per radian is obtained. Bending Work (BW) considers the work needed to bend the specimen.

FIGURE 17: SCHEMATIC DIAGRAM OF BENDING METHOD FTT



2.8.2. FTT COMPRESSION

The thickness parameter is measured when the fabric is pressed between the upper and lower test plate (Figure 17), the forces are controlled by the compression sensor, while the interval between the plates is captured with a laser distance sensor. The method is different and the force is higher compared to the ISO 5084: 1996 [48]. By comparing test results of both methods using 11 fabrics slight differences are observed, although the data shows a significant correlation. Musa, et al. [46] advises to follow the standard to test thickness.

2.8.3. FTT SURFACE ROUGHNESS AND FRICTION

The surface properties are measured in warp and weft through downwards and upwards movement of the test plates. Moreover, graphs presenting surface frictions and surface roughness are part of the data [49].

2.9. ZWICKROELL

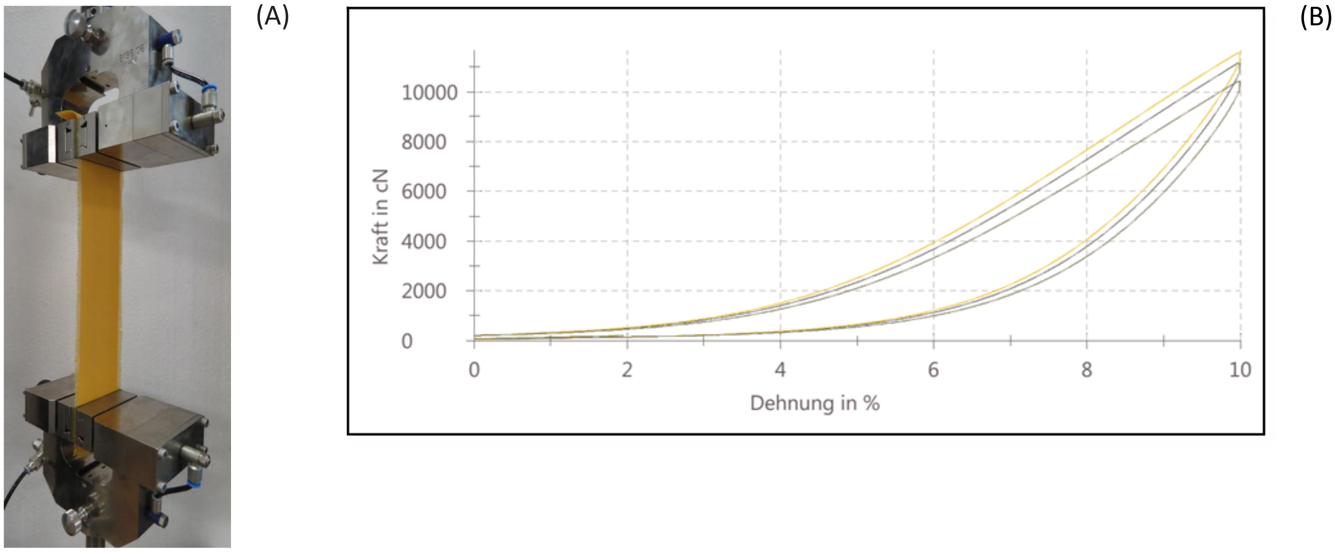
The company ZwickRoell [47] develops a broad variety of testing machines for very different materials of various industry branches from metal to wood or paper and textiles. ZwickRoell does not provide specific testing machines to obtain parameters for fabric simulations. The most suitable machine from the series *ZwickiLinie* has, thus, been chosen for this test series. Possible forces, distances, clamping length, and the speed correspond to what are needed for textile measurements. The main goal was to measure the fabrics in a way so that the single tests represent what actually happens during the wear of garments [4], [49]. The tensile, shear, bending, and friction properties have been measured.

The ZwickRoell machine is flexible and simply captures strain-stress relationships for materials. Measurements can be force-driven or distance-driven executed. ZwickRoell has a lot of standard measurements already integrated within their software.

2.9.1. TENSILE MEASUREMENT

The tensile measurement has been executed according to DIN 53835-13 [54]. The knits specimens were cut with 50 mm width, the woven fabrics with a 100 mm width. If necessary, larger clamps are available. The knits have been stretched 20%, woven fabrics 10%, and related forces has been recorded. Each measurement has been executed in 3 cycles to capture the hysteresis behavior of the material. The measurement speed was at 100 mm/min (Figure 18).

FIGURE 18: (A) CYCLIC TENSILE MEASUREMENT BY ZWICKROELL, (B) OBTAINED STRAIN-STRESS CURVES



2.9.2. SHEAR MEASUREMENT

For the shear measurement, the same principle as for the tensile measurement has been applied. However, the specimen have been cut in the bias direction of 45°.

2.9.3. BENDING MEASUREMENT

The bending measurement has been executed in the form of a 2-point bending test. From the general principle, it can be compared to the torque-curvature Kawabata measurement. The specimen size is 50 x 50 mm. The bending test has been executed similar to the DIN 53121 for paper. The bending has been executed to an angle of 90° (Figure 19). Several tests have been executed to choose this angle. These tests demonstrated that the force is again lower after 90°. Moreover, friction forces are becoming a larger influence when angles higher than 90° are driven. Various distances have been tested. The system delivers stress-strain profiles for each measurement. The bending stiffness has been derived from the strain-stress curve (Figure 20). This process can also be automated by the ZwickRoell software.

FIGURE 19: BENDING MEASUREMENT BY ZWICKROELL

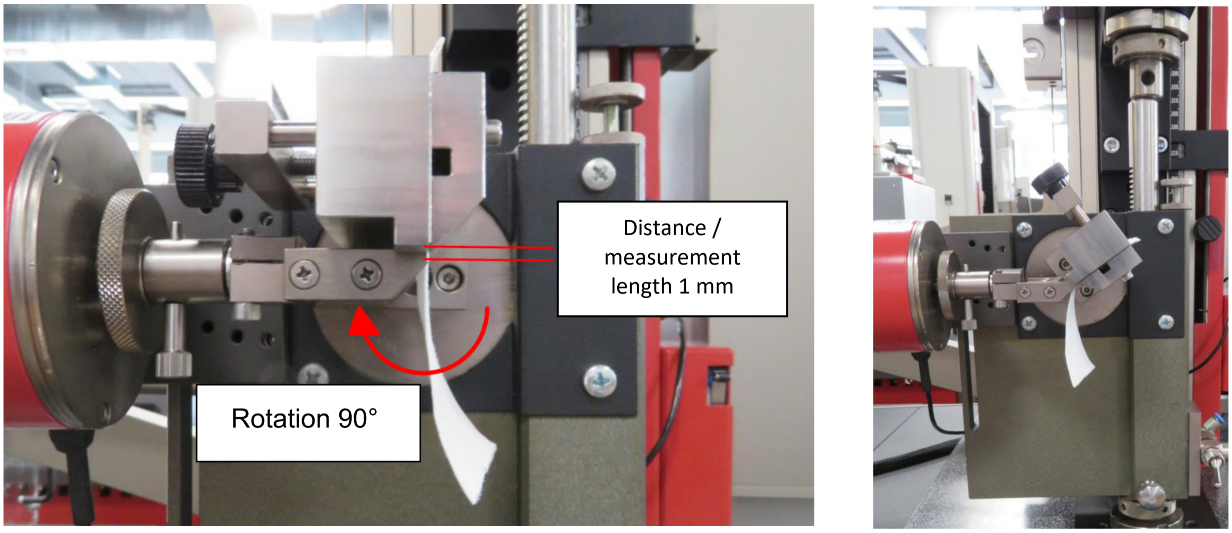
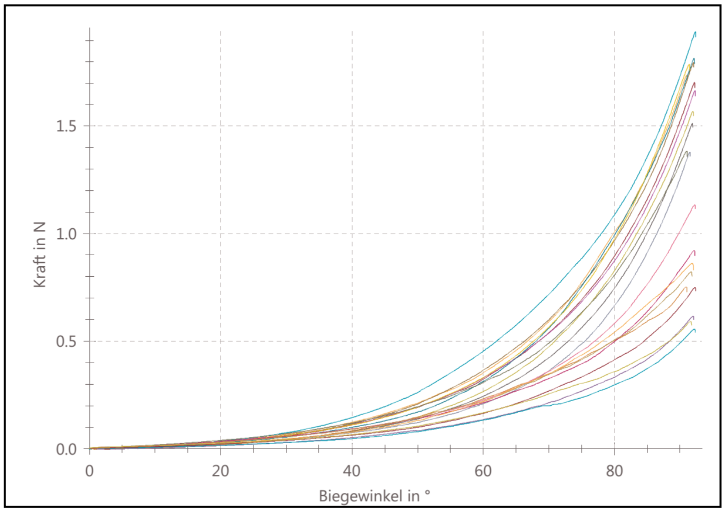


FIGURE 20: BENDING STRAIN-STRESS BEHAVIOR



2.9.4. FRICTION MEASUREMENT

For the friction measurement, an equipment for plastic sheet tests has been used. The used slide corresponds to ISO 8925 for plastic sheets. The slide has a weight of 212 g. The fabric has been tested against a piece of smooth leather that attempts to imitate human skin and to obtain a friction parameter for body-to-garment simulations. The same apparatus was used to test the friction of a fabric against a fabric (Figure 21, Figure 22).

The mean value of the friction is strongly influenced by the speed. Tests with various speeds have been executed in order to determine the differences. Test with slower speed (100 mm/min) are usually a little “bumpier” and unclean (stick-slip phenomenon). Especially for the tests “fabric to fabric” the slide moves disturbed on the material. This leads to stronger deflections in the curves and an unclear measurement. If a higher speed of about 500 mm/min is used, the received graphic curve is much smoother. Static and dynamic friction can easily be captured with this measurement (Figure 23).

FIGURE 21: LEFT AND RIGHT FRICTION MEASUREMENT, SLIDE MOVING OVER A FABRIC

FIGURE 22: A LOW TENSION HAS BEEN APPLIED TO AVOID BUCKLING DURING THE MEASUREMENT

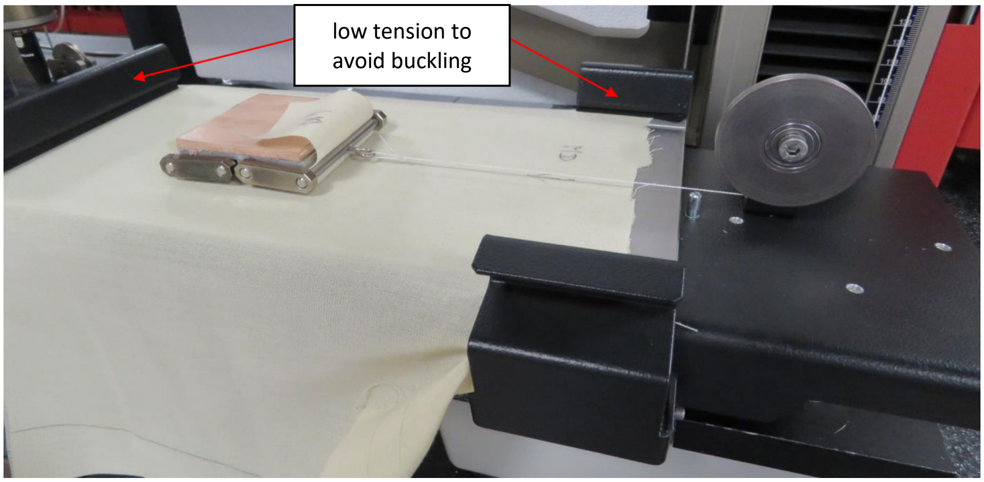
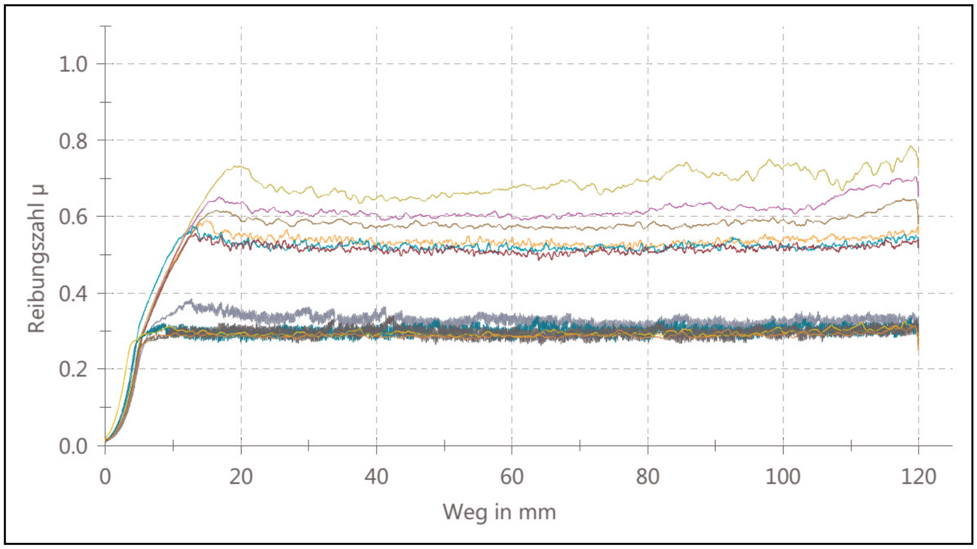


FIGURE 23: FRICTION MEASUREMENT PROFILES FOR ALL FABRICS AT TWO SPEEDS



2.10. MEASUREMENT PRINCIPLES SIMILARITIES AND DIFFERENCES

As described in 1.1, textiles are viscoelastic materials. They show characteristics of both fluids and solids and are not able to maintain a constant tension under a constant deformation. Tensions are gradually decreasing (relaxation). This effect is precisely the fabrics plasticity behavior. The fluid characteristic of textiles allows them to retain energy during stress. Upon the removal of the stress, deformations are only partly recovered (elastic recovery). This characteristic is defined as the fabric's viscosity behavior. Due to this behavior, the measurement speed influences the measurement result. Moreover, because of the viscosity behavior of textiles, a new fabric sample should be taken for each tensile test to obtain a correct measurement result. A second measurement with the same fabric sample would not be correct as the textile is partially expanded from the first measurement [4].

Because of the inherent variability of textile materials, it is strongly recommended to use at least three fabric specimens for each property to obtain an accurate measurement. Some fabrics are more stable; others have a high variability if multiple swatches of the same material are measured [19]. Moreover, the unavoidable human interference when touching the fabrics also influences the measurement.

Finally, since textiles are non-uniform materials, the swatch size and uniformity in this also plays a major role.

The tables in 2.10 illustrate the differences and/or similarities between the measurement principles for each property. The "v" in the cells indicates if the topic in the heading applies for the measurement system.

2.10.1 BENDING

TABLE 5: BENDING MEASUREMENT PRINCIPLES

	Cantilever principle	**Pure bending**	**Other**	**Digital data output and automated calculations**	**Digital charts and slopes**	**Verification or standard**
FST	v	…	…	NO	NO	BS 3356:1990 ASTM D1388 Din 53362
KES	…	v	…	v	v	Validated by WW research
FAST	v	…	…	v	NO	Validated by WW research, 41.5° corner
FAB	…	…	v	v	On request	NO
CLO Kit	v	…	…	NO	NO	NO
Optitex Mark10	v	…	…	unknown	unknown	NO
FTT	…	…	v	v	v	NO
ZwickRoell	…	v	…	v	v	DIN 53121
Comment—Bending is intricate to measure. The measurement is easily influenced by displacement of air and vibrations. The KES FB 2 is often placed on a stabilized table to avoid vibrations. We need to consider this when selecting instruments.						

2.10.2 TENSILE

TABLE 6: TENSILE MEASUREMENT

	Force driven	Length driven	Digital data output and automated calculations	Digital charts and measurement slopes	Verification or standard
KES	v	…	v	v	Validated by WW research
FAST	v	…	v	No	Validated by WW research
FAB	…	v	v	On request	NO
CLO Kit	…	v	NO	NO	NO
Optitex Mark10	…	v	v exported to excel	Depending on the Gauge	Unknown
FTT	…	…	…	…	…
ZwickRoell	…	v	v	v	DIN 53835-13 (3 repetitions)

Comment—Tensile measurement can be obtained from modern tensile strength testers used in the industry with motor controlled extension such as ZwickRoell, Mark10, Instron [52] or Titan (James Heal) [53]. The standard DIN 53835-13 [54] is very well suitable for the tensile measurement. It will, however, be important to extend this standard to a cyclic measurement to also capture the hysteresis behavior of fabrics. The suitability of the standards for tensile testing, as for example, ISO 13934-2:2014 [55] tensile properties of fabrics-part 2: determination of maximum force using the grab method or ISO 20932-1:2018 [56] for determination of the elasticity of fabrics, needs to be investigated for the purpose to retrieve simulation properties. Shear measurement discussed in the Section 2.7 could be included in this test. Moreover, it is possible to extend the testers to measure Bending and Friction as shown by ZwickRoell.

2.10.3 SHEAR

TABLE 7: SHEAR MEASUREMENT

	Shearing the specimen to 8°	Extension on the bias of the fabric (45°)	Force driven	Length driven	Verification or standard
KES	v	…	…	v	Validated by WW research
FAST	…	v	v	…	Validated by WW research
FAB	…	v	v	…	No
CLO Kit	…	v	v	…	No
Optitex Mark10	…	v	v	…	Unknown
FTT	—	—	—	-	n/a
ZwickRoell	…	v	…	v	DIN 53835-13 (3 repetitions)

Comment—The shear derived from the bias extension of the fabric (45°) according the same principle as the tensile test, see comment at tensile measurement Table 6, corresponds to how this parameter is integrated in most state of the art simulation systems.

2.10.4 FRICTION

TABLE 8: FRICTION MEASUREMENT

	Metal loop (KES) or metal plate (Mark 10, FTT) moving over the fabric	Slide covered with fabric or leather (skin) moving over fabric	Dynamic and static friction is measured	Digital charts and slopes	Verification or standard
KES	v	…	v	v	Validated by WW research
FAST	…	…	…	…	…
FAB	…	…	…	…	…
CLO Kit	…	…	…	…	…
Optitex Mark10	v	…	Unknown	Unknown	Unknown
FTT	v	…	v	v	…
ZwickRoell	…	v	v	v	ISO 8925
Comment—In the case of virtual garment simulations friction is the resistance that a garment encounters when moving over the body or against another fabric, for example under the arm. The friction coefficient for fabrics is particularly difficult to define, as a fabric does not possess the same friction characteristic on both sides of the fabric, neither in warp and weft direction. Moreover, it highly depends against what other material a fabric is rubbed, for example skin or leather. The friction coefficient of the skin changes greatly with the moisture content of the skin. Metal possesses a much lower friction coefficient as for example skin or fabric and is therefore not suitable. Differentiations are made between static and dynamic friction. Static friction is the initial force at which a fabric begins to glide over a surface. Dynamic friction occurs when two objects are moving relative to each other during sliding. For most materials, static friction is higher than dynamic friction [4].					

3

SWOT ANALYSIS OF THE MEASUREMENT TECHNOLOGIES

3.1 INTRODUCTION TO THE SWOT ANALYSIS

The analysis are based on the review and in some cases observations during tests with the instruments. The purpose is to give an overview and insight into the differences, as well as the similarities between the methods used to obtain bending, shear, tensile and friction properties.

3.2 SWOT BENDING PROPERTIES ACCORDING STANDARD CANTILEVER METHOD

Strong	— Simple; — Cheap as no expensive force sensor is required; — Standardized measurement (BS, ASTM, DIN, ERT).
Weak	— Not automated, due to this prone to manual error; — Not suitable for very limb or stiff fabrics; — Jersey fabrics tend to curl up at the edges; — Limited test, e.g. only bending; — Very small swatch size.
Opportunity	— Standardized technology suitable to verify other technologies.
Threat	— Size of the swatch may result in incomparable data.
BS 3356:1990 [22] is reviewed based on secondary publications. ASTM D1388-96 (2002) [30] is not reviewed. It needs to be investigated if suitable automated versions are available. Recommendation based on the review: If this instrument needs to be considered in-depth review and testing will be required.	

3.3 SWOT KAWABATA EVALUATION SYSTEM—KES

<table>
<tr><td>Strong</td><td>— Validated by worldwide research;
— Automated system;
— Still available with updated automated versions;
— Measures bending, shear, tensile, friction and compression;
— Graphs with full curves representing the raw measured data;
— Nonlinear shear and tensile measurement: including recovery data;
— Pure bending and hysteresis data;
— Suitable to simulate fabric drape, with r = 0.97, p<0.0001.</td></tr>
<tr><td>Weak</td><td>— Hysteresis behavior of fabrics is not captured;
— The shear measurement does not correspond to how this fabric property is modeled in state of the art simulation systems;
— Metal wire is not suited for friction measurements;
— Higher price range;
— Not developed to retrieve fabric simulation properties;
— Values are not presented in SI units.</td></tr>
<tr><td>Opportunity</td><td>— Haptic data.</td></tr>
<tr><td>Threat</td><td>— Availability of skilled operators;
— Intricacy of the instrument.</td></tr>
<tr><td colspan="2">The KES system is still under development by KatoTech and is used for haptic data by fabric and textile industries, automotive, cosmetics, food, medical, and pharmaceutical to name a few [57].

<u>Recommendation based on the review</u>:
A sophisticated system, with opportunities in the connection with haptic data. The measurement principles of the tensile, shear, and friction properties are suitable to represent fabric drape; however, to represent the behavior during wearing, the suitability needs to be further investigated. Due to its price and dedicated handling not easy to apply on large scale in the fashion industry.</td></tr>
</table>

3.4. SWOT FABRIC ASSURANCE BY SIMPLE TESTING—FAST

Strong	— Validated by research worldwide; — Automated system; — Lower price; — Robust and easy in use; — Measures bending, shear, tensile and compression; — Suitable to simulate fabric drape, with $r = 0.97$, $p<0.0001$; — Method fabric performance data for cutting and sewing is provided as clear part of the output data.
Weak	— Tensile: test with three loads provides too little information about a fabrics tensile behavior — Tensile: Maximum elongation of 21%; — Tensile: it is a force driven measurement that suits to woven fabrics. The applied force is much too low for knits as it does not represent what happens during wearing of garments; — Friction is not measured; — Bending: Limitations for extremely limp and stiff material as well as with material which tends to curl up; — Values are not presented in SI units.
Opportunity	— Fabric performance data for cutting and sewing is provided as clear part of the output data.
Threat	— Not further in development.
Although no further development is taking place, the software undergoes updates to newer Windows® versions. <u>Recommendation based on the review:</u> Validated by multiple research, automated system easy in use and robust. The limitations for the tensile property makes the use limited. Lack of friction test needs to be resolved by additional tests.	

3.5 SWOT FABRIC ANALYSER BY BROWZWEAR (FAB)

Strong	— One instrument to measure bending, shear and tensile; — Developed with the objective to retrieve simulation properties; — Mass, thickness, bend, stretch, linearity and shear are measured; — Automatically creates the virtual fabric parameter; — Graphs with full curves representing the raw measured data; — Clear instruction video and manuals.
Weak	— Friction and compression are not measured; — Placement of the swatches; — Screws for clamps cause errors, sensibility is unclear; — Green control area for correct placement of the swatch is very sensitive, unclear and manually easily influenced; — Rolled up swatch might influence the bending output; — Manual interference with pen is required to achieve the bending direction, this might influence the stability in the fabric; — Testing sequence of the properties might be prone to error; — Bending data might be influenced by vibrations of the instrument and/or in the surrounding; — Not a clear testing protocol; — Average results are presented; — Not yet validated; — Retrieving the raw measured data is not user friendly; — Values are not presented in SI units.
Opportunity	— Further development of the system.
Threat	— Instability of the instrument; — Conflict of interest due to development of this mechanical physical measurement instrument by a software developer; — Not a uniform system; — Simplicity might get lost during improvements.

Recommendation based on the review:
The concept of one instrument to measure and calculate automatized the required properties is attractive; nevertheless, friction and compression are not measured;
In depth investigation of the variance between the output data is required;
In depth validation of the output data is required;
Transparency regarding the used measurement methods is required;
Independency and transparency must be safeguarded;
Accuracy of the measurement technology must be safeguarded;
Improvement for the testing sequence: start with bending or use a new swatch for bending.
Use at least three fabric specimens to repeat each test;
The use of SI units would make the data better comparable.

3.6 SWOT CLO FABRIC KIT 2.0

Strong	— Clear instruction video regarding testing with the KIT.
Weak	— Not automated, due to this prone to manual error, in 4 phases of the process (interpretation, reading, writing and inserting in the emulator); — Measurements might be influenced by (in)stability of the instrument and/or vibrations in the surrounding; — Bending: not suitable for very limb or stiff fabrics; — Bending: Jersey fabrics tend to curl up at the edges. The solution with reverse testing might influence the bending properties; — No average results are used; — Only one swatch is tested per weave direction; — Handling of the swatches during the weight and thickness measurement; — Bending is related to the cantilever principle; however, not according the standard; — Bending differences between face up and down are not taken in consideration; — Price in relation to the results.
Opportunity	— Easily comprehensible instruction video also gives non-expert users a quick idea about fabric measurements. However, this could misled non-expert users to interpret the measurements as precise enough for all uses. Further development is required.
Threat	— What is the impact of the rolling system on the fabrics measurements, compared to the sliding system with the cantilever? — Conflict of interest due to development of this mechanical physical measurement instrument by a software developer.
Recommendation based on the review: Not validated. Not automated, its instability and manual interference makes it prone to error; also, the deviation from the standards makes it less suitable for use in a professional situation.	

3.7 SWOT OPTITEX MARK 10

Mark 10 is only reviewed and discussed with a user, not tested by the authors of this report.

Strong	— Tensile measurement (comparable to ZwickRoell) is done with a regular and objective instrument already available in the industry; — Tensile measurement is motor controlled; — Supplier of the Mark 10 has a transparent website with prices.
Weak	— The protocol for the tensile measurement should be changed to a cyclic measurement to capture the fabric hysteresis behavior; — Bending measurement is prone to error due to the manual interference and not following a standard; — Manual inserting of the measurements. (Discrepancy between what Optitex states in 2013 regarding the automated input in the simulation software and the procedure obtained from the user during the interview.)
Opportunity	— Customization options of the device to measure other properties; — Company website of Mark 10 shows they are familiar with standards.
Threat	— Friction measurement might be less accurate compared to the method observed at ZwickRoell, or the principle offered by Mark 10 on their website. — Conflict of interest due to development of this mechanical physical measurement instrument by a software developer.
Recommendation based on the review: The first impression of the company and base instrument gives a positive feel. From the website and images, the instrument gives a robust and solid appearance.	
Limitation of this review: We have not observed and tested the instrument. To achieve an in-depth overview additional tests need to be done and the measured and calculated characteristic values need to be reviewed.	

3.8 SWOT FABRIC TOUCH TESTER

FTT is only reviewed, not tested by the authors of this report.

<table>
<tr><td>Strong</td><td>— Although not directly comparable, the FTT bending measurements show correlation with the cantilever method;
— Use of today’s technical technology;
— Automated measurement;
— The principle of 1 swatch to measures all properties simultaneously in short time;
— Measured area with a width of 11 cm;
— Bending and surface properties are measured;
— The bending curve of BW gives additional information;
— Graphs with full curves representing the measured data.</td></tr>
<tr><td>Weak</td><td>— Not developed to retrieve fabric simulation properties;
— Not clear if the bending measurements are useable to simulate fabric;
— Shear and tensile are not measured;
— Due to recent introduction limited validation available;
— 10 tests per fabric requires 10 swatches;
— Thickness is less accurate than ISO 5084: 1996 [48].</td></tr>
<tr><td>Opportunity</td><td>— Through the way bending is measured and captured, more information might be obtained for simulation;
— Properties for physical touch (haptic and moisture) are obtained, if these properties need to be tested, it could be an interesting combination with a tensile tester.
— No conflict of interest as the company does not provide software.</td></tr>
<tr><td>Threat</td><td>— Suitability of the measured properties.</td></tr>
<tr><td colspan="2">Recommendation based on the review:
The concept of 1 instrument to measure and calculate automatized multiple properties from 1 swatch is attractive. Nevertheless, tensile and shear are not measured and need to be obtained with a tensile tester. Suitability of the retrieved fabric properties required for cloth simulation needs to be tested and discussed with the software suppliers.
If bending and surface properties are suitable for garment simulation, a tensile tester in combination with the FTT might be interesting for companies who need also the properties for physical touch.</td></tr>
<tr><td colspan="2">Limitation of this review:
We have not observed and tested the instrument. To achieve an in-depth overview additional tests need to be done and the measured and calculated characteristic values need to be reviewed.</td></tr>
</table>

3.9 SWOT ZWICKROELL

Strong	— The measurements device is highly flexible and can be adjusted according to various user needs; — The device includes a software package that allows an individual processing of the available measured raw data; — A lot of standard measurement protocols are integrated within the measurement software; — Units can be chosen and directly be converted if necessary; — The machine and software and principle is developed by them. Various existing measurement standards for a broad variety of materials are available.
Weak	— The device needs an introduction for an optimal usage; — Mid-price range.
Opportunity	— The machines are used in various industry branches and this experience could help advance the standardization process for textile measurements for virtual garment simulations; — No conflict of interest as the company does not provide software.
Threat	— Software provider would have to work with the measurement company on the automatic processing of the raw data and maybe share confidential knowledge.
Recommendation based on the review: ZwickRoell is a flexible system that could help with its large experience from other branches to advance the development of standards for fabric measurements for virtual garment simulations.	

4

CONCLUSION AND FUTURE WORK

Some 3D software developers use currently available measurement technologies to obtain the physical and mechanical properties, required to simulate a garment. Others develop their own instruments, in both cases with the purpose to facilitate the user’s needs to digitalize the mechanical and physical behavior of their own material. The latter is a key requirement to enable true virtual fitting, based on the measured properties. The cloth should be simulated exactly as it is, not more appealing, but representing the shortcomings of the material as well as the faults in the pattern in an accurate way.

In general, the same properties are measured in most of the cases according to a similar principle with slight differences, often not following already existing standards for the methods used. Testing protocols are unclear and tests are done under random conditions: swatch sizes differ and palliative measures are taken to retrieve the properties. In some cases, only one fabric specimen is tested. Calculation and output data is in most cases not transparent. It is unclear how the inaccuracies are corrected in the software, or to what extend the software is able to use the refinement and interaction between the properties.

Bending measurement is executed according different principles, such as the cantilever principle (FAST, O-Mark 10 and CFK2.0) or cyclic bending (KES and ZwickRoell). While the cantilever principle is closely related to the hang or fabric drape of a garment, other bending tests represents the pure bending curve. It will be important to investigate more in-depth if the cheaper cantilever is accurate enough or if the more expensive pure bending tests are better suitable for garment simulations.

Tensile properties are measured by applying forces (FAST) or motor controlled length extensions (KES, ZwickRoell, Optitex, etc.) in multiple cycles (ZwickRoell) with a tensile tester. The instruments can be customized to the purpose we need for simulation.

In most cases the shear is derived from the bias extension according the same principle as the tensile test, what corresponds to how this parameter is integrated in most state-of-the-art simulation systems.

Measurement principles have always been developed and optimized and finally been standardized for a certain purpose. Kawabata and FAST principles have been optimized to imitate the subjective hand evaluation, manipulating a fabric in the hand. Measurements for virtual garments simulations, however, have to imitate something different, namely what happens to a fabric during the wear of garments. Discussions about a future standard should keep this basic and main requirement in mind. Improvement for the very short time could be the following:

- Do all test under standard atmospheres for condition and testing, for example ISO 139:2005 (en)
- Follow a standard procedure to measure weight—this includes using a scientific scale.
- Follow the standard procedure, for example BS 3356:1990 [22], ASTM D1388-96 (2002) [30], if a cantilever principle is used to test bending. For example in the case of CLO and in some cases Optitex.
- Build on the standard procedure to test tensile, such as ISO 13934-2:2014 [55], or ISO 20932-1:2018 [56], or DIN 53835-13 [54] with universal strength test devices used in the industry, such as: ZwickRoell, Mark10, Instron, Titan, etc. The standard usually aims at testing the strength until it tears, the required speed and swatch width to measure elongation and force needs to be defined.

- Build on a standard to measure thickness, such as for example compression/thickness from ISO 5084: 1996 [48].
- Use/build on a standard procedure to test friction, for example ASTM D1894 [58] and ISO 8295 [59].
- Investigate how testing aiming at material simulation is executed in other industries.
- Increase comparability with the International System of Units (SI Units) for the output data.
- Create awareness: fabric testing is time and cost intensive and requires dedication and accuracy!
- Continue to work on the standardization process, namely work on the establishment of a suitable national committee that could bring this process to an international level. Prior to this, create a mutual agreement for testing the fabric properties.

To improve the physical and mechanical measurement of the properties required for garment simulation, the next step to be taken is a transparent discussion with the software suppliers, and for this we would like to refer to the last part of the introduction.

5

CITATIONS

[1] Product Innovation Apparel Milan 11 and 12 October 2018. [Online]. Available: http://events.pi.tv/2018/apparel_eu/ (Accessed 1 October 2018).

[2] Product Innovation Apparel 26 and 27 October Berlin 2017, [Online]. Available: http://events.pi.tv/2017/apparel_berlin/programme (Accessed 5 October 2017).

[3] A. Berg, M. Heyn, E. Hunter, F. Rölkens, P. Simon, and H. Yankelevich, "Measuring the fashion world," *McKinsey & Company*, 2018, [Online]. Available at: https://www.mckinsey.com/industries/retail/our-insights/measuring-the-fashion-world (Accessed 5 May 2019).

[4] C. Luible, "Study of mechanical properties in the simulation of 3D garments," These no. 678, University of Geneva, September 2008.

[5] D. Terzopoulos, J. Platt, and A. Barr, "Elastically Deformable Models," *Computer & Graphics,* Elsevier, Volume 21, Nr.4, 1987.

[6] B. Lafleur, N. Magnenat-Thalmann, and D. Thalmann, "Cloth Animation with Self-Collision Detection," *IBIP conference on Modelling in Computer Graphics proceedings*, Springer-Verlag, 1991.

[7] B.J. Collier, 'Measurement of fabric drape and its relation to fabric mechanical properties and subjective evaluation', Clothing and Textiles Research Journal, 10: 46, pp. 46–52, 1991. [Online]. DOI: 10.1177/0887302X9101000107.

[8] Y. Yang, and N. Magnenat-Thalmann, "Techniques for Cloth Animation, New trends in Animation and Visualization," book published by John Wiley & Sons Ltd, ISBN 0-471-93020 2, 1991, pp. 242–256.

[9] M. Carignan, Y. Yang, N. Magnenat-Thalmann, and D. Thalmann, "Dressing Animated Synthetic Actors with Complex Deformable Clothes," Computer Graphics (Siggraph`92 proceedings), AddisonWesley, 26(2), 1992.

[10] D. Baraff, and A. Witkin, "Large Steps in Cloth Simulation," Computer Graphics (SIGGRAPH`98 proceedings), Addison-Wesley, 32, pp. 106−117, 1998.

[11] P. Volino, and N. Magnenat-Thalmann, "Virtual Clothing," Springer, ISBN 3-540-67600-7, 2000.

[12] J. Metzger, S. Kimmerle, and O. Etzmuss, "Hierarchical Techniques in Collision Detection for Cloth Animation," Journal of WSCG, digital library, Volume 11, No. 1, ISSN 1213-6972, 2003.

[13] K. Keckeisen, M. Feurer, and M. Wacker, "Tailor Tools for Interactive Design of Clothing in Virtual Environments," Proceedings of ACM VRST, 2004, pp.182−185.

[14] P. Volino, and N. Magnenat-Thalmann, "Accurate Garment Prototyping and Simulation," Computer-Aided Design & Applications, CAD Solutions, Vol. 2, No. 1-4, 2005, pp. 645−654.

[15] P. Volino, and N. Magnenat-Thalmann, "Simple Linear Bending Stiffness in Particle Systems," SIGGRAPH-Eurographics Symposium on Computer Animation 2006 proceeding, 2006, pp. 101−105.

[16] A. Sahoo, D. sluiter, S. Gagnon, A.A.M. Kuijpers, and C. Luible, Driving the Uniformity of Material Measurements for Accurate Virtual Simulation, Product Innovation Apparel 26 and 27 October Berlin 2017, [Online]. Available: http://events.pi.tv/2017/apparel_berlin/programme (Accessed 5 October 2017).

[17] C.E. Cusick, "A Study of fabric drape," PhD thesis, University of Manchester, 1962, p.p.16, 106-109.

[18] Y.J. Jeong, and D.G. Phillips, “A study of fabric-drape behaviour with image analysis, Part II: The effects of fabric structure and mechanical properties on fabric drape,” Journal of the Textile Institute, 89:1, pp. 70−79, 1998, [Online]. DOI: 10.1080/00405009808658598 (Accessed: 20 September 2013).

[19] A.A.M. Kuijpers, “Evaluation of Physical and Virtual Fabric Drape Based on Objective Fabric Properties,” MPhil thesis University of Manchester, [Online]. https://www.research.manchester.ac.uk/portal/en/theses/evaluation-of-physical-and-virtual-fabric-drape-created-from-objective-fabric-properties(502d8339-ebf8-4b0b-9a9b-ccc30a007a8a).html, 2017, p.109, p. 127, pp.99−101.

[20] F.T. Peirce, “The ‘handle' of cloth as a measurable quantity,” Journal of the Textile Institute, 21:9, 1930, pp. 377-416, [Online]. DOI: 10.1080/19447023008661529 (Accessed 20 September 2013).

[21] F.T. Peirce, “The geometry of cloth structure,” Journal of the Textile Institute, 28:3, 1937, pp. 45−96, [Online]. DOI: 10.1080/19447023708658809 (Accessed 20 September 2013).

[22] BS 3356:1990, Method for determination of bending length and flexural rigidity of fabrics. British Standards Institution, 31 August 1990.

[23] J. Hu, *Structure and mechanics of woven fabrics*. Cambridge England: Woodhead publishing limited, 2004, p.21.

[24] C.E. Cusick, “A Study of fabric drape,” PhD thesis, University of Manchester, 1962.

[25] J. Fan, W. Yu, L. Hunter, “Clothing appearance and fit: Science and technology,” Woodhead publishing in textiles, ISBN 1 85573 745 0, 2004, pp. 90−95.

[26] R. Postle, “Objective evaluation of the mechanical properties and performance of fabrics and clothing,” in Objective evaluation of apparel fabrics, Proceedings 2nd Australian-Japan Symposium, Melbourne, 1983, The Textile Machinery Society of Japan, J-stage, Osaka, 1983.

[27] Y. Li, “The Science of Clothing Comfort,” Journal of the Textile Institute, Taylor & Francis, Textile Progress, Vol. 31, 1940, No.1/2.

[28] S. Kawabata, “The standardization and analysis of hand evaluation” (2nd Edition). The hand evaluation and standardization committee, Textile Machinery Society of Japan, Osaka, 1980.

[29] D.E. Breen, D.H. House, and M.J. Wozny, “A particle based model for simulating the draping behaviour of woven cloth,” Textile Research Journal, 64:633, pp. 633-685, 1994, [Online]. DOI: DOI: 10.1177/004051759406401106 (Accessed: 22 August 2014).

[30] ASTM D1388-96 (2002), Standard Test Method for Stiffness of Fabrics, [Online]. https://www.astm.org/DATABASE.CART/HISTORICAL/D1388-96R02.htm

[31] A. De Boos, and D. Tester, “FAST—Fabric Assurance by Simple Testing,” Textile and Fiber Technology, Report No. WT92.02, ISBN 0 643 06025 1, 1994.

[32] P.G. Minazio, “FAST—Fabric Assurance by Simple Testing,” International Journal of Clothing Science and Technology, Emerald, Vol. 7, No. 2/3, 1995.

[33] Browzwear, “See your fabrics in true-to-life 3D with Browzwear’s new Fabric Analyzer,” News, 2017, [Online]. https://browzwear.com/see-fabrics-true-life-3d-browzwears-new-fabric-analyzer/ (Accessed: 7 September 2018).

[34] Browzwear, “Automatic fabric properties analysis,” 2018, [Online]. https://browzwear.com/products/fabric-analyzer/ (Accessed: 7 September 2018).

[35] Browzwear, Fabric Analyzer, 2019, [Online]. https://support.browzwear.com/Fabric%20Analyzer/fabric-analyzer.htm (Accessed: 21 August 2019).

[36] Browzwear, Thickness Test, 2019, [Online]. https://support.browzwear.com/Fabric%20Analyzer/thickness.htm (Accessed: 28 October 2019).

[37] Browzwear, Using the FAB, 2019, [Online]. https://support.browzwear.com/Fabric%20Analyzer/using-fab.htm (Accessed: 28 October 2019).

[38] Browzwear,Fabric Analyzer Videos, 2019, [Online]. https://support.browzwear.com/Fabric%20Analyzer/videos.htm (Accessed: 28 October 2019).

[39] CLO3D, CLO Fabric Kit 2.0, 2018, [Online]. https://www.youtube.com/watch?v=HA7HoK6_4Fk (Accessed: 7 September 2018).

[40] Optitex Help Center, Optitex Fabric Testing, Fabric Testing User Guide [Online], http://help.optitex.com/#t=Utilities_NEW%2FFabric_Testing_Unit.htm&rhsearch=fabric&rhhlterm=fabric&rhsyns=%20 (Accessed: 8 December 2019).

[41] ESM303 Motorized Tension / Compression Test Stand, 2019, [Online]. http://www.mark-10.com/instruments/stands/esm303.html (Accessed 1 October 2019).

[42] Mark 10, Coefficient of friction fixture, 2018, [Online]. http://www.mark-10.com/pdf/DataSheetGrips.pdf (Accessed 1 October 2018).

[43] ASTM D1777-96, Standard Test Method for Thickness of Textile Materials, [Online] https://www.astm.org/Standards/D1777.htm.

[44] HKRITA, "Commercialisation news," 2018, [Online]. Available at: http://www.hkrita.com/en-us/commercializationNews/index (accessed 25 August 2018).

[45] SDL Atlas, FTT: Fabric Touch Tester, 2018, [Online]. Available at: https://sdlatlas.com/products/ftt-fabric-touch-tester#product-details (accessed 25 August 2018).

[46] A.B.H. Musa, B. Malengier, S. Vasile, L.V. Langenhove, and A.D. Raeve, "Analysis and comparison of thickness and bending measurements from fabric Touch tester (FTT) and standard methods," *Autex research journal,* 18:1, pp 51-60, 2018, [Online]. DOI: https://doi.org/10.1515/aut-2017-0011 (Accessed 27 August 2018).

[47] A.B.H. Musa, B. Malengier, S. Vasile, and L.V. Langenhove , "Practical Considerations of the FTT Device for Fabric Comfort Evaluation, Journal of Fashion Technology & Textile Engineering, S4:003, 2018, [Online]. doi:10.4172/2329-9568.S4-003, https://www.scitechnol.com/peer-review/practical-considerations-of-the-ftt-device-for-fabric-comfort-evaluation-Pqo7.php?article_id=7194, (Accessed 27 August 2018).

[48] ISO 5084:1996, Textiles—Determination of thickness of textiles and textile products. [Online] https://www.iso.org/standard/23348.html.

[49] SDL Atlas, "FTT®: Fabric Touch Tester," 2019, [Online]. https://sdlatlas.com/products/ftt-fabric-touch-tester#product-details (Accesses 15-9-2019).

[50] ZwickRoell, 2018, [Online] https://www.zwickroell.com

[51] C. Luible, C. Charbonnier, "Fashioning Movement, proceedings of the Symposium Fashion Responsive," 2016, SDN network.

[52] Instron, 2018, [Online], https://www.instron.co.uk/

[53] James Heal, 2018, [Online], https://www.james-heal.co.uk/

[54] DIN 53835-13:1983-11, Testing of textiles; determination of the elastic behaviour of textile fabrics by a single application of tensile load between constant extension limits, [Online]. https://www.beuth.de/en/standard/din-53835-13/1071078

[55] ISO 13934-2:2014 Textiles—Tensile properties of fabrics—Part 2: Determination of maximum force using the grab method, [Online]. https://www.iso.org/standard/60677.html (Accessed: 30 August 2019).

[56] ISO 20932-1:2018 Textiles—Determination of the elasticity of fabrics—Part 1: Strip tests, [Online].

https://www.iso.org/standard/69489.html (Accessed: 30 August 2019).

[57] KatoTech, Search by industry, 2018, [Online]. http://english.keskato.co.jp/products/industry.html#panel01 (Accessed: 27 September 2018).

[58] ASTM D1894-14, Standard Test Method for Static and Kinetic Coefficients of Friction of Plastic Film and Sheeting. [Online] https://www.astm.org/Standards/D1894.htm.

[59]ISO 8295:1995, Plastics—Film and sheeting—Determination of the coefficients of friction. [Online] https://www.iso.org/standard/20760.html.

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